Traffic Demand-based Grouping for Fairness among the RAW Groups of Heterogeneous Stations in IEEE 802.11ah IoT Networks

A Thesis submitted to the
Department of Electronics and Communication Engineering, in partial fulfillment of the requirements for the degree of Master of Science (Engineering) in Electronics and Communication Engineering

By

Most. Anju Ara Hasi
Student ID: 1905484

Supervised by

Md. Abubakar Siddik
Assistant Professor, Dept. of ECE

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
FACULTY OF POST GRADUATE STUDIES
HAJEE MOHAMMAD DANESH SCIENCE AND TECHNOLOGY UNIVERSITY

The thesis titled "**Traffic Demand-based Grouping for Fairness among the RAW Groups of Heterogeneous Stations in IEEE 802.11ah IoT Networks**" submitted by Most. Anju Ara Hasi, Roll No. 1905484 and Session January-June' 2022, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science (Engineering) in Electronics and Communication Engineering, abbreviated as M. Sc. (Engineering) in ECE.

BOARD OF THESIS EVALUATION

1. **Md. Abubakar Siddik** — **Supervisor**
   Assistant Professor
   Department of ECE, HSTU, Dinajpur.

2. **Dr. Md. Dulal Haque** — **Co-supervisor**
   Associate Professor
   Department of ECE, HSTU, Dinajpur.

3. **Dr. Nasrin Sultana** — **Examiner (Internal)**
   Associate Professor
   Department of ECE, HSTU, Dinajpur.

4. **Dr. Mostofa Kamal Nasir** — **Examiner (External)**
   Professor
   Department of CSE, MBSTU, Tangail.

BOARD OF THESIS DEFENSE

1. **Dr. Md. Mahabub Hossain** — **Member (Chairman)**
   Professor
   Department of ECE, HSTU, Dinajpur.

2. **Md. Mehedi Islam** — **Member (Internal)**
   Professor
   Department of ECE, HSTU, Dinajpur.

3. **Dr. Nasrin Sultana** — **Member (Internal)**
   Associate Professor
   Department of ECE, HSTU, Dinajpur.

4. **Dr. Md. Maniruzzaman** — **Member (External)**
   Professor
   Department of ECE, Khulna University, Khulna.

Declaration

This is to certify that the work presented in this thesis entitled, "**Traffic Demand-based Grouping for Fairness among the RAW Groups of Heterogeneous Stations in IEEE 802.11ah IoT Networks**", is the outcome of the research carried out by Most. Anju Ara Hasi under the supervision of Md. Abubakar Siddik, Department of Electronics and Communication Engineering, Hajee Mohammad Danesh Science and Technology University Dinajpur-5200, Bangladesh.

It is hereby declared that this thesis and any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Candidate

Most. Anju Ara Hasi
Student ID: 1905484
Dept. of ECE, HSTU

Dedication

THIS THESIS IS DEDICATED

TO

MY PARENTS AND FRIENDS

Contents

List of Tables

List of Figures

List of Abbreviations

AID	Association Identifier
AIFS	Arbitration Inter Frame Space
AIFSN	Arbitration Inter Frame Space Number
AP	Access Point
BSS	Basic Service Set
CAC	Centralized Authentication Control
CCA	Clear Channel Assessment
CFP	Contention Free Periods
CP	Contention Period
CSB	Cross Slot Boundary
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
CW	Contention Window
2-D	2- Dimentional
DAC	Distributed Authentication Control
DCF	Distribution Co-ordination Function
DIFS	Distributed Inter-Frame Space
DTIM	Delivery Traffic Indication Map
EDCA	Enhanced Distribution Channel Access
GI	Guard Interval
HCCA	Hybrid Controlled Channel Access
HCF	Hybrid Co-ordination Function
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineering
IoT	Internet of Things
LPWAN	Low - Power Wide Area Network
MAC	Medium Access Control
MCS	Modulation and Coding Schemes
MIMO	Multiple Input Multiple Output

MoROA	Model-Based RAW Optimization Algorithm
NSS	Number of Spatial Streams
OFDM	Orthogonal Frequency Division Multiplexing
PCF	Point Coordination Function
PHY	Physical Layer
QoS	Quality of Services
RAW	Restricted Access Window
RPS	RAW Parameters Set
S1G	Sub 1 GigaHertz
SID	Short Identifier
SIFS	Short Inter Frame Space
SP	Service Point
STA	Station
TIM	Traffic Indication Map
TWT	Target Wake-up Time
Wi-Fi	Wireless Fidelity
WPAN	Wireless Personal Area Network

List of symbols

$P_{i,j,k}$	Stationary probability distribution of i category STA, j backoff stage and k backoff counter value
$P_{i,coll}$	Collision probability of i category STA
$P_{i,idle}$	Channel idle probability of i category STA
$P_{i,succ}$	Successful transmission probability of i category STA
P_{succ}	Successful transmission probability of all category STAs
P_{busy}	Channel busy probability
$P_{i,empty}$	Stationary probability of empty state
$P_{i,cont}$	Contention probability of i category STAs
$P_{i,lock}$	Probability that the current CSMA slot is not enough for transmitting a frame
P_{last}	Probability that the current CSMA slot is the last slot
$m + x$	Maximum re-transmission limit
ρ_i	Packet arrival probability in saturated state
q_i	Packet arrival probability in non-saturated state
W_j	Contention window size of j backoff stage
CW_{max}	Maximum contention window size
CW_{min}	Minimum contention window size
τ_i	Transmission probability
n_i	Total number of i category STA
c	STAs category
λ_i	Packet arrival rate
T_{CS}	Average contention time
T_{slot}	Idle slot time
T_{succ}	Successful transmission time
T_{coll}	Collision time
D_i	Overall service time of category i

T_{beacon}	Beacon interval
K	Number of RAW groups k
G_g	Set of STAs in a RAW group
T_{RAW}	Length of RAW groups
λ_l	Packet arrival rate
L_l	Packet length
R_l	Transmission rate
D_l	Traffic demand of each STA
$D_{g,max}$	Maximum RAW group demand
S	Set of STAs
$\hat{S}$	Temporary STA set
N_g	Number of STA in a RAW group
$T_{r,RAWslot}$	RAW slot duration
$T_{RAWslot}$	RAW slot duration in time
$L_{RAWslot}$	Length of RAW slot
L_{succ}	Number of slot for successful transmission
T_{pspoll}	Duration of PS Poll frame
$T_{pspollack}$	Duration of PS Poll ACK frame
T_{DATA}	Duration of DATA frame
T_{ACK}	Duration of ACK frame
$T_{framebody}$	Duration of framebody
P_{tx}	Energy consumption in transmission state
P_{rx}	Energy consumption in receiving state
P_{idle}	Energy consumption in idle state

Acknowledgment

All praises are for the almighty Allah for giving me the strength, without which I could not afford to attempt this research work.

I would like to express my sincere and heartiest gratitude to my honorable thesis supervisor Md. Abubakar Siddik, Assistant Professor, Department of Electronics and Communication Engineering (ECE), Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur for his continuous motivation, guidance and keen encouragement which helped me throughout the time of my research work. Nothing is comparable to his keen advice and the freedom he provided for me in research. I am grateful to him for his cooperation throughout my thesis work. I would like to thank all honorable department members.

I would like to thank all the members of the board of examiners for their precious time in understanding my work and their insightful comments. I would like to thank to all of my friends for their cooperation. Last but not least, I am grateful to my parents for their continuous supports and cooperation.

Abstract

The emerging technology Internet of Things (IoT) has introduced a new dimension of communications by providing connectivity in dense networks with long coverage range. Legacy IEEE 802.11 standard developed for sparse networks with short coverage range which is not suitable for IoT. To address this issue, the IEEE TGah has developed IEEE 802.11ah standard to support dense networks by introducing restricted access window (RAW) mechanism. The grouping strategy and RAW parameters of RAW mechanism have not been yet fully addressed in IEEE 802.11ah standard and are still an open issue. However, most existing grouping algorithms focus on either even distribution of stations (STAs) or maximization of channel utilization to achieve fairness among RAW groups assuming that the network is saturated which is more impractical. Fair resource allocation depends on traffic demand when the network is non-saturated. Therefore, we propose a grouping algorithm that considers the non-saturation condition of STAs to enhance fairness. Moreover, we design a mathematical model to analyze the performance of RAW mechanism for STAs with heterogeneous traffic demands. We evaluate the proposed grouping algorithm via analytical model which has been solved by Maple. In this work, we compare the performance between IEEE 802.11ah based grouping scheme and legacy DCF by using the analytical result in order to indicate the importance of using IEEE 802.11ah standard in dense IoT network. The analytical results shows that in a dense IoT network RAW grouping scheme provide superior performance than legacy DCF in terms of reliability, normalized throughput, access delay and energy consumption. Further, we use Jain's fairness index to establish that proposed traffic demand-based grouping algorithm provide fair resource allocation among the RAW groups of heterogeneous STAs. Our traffic demand-based grouping algorithm outperforms other existing grouping algorithms, particularly for non-saturated networks.

Chapter 1

Introduction

1.1 Background

In the era of advanced technology, the Internet of Things (IoT) introduces a novel dimension of communication technology where connectivity is available to get any service by anyone from anyplace at anytime on anything using any network. For making this dream into reality, it is essential to develop an emerging wireless communication technology which could fulfill the various requirements of IoT applications such as large coverage range, high scalability, low power consumption, fairness, bounded delay and stable throughput [1]. To address these requirements traditional Wi-Fi is not suitable for a IoT network for the following reasons [2]

- Devices such as STAs and smart meters are designed to last for several years on a single battery. Long time monitoring of STAs is not possible with the use of higher power consumption of legacy Wi-Fi.
- Most of the IoT networks are being designed to support dense installations. But existing Wi-Fi has been intended for a sparse network with high throughput.
- Traditional Wi-Fi, which is operating in 5 GHz and 2.4 GHz, has a very limited range, which makes it unsuitable for real time monitoring.

Due to these drawbacks of the classical Wi-Fi standard and the increased demand of end users, the IEEE 802.11 working group initiated work on a new standard called 802.11ah in 2010. The IEEE 802.11ah task group (TGah) specifies the MAC and PHY layer specifications [3], operated at sub 1 GHz license exempt bands, mainly aimed to provide enhanced connectivity with a longer transmission range and an increased number of stations per access point. Provision for a range of throughput options from 150 Kbps to 40 Mbps is also a special feature targeted by this technology [4]. IEEE 802.11ah has several novel features viz. target wake time (TWT), relay access point, TIM segmentation, bi-directional TXOP, hierarchical organization, BSS color, restricted access window (RAW), group sectorization, fast authentication and association, short MAC header, response indication deferral (RID), channelization and transmission modes for IoT network [5]. The RAW feature focuses on enhancing scalability, partitions stations (STAs) into groups and permits channel access to one group during a RAW slot to reduce collisions for dense IoT networks [6]. Specially with RAW the AP divides all STAs into several groups, defines a set of time intervals called RAW slots and allocates each group to a RAW slot. Apart from reducing the collision probability, such an approach reduces energy consumption an important performance indicator for IEEE 802.11ah. Since the STAs can sleep almost always except for the allocated time intervals [7]. However, grouping strategy and RAW parameters such as number of RAW groups, duration of RAW slots, number of STAs per group have not been yet fully addressed in the draft of IEEE 802.11ah standard and are still an open issue. As a result, an efficient grouping strategy is required that could meet the requirements of IoT applications and substantially improve the efficiency of the networks.

1.2 Motivation and Objectives

Internet of Things (IoT) has a strong impact on almost all the areas of economy and human social life and it involves more and more devices, the majority being wireless [8]. To satisfy heterogeneous requirements of various wireless IoT systems, the community develops new technologies. Current low-power IoT communication technologies can be categorized into two groups: Wireless Personal Area Network (WPAN) and Low-Power Wide Area Network (LPWAN) technologies [9]. WPAN technologies such as Zig-Bee, Bluetooth Low Energy provide a medium data rate up to a few hundred kilo bits per second at short range of ten meters, while LPWAN technologies LoRa, SigFox, NB-IoT, eMTC, Wi-SUN and IEEE 802.11ah focus on long-range communications up to tens of kilometers and support low or medium data rate from a few hundred bits per second to a few megabits per second [10]. In terms of WPAN, Zig-Bee is developed based on IEEE 802.15.4 and supports a large number of devices and large coverage by the use of a mesh topology, while Bluetooth Low Energy consumes less energy. In terms of LPWAN, NB-IoT and eMTC are $5G$ technologies designed for IoT and operate in licensed frequency bands, while others work in ISM band. LoRa and e-MTC support high mobility, e-MTC supports critical service due to the high reliability and low latency, SigFox has the longest transmission range [11]. Due to the short transmission range of WPAN and insufficient throughput of both WPAN and LPWAN, they are only applicable in a limited set of IoT scenarios [12]. As such, a gap still exists for a low-power IoT communication technology that offers sufficient throughput up to tens of megabits per second over medium transmission ranges of a few kilometers. Traditional Wi-Fi which operates in a licensed frequency band with a limited range and a bandwidth of $5GHz$ and $2.4GHz$ [13]. For this the traditional Wi-Fi is not suitable for IoT network. Therefore, the new Wi-Fi standard IEEE 802.11ah, marked as Wi-Fi HaLow, is introduced as a LPWAN technology to fill this gap, as it has the highest data rate and medium transmission range between WPAN and most of the LPWAN technologies. In an IEEE 802.11ah network, a single AP services thousands of stations. As the number of stations increases, the network throughput and delay performance can decrease rapidly owing to excessive channel contention. As contention becomes problematic, the problem could be solved by limiting the number of stations contending at a time. Moreover, the IEEE 802.11ah standard implements restricted access window (RAW) mechanism to reduce the contention in the network [14]. The RAW mechanism partitions the network into several groups, splits the channel time into various RAW slots and assigns each group with a RAW slot. Only allocated STAs are allowed to transmit within corresponding RAW slots. However, the grouping strategy has not been specified in the standard and still an active open research area. Although the IEEE 802.11ah draft standard does not specify any grouping strategy, uniform grouping scheme is widely used as the default grouping scheme [15–17] . The uniform grouping scheme equally divides the network into several groups, evenly allocates the RAW slots to each group and provides similar services among them. Limited work has been reported on RAW grouping mechanism in IEEE 802.11ah. In [18] Model-Based RAW Optimization Algorithm (MoROA) STAs are grouped based on their traffic characteristics and tried to maximize throughput and fairness in terms on packet delivery ratio. In [19] a STAs grouping algorithm is designed based on the heterogeneity in traffic demands of STAs. However, the authors works on maximize channel utilization and do not ensure fairness among the RAW groups. Allocating a number of STAs in RAW groups may solve the problem partially, but to achieve better results, fairness has to be considered during group formation also. Fairness among the RAW groups is an important issue in every network.

Based on the above analysis, this paper aims to develop new grouping algorithm for achieving fairness among the RAW groups. The main objectives of the this research are outlined as follows

- To design an efficient grouping algorithm of RAW scheme for heterogeneous packet arrival rates of stations.
- To design analytical models for legacy IEEE 802.11 and IEEE 802.11ah standard.
- To solve the derived complex analytical models of legacy IEEE 802.11 and IEEE 802.11ah standard effectively using Maple.
- To determine the effectiveness of legacy IEEE 802.11 standard and IEEE 802.11ah standard in dense IoT network.
- To compare results of proposed grouping algorithm with the existing grouping algorithms.

1.3 Contributions

The main contributions of the paper are outlined as follows

- We develop a traffic demand-based grouping algorithm which takes into account the heterogeneous properties of STAs and converts them into a traffic demand. This algorithm assigns STAs into RAW groups in such a way that the demand is equal in each RAW group.
- We also present existing random grouping and uniform grouping algorithm to examine the comparison result with our proposed grouping algorithm.
- We develop a Markov chain-based analytical model for both saturated and non-saturated state to evaluate the performance of RAW mechanism of IEEE 802.11ah networks with heterogeneous STAs which adopt DCF protocol.
- We also develop a Markov Chain-based analytical model for both saturation and non-saturation state of traditional IEEE 802.11 standard to examine the comparison results with IEEE 802.11ah RAW based grouping mechanism.
- We examine through analytical model that grouping based IEEE 802.11ah standard provide better performance in terms of reliability, normalized throughput, access delay and energy consumption than legacy IEEE 802.11.

- We demonstrate through analytical model that our traffic demand-based grouping algorithm improves fairness among the RAW groups as compared to random and uniform grouping algorithm, particularly when the network is non-saturated.

1.4 Thesis Outline

The subsequent parts of the thesis are organized as follows

Chapter 2 presents literature review of IoT network, legacy IEEE 802.11 standard PHY and MAC layer, DCF access mechanism and IEEE 802.11ah standard PHY layer and MAC layer specification. Some related research on IEEE 802.11ah also presented in this chapter.

Chapter 3 presents a traffic demand-based grouping algorithm for fairness among the RAW groups of heterogeneous stations in IEEE 802.11ah IoT networks. In this chapter existing random grouping and uniform grouping also presented. Markov chain model for the IEEE 802.11ah RAW based grouping scheme and legacy DCF also analyzed in this chapter.

Chapter 4 investigates the performance between legacy DCF standard and IEEE 802.11ah standard in terms of reliability, normalized throughput, access delay and energy consumption. This chapter also provided a comparison result among random grouping, uniform grouping and proposed grouping algorithm.

Chapter 5 concludes the thesis and recommendations for future work is also available in this chapter.

1.5 Summary

This chapter introduces a background and related coexistence issues of Iot. Motivation, objectives and contributions of the research work are also presented here. Finally, organization of the thesis briefly described.

Chapter 2

Literature Review

2.1 Introduction

This chapter gives a review on IoT network, legacy IEEE 802.11 standard PHY and MAC layer specifications and its amendments, DCF access mechanism and IEEE 802.11ah standard PHY layer and MAC layer specifications. Some related research on IEEE 802.11ah also presented in this chapter.

2.2 Internet of Things (IoT)

The Internet of Things (IoT) is the network of physical objects or things embedded with electronics, software, sensors, and network connectivity, which enables these objects to collect and exchange data[20]. The IoT is enabled by the latest developments in RFID, smart sensors, communication technologies and Internet protocols. In the Internet of Things (IoT), it is possible to collect, record and analyze new data streams faster and more accurately by making devices gather and share information directly with each other and the cloud [21]. A simple IoT network is shown in Figure 2.1.

2.3 Architecture of IoT Networks

The IoT should be capable of interconnecting billions or trillions of heterogeneous objects through the internet, so there is a critical need for a flexible layered architecture. The ever increasing number of proposed architectures has not yet converged to a reference model [22]. Meanwhile, there are some projects like IoT-A [23] which try to design a common architecture based on the analysis of the needs of researchers and the industry. From the pool of proposed models, the basic model is a 3-layer architecture [24–26] consisting of the Application, Network, and Perception Layers. In the recent literature however, some other models have been proposed

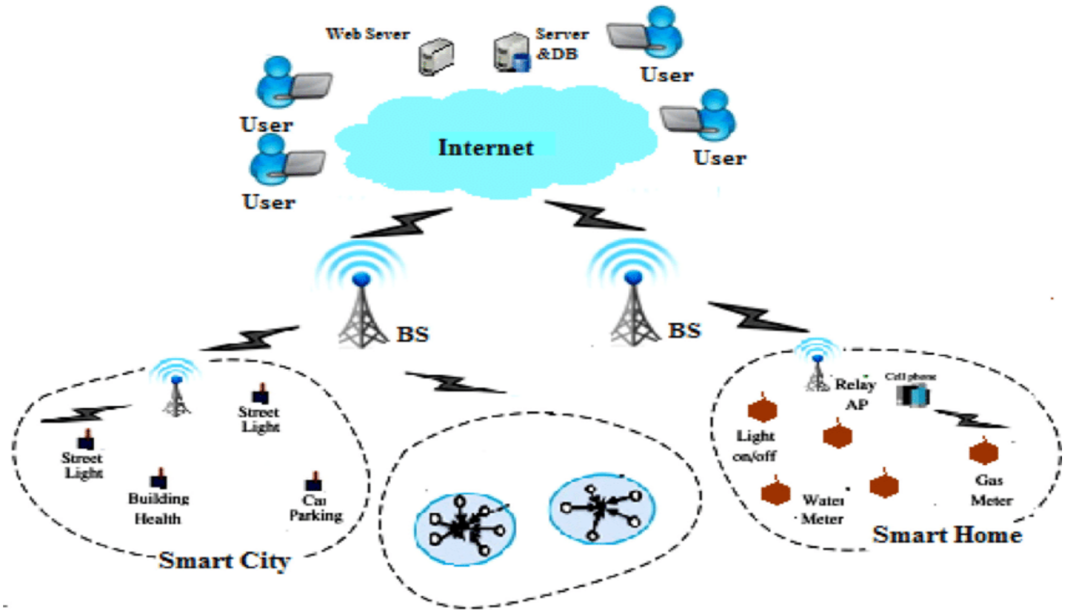

Figure 2.1: A Simple IoT network

that add more abstraction to the IoT architecture [24–29]. Figure 2.2 illustrates some common architectures among them is the 5-layer model (not to be confused with the TCP/IP layers) which has been used in [24–26]. Next, we provide a brief discussion on these five layers.

- **Objects Layer:** The first layer, the Objects (devices) or perception layer, represents the physical sensors of the IoT that aim to collect and process information. This layer includes sensors and actuators to perform different functionalities such as querying location, temperature, weight, motion, vibration, acceleration, humidity etc. Standardized plug-and-play mechanisms need to be used by the perception layer to configure heterogeneous objects [25], [26]. The perception layer digitizes and transfers data to the Object Abstraction layer through secure channels. The big data created by the IoT are initiated at this layer.

- **Object Abstraction Layer:** Object Abstraction transfers data produced by the Objects layer to the Service Management layer through secure channels. Data can be transferred through various technologies such as RFID, 3G,GSM,UMTS,WiFi,Bluetooth LowEnergy, infrared, ZigBee etc. Furthermore, other functions like cloud computing and data management processes are handled at this layer [25].

- **Service Management Layer:** Service Management or Middleware (pairing) layer pairs a service with its requester based on addresses and names. This layer enables the IoT

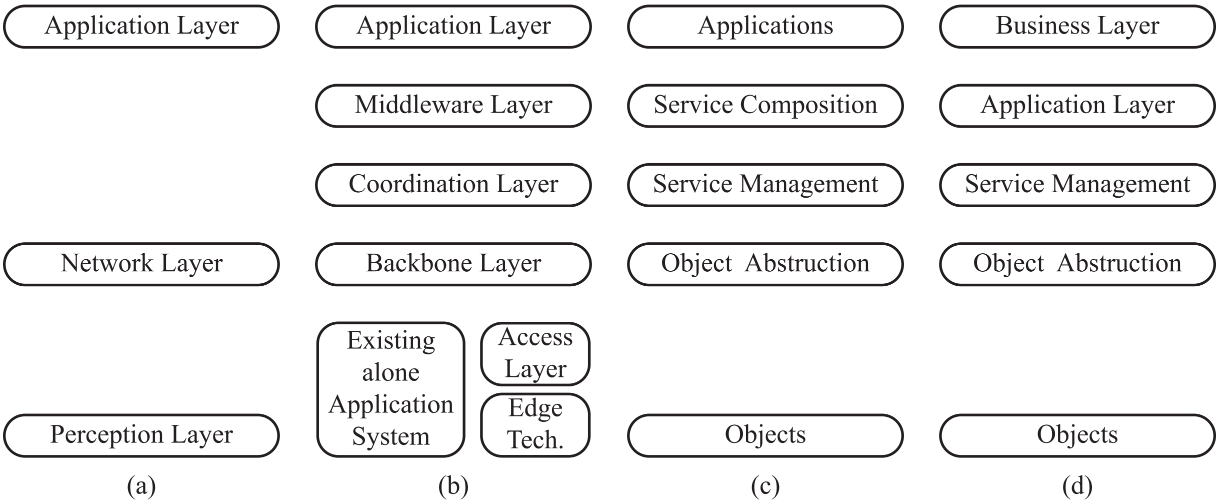

Figure 2.2: The IoT architecture (a) Three-layer, (b) Middle-ware based, (c) SOA based, (d) Five-layer

application programmers to work with heterogeneous objects without consideration to a specific hardware platform. Also, this layer processes received data, makes decisions and delivers the required services over the network wire protocols [24], [26], [28].

- **Application Layer:** The application layer provides the services requested by customers. For instance, the application layer can provide temperature and air humidity measurements to the customer who asks for that data. The importance of this layer for the IoT is that it has the ability to provide high-quality smart services to meet customers' needs. The application layer covers numerous vertical markets such as smart home, smart building, transportation, industrial automation and smart healthcare [24–27].

- **Business Layer:** The business (management) layer manages the overall IoT system activities and services. The responsibilities of this layer are to build a business model, graphs, flowcharts, etc. based on the received data from the Application layer. It is also supposed to design, analyze, implement, evaluate, monitor and develop IoT system related elements. The Business Layer makes it possible to support decision-making processes based on Big Data analysis. In addition, monitoring and management of the underlying four layers is achieved at this layer. Moreover, this layer compares the output of each layer with the expected output to enhance services and maintain users' privacy [24], [26].

2.4 Applications of IoT

The Internet of Things is a present communication system that imagine a near future, where devices of everyday life will be decorated with sensors, transceivers, actuators, micro-controllers and applicable communication protocols that will allow them to communicate with anyone from any place [10]. At present IoT is used in various field [25],[30–32]. Different kinds of IoT applications are presented in Table 2.1.

Table 2.1: Different types of IoT applications

IoT Applications	Consumer Applications	Smart Home
		Elder Care
	Organizational Applications	Medical and Healthcare
		Transportation
		V2X Communication
		Building and Home Automation
	Industrial Applications	Manufacturing
		Agriculture
		Maritime
	Infrastructure Applications	Metropolitan scale deployments
		Energy Management
		Environmental Monitoring
	Military Applications	Internet of Battlefield Things
		Ocean of Things
	Product Digitization	

2.5 Requirements of IoT Applications

Realizing the vision of the IoT is not an easy task due to the many challenges that need to be addressed. Examples of key challenges include availability, reliability, mobility, performance, scalability, interoperability, security, management and trust. Addressing these challenges enables service providers and application programmers to implement their services efficiently [5], [33–35]. IoT application requirement are described below

1. **Availability**

In IoT network availability means provide hardware and software services anywhere and anytime for customers. Software availability refers to provide services for everyone at different places and hardware availability refers to the existence of devices all the time that are compatible with the IoT functionalities and protocols.

2. **Large coverage range**

   Newer wireless technologies known as LWPANs offer a lower-cost option for Internet of Things applications that demand longer-range paths. Large coverage range is one of the most important requirement for IoT applications.

3. **Bounded Delay**

   It is a term used to describe a network in which the total delay experienced by data traversing the network can be guaranteed not to exceed some predetermined value.

4. **Reliability**

   Reliability means proper working of the system based on its specification. Its aims to increase the success rate of IoT service delivery. In emergency response application reliability become more critical and more important.

5. **Low power Consumption**

   Most of the IoT devices are battery operated and it is not easy to replace their battery due to the end of battery life time. Thus, IoT devices required less power consumption.

6. **Fairness**

   Fairness means all the IoT devices get equal opportunity to access the channel. It is an important feature for IoT applications.

7. **Higher Scalability**

   Iot network scalability refers to the ability to add new devices, services and functions for customers without negatively affecting the quality of existing services. Adding new operations and supporting new devices is not an easy task especially in the presence of diverse hardware platforms and communications protocols.

8. **Mobility**

   Mobility is another important requirement for IoT network implementation because most of the services are expected to be delivered to mobile users. Connecting users with their desired services continuously while on the move is an important premise of the IoT.

9. **Performance**

   IoT services performance evaluating is a big challenge, because it depends on not only the performance of the components but also the underlying technologies. The IoT needs to continuously improve and develop its services to meet customers requirements.

10. **Maximum Channel Utilization**

    Maximum channel utilization is an important challenge for IoT network. IoT network core function is to exchange information between billions or trillions of internet connection objects and it's aims to ensure maximum channel utilization.

11. **Management**

    The connection of billions or trillions of smart devices presents service providers with daunting issues to manage the Fault, Configuration,Accounting, Performance and Security aspects of these devices. This large number of IoT devices management is more challenging.

12. **Interoperability**

    End-to-end interoperability is another challenge for the IoT due to the need to handle a large number of heterogeneous things that belong to different platforms. Interoperability should be considered by both application developers and IoT device manufactures.

13. **Security and Privacy**

    Security presents a significant challenge for the IoT implementations due to the lack of common standard and architecture for the IoT security. In IoT network, it is not easy to guarantee the security and privacy of users.

2.6 Legacy IEEE 802.11 Standard

IEEE 802.11 is part of the IEEE 802 set of local area network (LAN) technical standards and specifies the set of media access control (MAC) and physical layer (PHY) protocols for implementing wireless local area network (WLAN) computer communication. IEEE 802.11 standard named as Wi-Fi is suitable for wireless local area networks (WLANs)[36]. The Institute of Electrical and Electronics Engineering (IEEE) standards association has developed several global standards in the area of wireless communications such as Wi-Fi, Bluetooth, and Zigbee[37]. The IEEE 802.11 technology operates in $2.4GHz$ and $5GHz$ industrial, scientific and medical

(ISM) bands [38]. The Wi-Fi technology is originally designed for human to human communication through wireless connection. Computers, smart phones and tablets are some of the most common devices which can use Wi-Fi technology[39]. These devices can connect to the network, such as Internet via wireless access points (APs). With the development of mobile Internet application and popularity of the smart phone usage, there is a huge demand for high data rate services through Wi-Fi connection. Therefore, the throughput enhancement is one of the most important theme in the Wi-Fi standard development. The IEEE 802.11 specification only regulates the PHY and MAC layer of Wi-Fi technology and the Wi-Fi network uses the same link layer protocol to connect with other local area networks for example, Ethernet.
The IEEE 802.11 standard association updates the Wi-Fi standard through amendments which define new features and concepts [40]. Several representative amendments are listed to show the development of the Wi-Fi technology as follows

- **IEEE 802.11a** is a PHY layer technology, orthogonal frequency-division multiplexing (OFDM), it first introduced to enhance the throughput. Also, the $5GHz$ ISM band is first used since the $2.4GHz$ band has already been crowded. This amendment is incorporated into the published standard IEEE 802.11-1999 [13].
- **IEEE 802.11b** standard has a maximum raw data rate of $11Mbit/s$ and uses the same media access method defined in the original standard. 802.11b products appeared on the market in early 2000, since 802.11b is a direct extension of the modulation technique defined in the original standard . The dramatic increase in throughput of 802.11b along with simultaneous substantial price reductions led to the rapid acceptance of 802.11b as the definitive wireless LAN technology. Devices using 802.11b experience interference from other products operating in the $2.4GHz$ band [41].
- **IEEE 802.11g** June 2003, a third modulation standard was ratified: 802.11g. This works in the $2.4GHz$ band like 802.11b, but uses the same OFDM based transmission scheme as 802.11a. It operates at a maximum physical layer bit rate of $54Mbit/s$ exclusive of forward error correction codes, or about $22Mbit/s$average throughput [13].
- **IEEE 802.11n** is an amendment that improves upon the previous 802.11 standards, its first draft of certification was published in 2006. The 802.11n standard was retroactively labelled as Wi-Fi 4 by the Wi-Fi Alliance. The standard added support for multiple-input multiple-output antennas (MIMO). 802.11n operates on both the $2.4GHz$ and the $5GHz$

bands. Support for $5GHz$ bands is optional. Its net data rate ranges from $54Mbit/s$ to $600Mbit/s$ [13]. The IEEE has approved the amendment and it was published in October 2009.

- **IEEE 802.11ac** is a very high throughput of $1Gbps$ is accomplished through the use of downlink multi-user MIMO technology and the maximum order of quadrature amplitude modulation (QAM) has been increased to 256 [42]. It is approved in 2014.
- **IEEE 802.11ad** amendment operate in the $60GHz$ millimeter wave spectrum. This frequency band has significantly different propagation characteristics than the $2.4GHz$ and $5GHz$ bands where Wi-Fi networks operate. Products implementing the 802.11ad standard are being brought to market under the WiGig brand name. The peak transmission rate of 802.11ad is $7Gbit/s$. IEEE 802.11ad is a protocol used for very high data rates about $8Gbit/s$ and for short range communication about $1-10$ $meters$. The standard is not too well known, although it was announced in 2009 and added to the IEEE 802.11 family in December 2012 [42].
- **IEEE 802.11ah** published in 2017 defines a WLAN system operating at $sub-1GHz$ license-exempt bands. Due to the favorable propagation characteristics of the low frequency spectra, 802.11ah can provide improved transmission range compared with the conventional 802.11 WLANs operating in the $2.4GHz$ and $5GHz$ bands. 802.11ah can be used for various purposes including large scale sensor networks, extended range hotspot and outdoor Wi-Fi for cellular traffic offloading, whereas the available bandwidth is relatively narrow. The protocol intends consumption to be competitive with low power Bluetooth, at a much wider range [3].
- **IEEE 802.11ai** is an amendment to the 802.11 standard that added new mechanisms for a faster initial link setup time [43].
- **IEEE 802.11aj** a derivative of 802.11ad for use in the $45GHz$ unlicensed spectrum available in some regions of the world [43]. It also provides additional capabilities for use in the $60GHz$ band. Alternatively known as China Millimeter Wave (CMMW).
- **IEEE 802.11aq** is an amendment to the 802.11 standard that will enable pre-association discovery of services. This extends some of the mechanisms in 802.11u that enabled device discovery to discover further the services running on a device or provided by a network.

- **IEEE 802.11ax** is the successor to 802.11ac, marketed as Wi-Fi 6 and Wi-Fi 6E by the Wi-Fi Alliance. It is also known as High Efficiency Wi-Fi, for the overall improvements to Wi-Fi 6 clients under dense environments. The IEEE 802.11ax-2021 standard was approved on February 9, 2021 [44].

- **IEEE 802.11ay** is a standard that is being developed, also called EDMG (Enhanced Directional Multi Giga) bit PHY. It is an amendment that defines a new physical layer for 802.11 networks to operate in the $60GHz$ millimeter wave spectrum. It will be an extension of the existing 11ad, aimed to extend the throughput, range and use-cases. The peak transmission rate of 802.11ay is $40Gbit/s$. The main extensions include MIMO up to 4 streams and higher modulation schemes and the expected range is $300 - 500m$ [45].

- **IEEE 802.11ba** is a Wake-up Radio (WUR) Operation an amendment to the IEEE 802.11 standard that enables energy efficient operation for data reception without increasing latency. The target active power consumption to receive a WUR packet is less than $1milliwatt$ and supports data rates of $62.5kbit/s$ and $250kbit/s$ [46]. The WUR PHY uses MC-OOK to achieve extremely low power consumption.

- **IEEE 802.11be** is a Extremely High Throughput (EHT) potential next amendment to the 802.11 IEEE standard and will likely be designated as Wi-Fi 7. It will build upon 802.11ax, focusing on WLAN indoor and outdoor operation with stationary and pedestrian speeds in the $2.4GHz$, $5GHz$, and $6GHz$ frequency bands [47].

2.6.1 PHY Layer Specifications

The PHY layer is the lowest layer in the protocol architecture which enables the signal waveform to transmit in the wireless medium. It specified bit rates of 1 or $2mb/s$ and $20MHz$ bandwidth [36]. It specified three alternative physical layer technologies

- Diffuse infrared operating at $1Mbit/s$
- Frequency-hopping spread spectrum operating at $1Mbit/s$ or $2Mbit/s$
- Direct-sequence spread spectrum operating at $1Mbit/s$ or $2Mbit/s$

The latter two radio technologies used microwave transmission over the Industrial Scientific Medical (ISM) frequency band at $2.4GHz$ [48]. Its specified data rate was to be transmitted via infrared (IR) signals or by either frequency hopping or directsequence spread spectrum (DSSS) radio signals.

The Clear Channel Assessment (CCA) is a logical function in the physical layer for carrier sensing and collision detection. Through this function, the Wi-Fi device can determine the current state of the wireless channel. One way of CCA is that it measures the energy level in the wireless medium and detect whether the level is above the threshold or not. If the measured energy level is above the threshold, the device determines the channel is busy and otherwise it determines it is idle. The energy can be generated by any types of signal operated in the ISM band. These signals can be Wi-Fi signals or others, such as Bluetooth and Zigbee. The CCA function can also determine the wireless channel condition without measuring the energy level of the medium. In this case, the STA determines that the channel is busy if it detects a carrier with the characteristics of the Wi-Fi standard.

2.6.2 MAC Layer Specifications

A representation of the MAC architecture is shown by Figure 2.3. The DCF provides the fundamental contention-based channel access method. This function deals with the asynchronous best effort traffic in which all users attain equal chance to access the medium. The Point Coordination Function (PCF) is an optional method which can support contention-free channel access. It is based on polling controlled by the AP and can meet the requirement of real time communications, for instance, voice and video streaming. The PCF is currently replaced by

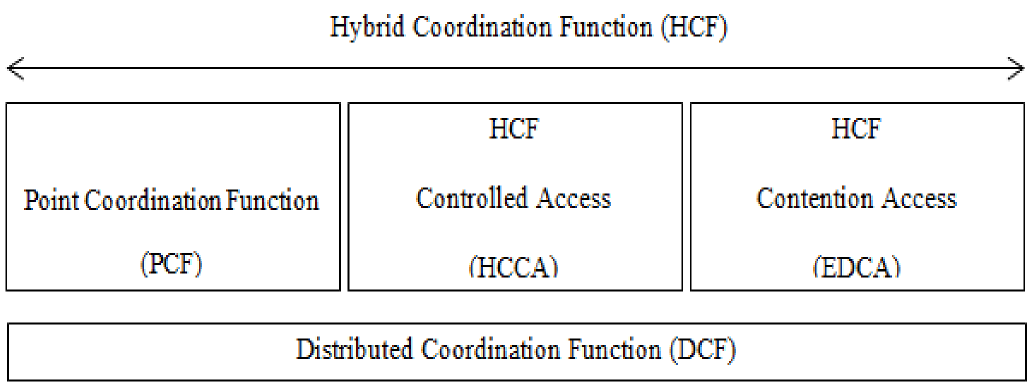

Figure 2.3: Legacy IEEE 802.11 MAC architecture

Hybrid Coordination Function (HCF) which combines the contention-based and contention-free method. The HCF is composed of a contention-based function called Enhanced Distributed Channel Access (EDCA) and a control-based function named Hybrid Controlled Channel Access (HCCA). These functions aims to provide required quality of service (QoS) in which the traffic categories are defined to support prioritized transmission. The HCCA allows contention-free channel access while EDCA does not [48]. Since the thesis scope is the contention-based channel access, only the details of DCF is discussed here.

2.6.2.1 Distributed Coordination Function

The DCF is a distributed channel access manner by which the STA itself can determine the time and method to access. It is also known as carrier sense multiple access with collision avoidance (CSMA/CA). The fundamental mechanism of CSMA/CA is ''Listen before Talk" in which STAs listen to the channel before transmitting data. Thus, the STA is required to contend with others in order to access the channel. The complete diagram of this procedure is illustrated by Figure 2.4.

F When a STA generates a packet which is required to deliver, it first senses if the medium is

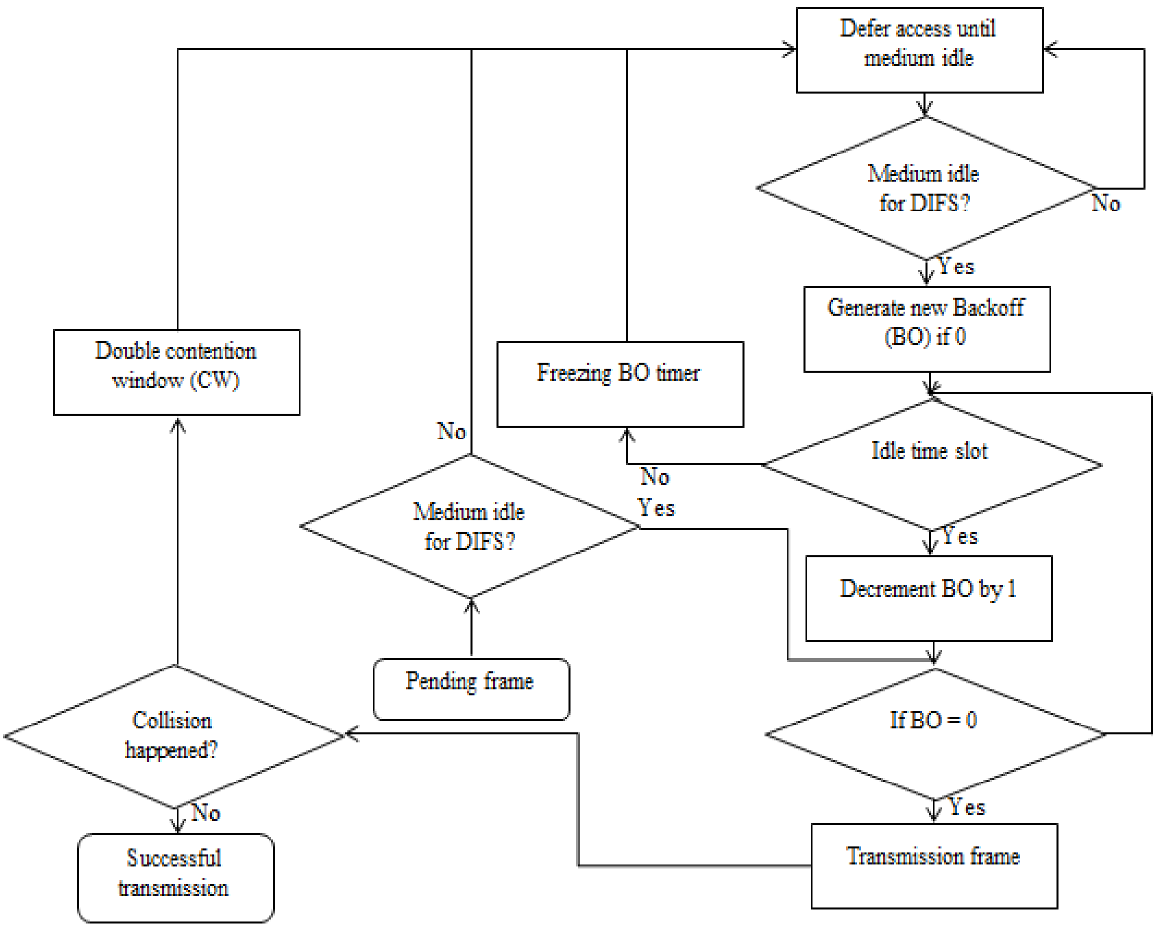

Figure 2.4: DCF channel access mechanism

idle for a period of time of DCF interframe space (DIFS). If the channel becomes busy during

DIFS, STA keeps sensing the channel until it becomes idle again. After the channel is sensed idle for DIFS, the STA generates a random backoff counter which is uniformly distributed between 0 and contention window (CW) and initializes the backoff procedure. The backoff time is slotted and the STA senses the channel condition slot by slot. Every time the STA determines that the channel is idle for one backoff slot, it decreases the backoff counter by one. When the backoff counter decreases to zero, the STA starts transmitting data. The channel sensing time in backoff is equal to the product of the backoff counter and backoff slot. The backoff counter is frozen if the channel becomes busy; and continues decreasing after channel is sensed idle for DIFS. The size of the CW is initialized to be the minimum value and one backoff slot duration is fixed based on the PHY layer characteristic.

The backoff procedure provides a random channel access method which can avoid collision relatively but cannot ensure a reliable transmission. Therefore, STAs need to receive an acknowledgement (ACK) frame to confirm that the transmission is successful. A time interval called short interframe space (SIFS) is used to separate two consecutive frames in the same dialogue, for example, data and ACK. This amount of time enables the receiver to have adequate time to process the data [49].

A collision occurs when two or more STAs transmit data simultaneously. The STA is not able to detect a collision while transmitting since the duplex radio does not exist. Therefore, once an STA starts a transmission, it will continue until the transmission finishes whether a collision occurs or not. After the transmission, if the STA cannot receive the ACK, it can identify that a collision may have occurred and double the size of its CW in the next transmission attempt. Therefore, the STA retransmits the packets with a doubled CW than its previous transmission and discards the packet after maximum number of retransmission limit [49].

DIFS is the minimal channel sensing time before transmission since the STA may generate the backoff counter with the value of zero. The relationship between SIFS and DIFS is illustrated by Formula (2.1), where $\alpha SlotTime$ represents the duration of one backoff slot [50].

$$DIFS = SIFS + \alpha SlotTime * 2 \tag{2.1}$$

The reason why SIFS is shorter than DIFS is to prioritize the ACK frame transmission and enable the current dialogue to continue. If other STA initializes the channel access inside SIFS period, the ACK frame will be transmitted before other STA finishes DIFS sensing. After the STA finishes transmitting the data, it waits for a time interval called $ACKTimeout$ to receive the ACK frame. After the period of $ACKTimeout$, if the STA does not receive the ACK, it determines that a collision may have occurred. The value of $ACKTimeout$ is illustrated by equation (2.2), where $\alpha PHYRxStartDelay$ indicates the delay caused by the PHY layer [50] .

$$ACKTimeout = SIFS + \alpha SlotTime + \alpha PHYRxStartDelay \tag{2.2}$$

2.6.2.2 Point Coordination Function

Point coordination function (PCF) is a media access control (MAC) technique used in IEEE 802.11 based WLANs, including Wi-Fi. It resides in a point coordinator also known as access point (AP), to coordinate the communication within the network. The AP waits for PIFS duration rather than DIFS duration to grasp the channel. PIFS is less than DIFS duration and hence the point coordinator always has the priority to access the channel.

The PCF is located directly above the distributed coordination function (DCF), in the IEEE 802.11 MAC architecture. Channel access in PCF mode is centralized and hence the point coordinator sends CF-Poll frame to the PCF capable station to permit it to transmit a frame. In case the polled STA does not have any frames to send, then it must transmit null frame. Due to the priority of PCF over DCF, STAs that only use DCF might not gain access to the medium. To prevent this, a repetition interval has been designed to cover both (Contention free) PCF & (Contention Based) DCF traffic. The repetition interval which is repeated continuously, starts with a special control frame called beacon frame. When STAs hear the beacon frame, they start their network allocation vector for the duration of the contention free period of the repetition period.

2.6.2.3 Hybrid Coordination Function

The Hybrid Coordination Function (HCF) is used to ensure the quality of service in WLANs according to 802.11. The HCF coordination function is functionally based on the radio channels and provides defined channel capacities at any time via the base station.

HCF works in conjunction with an Enhanced Distributed Coordination Function(DCF) of the Enhanced Distributed Coordination Function(EDCF). It includes two access methods, distributed and competitive access, Enhanced Distributed Channel Access(EDCA), and centrally controlled and non-competitive access, HCF Controlled Channel Access(HCCA). To delineate these access methods, the time period between 802.11 frames is divided into two: the non-competitive, Contention Free Period(CFP) and the competitive, Contention Period(CP). In the CFP period, access to the transmission medium is by means of HCCA and in the CP period by means of both HCCA and EDCA.

2.7 IEEE 802.11ah Standard

IEEE 802.11ah, standard marketed as Wi-Fi HaLow, is a new sub-1GHz Wi-Fi technology for the Internet of Things (IoT), aiming to address the major challenge of the IoT: providing connectivity among a large number of power constrained stations deployed over a wide area. In order to achieve this goal, several novel features are introduced in IEEE 802.11ah in both the Physical Layer (PHY) and Media Access Control (MAC) layer [3]. These features have been extensively studied from various perspectives in the past years. A brief of this standard that relates to this research is described in this section.

2.7.1 PHY Layer Specifications

IEEE 802.11ah sub-1GHz PHY defines Orthogonal Frequency Division Multiplexing (OFDM) which is 10 times down-clocked operation of IEEE 802.11ac's PHY. It supports 1, 2, 4, 8 and 16 MHz channel bandwidths with sub-1GHz, AP STA supports 1 and 2 MHz mandatory. Sub-1GHz frequency bands use narrow bandwidth allows it to improve coverage range (up to 1 km) with considerably less power consumption than traditional Wi-Fi technologies, which use frequencies in the 2.4 and 5 GHz bands. IEEE 802.11ah uses different sets of MCSs (modulation and coding schemes), NSS (Number of Spatial Streams) and GI (Guard Interval) for different channel width, thus results in different data rate. Sub-1GHz band supports MCS value 0 to 7 and MCS 10. To support multiple input and multiple output NSS ranges from 1 to 4 and GI 8 or 4 [3].
S1G non-AP STA shall support the following features

- $1MHz$ and $2MHz$ channel width
- supports $S1G - 1M$, $S1G - SHORT\ PPDU$
- $S1G - LONGPPDU$, if channel width $\leq 4MHz$
- support $MCSs$ 0 to 2 and MCS 10
- binary convolutional coding
- fixed Pilots

An S1G AP STA shall support the following features

- support single user
- channel width $1MHz$ and $2MHz$ and Nss value 1
- single spatial stream MCSs 0 to 7, and MCS10 for 1 MHz PPDU only
- supports S1G-1M, S1G-SHORT PPDU
- S1G-LONG PPDU, if channel width $\leq$ 4 MHz
- binary convolutional coding
- fixed pilot

In this work we consider S1G AP STA. IEEE 802.11ah supports three different PLCP protocol data unit (PPDU) formats, i.e., $S1G-1M$, $S1G-SHORT$ and $S1G-LONG$. $S1G-1M$ is used for channel width $1MHz$. For the other channel widths, $S1G-SHORT$ is for Single-User (SU) transmission and $S1G-LONG$ is for Multi-User (MU) and SU transmissions. In this work we consider $S1G-LONGPPDU$ frame format because our model support multi-user and single user transmission with a single access-point (AP). PPDU frame format is shown in Figure 2.5 [3].

2.7.2 MAC Layer Specifications

Several MAC augmentations are stated by IEEE 802.11ah to the legacy standards. To provide prioritised QoS, restricted QoS and target wakeup QoS IEEE 802.11ah standard supports a

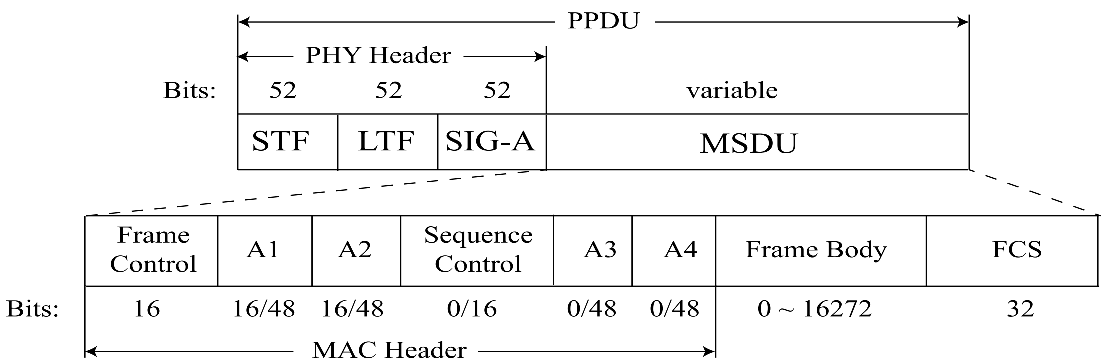

Figure 2.5: PPDU frame format

MAC layer architecture shown in Figure 2.6. MAC layer architecture consists of a Hybrid Coordination Function (HCF) contention access EDCA, Restrict Access Window (RAW) contention access and Target Wakeup Time (TWT) contention access mechanism [3].

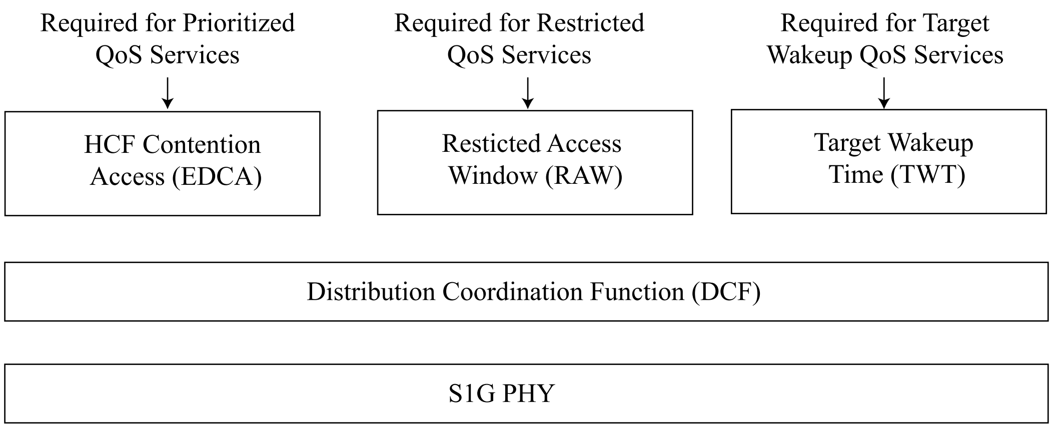

Figure 2.6: IEEE 802.11ah MAC architecture

Some MAC Layer feature are described below

1. **Fast authentication and association**

   At first all the STAs start to set up a link with the AP. A STA sends an authentication request and association request to the AP. Using this request message the AP learn about the STA. The AP sends back an authentication response and association response to inform the STA network parameters and assigns an AID. In traditional Wi-Fi networks the STAs employ the DCF for channel access as the number of STAs is usually small. When large number of STAs try to associate at the same time the link set-up take a long time due to collision of the authentication and association messages. This becomes an issue in IEEE 802.11ah, due to the large number of devices in IoT networks. To address this issue, two effective fast authentication and association control mechanisms are proposed for IEEE 802.11ah.

   In Centralized Authentication Control (CAC), the AP dynamically changes the portion of STAs that are allowed to send request messages. Specifically, the AP sets a threshold and broadcasts it to all stations by sending beacon frames. The beacon is a management frame and contains network information and transmitted periodically by the AP to announce the presence of a wireless network and to synchronize all STAs. When a STA is initialized, it generates a random back-off value and tries to send request message to the AP if the random value is smaller than the threshold obtained from the received beacon. Otherwise, it postpones authentication/association until the next beacon arrives.

In Distributed Authentication Control (DAC), a beacon interval is divided into sub-intervals called Authentication Control Slots (ACSs). Stations randomly select a beacon interval and a ACS to send their request. If a station does not succeed to authenticate, it resends the request in the next m_{th} beacon interval and i_{th} ACS, the values of m and i are generated based on the truncated binary exponential backoff mechanism.

2. **Restricted Access Window (RAW)**

RAW the STA grouping mechanism, is proposed to mitigate collisions and improve performance in dense IoT networks. It is a combination of TDMA and CSMA/CA, which splits STAs into groups and only allows STAs assigned to a certain group to access the channel using DCF or EDCA at specific times. In IEEE 802.11 system, the AP gives an Association Identifier (AID) during the association stage. IEEE 802.11ah standard introduce a 13 bit hierarchical AID structure to extends the length of the traffic Indication Map (TIM) up to 8192 bits to support a 8192 STAs. Every bit in the TIM bitmap corresponds to a device if the AP has a data packet destined to it. The AP broadcast periodically delivery- Traffic Indication Map (DTIM) beacon which is the bitmap of the Traffic Indication Map (TIM) beacons [51]. The duration between two consecutive TIM beacon is consist of multiple RAW periods and Contention Free Periods (CFP). Further, each RAW consists of several RAW slots. In this RAW slot a group of designated STAs contends for accessing the channel followed by DCF or EDCA mechanism [52]. The RAW structure is shown in Figure 2.7.

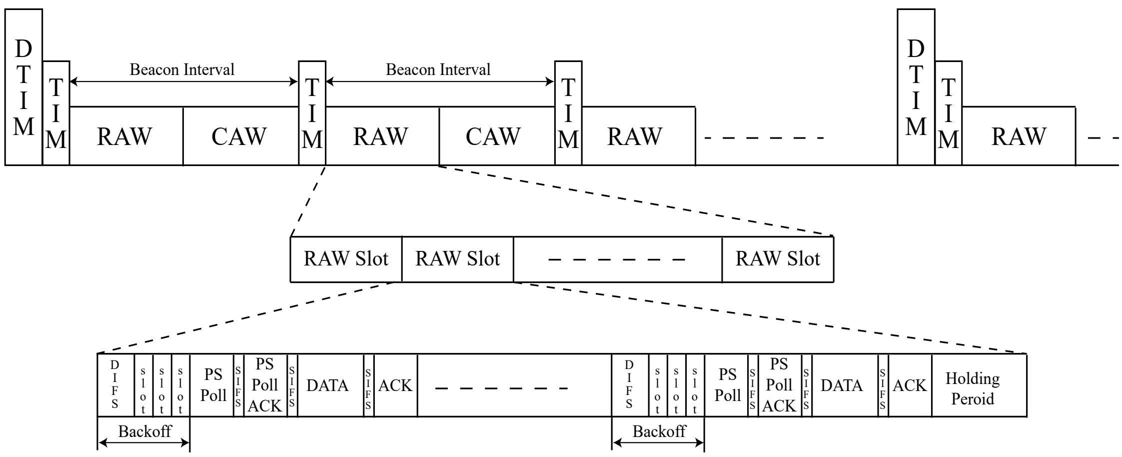

Figure 2.7: IEEE 802.11ah RAW structure

To enhance network throughput performance, enables fair channel access among the contending STAs and reducing collision probability the channel is only shared by the STAs belonging to a RAW slot. Therefore, inform the STAs in which RAW slot it is assigned the AP broadcasts a beacon RAW parameters set (RPS) information element (IE) that specifies the start time of the RAW, RAW duration, AID of the assigned STAs [11]. A field called cross slot boundary (CSB) is present in the RPS element. If the CSB field is set to 0 that means the STA differ from transmission due to in-sufficient time to transmit the frame. On the other hand CSB field is set to 1 for cross slot boundary condition. In cross slot boundary condition a STA can transmit frame if it does not finish transmission prior to the end of the current RAW slot. After the end of the assigned RAW slot duration the designated STAs is a RAW slot go to sleep mode until their assigned RAW slot arrived in the next beacon interval.

3. **Group sectorization**

   Group sectorization is consist of time and space-division multiplexing. It divides the coverage area of a Basic Service Set (BSS) into sectors and each sector contain a subset of STAs. It's aim to mitigate hidden STA problem, contention or interference. The sectorization is achieved by the AP transmitting or receiving through a set of antenna beams to cover different sectors of the BSS, except that the AP may alternate the omnidirectional beacons and the sectorized beacons and all STAs can transmit of their geographical locations during the omni beacon interval in the BSS. Group sectorization is a simplified version of RAW, as STAs are grouped only based on location. The difference is that it allows more than one sectors to be active at the same time and is only suitable for APs and STAs with directional antennas.

4. **TIM segmentation**

   For STAs in Power Save (PS) mode, a TIM element is included in each TIM beacon to indicate the STAs set for which the AP has buffered packets. If no buffered packets are destined for a STA, it returns to the doze state. Otherwise, it sends a PS-Poll frame to retrieve the buffered packets. However, for STA that have little downlink traffic from the AP, receiving every beacon frame is not energy efficient and becomes the bottleneck of the whole power management framework. To address this issue, an advanced power saving mechanism is introduced called TIM segmentation, which splits the TIM information into N segments and the information of each TIM group is carried by its corresponding

TIM beacon. Delivery Traffic Indication Map (DTIM) beacons are for TIM group-level signaling and TIM beacons are for STA-level signaling. All STAs wake up periodically to receive the DTIM beacon and check whether the AP has pending data for their own TIM group. If so, STAs wake up again to listen to their corresponding TIM beacon, otherwise resume sleep mode until the next DTIM announcement.[52]

5. **Target Wake-up Time (TWT)**

   TWT is a method of reducing power consumption for the STAs which transmit frame sporadically. In TWT, STAs can negotiate with the AP a series of time instances called TWT Service Period (SP) about when they should wake up to exchange frames. Therefore they are not required to wake up even for receiving beacons and can stay in a power saving state for very long periods of time. Either the AP or a STA starts TWT negotiation. The AP or TWT STA can end the TWT by transmitting a tear-down frame. The main TWT parameters are target wake time, minimum wake duration, wake interval, flow type. Target wake time indicates when the first TWT interval begins, minimum wake duration is the minimum value of TWT SP, TWT wake interval equals to the average time between successive TWT SPs and flow type indicates whether a trigger packet should be sent before transmitting data packets during SP.

6. **Hierarchical organization**

   The AID is a 14-bit long unique value assigned to a STA by the AP during association handshake and ranges 1–2007. In particular, AID = 0 is reserved for group addressed traffic. Therefore, an AP cannot have more than 2007 associated STA. To support large scale networks, the maximal AID value is increased to 8191 in IEEE 802.11ah. To simplify operations with such a huge number of associated STA, the hierarchical organization mechanism is proposed to organizes stations by 13-bit AIDs according to a four-level structure, including 2-bit pages, 5-bit blocks, 3-bit sub-blocks and 3-bit stations.

7. **BSS color**

   Dense deployment of IEEE 802.11 networks can lead to Overlapping Basic Service Sets (OBSSs), resulting in interference among STAs from different BSSs and degraded network performance. To solve the OBSS problem, a novel feature named BSS Color is introduced into IEEE 802.11ah. In BSS Color, each BSS is assigned to a unique color and such information is encoded in the PHY header of each packet. During packet reception, if a

STA detects the packet has a different BSS color from its own, it terminates the ongoing packet reception process to reduce power consumption and interference.

8. **Short MAC header**

   In legacy IEEE 802.11 networks, the MAC frame header contains at most four 6-byte MAC addresses, leading to a total header length of 40 bytes. Thus, for a 100-byte payload, the MAC header overhead is 40 percent. For smaller payload the overhead is even higher. To reduce the overhead IEEE 802.11ah defines a new backward incompatible format of shortened headers for data, management and control frames with a length of from 10 to 24 bytes depending on the context. In the short MAC frame headers, the Duration/ID field, Quality of Service (QoS) and High Throughput (HT) fields are excluded and the 6-bytes address field is replaced by a 2-bytes Short identifier (SID) field. Both legacy and short MAC frame headers are supported by IEEE 802.11ah.

9. **Response Indication Deferral**

   As the short MAC header contains no Duration/ID field, which is required by Net Allocation Vector (NAV) for virtual carrier sensing, a novel channel access mechanism called Response Indication Deferral (RID) is introduced in IEEE 802.11ah. In the PHY header, there is a 2-bits response indication field that defines four types of responses, i.e. the ways of calculating the value of the RID timer. Right after the reception of the PHY header of a frame, the STA sets the RID timer based on the value of the response indication field and starts counting down until the values of the RID timer comes down to 0, indicating the channel becomes idle.

10. **Relay**

    To support IoT scenarios with large coverage, IEEE 802.11ah extends the transmission range between an AP referred to as the root AP and STA with a relay. A relay logically consists of a relay AP and a relay STA. The relay AP is associated to STA and the relay station is associated to a root AP. For downlink transmission the packets are transmitted by the root AP to the relay STA and the relay STA forwards the packets to the relay AP, which then transmits the packets to the STA and vice versa for uplink transmission. To simplify the forwarding mechanism the relay is limited to a two-hop link between a STA and the root AP.

2.8 Related Works

There are several literature's that proposed the grouping scheme of RAW mechanism to improve the network performance and/or to ensure fairness among contending STAs. T. Chang et al. [53] designed a load-based grouping algorithm to enhance channel utilization of each RAW group. In this scheme, the authors have done STA grouping by considering heterogeneous traffic demand such as sampling rate and packet length. The author calculated expected traffic demand based on sampling rate and packet length but traffic demand also related to heterogeneous bit rate of contending STAs. Number of RAW groups and RAW slot duration is fixed and AP assigns a STA in a RAW group based on traffic demand. The performance of this load balanced sensor grouping algorithm is evaluated by simulation. This grouping scheme maximize the channel utilization and provide a comparison result with random grouping only. However, the authors do not ensure fairness among the RAW groups and unsaturated network and only homogeneous bit rate is considered. A novel analytical model to estimate the association delay of IEEE 802.11ah protocol was proposed in [14]. In this work, the authors showed that their exist an optimum RAW group size that minimum association delay of STAs. An enhance authentication control algorithm which utilizes the optimum RAW group size to provide the minimum association delay is proposed. The numerical and analytical result showed that the proposed method estimate minimum association delay but their grouping strategy is not clear. However, channel utilization, fairness, number of RAW groups and RAW slot duration are not addressed in this paper and mainly focus centralized authentication control.

N. Nawaz et al. [54] designed a analytical model where RAW slot duration is chosen according to number of STAs per group for uniform grouping scheme. The STAs are considered to be in saturation so that all STAs have data packets readily available in their buffers and assume that there are no hidden STAs in the network and the channel is in an ideal condition where there are no communication errors. The authors demonstrate that the throughput under proposed scheme can be significantly enhanced when compared to a conventional implementation. However, this model could not solve the optimization issues when heterogeneous and non-saturated traffic issues are considered and the RAW slot duration variation strategy is not clear in this paper. A Model-Based RAW Optimization Algorithm (MoROA) based on surrogate model was proposed to determine the optimum RAW parameters for dynamic traffic pattern of heterogeneous STAs [18]. The authors use surrogate model to determine the optimal RAW configuration under a variety of network and traffic conditions and supports heterogeneous

STAs with different MCS and average packet sizes. The surrogate model accuracy is compared through simulation result. In this work, Performance of MoROA is compared to traditional 802.11 channel access methods and result less error with higher throughput in dense heterogeneous networks. However, in this work real time network scenario is not clear and the simulation result compare with traditional DCF mechanism except compare with other grouping algorithm in IEEE 802.11ah. In [55], the performance degradation in the IEEE 802.11ah networks resulting from hidden terminals has been analyzed first, and then the hidden matrix-based regrouping (HMR) scheme has been proposed to resolve this problem. The idea behind this approach is to detect hidden terminals at the AP. Thereafter, the hidden STA matrix is generated, and the STAs experiencing hidden terminal are moved to another group. Simulations result showed that HMR algorithm eliminates most of hidden STA pairs and improve the performance of the 802.11ah network significantly in terms of the number of hidden STA pairs and power-save poll (PS-Poll) transmission end time. However, the authors focus on hidden STAs problem only. A novel real-time grouping algorithm has been proposed in [56] based on the current traffic situation. The proposed algorithm considers both dynamic and heterogeneous traffic conditions. The parameter estimation takes place in the AP and it uses the available information obtained by access point (AP) during the last beacon interval. This algorithm is run at the beginning of each beacon interval making it real-time. TAROA determines the RAW parameters and assigns STAs to RAW slots based on this estimated transmission frequency. The simulation results shows that, compared to enhanced distributed channel access/distributed coordination function (EDCA/DCF), the TAROA algorithm can highly improve the performance of IEEE 802.11ah dense networks in terms of throughput, especially when hidden nodes exist in static traffic condition. A method has been developed for the optimal RAW size selection in [57]. Based on the success probability observed in the network, the number of devices contending for the uplink access is estimated. Using the success probability, an AP can estimate the number of devices for the uplink access. By the proposed algorithm, many devices can access the uplink channel efficiently. Then, the optimal RAW size is computed utilizing the relationship between the number of contending devices and the RAW size. Therefore, the simulation results show that the proposed algorithm has higher success access probability than the legacy schemes.

In [19], the authors proposed a traffic-aware grouping scheme to enhance channel utilization for a large-scale IoT networks in heterogeneous traffic conditions. In this scheme, the authors have done STA grouping by considering heterogeneous traffic demand such as sampling rate and packet length and transmission bit rate. The author calculated expected traffic demand based on sampling rate, packet length and transmission bit rate of contending STAs. Number of RAW groups and RAW slot duration is fixed and AP assigns a STA in a RAW group based on traffic demand. The performance of this traffic aware sensor grouping algorithm is evaluated by simulation. This grouping scheme maximizes the channel utilization and ensuring fairness among RAW groups in saturated condition. However, this algorithm could not perform as well in non- saturated traffic conditions. In [58], a heuristic method was developed to solve unfair grouping problem of IEEE 802.11ah. Fairness among the RAW groups is achieved by a CW selection and CW adjustment methods. In this scheme, a weight-based contention window selection method, and a method that dynamically adjusts the contention windows of STAs in accordance with their channel utilization are developed and weight assignment has been achieved by utilizing the amount of data each STA generates per second. Results from extensive simulations conducted in a dense IoT network show that the proposed fairness model achieves a superior performance than the existing methods in terms of throughput, packet delay, energy efficiency, and fairness. However, it is difficult to select and optimize weight based CW and this grouping method is impractical due to choose of homogeneous traffic condition of STAs. In [59], fair and efficient resource allocation method for IEEE 802.11ah with heterogeneous data rate was proposed. AP distributes STAs into RAW groups based on transmission data rates of STA only. The authors use Markov chain to derive the analytical model. In this work, numerical and experimental results showed that data rate based grouping can significantly improve the aggregate network throughput performance, as compared to the conventional random grouping and Jain's fairness index (JFI) also used to compare fairness among the RAW group. However, this algorithm forms only one RAW group for homogeneous transmission data rates of the network and it behaves as DCF protocol of IEEE 802.11. Thus, it fails to achieve the goal of IEEE 802.11ah RAW mechanism in homogeneous data rate network scenario. Data rate based grouping [60] was proposed to improve network performance for heterogeneous channel conditions. AP distributes STAs into RAW groups based on transmission data rates of STA only. In this work, a analytical model is derived but how it is not clear and the analytical results evident that the proposed data rate based grouping scheme can resolve the performance anomaly and improves the aggregate throughput than uniform grouping. Fairness among the RAW group is not investigate here. However, this algorithm forms only one RAW group for homogeneous transmission data rates of the network and it behaves as DCF protocol of IEEE

802.11. Thus, it fails to achieve the goal of IEEE 802.11ah RAW mechanism in homogeneous data rate network scenario.

In [61], a dynamic channel grouping scheme was developed based on agglomerative hierarchical clustering to enhance normalized throughput and fairness among the RAW groups considering homogeneous packet arrival rates. In this scheme, evaluation of the network is done after every beacon interval and optimum station grouping and group parameters are broadcasted before the start of a next beacon interval. The proposed model was tested against uniform grouping and random grouping. The results of proposed grouping scheme show the improvement in normalized throughput and fairness compared random and uniform grouping algorithm. However, practical heterogeneous traffic conditions are not considered in this approach. In [62], a randomness region based grouping scheme were proposed to control the number of hidden STAs and to minimize frame collision among the STAs. The proposed model was solved by Markov model analytical and simulation. The proposed Markov model and NS3 simulation results reveal that the proposed algorithms outperform then random grouping algorithms in terms of throughput, packet loss, packet collision rate, and fairness index. These proposed algorithms ignore the traffic condition of STAs but consider the location of STAs for grouping and regrouping purpose. Ali et al. [63] presented an Markov chain-based analytical model to analyze the performance of RAW mechanism under EDCA protocol for non-saturated traffic load and noisy channel condition. However, RAW parameters and grouping strategy are not consider in this work. In [64], both homogeneous and heterogeneous traffic patterns have been considered for evaluating the performance. The performance parameters like throughput, latency and power consumption are evaluated under varying number of stations and groups. It is observed that the performance variations between different RAW duration values vary due to setting and resetting of the backoff values in each RAW slot. The frequent switching among the backoff states reduces RAW performance. Very short RAW duration increases the number of beacons thereby increasing control overheads. However, the long RAW duration reduces overhead with higher throughput but increases latency.

Wayan Damayanti et. al.[65] proposed a collision chain mitigation method. The collision chain mitigation method identifies the current on-going collision chain and interrupts the collision by broadcasting message. After receiving that message, no station is allowed to contend except the stations those have transmitted before collision. Along with mitigation methods, it further reduces the hidden stations by grouping and regrouping strategies. The simulated

Table 2.2: Summary of related works

Ref. & year	Traffic Condition	Grouping Basis	Performance metrics	Compare	Limitations
2015 [53]	Saturated	Packet length, Sampling rate	Average channel utilization	Random	Homogeneous bit rate is considered
2017 [14]	Not clear	No. of contending STA	Group size & association time	N/A	Grouping not clear
2017 [54]	Saturated	RAW slot duration	Throughput	Conv. RAW	Homogeneous traffic considered
2018 [18]	Real time	Heterogeneous STAs, packet size	Throughput, Delay & Fairness	Legacy DCF	Real time scenario is not clear
2016 [55]	Not clear	No. of STA	Frequency & hidden STAs pairs	Conv. RAW	Throughput, fairness, delay are not find
2017 [56]	Real time	Heterogeneous traffic	Throughput, packet loss & latency	Legacy DCF / EDCA	Performance degrades in dynamic traffic
2014 [57]	Saturated	Success probability	Success probability	Legacy DCF	RAW size is determination is impractical
2016 [64]	Saturated	Traffic pattern	Throughput, latency & average active time	N/A	Performance parameter tested in fixed scenario
2016 [65]	large-scale	Threshold value	Throughput & delay	Conv. RAW	Computational complexity
2015 [66]	Saturated	Energy threshold	Throughput, fairness, energy	N/A	Only homogeneous traffic considered
2014 [67]	Saturated	Uplink, downlink segment duration	Packet delivery ratio, energy efficiency	N/A	Divide downlink, uplink in real time traffic is challenging
2019 [19]	Saturated	Heterogeneous traffic	Channel utilization & fairness	Random	Could not perform in unsaturated network

Table 2.2: Summary of related works (continued)

Ref. & year	Traffic Condition	Grouping Basis	Performance metrics	Compare	Limitations
2019 [58]	Real time	Contention window (CW)	Throughput, packet delay, energy efficiency & fairness	Random, GS-FMM	Difficult to select and adjust optimum CW
2019 [59]	Saturated	Data rate	Aggregate throughput & fairness	Random	Goal of RAW is fail in homogeneous data rate
2020 [60]	Not clear	No. of STAs & data rate	Aggregate normalized throughput	Uniform	Goal of RAW is fail in homogeneous data rate
2020 [61]	Real time	No. of STAs	Normalized throughput & fairness	Random, uniform	Heterogeneous traffic & hierarchical clustering not consider
2020 [62]	Saturated	No. of packets	Throughput, fairness, packet loss & collision rate	Random	Ignore traffic condition of STAs only location is considered
2019 [63]	Non-saturated	Heterogeneous arrival rate	Success, collision, idle probability	N/A	RAW parameters & grouping not clear
Proposed grouping	Saturated, non-saturated	Sampling rate, packet lengths, transmission bit rate	Reliability, throughput, access delay, energy consumption & fairness	Legacy DCF, random, uniform	Only DCF method is used & impact of RAW duration is not consider

results show that both grouping and mitigation scheme have improved the throughput performance. The new holding scheme introduces various methods namely Fixed, Decrement, Variable and Hybrid, for counting its backoff slot during holding period [66]. In the hybrid holding scheme, a station decides its backoff based on the proximity of AP. The stations in Hybrid scheme use fixed scheme for the nearer distance and Variable scheme for the far distance from AP. Having prior knowledge about backoff states of all the stations with AP, grouping of station is carried out by sorting backoff counters in the ascending order. Albert Bel et. al.[67] proposed Channel Access Slots (CAS) based channel access protocol divides RAW duration into uplink and downlink segments which in turn is divided into CAS periods. The CAS period is optimally calculated for both segments to increase the channel occupancy. This method refreshes the exponential backoff and retransmission counters to its initial values in every CAS. In the current contention period, the previous CAS collision is not considered. The periodic reset of backoff is used to ensure the fair access among stations within CAS. The simulation results have shown that the uplink and downlink segments have resulted in good performance towards energy saving. It explicates that this scheme is suitable for battery-operated networks. The above literature was summarized in Table 2.2. To the best of our knowledge, none of the existing research works have considered traffic demand of heterogeneous (different packet arrival rates, packet length, transmission data rates) STAs to design a grouping algorithm of RAW for ensuring fairness among the RAW groups.

2.9 Performance Evaluation Tool

In this work, we have used Maple software to evaluate the analytical model. Maple is a symbolic and numeric computing environment as well as a multi-paradigm programming language. It covers several areas of technical computing, such as symbolic mathematics, numerical analysis, data processing, visualization, and others. A toolbox, MapleSim, adds functionality for multidomain physical modeling and code generation.

2.10 Summary

This chapter gives a related study on IoT, legacy IEEE 802.11 standard and its amendments, DCF access mechanism and IEEE 802.11ah standard PHY and MAC layer details.

Chapter 3

Proposed Traffic Demand-based Grouping Algorithm

3.1 Introduction

As Information and Communication Technology (ICT) develops, human's desire to automate everything will reshape their lives completely in the aspects of economics, politics and social life. Emerging applications and services of the smart systems will require a large number of smart devices, such as robots, sensors and controllers. The development of ICT has turned to be aimed at the interconnection between people and people, people and objects and objects and objects and finally making all things connected. To making this dream into reality IEEE 802.11 TGah making an amendments named IEEE 802.11ah (HaLow) technology where grouping strategy is still not clear. In this chapter proposed and existing grouping algorithm have been presented. IEEE 802.11ah and Legacy DCF analytical model and performance metrics also presented in this chapter.

3.2 System model

In this paper, we consider an IEEE 802.11ah based IoT network consists of an access point (AP) and n number of STAs which forming a star topology configuration. A simple IoT network scenario is shown in Figure 3.1. The AP generates a beacon control frame at the beginning of each beacon interval, denoted by T_{beacon}. The STAs are grouped into K number of RAW groups, denoted by G_g, $(g = 1, 2, ..., K)$ and each RAW group is assigned in a RAW slot. We assume that the RAW access phase is divided into K number of equal length of RAW groups, which is set to $T_{RAW} = T_{beacon}/K$. Let, each STA l has a packet arrival rate λ_l, packet length L_l and transmission data rate R_l [19] . The desired traffic demand of STA l is denoted by D_l and defined as the desired average channel access time needed by STA l to successfully transmits a frame in a beacon period as follows

$$D_l = \frac{T_{beacon}\lambda_l L_l}{R_l} \tag{3.1}$$

Our main objective is to divide STAs into K number of RAW groups according to their desired traffic demands such that the traffic demands can be equally distributed among the RAW groups.

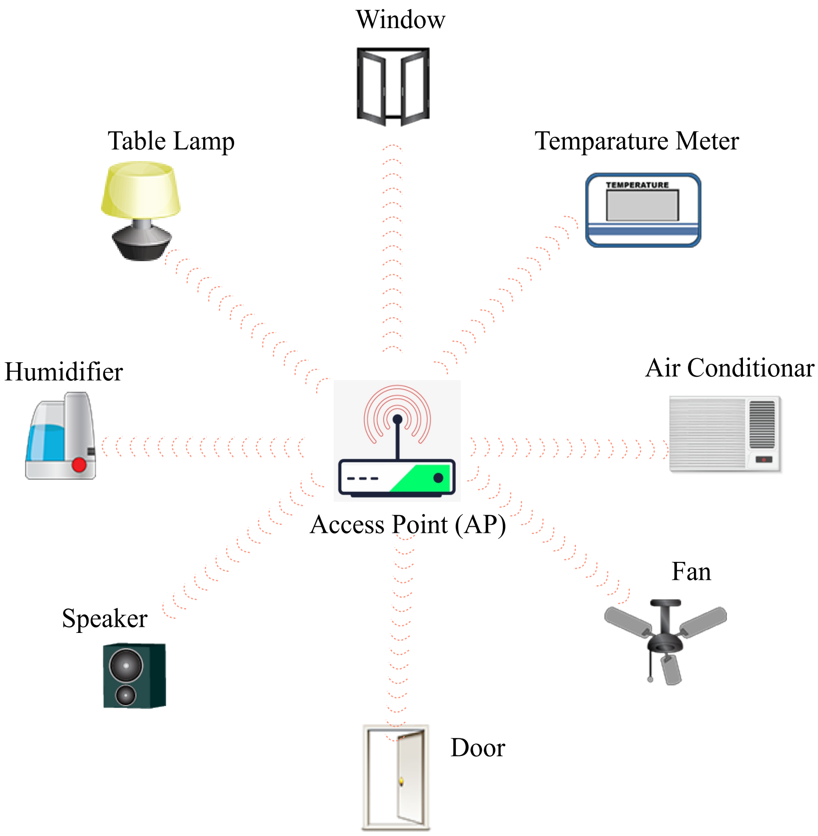

Figure 3.1: Simple IoT network scenario

3.3 Existing Grouping Algorithms

3.3.1 Random Grouping Algorithm

Here, we present an algorithm for random grouping in IEEE 802.11ah WLAN. The main concept of random grouping algorithm is to assign each STA into K number of empty RAW groups randomly without consider their traffic demand and number of STAs in RAW group. Algorithm 1 describes the procedure for implementing random grouping. Initially, a set of STA $S = \{s_1, s_2, ..., s_n\}$, K number of empty RAW groups G_g $(g = 1, 2, ..., K)$ is considered. In this grouping process the AP first select STA s_l from sensor set S and insert this s_l STA in group G_g where group g is selected randomly by using $g = rand()~\%~K + 1$. After inserting STA s_l in

G_g group remove it from sensor set S. The above process will continue for all unassigned STAs until S become empty and then group formation for all G_g is completed. Finally, AP assign 13 bits AID for each STA and broadcast RAW Parameter Set (RPS) information to all STAs to inform their designated group using beacon frame. Figure 3.2 represent a random grouping algorithm flowchart.

Algorithm 1 Random grouping algorithm

Input: set of STAs S, number of RAW groups K, set of STAs in g RAW group G_g
Initialization: $S \leftarrow \{s_1, s_2, ...s_n\}$, $G_g \leftarrow \{\}$
while $S \neq \{\}$ **do**
    select STA s_l from S
    $g = rand()\ \%\ K + 1$
    $G_g \leftarrow G_g \cup \{s_l\}$
    $S \leftarrow S - \{s_l\}$
end while
Return: G_g for $g = 1, 2, ..., K$

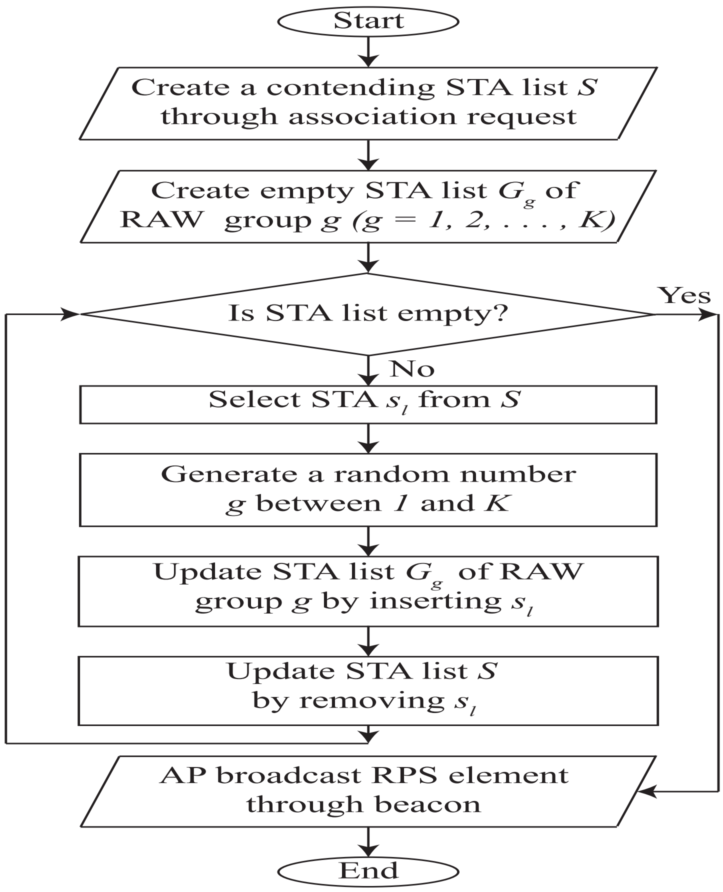

Figure 3.2: Flow chart of random grouping algorithm

3.3.2 Uniform Grouping Algorithm

Algorithm 2 Uniform grouping algorithm

Input: set of STAs S, number of RAW groups K, set of STAs in g RAW group G_g, total number of STAs N_S, total number of RAW group N_G, number of STAs in g RAW group N_g
Initialization: $N_g \leftarrow 0$, $S \leftarrow \{s_1, s_2, ...s_n\}$, $G_g \leftarrow \{\}$
compute $N_{min} = ceil(\frac{N_S}{N_G})$
for $g = 1$ to K **do**
    for $j = 1$ to N_{min} **do**
        select STA s_l from S
        $G_g \leftarrow G_g \cup \{s_l\}$
        $N_g \leftarrow N_g + 1$
        $S \leftarrow S - \{s_l\}$
    end for
end for
while $S \neq \{\}$ **do**
    if $N_g = min\{N_1, N_2, ..., N_K\}$ **then**
        select STA s_l from S
        $G_g \leftarrow G_g \cup \{s_l\}$
        $N_g \leftarrow N_g + 1$
        $S \leftarrow S - \{s_l\}$
    end if
end while
Return: G_g for $g = 1, 2, ..., K$

In this section, we present an algorithm for uniform grouping in IEEE 802.11ah WLAN. In uniform grouping algorithm the STAs are assigned into K number of empty RAW groups in such a way that the assign STAs are uniform in each RAW groups. Algorithm 2 describes the procedure for implementing uniform grouping. Initially, a set of STA $S = \{s_1, s_2, ..., s_n\}$, K number of empty RAW groups G_g $(g = 1, 2, ..., K)$ is considered. The AP first calculates total number of competing STAs N_S from the STA set S and total number of group N_G. After calculating N_S and N_G the AP compute $N_{min} = ceil(\frac{N_S}{N_G})$. N_{min} is the minimum equal number of STAs in RAW groups G_g. After that the AP select STA s_l from S insert it into group G_1 , increment the value of N_g and remove s_l from sensor set S. The s_l STAs are insert into G_1 group till the value of N_{min}. After the formation of G_1 group the above procedure will continue for all value of g. If their are some STAs cannot assign any RAW group due to $N_{min} = ceil(\frac{N_S}{N_G})$ condition, then AP assign the unassigned STA in group G_g where N_g is minimum. The above process will continue for all unassigned STAs until S become empty and then group formation for all G_g is finally completed. Finally, AP assign 13 bits AID for each STA and broadcast RAW Parameter Set (RPS) information to all STAs to inform their designated group using beacon frame. Uniform grouping procedure in flowchart is shown in Figure 3.3.

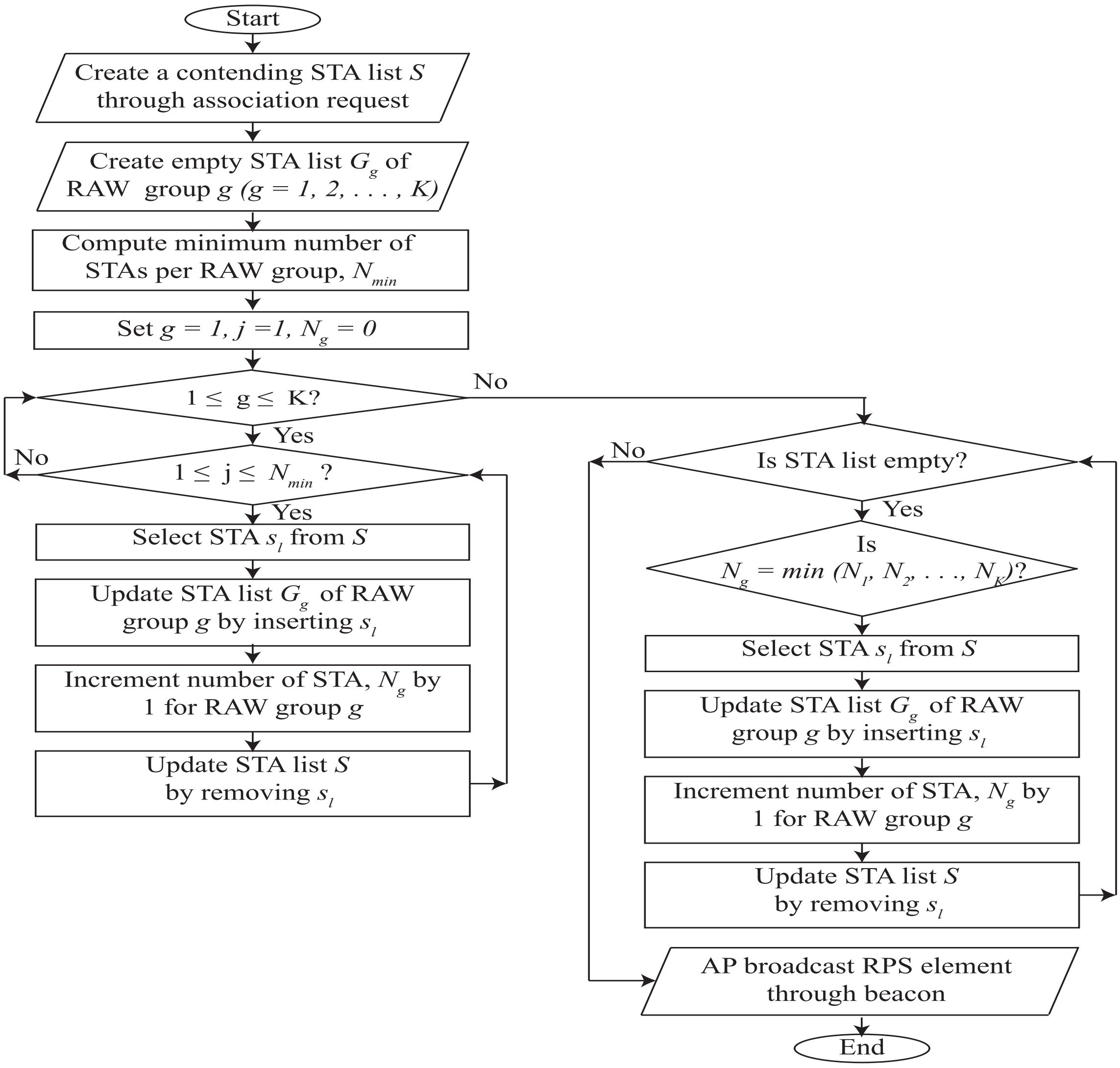

Figure 3.3: Flow chart of uniform grouping algorithm

3.4 Proposed Grouping Algorithm

The main idea of our proposed grouping algorithm is to assign each STA into K number of empty RAW groups such that traffic demand of STAs are evenly distributed and achieves fairness of throughput among the RAW groups, shown in Algorithm 3. Initially, a set of STA $S = \{s_1, s_2, ..., s_n\}$, K number of empty RAW groups G_g and group demand $D_g = 0$ is

Algorithm 3 Proposed grouping algorithm

Input: set of STAs S, number of RAW groups K, set of STAs in g RAW group G_g, traffic demand of each STA D_l, Demand of g RAW group D_g, maximum RAW group demand $D_{g,max}$, number of STAs in a RAW group N_g, buffer set of STAs $\hat{S}$
Initialization: $D_g \leftarrow 0$, $N_g \leftarrow 0$, $\hat{S} \leftarrow 0$, $S \leftarrow \{s_1, s_2, ...s_n\}$, $G_g \leftarrow \{\}$,
for $g = 1$ to K **do**
  while $S \neq \{\}$ **do**
    select STA s_l from S
    if $(D_g + D_l \leq D_{g,max})$ **then**
      $G_g \leftarrow G_g \cup \{s_l\}$
      $S \leftarrow S - \{s_l\}$
      $D_g \leftarrow D_g + D_l$
    else
      $\hat{S} \leftarrow \hat{S} \cup \{s_l\}$
      $S \leftarrow S - \{s_l\}$
    end if
  end while
  $S \leftarrow \hat{S}$
  Set $\hat{S}$ empty
end for
while $S \neq \{\}$ **do**
  if $N_g = min\{N_1, N_2, ..., N_K\}$ **then**
    $G_g \leftarrow G_g \cup \{s_l\}$
    $N_g \leftarrow N_g + 1$
    $S \leftarrow S - \{s_l\}$
  end if
end while
Return: G_g for $g = 1, 2, ..., K$

considered. The AP first calculates each STA demand D_l using Equation (3.1) and maximum expected group demand $D_{g,max}$, where $D_{g,max} = \frac{\sum_{l=1}^{n} D_l}{K}$. The AP assign a STA s_l in group G_1 if $D_1 + D_l \leq D_{g,max}$ is satisfied, otherwise s_l is assigned into a temporary STA set $\hat{S}$ and remove s_l from S. The above procedure will continue until S become empty and consequently, formation of group G_1 is initially completed. Again to form the next group, AP assign all STAs of $\hat{S}$ to S and reset $\hat{S}$. Similar action is performed for all the remaining RAW group G_g. If there are some STAs cannot assign to any RAW group due to $D_g + D_l \leq D_{g,max}$ condition, then AP calculates the number of STAs N_g for each group G_g. The unassigned STA is assigned in a group where N_g is minimum. The above process will continue for all unassigned STAs until S become empty and then group formation for all G_g is finally completed. Finally, AP assign 13 bits AID for each STA and broadcast RAW Parameter Set (RPS) information to all STAs to inform their designated group using beacon frame. Proposed grouping algorithm procedure in flowchart is shown in Figure 3.4.

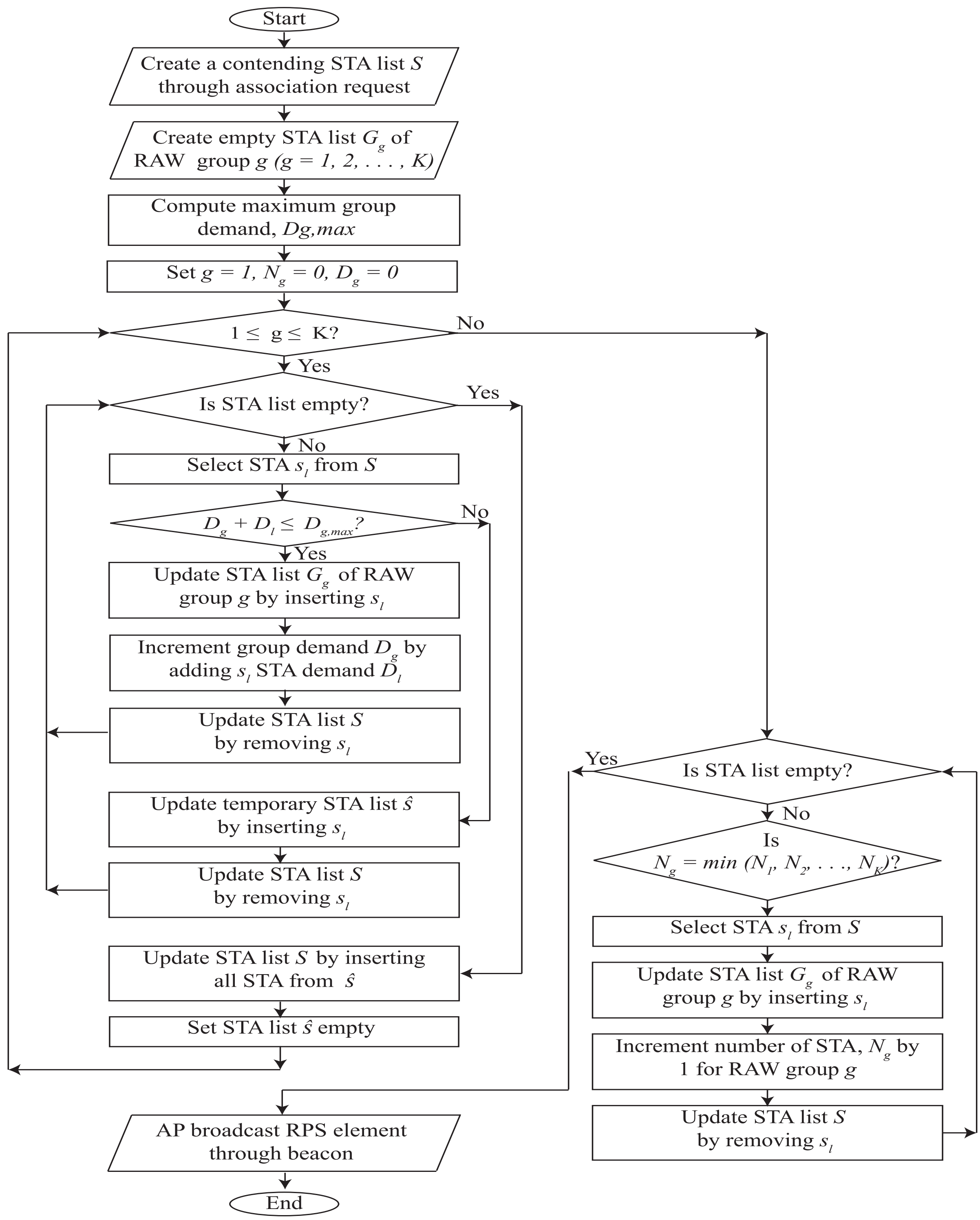

Figure 3.4: Flow chart of proposed grouping algorithm

3.5 Analytical Model for Legacy IEEE 802.11

In a dense IoT network we use IEEE 802.11ah standard instant of IEEE 802.11. To compare the performance between IEEE 802.11ah and legacy IEEE 802.11 in this section we first develop an analytical model for legacy IEEE 802.11. For this at first we designed a 2-D Markov chain for each STA of category c shown in Figure 3.5. The 2-D Markov chain represents the backoff process of c category STA having stationary distribution $b_{i,j,k}$ where, i, j and k indicates category of STA, backoff stage number and backoff counter value.

According to DCF protocol, during the backoff procedure j is set to zero initially for a new packet and increases one for every collision until it reaches maximum retry limit $m + x$. For zero backoff stage the backoff counter value k select randomly from $[0, W_0]$. The backoff counter value k is decremented by one if the channel is sensed idle otherwise freeze its counter decrements. When backoff counter value k is zero STA transmit its packet. For every successful transmission, backoff stage number is reset to zero with a new backoff counter value if the STA has at least one packet to transmit. If there is no packet to transmit the STA enters into the empty stage waiting for a frame. For every failure transmission the STA goes to a new backoff stage with a new backoff counter value and continue the backoff procedure. The contention window is chosen using the following rules

$$W_j = \begin{cases} 2^j \times (CW_{min} + 1) - 1 & ; \ 0 \leq j \leq m \\ CW_{max} & ; \ m + 1 \leq j \leq m + x \end{cases} \tag{3.2}$$

From the Markov chain we can write the one step transition probabilities as follows

$$\begin{cases} P_{(i,empty)|(i,j,0)} = (1 - \rho_i) P_{i,idle} \ ; \ 0 \leq j \leq m + x \\ P_{(i,empty)|(i,m+x,0)} = (1 - \rho_i)(1 - P_{i,idle}) \\ P_{(i,empty)|(i,empty)} = 1 - q_i \\ P_{(i,0,k)|(i,empty)} = \frac{q_i}{W_0}(1 - P_{i,idle}) \ ; \ 0 \leq k \leq W_j \\ P_{(i,0,k)|(i,j,0)} = \frac{\rho_i}{W_0} P_{i,idle} \ ; \ 0 \leq j \leq m + x \text{ and } 1 \leq k \leq W_0 \\ P_{(i,0,k)|(i,m+x,0)} = \frac{\rho_i}{W_0}(1 - P_{i,idle}) \ ; \ 1 \leq k \leq W_0 \\ P_{(i,j,k)|(i,j,k)} = 1 - P_{i,idle} \ ; \ 0 \leq j \leq m + x \text{ and } 1 \leq k \leq W_j \\ P_{(i,j,k)|(i,j,k-1)} = P_{i,idle} \ ; \ 0 \leq k \leq W_j \\ P_{(i,j,k)|(i,j-1,0)} = \frac{1}{W_j}((1 - P_{i,idle}) \ ; \ 1 \leq j \leq m + x \ \text{ and } 1 \leq k \leq W_j \end{cases} \tag{3.3}$$

According to the Markov chain, for states $(i, 0, k)$ and $1 \leq k \leq W_0$ we have,

$$\begin{cases} b_{i,0,W_0} = (1-P_{i,idle})b_{i,0,W_0} + \frac{q_i}{W_0+1}(1-P_{i,idle})b_{i,empty} + \frac{\rho_i}{W_0+1}P_{i,idle}\sum_{j=0}^{m+x} b_{i,j,0} \\ \qquad +\frac{\rho_i}{W_0+1}(1-P_{i,idle})b_{i,m+x,0} \\ b_{i,0,W_0-1} = P_{i,idle}b_{i,0,W_0} + (1-P_{i,idle})b_{i,0,W_0-1} + \frac{q_i}{W_0+1}(1-P_{i,idle})b_{i,empty} + \frac{\rho_i}{W_0+1}P_{i,idle} \\ \qquad \sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,idle})b_{i,m+x,0} \\ \qquad \vdots \\ b_{i,0,2} = P_{i,idle}b_{i,0,3} + (1-P_{i,idle})b_{i,0,2} + \frac{q_i}{W_0+1}(1-P_{i,idle})b_{i,empty} + \frac{\rho_i}{W_0+1}P_{i,idle} \\ \qquad \sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,idle})b_{i,m+x,0} \\ b_{i,0,1} = P_{i,idle}b_{i,0,2} + (1-P_{i,idle})b_{i,0,1} + \frac{q_i}{W_0+1}(1-P_{i,idle})b_{i,empty} + \frac{\rho_i}{W_0+1}P_{i,idle} \\ \qquad \sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,idle})b_{i,m+x,0} \end{cases} \tag{3.4}$$

Now, we can represent zero backoff stage generally by solving all the equations in 3.4 as follows

$$b_{i,0,k} = \frac{(W_0+1)-k}{(W_0+1)}\left\{\frac{\rho_i+(1-\rho_i)(1-P_{i,idle})}{P_{i,idle}}\right\}b_{i,0,0}, \quad \text{for} \quad i \in [1,c] \quad \text{and} \quad k \in [1, W_0] \tag{3.5}$$

The stationary probabilities for the states (i, j, k) and $1 \leq k \leq W_j$, we have

$$\begin{cases} b_{i,j,W_j} = \frac{(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{i,idle})b_{i,j,W_j} \\ b_{i,j,W_{j-1}} = \frac{(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{i,idle})b_{i,j,W_{j-1}} + P_{i,idle}b_{i,j,W_j} \\ \qquad \vdots \\ b_{i,j,2} = \frac{(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{i,idle})b_{i,j,W_2} + P_{i,idle}b_{i,j,W_2+1} \\ b_{i,j,1} = \frac{(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{i,idle})b_{i,j,W_1} + P_{i,idle}b_{i,j,W_1+1} \end{cases} \tag{3.6}$$

Equation (3.6) is the general expression for all backoff stages j, $1 \leq j \leq m+x$. By summing all the equations in equation (3.6), stationary probabilities of j^{th} backoff stage can be represented as following

$$b_{i,j,k} = \frac{(W_j+1)-k}{(W_j+1)}\left\{\frac{(1-P_{i,idle})}{P_{i,idle}}\right\}b_{i,j-1,0}, \quad \text{for} \quad i \in [1,c], \quad j \in [1, m+x] \quad \text{and} \quad k \in [1, W_j] \tag{3.7}$$

From one stage transition probability we can obtain the $b_{i,j,0}$ state transition probability as

$$b_{i,j,0} = P_{i,idle}b_{i,j,1} \tag{3.8}$$

By adding all the equations in 3.6 and 3.8 we represent $b_{i,j,0}$ as

$$b_{i,j,0} = \frac{(W_j+1)-k}{(W_j+1)}\left\{\frac{(1-P_{i,idle})}{P_{i,idle}}\right\}b_{i,j-1,0}\ , \quad \text{for} \quad i \in [1,c], \text{and } j \in [0, m+x] \tag{3.9}$$

We can explore equation 3.9 for all values of $j \in [1, m+x]$ and we have

$$\begin{cases} b_{i,1,0} = (1 - P_{i,idle}) b_{i,0,0} \\ b_{i,2,0} = (1 - P_{i,idle}) b_{i,1,0} \\ \quad\vdots \\ \quad\vdots \\ b_{i,m+x-1,0} = (1 - P_{i,idle}) b_{i,m+x-2,0} \\ b_{i,m+x,0} = (1 - P_{i,idle}) b_{i,m+x-1,0} \end{cases} \tag{3.10}$$

By adding all the equations in 3.10 the general expression can be written as

$$b_{i,j,0} = (1 - P_{i,idle})^j b_{i,0,0} \tag{3.11}$$

Now, from equation 3.7 and 3.11 we can write the general expression as follows

$$b_{i,j,k} = \frac{(W_j + 1) - k}{(W_j + 1)} \left\{ \frac{(1 - P_{i,idle})^j}{P_{i,idle}} \right\} b_{i,0,0} \quad \text{for } 1 \le j \le m + x \text{and } 0 \le k \le W_j \tag{3.12}$$

We introduce $(i, empty)$ state to introduce both saturation and non-saturation condition. The stationary probability of empty state $b_{i,empty}$ can be calculated as

$$b_{i,empty} = \frac{(1 - \rho_i)}{q_i} \; b_{i,0,0} \tag{3.13}$$

By imposing the normalized condition in the Markov chain, we get

$$b_{i,empty} + \sum_{j=0}^{m+x} b_{i,j,0} + \sum_{j=1}^{m+x} \sum_{k=1}^{W_j} b_{i,j,k} + \sum_{k=1}^{W_0} b_{i,0,k} = 1 \tag{3.14}$$

By substituting equation 3.5, 3.11, 3.12 and 3.13 we can determine the stationary probability of $(i, 0, 0)$ state as

$$b_{i,0,0} = 1 \Big/ \Big[\textstyle\sum_{j=0}^{m+x} (1 - P_{i,idle})^j + \sum_{j=1}^{m+x} \sum_{k=1}^{W_j} \left\{ \frac{(W_j+1)_k}{(W_j+1)} \frac{(1-P_{i,idle})^j}{P_{i,idle}} + \sum_{k=1}^{W_0} \right. \\ \left. \left\{ \frac{(W_0+1)_k}{(W_0+1)} \frac{\rho_i + (1-\rho_i)(1-P_{i,idle})}{P_{i,idle}} \right\} + \frac{(1-\rho_i)}{q_i} \right] \tag{3.15}$$

A STA transmit a frame either when the STA in $(i, j, 0)$ state or the channel is idle. So, transmission probability can determine as

$$\tau_i = \left[\sum_{j=0}^{m+x} (1 - P_{i,idle})^j + (1 - \rho_i) P_{i,idle} \right] b_{i,0,0} \tag{3.16}$$

Channel idle probability $(P_{i,idle})$ is that the channel is sensed idle by a STA and can be calculated as

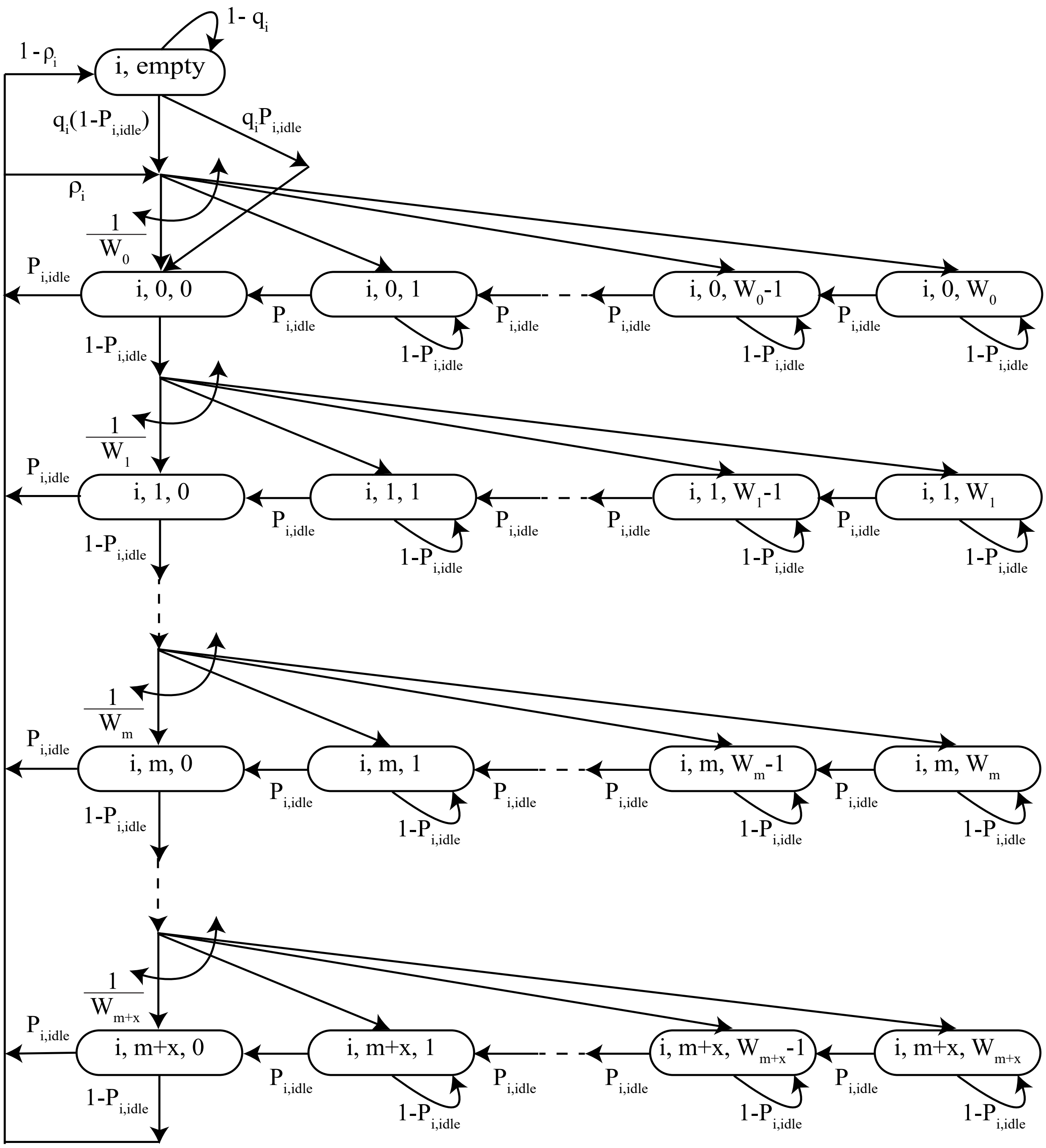

Figure 3.5: Markov chain for legacy IEEE 802.11 of a c category STA

$$P_{i,idle} = \frac{\prod_{i=1}^{c}(1-\tau_i)^{n_i}}{1-\tau_i} \tag{3.17}$$

Channel busy probability (P_{busy}) is that at least one STA transmit a frame or a collision occur and $P_{i,succ}$ is the successful transmission probability and can be calculated as

$$P_{busy} = 1 - \prod_{i=1}^{c}(1-\tau_i)^{n_i} \tag{3.18}$$

$$P_{i,succ} = \frac{\tau_i \prod_{i=1}^{c}(1-\tau_i)^{n_i}}{1-\tau_i} \tag{3.19}$$

Now, successfully transmission probability P_{succ} for all category STAs is determined as

$$P_{succ} = \sum_{i=1}^{c} n_i P_{i,succ} \tag{3.20}$$

Collision probability ($P_{i,coll}$) is that more than two STAs transmit frame at a same time and can be obtained as

$$P_{i,coll} = \frac{\tau_i(1-\prod_{i=1}^{c}(1-\tau_i)^{n_i})}{1-\tau_i} \tag{3.21}$$

Packet arrival probability in the non-saturated state is q_i and can be defined as

$$q_i = 1 - e^{-\lambda_i T_{CS}} \tag{3.22}$$

The average contention time T_{CS} can be calculated as

$$T_{CS} = (1-P_{busy})T_{slot} + P_{succ}T_{succ} + (P_{busy} - P_{succ})T_{coll} \tag{3.23}$$

Packet arrival probability in the saturated state is ρ_i and calculated as

$$\rho_i = \lambda_i D_i \tag{3.24}$$

where, D_i is the overall service time for transmitting a packet

$$\begin{aligned} D_i = &\textstyle\sum_{k=0}^{m+x} \{ \sum_{l=0}^{k} \frac{W_l}{2} T_{CS} + kT_{coll} + T_{succ} \} \{(1-P_{i,idle})\}^k P_{i,idle} + \sum_{l=0}^{m+x} \frac{W_l}{2} T_{CS} \\ &+ (m+x+1)T_{coll} \Big\{(1-P_{i,idle})\Big\}^{m+x+1} \end{aligned} \tag{3.25}$$

3.6 Analytical Model for IEEE 802.11ah

In this section, we present a analytical model to evaluate the performance of RAW mechanism for saturation and non-saturation traffic condition according to M/G/1 queuing model. At first a 2-D Markov chain model is designed for a sensor STA belonging to group g which is shown in Figure 3.6. The frame transmission process for a STA belonging to group g can be modelled by modifying Bianchi's model [68] according to the RAW mechanism and by considering saturated and non-saturated condition. There are some studies where Markov chain-based analytical model were presented to evaluate the performance of CSMA/CA mechanism [69–72]. In this Markov chain, the state of each STA of category c are represented by (i, j, k) where i, j and k indicates STA category, backoff stage number and backoff counter value, respectively. Each STA category c have same traffic demand. According to RAW mechanism of IEEE 802.11ah, a

STA can transmit frame only during its assigned RAW slot and defer from transmission during other RAW slots. We assume that a i category STA is assigned in a RAW slot r and performs

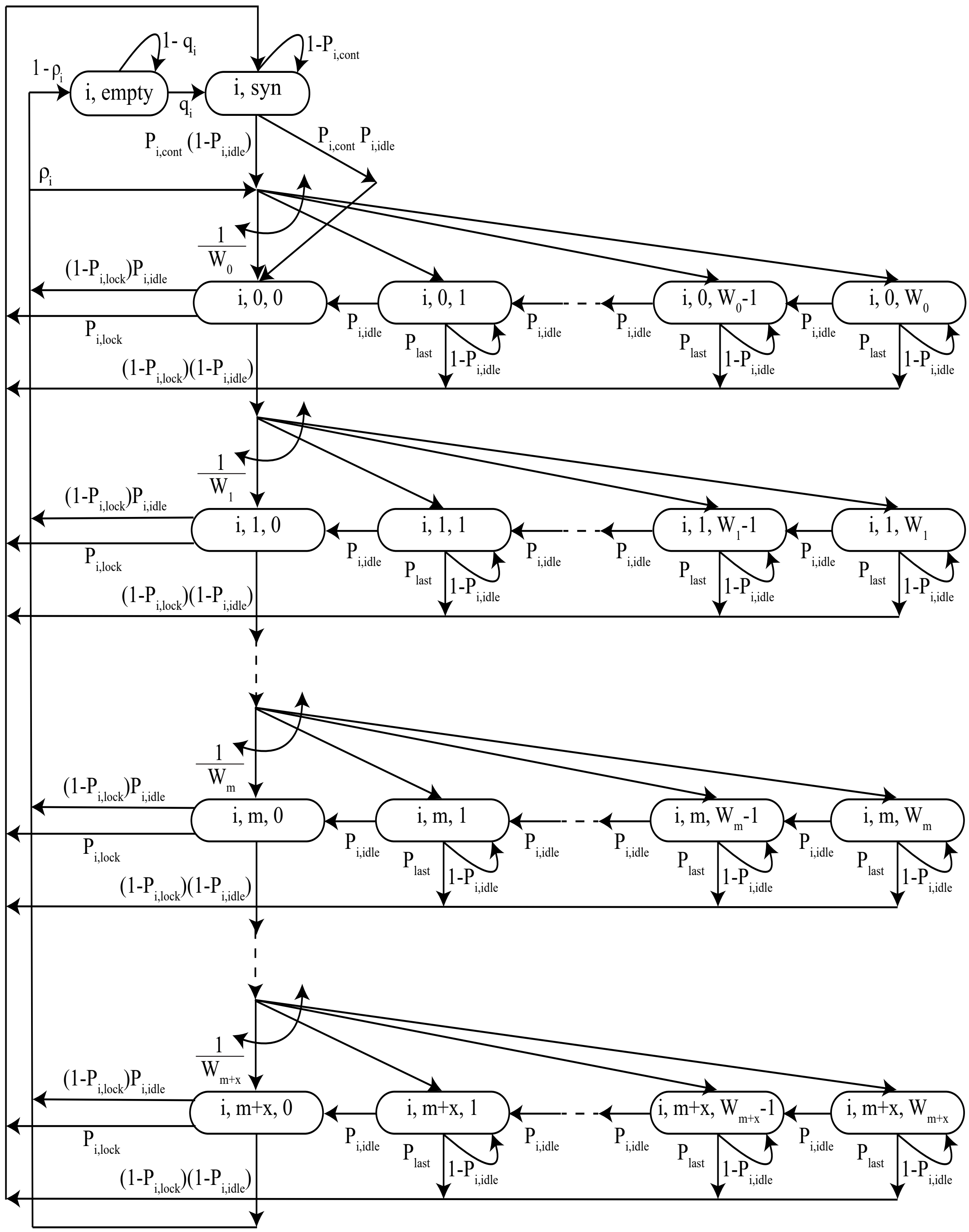

Figure 3.6: Markov chain for RAW based IEEE 802.11ah of a c category STA

the backoff procedure to transmit frame within assigned RAW slot duration $T_{r,RAWslot}$.

According to DCF protocol, during the backoff procedure the backoff stage j set to zero initially for a new packet and is incremented by one for every failure transmission until it reaches to the maximum retransmission limit $m + x$. The backoff counter value k is randomly selected from $[0, W_0]$ for backoff stage 0. The backoff counter value k is decremented by one if the channel is sensed idle and the current CSMA slot is not the last slot of the designated RAW group whereas if the current CSMA slot is the last slot, the STA will enter synchronous state and wait until next designated RAW group of the next beacon interval. If the channel is busy and the current CSMA slot is not the last slot of the designated RAW group, the backoff counter value k is freeze to its current value until the channel is sensed idle again. When the backoff counter value reaches to zero and remaining time of the current RAW group is sufficient for transmitting frame, the STA transmit the frame immediately whereas if remaining time is not sufficient, the STA will enter synchronous state and wait until next designated RAW slot of the beacon interval. If the frame is successfully transmitted, the backoff stage number is reset to zero and a new backoff counter value is selected when the STA has at least one frame to transmit. If there is no frame to transmit, the STA enters into empty state and wait until a new frame arrived. For every transmission failure the STA goes to the next backoff stage with a new backoff counter value and continue the backoff procedure. The contention window size for the backoff stage j is given by

$$W_j = \begin{cases} 2^j \times (CW_{min} + 1) - 1 \ ; & 0 \leq j \leq m \\ CW_{max} \ ; & m + 1 \leq j \leq m + x \end{cases} \tag{3.26}$$

The one-step transition probabilities between the states of the Markov chain are represented as follows

$$P_{(i,empty)|(i,j,0)} = (1 - \rho_i)(1 - P_{i,lock})P_{i,idle} \ ; \ 0 \leq j \leq m + x \tag{3.27}$$

$$P_{(i,empty)|(i,m+x,0)} = (1 - \rho_i)(1 - P_{i,lock})(1 - P_{i,idle}) \tag{3.28}$$

$$P_{(i,empty)|(i,empty)} = 1 - q_i \tag{3.29}$$

$$P_{(i,syn)|(i,empty)} = q_i \tag{3.30}$$

$$P_{(i,syn)|(i,j,k)} = P_{last} \ ; \ 0 \leq j \leq m + x \text{ and } 1 \leq k \leq W_j \tag{3.31}$$

$$P_{(i,syn)|(i,j,0)} = P_{i,lock} \ ; \ 0 \leq j \leq m + x \tag{3.32}$$

$$P_{(i,syn)|(i,syn)} = 1 - P_{i,cont} \tag{3.33}$$

$$P_{(i,0,k)|(i,syn)} = \frac{P_{i,cont}}{W_0} \ ; \ 0 \leq k \leq W_j \tag{3.34}$$

$$P_{(i,0,k)|(i,j,0)} = \frac{\rho_i}{W_0}(1 - P_{i,lock})P_{i,idle} \ ; \ 0 \leq j \leq m + x \text{ and } 1 \leq k \leq W_0 \tag{3.35}$$

$$P_{(i,0,k)|(i,m+x,0)} = \frac{\rho_i}{W_0}(1 - P_{i,lock})(1 - P_{i,idle}) \ ; \ 1 \leq k \leq W_0 \tag{3.36}$$

$$P_{(i,j,k)|(i,j,k)} = (1 - P_{last})(1 - P_{i,idle}) \ ; \ 0 \leq j \leq m + x \text{ and } 1 \leq k \leq W_j \tag{3.37}$$

$$P_{(i,j,k)|(i,j,k-1)} = (1 - P_{last})P_{i,idle} \ ; \ 0 \leq k \leq W_j \tag{3.38}$$

$$P_{(i,j,k)|(i,j-1,0)} = \frac{1}{W_j}(1 - P_{i,lock})(1 - P_{i,idle}) \ ; \ 1 \leq j \leq m + x \ \text{ and } 1 \leq k \leq W_j \tag{3.39}$$

where, each of the equations is described as follows

Equation 3.27 reflects that after a successful transmission if the queue is empty the STA enters into the empty state.

Equation 3.28 reflects that when the STA is at the maximum re-transmission limit at this stage after a collision if there is no frame to transmit then it enters in the empty state.

Equation 3.29 reflects that when the STA is in non-saturated condition and no frame arrived in the queue wait in the empty state until a frame arrived in the queue.

Equation 3.30 reflects that when a frame arrived in the empty queue the its enters into the synchronous state ant wait for RAW slot assignment.

Equation 3.31 reflects that when the STA in the saturated having a Back-off value but the CSMA slot is the last slot then enters in the synchronous state.

Equation 3.32 reflects that when the STA is saturated and the Back-off counter value is zero but there is not enough time to transmit frame then enters in the synchronous state.

Equations 3.33 and 3.34 reflect that STA remain in the synchronous state until coming its assigned RAWslot the next contention and select Backoff window when the assigned RAWslot came.

Equation 3.35 reflects that STA select a new backoff after a successful transmission when the STA is already saturated.

Equation 3.36 reflects that the STA is in the maximum retry stage, at this the STA select a new backoff after a packet drop due to collision when it is already saturated.

Equation 3.37 reflects that the STA freeze its backoff counter value when the channel is sensed busy and the CSMA clot is not the last slot.

Equation 3.38 reflects that if the channel is sensed idle and is not the last CSMA slot the STA decremented it's backoff counter value by 1.

Equation 3.39 reflects that if a collision occur and their is enough time to transmit the frame then the STA enters into the next backoff stage with a new backoff counter value.

According to the Markov chain in Figure 3.6, for the states $(i, 0, k)$, $1 \leq k \leq W_0$, we have

$$\begin{cases} b_{i,0,W_0} = (1-P_{last})(1-P_{i,idle})b_{i,0,W_0} + \frac{P_{i,cont}(1-P_{i,idle})}{W_0+1}b_{i,syn} + \frac{\rho_i}{W_0+1}(1-P_{i,lock})P_{i,idle} \\ \qquad \sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,lock})(1-P_{i,idle})b_{i,m+x,0} \\ b_{i,0,W_0-1} = (1-P_{last})P_{i,idle}b_{i,0,W_0} + (1-P_{last})(1-P_{i,idle})b_{i,0,W_0-1} + \frac{P_{i,cont}(1-P_{i,idle})}{W_0+1}b_{i,syn} + \\ \qquad \frac{\rho_i}{W_0+1}(1-P_{i,lock})P_{i,idle}\sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,lock})(1-P_{i,idle})b_{i,m+x,0} \\ \qquad \vdots \\ b_{i,0,2} = (1-P_{last})P_{i,idle}b_{i,0,3} + (1-P_{last})(1-P_{i,idle})b_{i,0,2} + \frac{P_{i,cont}(1-P_{i,idle})}{W_0+1}b_{i,syn} + \\ \qquad \frac{\rho_i}{W_0+1}(1-P_{i,lock})P_{i,idle}\sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,lock})(1-P_{i,idle})b_{i,m+x,0} \\ b_{i,0,1} = (1-P_{last})P_{i,idle}b_{i,0,2} + (1-P_{last})(1-P_{i,idle})b_{i,0,1} + \frac{P_{i,cont}(1-P_{i,idle})}{W_0+1}b_{i,syn} + \\ \qquad \frac{\rho_i}{W_0+1}(1-P_{i,lock})P_{i,idle}\sum_{j=0}^{m+x} b_{i,j,0} + \frac{\rho_i}{W_0+1}(1-P_{i,lock})(1-P_{i,idle})b_{i,m+x,0} \end{cases} \tag{3.40}$$

By solving all the equation in (3.40) the zero backoff stage can be represented as

$$b_{i,0,k} = \frac{\sum_{k1=0}^{W_0-k} C_i^{k1}}{(W_0+1)(1-(1-P_{last})(1-P_{i,idle}))}\left\{b_{i,syn} + \rho_i(1-P_{i,lock})\left(P_{i,idle}\sum_{j=0}^{m+x} b_{i,j,0} + (1-P_{i,idle})\right.\right. \\ \left.\left. b_{i,m+x,0}\right)\right\}, \qquad \text{for} \quad i \in [1, c] \quad \text{and} \quad k \in [1, W_0] \tag{3.41}$$

where, the quantity C_i is defined as follows

$$C_i = \frac{P_{i,idle}(1-P_{last})}{1-(1-P_{i,idle})(1-P_{last})} \tag{3.42}$$

According to the Markov chain, the stationary probabilities for the states (i, j, k), $1 \leq k \leq W_j$, we have

$$\begin{cases} b_{i,j,W_j} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{last})(1-P_{i,idle})b_{i,j,W_j} \\ b_{i,j,W_{j-1}} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{last})(1-P_{i,idle})b_{i,j,W_{j-1}} + (1-P_{last})P_{i,idle}b_{i,j,W_j} \\ \qquad \vdots \\ b_{i,j,2} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{last})(1-P_{i,idle})b_{i,j,W_2} + (1-P_{last})P_{i,idle}b_{i,j,W_2+1} \\ b_{i,j,1} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{W_j+1}b_{i,j-1,0} + (1-P_{last})(1-P_{i,idle})b_{i,j,W_1} + (1-P_{last})P_{i,idle}b_{i,j,W_1+1} \end{cases} \tag{3.43}$$

Equation (3.43) is the general expression for all backoff stages j, $1 \leq j \leq m+x$. By summing all the equations in equation (3.43), stationary probabilities of j^{th} backoff stage can be represented as following

$$b_{i,j,k} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))} \sum_{k=0}^{W_j-k} C_i^k \; b_{i,j-1,0} \qquad (3.44)$$
$$\text{for} \quad i \in [1,c], \quad j \in [1, m+x] \quad \text{and} \quad k \in [1, W_j]$$

From equation (3.38) we obtain

$$b_{i,j,0} = (1-P_{last}) P_{i,idle} \; b_{i,j,1} \quad ; \; 1 \leq j \leq m+x \qquad (3.45)$$

By adding all the equations in 3.43 and 3.45 we represent $b_{i,j,0}$ as

$$b_{i,j,0} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \; b_{i,j-1,0} \quad \text{for} \quad i \in [1,c] \quad \text{and} \quad j \in [0, m+x] \qquad (3.46)$$

We can explore equation (3.46) for all the values of j, $1 \leq j \leq m+x$ and we have

$$\begin{cases} b_{i,1,0} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \; b_{i,0,0} \\ b_{i,2,0} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \; b_{i,1,0} \\ \quad \vdots \\ \quad \vdots \\ b_{i,m+x-1,0} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \; b_{i,m+x-2,0} \\ b_{i,m+x,0} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \; b_{i,m+x-1,0} \end{cases} \qquad (3.47)$$

By adding all the equations in 3.47 the general expression can be written as

$$b_{i,j,0} = \prod_{j=1}^{j} \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \; b_{i,0,0}; j \in [1, m+x] \qquad (3.48)$$

Now, from equation 3.44 and 3.48 we can write the general expression as follows

$$b_{i,j,k} = \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))} \sum_{k1=0}^{W_j-k} C_i^{k1} \left(\prod_{j=0}^{j} \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j} C_i^k \right) b_{i,0,0} \qquad (3.49)$$
$$\text{for} \quad i \in [1,c] \quad , \quad j \in [0, m+x] \quad \text{and } k \in [1, W_j]$$

To analyze both saturation and non-saturation traffic conditions, we introduce another state in the Markov chain is denoted by $(i, empty)$, which represents the state of a STA of category c_i. When the queue is empty after a successful transmission or a frame drop then the sensor STA enters into empty state. The stationary probability of empty state, $(b_{i,empty})$ can be determined from the Markov chain as follows

$$b_{i,empty} = \frac{(1-\rho_i)}{q_i} \left(\sum_{j=0}^{m+x} (1-P_{i,lock}) P_{i,idle} b_{i,j,0} + (1-P_{i,lock})(1-P_{i,idle}) b_{i,m+x,0} \right) \qquad (3.50)$$

Putting the value of $b_{i,j,0}$ and $b_{i,m+x,0}$ we get $b_{i,empty}$ as follows

$$\begin{aligned} b_{i,empty} = \tfrac{(1-\rho_i)}{q_i}\Bigg[(1-P_{i,lock})P_{i,idle}\Bigg\{1+\textstyle\sum_{j=1}^{m+x}\Bigg(\prod_{j=1}^{j}\tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\Bigg)\Bigg\} \\ +(1-P_{i,lock})(1-P_{i,idle})\Bigg(\textstyle\prod_{j=1}^{m+x}\tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\Bigg)\Bigg]\ b_{i,0,0} \end{aligned} \tag{3.51}$$

In this work, we consider non-crossing boundary condition for this a synchronous state denoted as $b_{i,syn}$ also introduced. A STA enters into a synchronous state in three condition

- Backoff counter value is zero but their is not enough time to transmit a frame
- Backoff counter value is not zero but this is the last CSMA slot
- STA remains in this state until it's assigned RAW slot come

The synchronous state $b_{i,syn}$ can be expressed as follows

$$b_{i,syn} = q_i\ b_{i,empty} + \sum_{j=0}^{m+x}\sum_{k=1}^{W_j} b_{i,j,k}\ P_{last} + \sum_{j=0}^{m+x} b_{i,j,0}\ P_{i,lock}$$

$$\begin{aligned} b_{i,syn} &= q_i\ b_{i,empty} + \textstyle\sum_{j=0}^{m+x}\sum_{k=1}^{W_j} b_{i,j,k}\ P_{last} + \sum_{j=0}^{m+x} b_{i,j,0}\ P_{i,lock} \\ &= q_i\ b_{i,empty} + \textstyle\sum_{k=1}^{W_0} b_{i,0,k}.P_{last} + \sum_{j=1}^{m+x}\sum_{k=1}^{W_j} b_{i,j,k}\ P_{last} + \sum_{j=0}^{m+x} b_{i,j,0}\ P_{i,lock} \end{aligned} \tag{3.52}$$

By substituting equations 3.41, 3.48 and 3.49 we can obtain the stationary probability of synchronous state as follows

$$\begin{aligned} b_{i,syn} = \frac{1}{\left(1-\frac{P_{last}\sum_{k=1}^{W_j}\left(k(C_i)^{W_j-k}\right)}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\right)P_{i,cont}}\Bigg[q_i b_{i,empty} + P_{last}\Bigg\{\textstyle\sum_{j=1}^{m+x}\Bigg(\sum_{k=1}^{W_j} \\ \tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\textstyle\sum_{k=0}^{W_j-k}C_i^k\Bigg)\Bigg(\prod_{j=1}^{j-1}\tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\Bigg)\Bigg\}b_{i,0,0}+ \\ P_{i,lock}\Bigg\{1+\textstyle\sum_{j=1}^{m+x}\Bigg(\prod_{j=1}^{j}\tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\Bigg)\Bigg\}b_{i,0,0} + \sum_{k=1}^{W_j}\left(k(C_i)^{W_j-k}\right) \\ \tfrac{P_{last}}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\Bigg\{\rho_i(1-P_{i,lock})P_{i,idle}\Bigg(1+\textstyle\sum_{j=1}^{m+x}\Bigg(\prod_{j=1}^{j}\tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \\ \textstyle\sum_{k=0}^{W_j}C_i^k\Bigg)\Bigg)+\rho_i(1-P_{i,lock})(1-P_{i,idle})\Bigg(\prod_{j=1}^{m+x}\tfrac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\Bigg)\Bigg\}\ b_{i,0,0}\Bigg] \end{aligned} \tag{3.53}$$

By imposing the normalization condition in Markov chain, we get

$$b_{i,empty} + b_{i,syn} + \sum_{j=0}^{m+x} b_{i,j,0} + \sum_{k=1}^{W_0} b_{i,0,k} + \sum_{j=1}^{m+x}\sum_{k=1}^{W_j} b_{i,j,k} = 1 \tag{3.54}$$

By substituting equations 3.41, 3.48, 3.49, 3.51 and 3.53 in equation 3.54 we can determine the stationary probability of $(i,0,0)$ state as

$$b_{i,0,0} = \left[1 - b_{i,empty} - b_{i,syn}\left\{1 + \frac{P_{i,cont}\sum_{k=1}^{W_j}\left(k(C_i)^{W_j-k}\right)}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\right\}\right] \Big/ \left[1 + \left\{\sum_{j=1}^{m+x} \left(\prod_{j=1}^{j}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right\} + \left\{\sum_{j=1}^{m+x}\left(\sum_{k=1}^{W_j}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))} \sum_{k=0}^{W_j-k}C_i^k\right)\left(\prod_{j=1}^{j-1}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right\} + \left\{\frac{\sum_{k=1}^{W_j}\left(k(C_i)^{W_j-k}\right)}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))} \left\{\rho_i(1-P_{i,lock})P_{i,idle}\left(1+\sum_{j=1}^{m+x}\left(\prod_{j=1}^{j}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right) + \rho_i(1-P_{i,lock})(1-P_{i,idle})\left(\prod_{j=1}^{m+x}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right\}\right\}\right] \tag{3.55}$$

Consequent to the Markov chain, a STA will transmit a frame either when the STA is in $(i,j,0)$ state or the STA sensed the channel is idle in its designated RAW slot from the synchronous state. Thus, transmission probability is obtained as

$$\tau_i = \sum_{j=0}^{m+x} b_{i,j,0} + P_{i,cont}P_{i,idle}b_{i,syn} \tag{3.56}$$

By substituting equations 3.46 and 3.53 in equation 3.57 we can determine

$$\tau_i = \left(1+\sum_{j=1}^{m+x}\left(\prod_{j=1}^{j}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right)b_{i,0,0} + P_{i,cont}P_{i,idle} \frac{1}{\left(1-\frac{P_{last}\sum_{k=1}^{W_j}\left(k(C_i)^{W_j-k}\right)}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\right)P_{i,cont}} \left[q_i b_{i,empty} + P_{last}\left\{\sum_{j=1}^{m+x}\left(\sum_{k=1}^{W_j} \frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\sum_{k=0}^{W_j-k}C_i^k\right)\left(\prod_{j=1}^{j-1}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right\}b_{i,0,0} + P_{i,lock}\left\{1+\sum_{j=1}^{m+x}\left(\prod_{j=1}^{j}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right\}b_{i,0,0} + \sum_{k=1}^{W_j}\left(k(C_i)^{W_j-k}\right) \frac{P_{last}}{(W_j+1)(1-(1-P_{last})(1-P_{i,idle}))}\left\{\rho_i(1-P_{i,lock})P_{i,idle}\left(1+\sum_{j=1}^{m+x}\left(\prod_{j=1}^{j}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)} \sum_{k=0}^{W_j}C_i^k\right)\right) + \rho_i(1-P_{i,lock})(1-P_{i,idle})\left(\prod_{j=1}^{m+x}\frac{(1-P_{i,lock})(1-P_{i,idle})}{(W_j+1)}\sum_{k=0}^{W_j}C_i^k\right)\right\} b_{i,0,0}\right] \tag{3.57}$$

where, $P_{i,cont}$ as the probability that the STA i start contention procedure in its designated RAW group,

$$P_{i,cont} = \frac{T_{RAWslot}}{T_{RAW}} \tag{3.58}$$

For non-crossing boundary condition we introduced $P_{i,lock}$ as the probability that current CSMA slot is not enough for transmitting a frame and P_{last} is the probability that current CSMA slot is last slot. Then the STA enters into the synchronous state waiting for its assigned RAW slot in the next beacon period

$$P_{i,lock} = \frac{L_{succ}}{L_{RAWslot}} \tag{3.59}$$

$$P_{last} = \frac{1}{L_{RAWslot}} \tag{3.60}$$

where, $T_{RAWslot}$, $L_{RAWslot}$ and L_{succ} are the RAW slot duration in time, length of the RAW slot and number of slot for successful transmission, respectively.

$$\begin{aligned} T_{RAWslot} &= \tfrac{T_{RAW}}{n_{RAWslot}} \\ L_{RAWslot} &= \tfrac{T_{RAWslot}}{T_{slot}} \\ L_{succ} &= \tfrac{T_{RAWslot}}{T_{slot}} \end{aligned} \tag{3.61}$$

Channel idle probability ($P_{i,idle}$) is the probability that a CSMA slot is idle sensed by a STA of category i and defined as

$$P_{i,idle} = \frac{\prod_{i=1}^{c}(1-\tau_i)^{n_i}}{1-\tau_i} \tag{3.62}$$

Channel busy probability (P_{busy}) is that at least one STA transmit a frame over the channel and $P_{i,succ}$ is the probability that i category STAs successfully transmit their frame and can be define as

$$P_{busy} = 1 - \prod_{i=1}^{c}(1-\tau_i)^{n_i} \tag{3.63}$$

$$P_{i,succ} = \frac{\tau_i \prod_{i=1}^{c}(1-\tau_i)^{n_i}}{1-\tau_i} \tag{3.64}$$

Now, the summation of all category STAs successfully transmission probability P_{succ} can be calculated as

$$P_{succ} = \sum_{i=1}^{c} n_i P_{i,succ} \tag{3.65}$$

Transmission collision probability ($P_{i,coll}$) is that when at least two STAs transmit frame at the same time on channel. The transmission collision probability of a STA of category C_i can be calculated as following

$$P_{i,coll} = \frac{\tau_i(1-\prod_{i=1}^{c}(1-\tau_i)^{n_i})}{1-\tau_i} \tag{3.66}$$

In this work, since we assumed that packets arrival rate of a STA of category i is Poisson process. Therefore, if q_i is the probability that at least one packet will arrive in the empty queue, with arrival rate λ_i and the average contention period $T_{i,CS}$.

$$q_i = 1 - e^{-\lambda_i T_{i,cs}} \tag{3.67}$$

The average contention time T_{cs} can be calculated as

$$T_{i,cs} = (1 - P_{busy})T_{slot} + (1 - P_{i,lock})P_{succ}T_{succ} + (1 - P_{i,lock})(P_{busy} - P_{succ})T_{coll} \tag{3.68}$$

The assumption of M/G/1 queues allows to compute the probability for i category STA that at least one packet will arrive in a non-empty queue after the previous transmission is finished (saturation condition) in the following way

$$\rho_i = \lambda_i D_i \tag{3.69}$$

where, D_i is the overall service time of transmitting a packet of i category STA. It is a sum of the following : (i) average contention delay, (ii) frame blocking delay, (iii) collision delay, (iv) transmission delay and (v) re-transmission delay. We can calculate D_i as follows

$$D_i = \left\{ \sum_{k=0}^{m+x} \sum_{l=0}^{k} \frac{W_l}{2} T_{i,CS} + kT_{coll} + T_{succ} \right\} \left\{(1 - P_{i,lock})(1 - P_{i,idle})\right\}^k$$
$$\left\{(1 - P_{i,lock})P_{i,idle}\right\} + \sum_{l=0}^{m+x} \frac{W_l}{2} T_{i,CS} + (m + x + 1)T_{coll} \left\{(1 - P_{i,lock})(1 - P_{i,idle})\right\}^{m+x+1} \tag{3.70}$$

If the channel is idle, the duration of the state is one CSMA slot $T_{csma-slot}$. When the channel is sensed as busy its means that either successful transmission, transmission collision, or error transmission is occurred in the channel. If successful transmission is occurred, the duration of the state is the time of a successful transmission, which is estimated as follows

$$T_{succ} = T_{AIFS} + T_{pspoll} + T_{pspollack} + T_{DATA} + T_{ACK} + 3T_{SIFS} + 4\alpha \tag{3.71}$$

where, α is the propagation delay, T_{AIFS}, T_{pspoll}, $T_{pspollack}$, T_{DATA}, T_{ACK} and T_{SIFS} represents the duration of AIFS, pspoll,pspollack, DATA, ACK and SIFS in time, respectively.

$$\begin{aligned}
&T_{AIFS} = T_{SIFS} + AIFSN\ T_{slot} \\
&T_{pspoll} = \frac{h_{PHY}}{r_{basicdata}} \\
&T_{pspollack} = \frac{h_{PHY}}{r_{basicdata}} \\
&T_{ACK} = \frac{h_{PHY}}{r_{basicdata}} \\
&T_{DATA} = ceil\left(\frac{framebody + h_{MAC}}{\frac{r_{data}}{r_{basicdata}} l_{bitpersymbol}}\right) t_{symbol} + T_{PHY} \\
&T_{PHY} = \frac{h_{PHY}}{r_{basicdata}} \\
&T_{framebody} = ceil\left(\frac{framebody}{\frac{r_{data}}{r_{basicdata}} l_{bitpersymbol}}\right) t_{symbol} \\
&T_{coll} = T_{AIFS} + T_{pspoll} + T_{pspollack} + T_{SIFS} + 2alpha
\end{aligned} \tag{3.72}$$

Simplifying all the above derived equations of the proposed analytical model, we obtain 38 equations while we have 38 unknown variables of category i $(i = 1, 2, 3, 4)$: P_{busy}, P_{succ} $P_{i,idle}$, $P_{i,succ}$, $P_{i,empty}$, $P_{i,syn}$, C_i, τ_i, q_i, b_i, ρ_i. Finally, we solve the simplified equations using Maple 18 and then determine the performance metrics that are defined in following Section.

3.7 Performances Metrics

In this section, we derive the expressions of the performance metrics viz. normalized throughput, average access delay, reliability, energy consumption and fairness to explore the performance of the network.

3.7.1 Reliability

Reliability means packets are guaranteed to reach their destination complete and un-corrupted and in the order they were sent. The successfully transmission probability for a STA of category i is called reliability of the STA. In other words, reliability is the complementary probability with which a transmitted packet is dropped due to repeated transmission collision after $m+x+1$ attempts. Therefore, R_i is mathematically given as

$$R_i = 1 - \left(1 - P_{i,idle}\right)^{m+x+1} \tag{3.73}$$

Reliability for all assigned STA in a RAW slot can be calculated as

$$R = \frac{\sum_{i=1}^{c} R_i}{c} \tag{3.74}$$

3.7.2 Normalized Throughput

Throughput is a performance metric to evaluate how effectively the network bandwidth is utilized. Throughput of the network is measured as the total number of successful packet transmission over a specified time. The normalized throughput of i category STAs is defined as the ratio of time that category i STAs use for successful transmission of a frame and the average duration and mathematically expressed as

$$S_i = \frac{P_{i,succ}T_{framebody}}{(1-P_{busy})T_{slot} + P_{succ}T_{succ} + (P_{busy}-P_{succ})T_{coll}} \tag{3.75}$$

where $T_{framebody}$, T_{slot}, T_{succ} and T_{coll} is length of framebody in time, the duration of a CSMA slot, duration of a successful transmission and duration of a collision, respectively. The overall normalized throughput of RAW group g is defined as

$$S_g = \sum_{i=1}^{c} S_i \tag{3.76}$$

3.7.3 Access Delay

The average access delay of a STA of i category is defined as the average time for the instance when a packet is generated to the instance and when the packet is successfully transmitted or dropped. The average access delay depends on waiting time for permitted RAW slot for a STA of category i, average contention delay, collision delay, transmission delay and re-transmission delay. Thus, we can calculated average access delay as follows

$$\begin{aligned} T_{i,delay} = {} & \textstyle\sum_{k=0}^{m+x} \Big(\sum_{l=0}^{k} \frac{W_l}{2}\big((1-P_{busy})t_{slot} + (1-P_{i,lock})P_{succ}t_{succ} + (1-P_{i,lock}) \\ & (P_{busy}-P_{succ})t_{coll}\big) + kt_{coll} + t_{succ}\Big)((1-P_{i,lock})(1-P_{i,idle}))^k((1-P_{i,lock})P_{i,idle}) + \\ & \textstyle\sum_{l=0}^{m+x} \frac{W_l}{2}\Big((1-P_{busy})t_{slot} + (1-P_{i,lock})P_{succ}t_{succ} + (1-P_{i,lock})(P_{busy}-P_{succ})t_{coll}\Big) \\ & +(m+x+1)t_{coll}((1-P_{i,lock})(1-P_{i,idle})^{m+x+1} \end{aligned} \tag{3.77}$$

The total delay for a RAW group g is the ratio of sum of average access delay for all assigned STA in a RAW group and total STAs category c and can be calculated as

$$T_{delay} = \frac{\sum_{i=1}^{c} T_{i,delay}}{c} \tag{3.78}$$

3.7.4 Energy Consumption

The energy consumption of a STA is caused by several stages: (i) idle stage, when the channel is sensed idle by the STA, (ii) successful stage, when a STA transmits packet successfully and

(iii) collision stage, when a STA experience a collision [73, 74]. The mean energy consumption of a STA of category i (E_i) is computed as

$$E_i = E_{i,idle} + E_{i,succ} + E_{i,coll} \tag{3.79}$$

where $E_{i,idle}$, $E_{i,succ}$, $E_{i,coll}$ and $E_{i,error}$ are the energy consumption during idle stage, successful stage nd collision stage respectively. We can calculated them as

$$\begin{aligned}
E_{i,succ} &= \Big(T_{pspoll}\ P_{tx} + T_{pspollack}\ P_{rx} + T_{DATA}\ P_{tx} + T_{ACK}\ P_{rx} + 3\ T_{SIFS}\ P_{idle}\Big) P_{i,succ} \\
E_{i,coll} &= \Big(T_{pspoll}\ P_{tx} + T_{pspollack}\ P_{rx} + T_{SIFS}\ P_{idle}\Big) P_{i,coll} \\
E_{i,idle} &= P_{idle}\ T_{slot}\ P_{i,idle}
\end{aligned} \tag{3.80}$$

where, P_{tx}, P_{rx} and P_{idle} denote energy consumption in transmitting state, receiving state and idle state of a STA, respectively. Now, the average energy consumed in a RAW slot by the assigned STAs is calculated as

$$E = \frac{\sum_{i=1}^{c} n_i\ E_i}{c} \tag{3.81}$$

3.7.5 Fairness

Fairness measures used in network to determine whether users or applications are receiving a fair share of system resources. Fairness ensures that all STAs are getting a chance to transmit its packets during its allocated slot duration. The Jain's fairness index [75] is used to measure the fairness in resource allocation among different RAW groups and it mathematically expressed as

$$F = \frac{(\sum_{g=1}^{K} S_g)^2}{N_{RAWslot} \sum_{g=1}^{K} (S_g)^2} \tag{3.82}$$

where, S_g is the aggregated normalized throughput and $N_{RAWslot}$ is the number of RAW slots.

3.8 Summary

This chapter presents proposed grouping algorithm for fairness among the RAW groups and its analytical model. Some related existing grouping algorithm and legacy DCF analytical model and performance metrics also presented here.

Chapter 4

Performance Evaluation

4.1 Introduction

In this section we present our analytical results which is solved by Maple 18 and grouping result which is generated by C++ simulation. A performance comparison between RAW based IEEE802.11ah and Legacy DCF provided in this chapter. A comparison between existing and proposed grouping also presented in this chapter.

4.2 Analytical Results

In this section, we evaluate the performance of the proposed traffic demand-based grouping algorithm of IEEE 802.11ah network with heterogeneous traffic demand STAs. We assume an one-hop star topology IoT network where all the STAs and AP are IEEE 802.11ah devices. We consider four category STAs, a $4MHz$ bandwidth channel and a BPSK modulation with 1/2 coding scheme allows 26 bits to be transmitted $40\mu s$ with a long guard interval per OFDM symbol. We assume that each STA of category i has a packet arrival rate λ_i per minute in Poisson process. For simplicity, we assume that each category STA have a distinct packet arrival rate ($\lambda_1 = 2, \lambda_2 = 4, \lambda_3 = 6$ and $\lambda_4 = 8packets/sec$) whereas transmission data rate Rl and packet length Ll are same for all categories STA. and also consider CAW is zero and work only in the RAW period and each RAW is $1s$. In RAW scheme $PS-poll, PS-pollack$ and ack mechanism is used for both uplink and downlink transmission. The parameters for the model are shown in Table 4.1.

Table 4.1: PHY and MAC parameters of the system

Parameters	**Values**	**Parameters**	**Values**
AIFSN	2 *bits*	RAW duration	1 *s*
SIFS	160 μs	Number of RAW slot	4
Slot duration	52 μs	Node type	4
Propagation delay	6 μs	CW_{min}	7
Symbol	40 μs	CW_{max}	31
Data rate	650 *kbps*	Retry limit	7
Basic data rate	7800 *kbps*	P_{tx}	204 mW
PHY header	156 *bps*	P_{rx}	92 mW
MAC header	14 *bps*	P_{idle}	20 mW
Framebody	256 *bytes*		

4.3 Performance Comparison between IEEE 802.11ah and Legacy IEEE 802.11

IoT network is a dense network. In IoT network we are using IEEE 802.11ah standard instead of using legacy IEEE 802.11 standard. If we use legacy DCF protocol in dense IoT network scenarios all the STAs having frames in their MAC queue ready for transmission, compete simultaneously for channel access, which leads to very heavy collision. This ultimately reduce network throughput, increase access delay, provide lower reliability and higher energy consumption. Due to this reason we use IEEE 802.11ah protocol in dense IoT network which increase network throughput, reduce access delay, increase reliability and decrease energy consumption. To prove this in this section we represent the analytical result of legacy IEEE 802.11 DCF standard and IEEE 802.11ah DCF standard and compare their result.

4.3.1 Reliability

Figure 4.1 depicts the reliability against the number of STAs for both legacy DCF and IEEE 802.11ah grouping scheme. It is seen that the reliability decrease as the number of STA increases. This is because packet successful probability decreases as the the STAs increases in the network. From Figure 4.1 it is also seen when the number of STAs increases the reliability of legacy DCF is more affected than the grouping scheme. This is because in grouping scheme

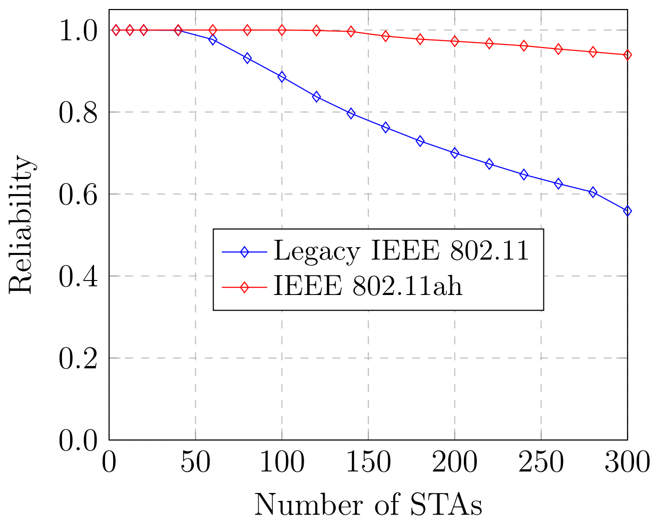

Figure 4.1: Comparing reliability of IEEE 802.11ah and legacy IEEE 802.11

the contending STAs are decreases by assigning the STAs in RAW group on the other hand a large number of STAs are trying to transmit packet in legacy DCF. However, the transmission successful probability is increases in proposed grouping scheme than legacy DCF and thus results higher network throughput than legacy DCF. The results high throughput and greater successful probability indicated better reliability of IEEE 802.11ah based grouping scheme than the legacy DCF scheme.

4.3.2 Normalized Throughput

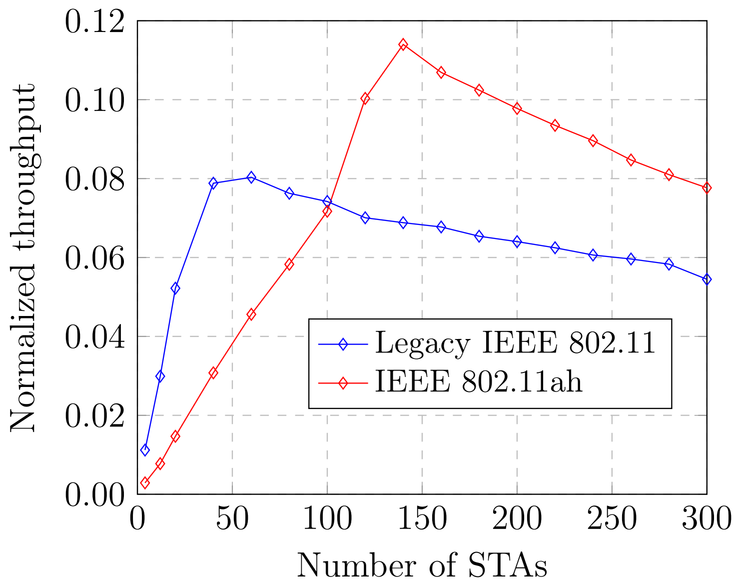

Figure 4.2: Comparing normalized throughput of IEEE 802.11ah and legacy IEEE 802.11

Figure 4.2 illustrate the normalized throughput of the proposed grouping algorithm for IEEE 802.11ah protocol and legacy DCF protocol versus the number of STAs. It is also shows the normalized throughput comparison of the proposed grouping algorithm for IEEE 802.11ah and conventional DCF. In both cases the normalized throughput decreases as the number of STAs increases, this is due to the fact that increase average channel access time and packet collision. The Legacy DCF scheme is highly affected by the increasing channel access time and packet collision when the number of STAs increase, which results the network throughput reduces significantly. From Figure 4.2 it is seen that, the network throughput of IEEE 802.11ah is improves as compare to legacy DCF. A peak normalize throughput of 0.12 and 0.08 was observed for proposed grouping scheme of IEEE 802.11ah and legacy DCF, respectively. Legacy DCF obtain peak value of throughput for 50 STAs and grouping scheme obtain peak value of throughput for 150 STAs. This is because, number of STAs is reduced by assigning STAs in different RAW groups using grouping algorithm. Moreover, the grouping based protocol decreases both average access delay and packet collision. So therefore it is clear that, the proposed grouping scheme for IEEE 802.11ah provide better network throughput as compare to the legacy DCF protocol.

4.3.3 Access Delay

Figure 4.3 shows the overall access delay of the network against the number of STAs for IEEE 802.11ah and legacy DCF. It is visible that the average channel access delay increase as the number of STAs increase for both grouping scheme and legacy DCF scheme. Due to the large

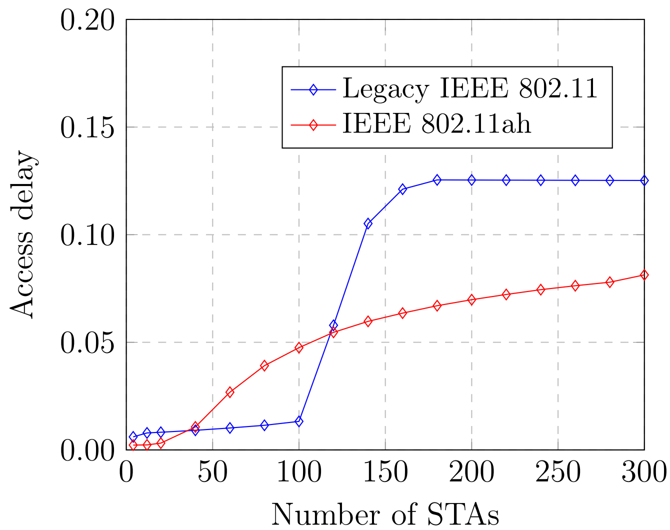

Figure 4.3: Comparing access delay of IEEE 802.11ah and legacy IEEE 802.11

number of STAs each STA experience a congestion problem in the network. Thus results more collision probability and re-transmission of packet. Figure 4.3 also depicts that the proposed grouping scheme for IEEE 802.11ah has lower access delay as compare to legacy DCF. This is because, the grouping scheme reduce collision probability and packet re-transmission probability by assigning STAs in RAW group.

4.3.4 Energy Consumption

Figure 4.4 presents energy consumption in mJ for IEEE 802.11 DCF and IEEE 802.11ah proposed grouping scheme with respect to number of varying STAs. From Figure it is seen that energy consumption increases as the number of STA decreases this is due to the fact that increase average delay and packet collision. The DCF scheme is highly affected than the grouping scheme. This is because in DCF all the STAs have packet to transmit and tying to transmit them in one channel at a time that causes higher access delay and higher packet collision. On the other hand in proposed grouping scheme the number of contending STAs decrease by assigning them into multiple RAWs thus results lower collision then legacy DCF. The assign STAs in one RAW group can only trying to access the channel and all the other STAs assigned in other RAW group they going to sleep mode till their assigned RAW slot reached. However the grouping based IEEE 802.11ah results lower energy consumption than legacy IEEE 802.11.

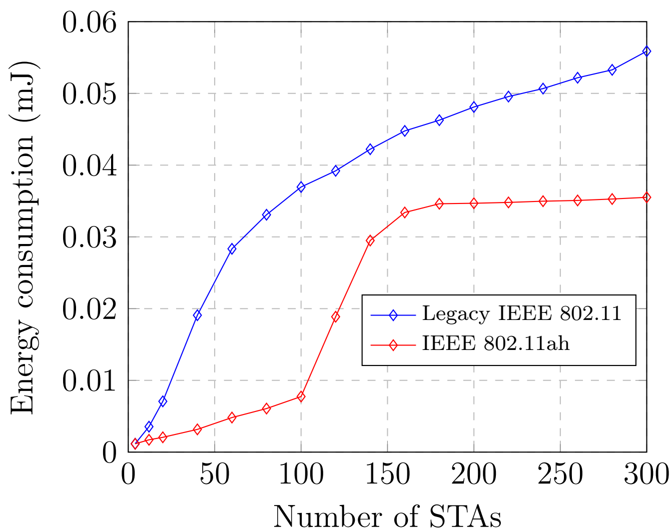

Figure 4.4: Comparing energy consumption of IEEE 802.11ah and legacy IEEE 802.11

Table 4.2: Number of STAs and their demand in RAW group for random grouping.

Random Grouping					
Scenario	N^{total}/D^{total}	Group 1 N_1^{total}/D_1^{total} $(N_1^1, N_1^2, N_1^3, N_1^4)$ $(D_1^1, D_1^2, D_1^3, D_1^4)$	Group 2 N_2^{total}/D_2^{total} $(N_2^1, N_2^2, N_2^3, N_2^4)$ $(D_2^1, D_2^2, D_2^3, D_2^4)$	Group 3 N_3^{total}/D_3^{total} $(N_3^1, N_3^2, N_3^3, N_3^4)$ $(D_3^1, D_3^2, D_3^3, D_3^4)$	Group 4 N_4^{total}/D_4^{total} $(N_4^{;}N_4^2, N_4^3, N_4^4)$ $(D_4^1, D_4^2, D_4^3, D_4^4)$
1	4/5.26	1/1.58 (0, 0, 1, 0) (0, 0, 1.58, 0)	1/0.53 (1, 0, 0, 0) (0.53, 0, 0, 0)	2/3.15 (0, 1, 0, 1) (0, 1.05, 0, 2.10)	0/0 (0, 0, 0, 0) (0, 0, 0, 0)
2	12/14.19	2/2.63 (0, 1, 1, 0) (0, 1.05, 1.58, 0)	3/2.63 (1, 2, 0, 0) (0.53, 2.1, 0, 0)	2/3.68 (0, 0, 1, 1) (0, 0, 1.58, 2.10)	5/5.25 (2, 1, 2, 0) (1.05, 1.05, 3.15, 0)
3	20/26.79	4/6.30 (0, 2, 0, 2) (0, 2.10, 0, 4.20)	3/4.73 (1, 0, 0, 2) (0.53, 0, 0, 4.20)	6/7.88 (0, 3, 3, 0) (0, 3.15, 4.73, 0)	7/7.88 (3, 1, 2, 1) (1.58, 1.05, 3.15, 2.10)
4	40/56.20	9/12.61 (1, 4, 1, 3) (0.53, 4.20, 1.58, 6.30)	12/17.33 (2, 1, 7, 2) (1.05, 1.05, 11.03, 4.20)	12/14.70 (4, 3, 2, 3) (2.10, 3.15, 3.15, 6.30)	7/11.56 (1, 1, 1, 4) (0.53, 1.05, 1.58, 8.40)
5	60/83.50	16/25.73 (2, 3, 3, 8) (1.05, 3.15, 4.73, 16.8)	17/22.58 (4, 4, 5, 4) (2.10, 4.20, 7.88, 8.40)	20/24.16 (5, 8, 3, 4) (2.63, 8.40, 4.73, 8.40)	7/11.03 (0, 2, 3, 2) (0, 2.10, 4.75, 4.20)
6	80/107.11	16/23.10 (2, 5, 4, 5) (1.05, 5.25, 6.30, 10.50)	23/28.88 (7, 6, 4, 6) (3.68, 6.30, 6.30, 12.6)	24/35.18 (4,3,11,6) (2.10, 3.15, 17.33, 12.60)	17/19.95 (4, 7, 4, 2) (2.10, 7.35, 6.30, 4.20)
7	120/155.94	30/36.23 (9, 9, 6, 6) (4.73, 9.45, 9.45, 12.6)	29/37.80 (4, 10, 12, 3) (2.10, 10.50, 18.90, 6.30)	31/39.90 (8,7,10,6) (4.20, 7.35, 15.75, 12.60)	30/42.01 (6, 8, 6, 10) (3.15, 8.40, 9.45, 21.01)
8	160/213.19	44/58.28 (7, 16, 12, 9) (3.68, 16.80, 18.90, 18.90)	44/60.39 (11, 10, 8, 15) (5.78, 10.50, 12.60, 31.51)	36/48.31 (8, 5, 18, 5) (4.20, 5.25, 28.36, 10.50)	36/46.21 (7, 13, 9, 7) (3.68, 13.65, 14.18, 14.70)
9	200/264.14	47/61.97 (11, 12 13, 11) (5.78, 12.60, 20.48, 23.11)	62/78.77 (15, 17, 19, 11) (7.88, 17.85, 29.93, 23.11)	17/74.04 (10, 15, 11, 17) (5.25, 15.75, 17.33, 35.71)	38/49.36 (9, 9, 13, 7) (4.73, 9.45, 20.48, 14.70)
10	260/343.43	63/79.29 (20, 13, 15, 15) (10.50, 13.65, 23.63, 31.51)	75/103.45 (15, 16, 26, 18) (7.88, 16.80, 40.96, 37.81)	67/88.74 (16, 15, 21, 15) (8.40, 15.75, 33.08, 31.51)	55/71.95 (10, 21, 11, 13) (5.25, 22.06, 17.33, 27.31)

4.4 Performance Comparison between Existing and Proposed Grouping Algorithm

We evaluate our proposed grouping algorithm using C++ where four RAW groups in RAW ($K = 4$) were considered. Table 4.2, Table 4.3 and Table 4.4 describes the scenario that we have generated from C++ simulation. We consider 10 random scenario and in Table 4.2, Table4.3

Table 4.3: Number of STAs and their demands in RAW group for uniform grouping.

Uniform Grouping					
Scenario	N^{total}/D^{total}	Group 1 N_1^{total}/D_1^{total} $(N_1^1, N_1^2, N_1^3, N_1^4)$ $(D_1^1, D_1^2, D_1^3, D_1^4)$	Group 2 N_2^{total}/D_2^{total} $(N_2^1, N_2^2, N_2^3, N_2^4)$ $(D_2^1, D_2^2, D_2^3, D_2^4)$	Group 3 N_3^{total}/D_3^{total} $(N_3^1, N_3^2, N_3^3, N_3^4)$ $(D_3^1, D_3^2, D_3^3, D_3^4)$	Group 4 N_4^{total}/D_4^{total} $(N_4^1 N_4^2, N_4^3, N_4^4)$ $(D_4^1, D_4^2, D_4^3, D_4^4)$
1	4/5.26	1/2.10 (0, 0, 0, 1) (0, 0, 0, 2.10)	1/1.58 (0, 0, 1, 0) (0, 0, 1.58, 0)	1/1.05 (0, 1, 0, 0) (0, 1.05, 0, 0)	1/0.53 (1, 0, 0, 0) (0.53, 0, 0, 0)
2	12/14.21	3/4.10 (1, 0, 1, 1) (0.53, 0, 1.58, 2.10)	3/3.16 (1, 1, 1, 0) (0.53, 1.05, 1.58, 0)	3/3.68 (0, 2, 1, 0) (0, 2.10, 1.58, 0)	3/3.16 (1, 1, 1, 0) (0.53, 1.05, 1.58, 0)
3	20/26.80	5/6.83 (1, 2, 0, 2) (0.53, 2.10, 0, 4.20)	5/5.78 (2, 1, 1, 1) (1.05, 1.05, 1.58, 2.10)	5/7.88 (0, 1, 3, 1) (0, 1.05, 4.73, 2.10)	5/6.31 (1, 2, 1, 1) (0.53, 2.10, 1.58, 2.10)
4	40/56.21	10/13.66 (3, 2, 1, 4) (1.58, 2.10, 1.58, 8.40)	10/14.71 (1, 2, 5, 2) (0.53, 2.10, 7.88, 4.20)	10/15.23 (1, 3, 2, 4) (0.53, 3.15, 3.15, 8.40)	10/12.61 (3, 2, 3, 2) (1.58, 2.10, 4.73, 4.20)
5	60/83.49	15/19.95 (4, 4, 2, 5) (2.10, 4.20, 3.15, 10.50)	15/18.38 (5, 3, 4, 3) (2.63, 3.15, 6.30, 6.30)	15/24.68 (0, 4, 5, 6) (0, 4.20, 7.88, 12.60)	15/20.48 (2, 6, 3, 4) (1.05, 6.30, 4.73, 8.40)
6	80/107.11	20/26.78 (5, 4, 6, 5) (2.63, 4.20, 9.45, 10.50)	20/26.25 (4, 5, 8, 3) (2.10, 5.25, 12.60, 6.30)	20/27.83 (4, 6, 3, 7) (2.10, 6.30, 4.73, 14.70)	20/26.25 (4, 6, 6, 4) (2.10, 6.30, 9.45, 8.40)
7	120/155.93	30/38.85 (6, 8, 12, 4) (3.15, 8.40, 18.90, 8.40)	30/37.28 (7, 10, 8, 5) (3.68, 10.50, 12.60, 10.50)	30/39.90 (8,7,6,6) (4.20, 7.35, 9.45, 18.90)	30/39.90 (6, 9, 8, 7) (3.15, 9.45, 12.60, 14.70)
8	160/213.20	40/55.66 (7, 8, 17, 8) (3.68, 8.40, 26.78, 16.80)	40/55.67 (5, 14, 11, 10) (2.63, 14.70, 17.33, 21.01)	40/54.09 (9, 10, 10, 11) (4.73, 10.50, 15.75, 23.11)	40/47.78 (12, 12, 9, 7) (6.30, 12.60, 14.18, 14.70)
9	200/264.13	50/65.11 (12, 11, 18, 9) (6.30, 11.55, 28.36, 18.90)	50/66.16 (10, 16, 12, 12) (5.25, 16.80, 18.90, 25.21)	50/67.74 (12, 12, 11, 15) (6.30, 12.60, 17.33, 31.51)	50/65.12 (11, 14, 15, 10) (5.78, 14.70, 23.63, 21.01)
10	260/343.43	65/85.07 (15, 18, 17, 15) (7.88, 18.90, 26.78, 31.51)	65/85.59 (16, 14, 21, 14) (8.40, 14.70, 33.08, 29.41)	65/86.17 (15, 19, 15, 16) (7.88, 19.95, 23.63, 33.61)	65/87.70 (15, 14, 20, 16) (7.88, 14.70, 31.51, 33.61)

and Table 4.4 show assigned number of STAs and their traffic demand in each group for random grouping, uniform grouping and proposed grouping, respectively.

In Table 4.2 it is seen that, number of STAs and their traffic demand both are different among the RAW groups for random grouping. Table 4.3 shows that in uniform grouping the number of STAs are equal among the RAW groups but demand are different and also Table 4.4 shows that the number of STAs in RAW groups are not equal but their demand are equal for

Table 4.4: Number of STAs and their demand in RAW group for proposed grouping.

Proposed Grouping					
Scenario	N^{total}/D^{total}	Group 1 N_1^{total}/D_1^{total} $(N_1^1, N_1^2, N_1^3, N_1^4)$ $(D_1^1, D_1^2, D_1^3, D_1^4)$	Group 2 N_2^{total}/D_2^{total} $(N_2^1, N_2^2, N_2^3, N_2^4)$ $(D_2^1, D_2^2, D_2^3, D_2^4)$	Group 3 N_3^{total}/D_3^{total} $(N_3^1, N_3^2, N_3^3, N_3^4)$ $(D_3^1, D_3^2, D_3^3, D_3^4)$	Group 4 N_4^{total}/D_4^{total} $(N_4^{\cdot} N_4^2, N_4^3, N_4^4)$ $(D_4^1, D_4^2, D_4^3, D_4^4)$
1	4/5.26	1/0.53 (1, 0, 0, 0) (0.53, 0, 0, 0)	1/1.05 (0, 1, 0, 0) (0, 1.05, 0, 0)	1/1.58 (0, 0, 1, 0) (0, 0, 1.58, 0)	1/2.10 (0, 0, 0, 1) (0, 0, 0, 2.10)
2	12/14.19	4/3.15 (2, 2, 0, 0) (1.05, 2.10, 0, 0)	3/3.68 (1, 0, 2, 0) (0.53, 0, 3.15, 0)	3/3.68 (0, 2, 1, 0) (0, 2.10, 1.58, 0)	2/3.68 (0, 0, 1, 1) (0, 0, 1.58, 2.10)
3	20/26.80	5/6.83 (2, 0, 1, 2) (1.05, 0, 1.58, 4.20)	5/6.83 (1, 2, 0, 2) (0.53, 2.10, 0, 4.20)	5/6.83 (0, 2, 3, 0) (0, 2.10, 4.73, 0)	5/6.31 (1, 2, 1, 1) (0.53, 2.10, 1.58, 2.10)
4	40/56.19	9/13.65 (2, 1, 2, 4) (1.05, 1.05, 3.15, 8.40)	11/14.18 (3, 2, 4, 2) (1.58, 2.10, 6.30, 4.20)	8/14.18 (0, 2, 1, 5) (0, 2.10, 1.58, 10.50)	12/14.18 (3, 4, 4, 1) (1.58, 4.20, 6.30, 2.10)
5	60/83.48	17/21 (4, 7, 2, 4) (2.10, 7.35, 3.15, 8.40)	12/21 (0, 2, 4, 6) (0, 2.10, 6.30, 12.60)	15/21 (4, 2, 4, 5) (2.10, 2.10, 6.30, 10.50)	16/20.98 (3, 6, 4, 3) (1.58, 6.30, 6.30, 6.30)
6	80/107.13	23/26.28 (7, 5, 10, 1) (3.68, 5.25, 15.75, 2.10)	19/26.25 (3, 7, 3, 6) (1.58, 7.35, 4.73, 12.60)	19/26.28 (4, 3, 5, 7) (2.10, 3.15, 7.88, 14.70)	19/26.26 (3, 6, 5, 5) (1.58, 6.30, 7.88, 10.50)
7	120/155.96	32/38.36 (7, 12, 9, 4) (3.68, 12.60, 14.18, 8.40)	32/38.33 (9, 8, 12, 3) (4.73, 8.40, 18.90, 6.30)	27/38.39 (4, 7, 6, 10) (2.10, 7.35, 9.45, 21.01)	29/38.38 (7, 7, 7, 8) (3.68, 7.35, 11.03, 16.80)
8	160/213.19	38/53.09 (6, 10, 11, 11) (3.15, 10.50, 17.33, 23.11)	43/53.03 (10, 14, 13, 6) (5.25, 14.70, 20.48, 12.60)	42/53.03 (10, 12, 13, 7) (5.25, 12.60, 20.48, 14.70)	37/53.04 (7, 8, 10, 12) (3.68, 8.40, 15.75, 25.21)
9	200/264.14	52/66.17 (16, 10, 14, 12) (8.40, 10.50, 22.06, 25.21)	49/66.17 (7, 18, 13, 11) (3.68, 18.90, 20.48, 23.11)	52/66.16 (13, 13, 17, 9) (6.83, 13.65, 26.78, 18.90)	47/66.16 (9, 12, 12, 14) (4.73, 12.60, 18.90, 29..41)
10	260/343.43	65/85.60 (16, 15, 19, 15) (8.40, 15.75, 29.93, 31.51)	65/85.60 (17, 15, 16, 17) (8.93, 15.75, 25.21, 35.71)	68/85.67 (17, 18, 23, 10) (8.93, 18.90, 36.23, 21.01)	62/85.59 (11, 17, 15, 19) (5.78, 17.85, 23.63, 39.91)

proposed grouping. In random grouping STAs are distributed randomly in each RAW group without consider their traffic demand. Thus, the number of STAs and traffic demand among the RAW groups both are different. In uniform grouping STAs are evenly distributed in RAW groups without consider their traffic demand. Thus, the number of STAs are identical in each group but traffic demand are different. On the other hand, in our proposed grouping STAs are assign in RAW groups based on their traffic demand thus, the number of STAs are varying in

RAW groups but their traffic demand are equal. An example of a scenario 5 for 60 STAs can be consider for all three grouping algorithms. For 60 STAs scenario in random grouping (Table 4.2) assign number of STAs and traffic demand both are different in RAW groups, in uniform grouping (Table 4.3) assign number of STAs are identical but traffic demand are varying in RAW groups. Consequently, in proposed grouping (Table 4.4) assign number of STAs are varying but traffic demand are same in RAW groups. In sparse network random and uniform grouping works good but in dense network the two grouping work similar and an example in scenario 7 for 120 STAs in Table 4.2 and Table 4.3 was seen.

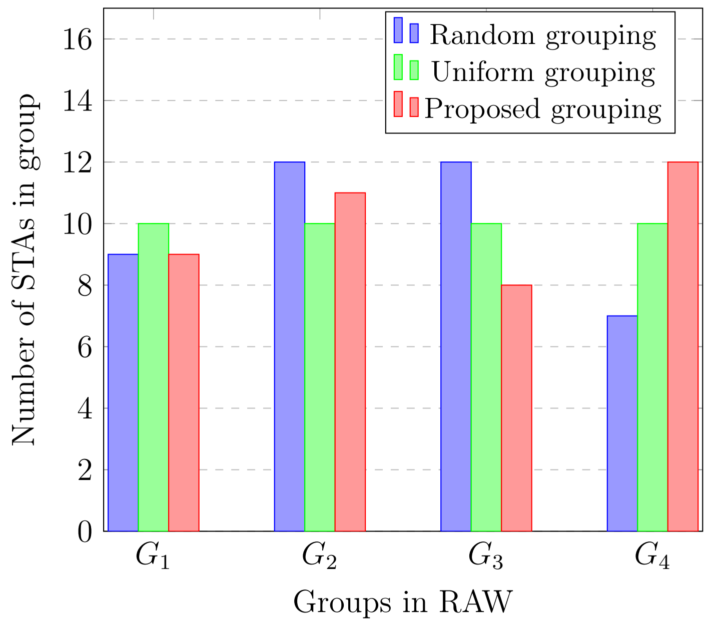

Figure 4.5: Number of STAs in RAW group

Figure 4.5 and Figure 4.6 show the number of STAs in each RAW group and the traffic demand of each RAW group under different grouping algorithms for 40 STAs network scenario. It is seen that random grouping algorithm randomly distributes the STAs in each RAW group, consequently, the number of STAs and traffic demand of each RAW group both are different. The uniform grouping algorithm evenly distributes the STAs in each RAW group hence, the number of STAs in each RAW group are same whereas traffic demand of each RAW group are different. Our proposed traffic demand-based grouping algorithm distributes the STAs in each RAW group according to their traffic demand. As a result, varying number of STAs are assigned in each RAW group whereas the traffic demand of each RAW group are equal.

Figure 4.7 shows the comparison of assign STAs fairness in RAW groups among random grouping, uniform grouping and proposed grouping.We have previously observed in Table 4.2,

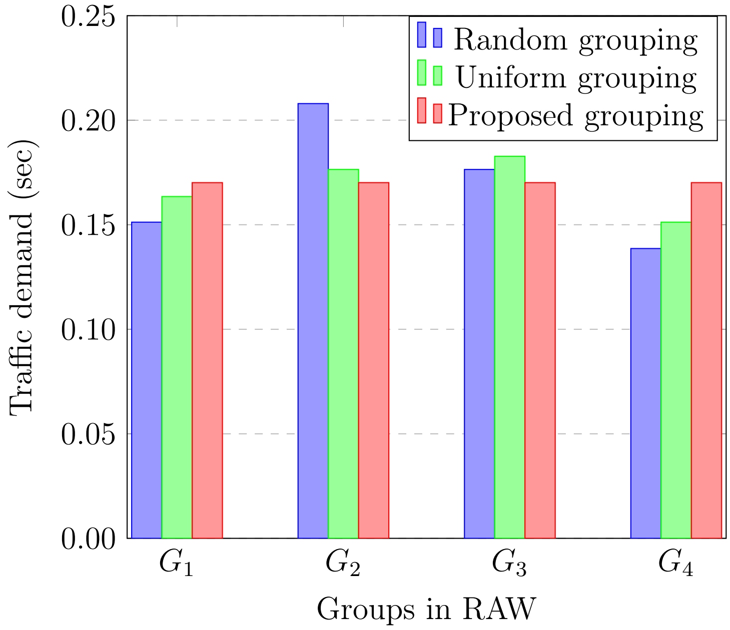

Figure 4.6: Traffic demand of RAW groups

Table 4.3 and Table 4.4 random grouping algorithm assigns STAs in RAW groups randomly, Uniform grouping algorithm assigns evenly STAs in each RAW groups and proposed grouping algorithm assigns STAs in RAW groups based on demand. As a result, random grouping algorithm distributes STAs unfairly in RAW groups and proposed grouping distributes STAs in RAW groups more fairly than random grouping. On the other hand uniform grouping algorithm distributes STAs in RAW groups better fairly nearly 100%. From Figure 4.7 it is seen that, proposed grouping algorithm distributes STAs in RAW groups fairly just like uniform

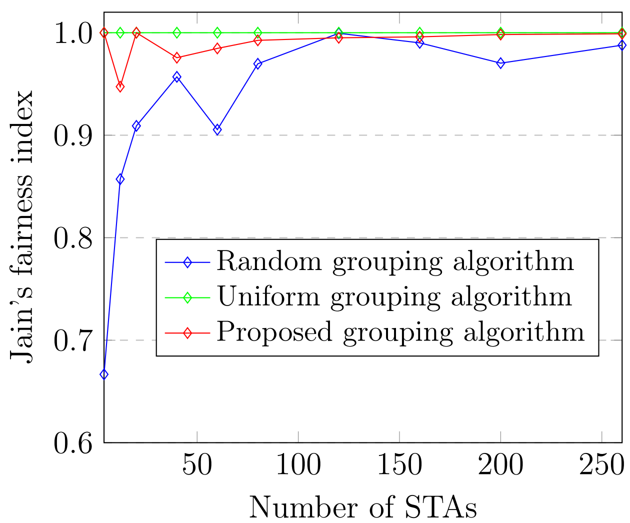

Figure 4.7: Comparison of assign STAs fairness in RAW groups

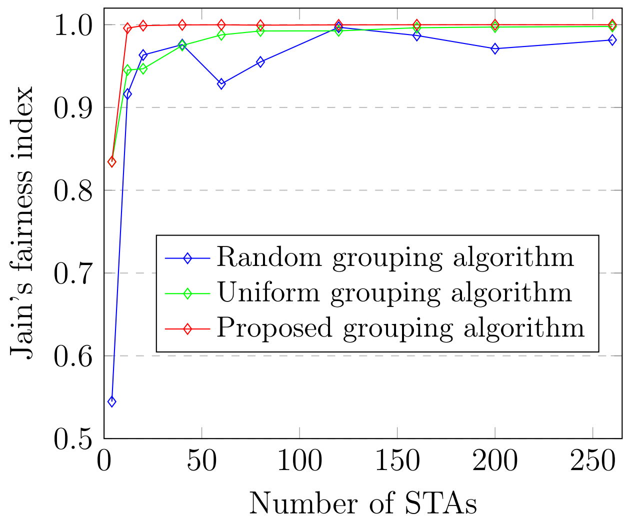

Figure 4.8: Comparison of demand fairness in RAW groups

grouping algorithm in dense network scenario.

Figure 4.8 shows the comparison of assign STAs demand fairness in RAW groups among random grouping, uniform grouping and proposed grouping. We have previously observed in Table 4.2, Table 4.3 and Table 4.4 random grouping algorithm assigns STAs randomly and uniform grouping algorithm evenly in RAW groups without consider STAs traffic demand. On the other hand proposed grouping algorithm assigns STAs in RAW groups based on demand. As a result, random grouping algorithm and uniform grouping algorithm achieve lower traffic demand fairness than proposed grouping algorithm.

Figure 4.9 shows the comparison of Jain's fairness index under random grouping, uniform

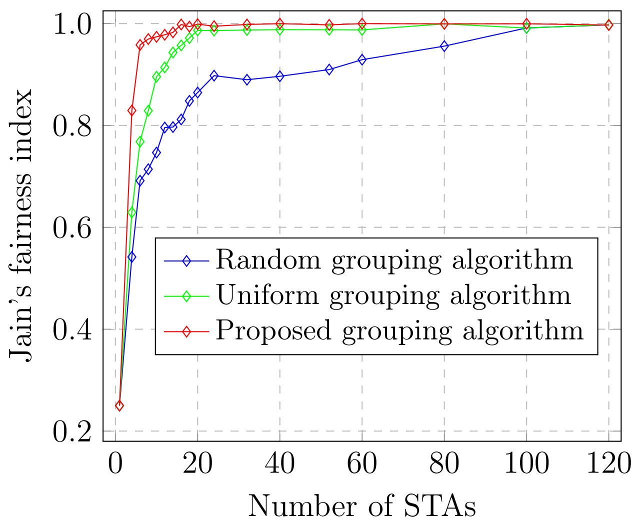

Figure 4.9: Comparison of channel utilization fairness in RAW groups

grouping and proposed grouping algorithm for distinct number of STAs. We have previously observed in Table 4.2, Table 4.3 and Table 4.4 uniform grouping algorithm assigns STAs equally in each RAW group where each RAW group contain various amount of traffic demand. Consequently, each RAW group achieve different normalized throughput and thus, degrade fairness among the RAW groups. Moreover, random grouping algorithm randomly assigns STAs in each RAW group where number of STAs and amount of traffic demand both are not evenly distributed. Consequently, each RAW group achieve more different normalized throughput and thus, degrade fairness among the RAW groups compared to uniform grouping. The comparison results shows that proposed grouping algorithm leads to fair resource allocation among the RAW groups compared to the other existing algorithms when network is non-saturated. This is because normalized throughput of the STAs depend on traffic demand when the network is non-saturated.

4.5 Summary

This chapter presents analytical result of RAW based IEEE 802.11ah and legacy IEEE 802.11 and compare the analytical result. This chapter also present the graphical and tabular result of proposed and existing grouping algorithm and compare fairness among them. Our proposed grouping algorithm provide better channel utilization fairness among the RAW groups.

Chapter 5

Conclusion and Future Works

5.1 Conclusion

In this paper, new low energy IoT oriented wireless standard called IEEE 802.11ah was studied. The IEEE 802.11ah standard which operates in sub-1 GHz band is expected to have 1 km coverage with at least 100 kbps data rate. Particular emphasis in the standard is supporting large number of low energy STAs. This large number of IoT STAs have heterogeneous properties and when this heterogeneous IoT STAs operating in ultra dense network scenarios may be affected by the packet collisions, delays and low network throughput. However, to support large number of low energy STAs it introduces a restricted access window mechanism and partitions STAs into groups, to handle higher contention from a large number of STAs. For fair channel utilization across the groups in this paper, we developed a traffic demand-based grouping algorithm of RAW mechanism for heterogeneous STAs. Moreover, an analytical model for IEEE 802.11ah based grouping scheme has been developed to evaluate the performance which is solved by Maple software. Jain's fairness index has been used to find the fairness of resource allocation among the RAW groups. The analytical results show that the proposed IEEE 802.11ah based grouping scheme provide better performance than the legacy IEEE 802.11 DCF in terms of reliability, normalized throughput, access delay and energy consumption. This results has been reflected the importance of using RAW based grouping scheme than legacy DCF in a dense Iot network. We also provided a fairness comparison using Jain's fairness index between the existing grouping algorithm and proposed grouping algorithm. The fairness comparison result shows that the proposed grouping algorithm is more fair as compared to random and uniform grouping algorithm when the network is specially non - saturated.

5.2 Future Works

In this work, we design an analytical model for DCF protocol of RAW mechanism and impact of RAW duration is not consider. In future, we will design a complete and accurate analytical model for EDCA protocol of RAW mechanism to analyze the performance of IoT network having heterogeneous STAs and try to find the impact of RAW duration in group.

Bibliography

[1] L. Tian, S. Santi, A. Seferagić, J. Lan, and J. Famaey, "Wi-Fi HaLow for the Internet of Things: An up-to-date survey on IEEE 802.11ah research," *Journal of Network and Computer Applications*, p. 103036, 2021.

[2] J. C. Araiza Leon, "Evaluation of IEEE 802.11 ah Technology for Wireless Sensor Network Applications," Master's thesis, 2015.

[3] "IEEE Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation," pp. 1–592, 2017.

[4] A. R. Devidas and M. V. Ramesh, "Wireless smart grid design for monitoring and optimizing electric transmission in India," in *2010 Fourth International Conference on Sensor Technologies and Applications*, pp. 637–640, 2010.

[5] S. Pattar, R. Buyya, K. R. Venugopal, S. Iyengar, and L. Patnaik, "Searching for the IoT resources: Fundamentals, requirements, comprehensive review, and future directions," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 2101–2132, 2018.

[6] W. Kassab and K. A. Darabkh, "A–Z survey of Internet of Things: Architectures, protocols, applications, recent advances, future directions and recommendations," *Journal of Network and Computer Applications*, vol. 163, p. 102663, 2020.

[7] E. Khorov, A. Krotov, A. Lyakhov, R. Yusupov, M. Condoluci, M. Dohler, and I. Akyildiz, "Enabling the Internet of Things with Wi-Fi halow—Performance evaluation of the restricted access window," *IEEE Access*, vol. 7, pp. 127402–127415, 2019.

[8] E. Khorov, A. Lyakhov, I. Nasedkin, R. Yusupov, J. Famaey, and I. F. Akyildiz, "Fast and reliable alert delivery in mission-critical Wi-Fi HaLow sensor networks," *IEEE Access*, vol. 8, pp. 14302–14313, 2020.

[9] T. Adame, A. Bel, B. Bellalta, J. Barcelo, and M. Oliver, "IEEE 802.11 AH: the WiFi approach for M2M communications," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 144–152, 2014.

[10] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of things: A survey on enabling technologies, protocols, and applications," *IEEE communications surveys & tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.

[11] U. Sangeetha and A. Babu, "Performance analysis of ieee 802.11 ah wireless local area network under the restricted access window-based mechanism," *International Journal of Communication Systems*, vol. 32, no. 4, 2019.

[12] A. Ali, G. A. Shah, M. O. Farooq, and U. Ghani, "Technologies and challenges in developing machine-to-machine applications: A survey," *Journal of Network and Computer Applications*, vol. 83, pp. 124–139, 2017.

[13] S. Kaushik, "An overview of technical aspect for WiFi networks technology," *International Journal of Electronics and Computer Science Engineering (IJECSE, ISSN: 2277-1956)*, vol. 1, no. 01, pp. 28–34, 2012.

[14] P. Sthapit and J.-Y. Pyun, "Station grouping strategy for minimizing association delay in IEEE 802.11ah," *IEICE Transactions on Communications*, vol. 100, no. 8, pp. 1419–1427, 2017.

[15] A. J. Gopinath and B. Nithya, "Mathematical and simulation analysis of contention resolution mechanism for IEEE 802.11 ah networks," *Computer Communications*, vol. 124, pp. 87–100, 2018.

[16] Y. Kim, G. Hwang, J. Um, S. Yoo, H. Jung, and S. Park, "Throughput performance optimization of super dense wireless networks with the renewal access protocol," *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3440–3452, 2016.

[17] E. Khorov, A. Lyakhov, and R. Yusupov, "Two-slot based model of the IEEE 802.11 ah restricted access window with enabled transmissions crossing slot boundaries," in *2018*

IEEE 19th International Symposium on" A World of Wireless, Mobile and Multimedia Networks"(WoWMoM), pp. 1–9, 2018.

[18] L. Tian, M. Mehari, S. Santi, S. Latré, E. De Poorter, and J. Famaey, "IEEE 802.11ah restricted access window surrogate model for real-time station grouping," in *2018 IEEE 19th International Symposium on" A World of Wireless, Mobile and Multimedia Networks"(WoWMoM)*, pp. 14–22, 2018.

[19] T.-C. Chang, C.-H. Lin, K. C.-J. Lin, and W.-T. Chen, "Traffic-aware sensor grouping for IEEE 802.11ah networks: Regression based analysis and design," *IEEE Transactions on Mobile Computing*, vol. 18, no. 3, pp. 674–687, 2018.

[20] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on LPWA technology: LoRa and NB-IoT," *Ict Express*, vol. 3, no. 1, pp. 14–21, 2017.

[21] S. Chieochan, E. Hossain, and J. Diamond, "Channel assignment schemes for infrastructure-based 802.11 WLANs: A survey," *IEEE Communications Surveys*, vol. 12, no. 1, pp. 124–136, 2010.

[22] S. Krčo, B. Pokrić, and F. Carrez, "Designing IoT architecture (s): A European perspective," in *2014 IEEE world forum on internet of things (WF-IoT)*, pp. 79–84, 2014.

[23] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of things for smart cities," *IEEE Internet of Things journal*, vol. 1, no. 1, pp. 22–32, 2014.

[24] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, "Future internet: the internet of things architecture, possible applications and key challenges," in *2012 10th international conference on frontiers of information technology*, pp. 257–260, 2012.

[25] Z. Yang, Y. Yue, Y. Yang, Y. Peng, X. Wang, and W. Liu, "Study and application on the architecture and key technologies for IOT," in *2011 International Conference on Multimedia Technology*, pp. 747–751, 2011.

[26] M. Wu, T.-J. Lu, F.-Y. Ling, J. Sun, and H.-Y. Du, "Research on the architecture of Internet of Things," in *2010 3rd international conference on advanced computer theory and engineering (ICACTE)*, vol. 5, pp. V5–484, 2010.

[27] L. Tan and N. Wang, "Future internet: The internet of things," in *2010 3rd international conference on advanced computer theory and engineering (ICACTE)*, vol. 5, pp. V5–376, 2010.

[28] M. A. Chaqfeh and N. Mohamed, "Challenges in middleware solutions for the internet of things," in *2012 international conference on collaboration technologies and systems (CTS)*, pp. 21–26, 2012.

[29] L. Atzori, A. Iera, and G. Morabito, "The internet of things: a survey. ComputNetw 54 (15): 2787–2805," 2010.

[30] D. Glaroudis, A. Iossifides, and P. Chatzimisios, "Survey, comparison and research challenges of IoT application protocols for smart farming," *Computer Networks*, vol. 168, p. 107037, 2020.

[31] J.-c. Zhao, J.-f. Zhang, Y. Feng, and J.-x. Guo, "The study and application of the IOT technology in agriculture," in *2010 3rd international conference on computer science and information technology*, vol. 2, pp. 462–465, 2010.

[32] M. U. Farooq, M. Waseem, S. Mazhar, A. Khairi, and T. Kamal, "A review on internet of things (IoT)," *International journal of computer applications*, vol. 113, no. 1, pp. 1–7, 2015.

[33] I. S. Udoh and G. Kotonya, "Developing IoT applications: challenges and frameworks," *IET Cyber-Physical Systems: Theory & Applications*, vol. 3, no. 2, pp. 65–72, 2018.

[34] K. Flüchter and F. Wortmann, "Implementing the connected e-bike: challenges and requirements of an IoT application for urban transportation," 2014.

[35] A. H. Hussein, "Internet of things (IOT): Research challenges and future applications," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 6, 2019.

[36] J. Lansford, A. Stephens, and R. Nevo, "Wi-Fi (802.11 b) and Bluetooth: enabling coexistence," *IEEE network*, vol. 15, no. 5, pp. 20–27, 2001.

[37] Y. C. Gültekin, W. J. van Houtum, S. Şerbetli, and F. M. Willems, "Constellation shaping for IEEE 802.11," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1–7, 2017.

[38] A. I. Al-Alawi, “WiFi technology: Future market challenges and opportunities,” *Journal of computer science*, vol. 2, no. 1, pp. 13–18, 2006.

[39] Y. Wenbo, W. Quanyu, and G. Zhenwei, “Smart home implementation based on Internet and WiFi technology,” in *2015 34th Chinese Control Conference (CCC)*, pp. 9072–9077, 2015.

[40] P. S. Henry and H. Luo, “WiFi: what’s next?,” *IEEE Communications Magazine*, vol. 40, no. 12, pp. 66–72, 2002.

[41] H. Velayos and G. Karlsson, “Techniques to reduce the IEEE 802.11 b handoff time,” in *2004 IEEE International Conference on Communications (IEEE Cat. No. 04CH37577)*, vol. 7, pp. 3844–3848, 2004.

[42] E. Perahia and M. X. Gong, “Gigabit wireless LANs: an overview of IEEE 802.11 ac and 802.11 ad,” *ACM SIGMOBILE mobile computing and communications review*, vol. 15, no. 3, pp. 23–33, 2011.

[43] E. Au, “The Latest Progress on IEEE 802.11 mc and IEEE 802.11 ai [Standards],” *IEEE Vehicular Technology Magazine*, vol. 11, no. 3, pp. 19–21, 2016.

[44] M. S. Afaqui, E. Garcia-Villegas, and E. Lopez-Aguilera, “IEEE 802.11 ax: Challenges and requirements for future high efficiency WiFi,” *IEEE wireless communications*, vol. 24, no. 3, pp. 130–137, 2016.

[45] Y. Ghasempour, C. R. Da Silva, C. Cordeiro, and E. W. Knightly, “IEEE 802.11 ay: Next-generation 60 GHz communication for 100 Gb/s Wi-Fi,” *IEEE Communications Magazine*, vol. 55, no. 12, pp. 186–192, 2017.

[46] M. C. Caballé, A. C. Augé, E. Lopez-Aguilera, E. Garcia-Villegas, I. Demirkol, and J. P. Aspas, “An alternative to IEEE 802.11 ba: Wake-up radio with legacy IEEE 802.11 transmitters,” *IEEE access*, vol. 7, pp. 48068–48086, 2019.

[47] C. Deng, X. Fang, X. Han, X. Wang, L. Yan, R. He, Y. Long, and Y. Guo, “IEEE 802.11 be Wi-Fi 7: New challenges and opportunities,” *IEEE Communications Surveys & Tutorials*, vol. 22, no. 4, pp. 2136–2166, 2020.

[48] I. C. S. L. M. S. Committee *et al.*, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *ANSI/IEEE Std. 802.11-1999*, 1999.

[49] L. Zheng, M. Ni, L. Cai, J. Pan, C. Ghosh, and K. Doppler, "Performance analysis of group-synchronized DCF for dense IEEE 802.11 networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 11, pp. 6180–6192, 2014.

[50] Y. Zhao *et al.*, "Analysis of Energy Efficiency in IEEE 802.11 ah," Master's thesis, 2015.

[51] M. Mahesh and V. Harigovindan, "Fuzzy based optimal and traffic-aware restricted access window mechanism for dense IoT networks," *Journal of Intelligent & Fuzzy Systems*, vol. 37, no. 6, pp. 7851–7864, 2019.

[52] E. R. Alvarado and I. Lavrinovica, "Improved Restricted Access Window Mechanism for IEEE 802.11 ah Performance Optimization," in *2021 25th International Conference Electronics*, pp. 1–6, 2021.

[53] T.-C. Chang, C.-H. Lin, K. C.-J. Lin, and W.-T. Chen, "Load-balanced sensor grouping for IEEE 802.11ah networks," in *2015 IEEE global communications conference (GLOBECOM)*, pp. 1–6, 2015.

[54] N. Nawaz, M. Hafeez, S. A. R. Zaidi, D. C. McLernon, and M. Ghogho, "Throughput enhancement of restricted access window for uniform grouping scheme in IEEE 802.11ah," in *2017 IEEE international conference on communications (ICC)*, pp. 1–7, 2017.

[55] S.-G. Yoon, J.-O. Seo, and S. Bahk, "Regrouping algorithm to alleviate the hidden node problem in 802.11 ah networks," *Computer Networks*, vol. 105, pp. 22–32, 2016.

[56] L. Tian, E. Khorov, S. Latré, and J. Famaey, "Real-time station grouping under dynamic traffic for IEEE 802.11 ah," *Sensors*, vol. 17, no. 7, p. 1559, 2017.

[57] C. W. Park, D. Hwang, and T.-J. Lee, "Enhancement of IEEE 802.11 ah MAC for M2M communications," *IEEE Communications Letters*, vol. 18, no. 7, pp. 1151–1154, 2014.

[58] L. R. Lakshmi and B. Sikdar, "Achieving fairness in IEEE 802.11ah networks for IoT applications with different requirements," in *ICC 2019-2019 IEEE International Conference on Communications (ICC)*, pp. 1–6, 2019.

[59] U. Sangeetha and A. Babu, “Fair and efficient resource allocation in IEEE 802.11ah WLAN with heterogeneous data rates,” *Computer Communications*, vol. 151, pp. 154–164, 2020.

[60] M. Mahesh, B. S. Pavan, and V. Harigovindan, “Data Rate-Based Grouping to Resolve Performance Anomaly of Multi-Rate IEEE 802.11ah IoT Networks,” *IEEE Networking Letters*, vol. 2, no. 4, pp. 166–170, 2020.

[61] T. S. Bobba and V. S. Bojanapally, “Fair and Dynamic Channel Grouping Scheme for IEEE 802.11ah Networks,” in *2020 IEEE 5th International Symposium on Telecommunication Technologies (ISTT)*, pp. 105–110, 2020.

[62] A. J. Gopinath and B. Nithya, “Performance evaluation of grouping and regrouping scheme for mitigating hidden station problem in IEEE 802.11ah network,” *Cluster Computing*, vol. 24, no. 3, pp. 1623–1642, 2021.

[63] M. Z. Ali, J. Mišić, and V. B. Mišić, “Performance evaluation of heterogeneous IoT nodes with differentiated QoS in IEEE 802.11ah RAW mechanism,” *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3905–3918, 2019.

[64] L. Tian, J. Famaey, and S. Latré, “Evaluation of the IEEE 802.11 ah restricted access window mechanism for dense IoT networks,” in *2016 IEEE 17th international symposium on a world of wireless, mobile and multimedia networks (WoWMoM)*, pp. 1–9, 2016.

[65] W. Damayanti, S. Kim, and J.-H. Yun, “Collision chain mitigation and hidden device-aware grouping in large-scale IEEE 802.11 ah networks,” *Computer Networks*, vol. 108, pp. 296–306, 2016.

[66] A. Hazmi, B. Badihi, A. Larmo, J. Torsner, M. Valkama, *et al.*, “Performance analysis of IoT-enabling IEEE 802.11 ah technology and its RAW mechanism with non-cross slot boundary holding schemes,” in *2015 IEEE 16th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pp. 1–6, 2015.

[67] A. Bel, T. Adame, B. Bellalta, J. Barcelo, J. Gonzalez, and M. Oliver, “CAS-based channel access protocol for IEEE 802.11 ah WLANs,” in *European Wireless 2014; 20th European Wireless Conference*, pp. 1–6, 2014.

[68] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function,” *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.

[69] J. Zheng and Q. Wu, "Performance modeling and analysis of the IEEE 802.11p EDCA mechanism for VANET," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2673–2687, 2015.

[70] K. Kosek-Szott, M. Natkaniec, and A. R. Pach, "A simple but accurate throughput model for IEEE 802.11 EDCA in saturation and non-saturation conditions," *Computer Networks*, vol. 55, no. 3, pp. 622–635, 2011.

[71] S. Rashwand, J. Mišić, and V. B. Mišić, "Analysis of CSMA/CA mechanism of IEEE 802.15.6 under non-saturation regime," *IEEE Transactions on parallel and Distributed Systems*, vol. 27, no. 5, pp. 1279–1288, 2015.

[72] X. Yuan, C. Li, Q. Ye, K. Zhang, N. Cheng, N. Zhang, and X. Shen, "Performance analysis of IEEE 802.15.6-based coexisting mobile WBANs with prioritized traffic and dynamic interference," *IEEE Transactions on Wireless Communications*, vol. 17, no. 8, pp. 5637–5652, 2018.

[73] M. Mahesh and V. Harigovindan, "Throughput and energy efficiency analysis of the IEEE 802.11 ah restricted access window mechanism," in *International Conference on Next Generation Computing Technologies*, pp. 227–237, 2017.

[74] C. Kai, J. Zhang, X. Zhang, and W. Huang, "Energy-efficient sensor grouping for IEEE 802.11 ah networks with max-min fairness guarantees," *IEEE Access*, vol. 7, pp. 102284–102294, 2019.

[75] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, "A quantitative measure of fairness and discrimination," *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*, 1984.

Appendices

Appendix A

Source Code (C++) of Grouping Algorithm

```
#include < iostream >
#include < vector >
#include < bits/stdc + +.h >
using namespace std ;
int main()
{
    string outputFilename = "utdg.csv";
    std :: ofstream outputStream(outputFilename.c_str(), ios :: app);
    outputStream << "Groups" << ",";
    outputStream << "C1" << ",";
    outputStream << "C2" << ",";
    outputStream << "C3" << ",";
    outputStream << "C4" << ",";
    outputStream << "Demand" << ",";
    outputStream << "N-STAs" << ",";
    outputStream << "A-N-STAs" << endl;
    intnumberofstations = 260;
    vector < int > stationlist;
    intnumberofsationtype = 4;
    intnumberofgroups = 4;
// randomly station demand generation begin
    vector < int > stationtype;
    stationtype.push_back(2);
    stationtype.push_back(4);
```

```
stationtype.push_back(6);
stationtype.push_back(8);
for ( int i = 0 ; i < numberofstations ; i + + )
    {
        int stationtypeindex = rand() % numberofsationtype + 0;
        stationlist.push_back (stationtype[stationtypeindex]);
    }
```

// **randomly station demand generation end**

```
float totaltrafficdemand = accumulate(stationlist.begin(), stationlist.end(), 0);
int Maxdemandpergroup = ceil(totaltrafficdemand/numberofgroups);
```

// **begin of grouping scheme**

```
vector < int > group1;
vector < int > group2;
vector < int > group3;
vector < int > group4;
int demandofgroup1 = 0;
for (int i = stationlist.size() − 1 ; i >= 0 ; i − − )
    {
    if (demandofgroup1 + stationlist[i] > Maxdemandpergroup)
        {
            continue;
        }
    if (demandofgroup1 + stationlist[i] <= Maxdemandpergroup)
        {
            group1.push_back(stationlist[i]);
            stationlist.erase(stationlist.begin() + i);
            demandofgroup1 = demandofgroup1 + stationlist[i];
            continue;
        }
    }
int demandofgroup2 = 0;
for (int i = stationlist.size() − 1 ; i >= 0 ; i − −)
```

```
    {
    if (demandofgroup2 + stationlist[i] > Maxdemandpergroup)
        {
            continue;
        }
    if (demandofgroup2 + stationlist[i] <= Maxdemandpergroup)
        {
            group2.push_back(stationlist[i]);
            stationlist.erase(stationlist.begin() + i);
            demandofgroup2 = demandofgroup2 + stationlist[i];
            continue;
        }
    }
int demandofgroup3 = 0;
for (int i = stationlist.size() - 1 ; i >= 0 ; i--)
    {
    if (demandofgroup3 + stationlist[i] > Maxdemandpergroup)
        {
            continue;
        }
    if (demandofgroup3 + stationlist[i] <= Maxdemandpergroup)
        {
            group3.push_back(stationlist[i]);
            stationlist.erase(stationlist.begin() + i);
            demandofgroup3 = demandofgroup3 + stationlist[i];
            continue;
        }
    }
int demandofgroup4 = 0;
for (int i = stationlist.size() - 1 ; i >= 0 ; i--)
    {
    if (demandofgroup4 + stationlist[i] > Maxdemandpergroup)
```

```
        {
            continue;
        }
    if (demandofgroup4 + stationlist[i] <= Maxdemandpergroup)
        {
            group4.push_back(stationlist[i]);
            stationlist.erase(stationlist.begin() + i);
            demandofgroup4 = demandofgroup4 + stationlist[i];
            continue;
        }
    }
        int sizeofgroup1 = group1.size();
        int sizeofgroup2 = group2.size();
        int sizeofgroup3 = group3.size();
        int sizeofgroup4 = group4.size();
        vector < int > sizevector;
        sizevector.push_back(sizeofgroup1);
        sizevector.push_back(sizeofgroup2);
        sizevector.push_back(sizeofgroup3);
        sizevector.push_back(sizeofgroup4);
int remainstationlistsize = stationlist.size();
while (stationlist.size()! = 0)
    {
        if(sizeofgroup1 == *min_element(sizevector.begin(), sizevector.end()))
        {
            group1.push_back(stationlist[remainstationlistsize − 1]);
            stationlist.pop_back();
            sizeofgroup1 + +;
            remainstationlistsize − −;
            continue;
        }
        else if(sizeofgroup2 == *min_element(sizevector.begin(), sizevector.end()))
```

```
{
    group2.push_back(stationlist[remainstationlistsize - 1]);
    stationlist.pop_back();
    sizeofgroup2++;
    remainstationlistsize--;
    continue;
}
else if(sizeofgroup3 == *min_element(sizevector.begin(), sizevector.end()))
{
    group3.push_back(stationlist[remainstationlistsize - 1]);
    stationlist.pop_back();
    sizeofgroup3++;
    remainstationlistsize--;
    continue;
}
else if(sizeofgroup4 == *min_element(sizevector.begin(), sizevector.end()))
{
    group4.push_back(stationlist[remainstationlistsize - 1]);
    stationlist.pop_back();
    sizeofgroup4++;
    remainstationlistsize--;
    continue;
}
}
```

// **end of grouping scheme**

```
int assignednumberofstations = group1.size() + group2.size() + group3.size()+
group4.size();
outputStream << "Group1" << ",";
outputStream << count(group1.begin(), group1.end(), 2) << ",";
outputStream << count(group1.begin(), group1.end(), 4) << ",";
outputStream << count(group1.begin(), group1.end(), 6) << ",";
outputStream << count(group1.begin(), group1.end(), 8) << ",";
```

```
        outputStream << accumulate(group1.begin(), group1.end(), 0) << ",";
        outputStream << group1.size() << endl;

        outputStream << "Group2" << ",";
        outputStream << count(group2.begin(), group2.end(), 2) << ",";
        outputStream << count(group2.begin(), group2.end(), 4) << ",";
        outputStream << count(group2.begin(), group2.end(), 6) << ",";
        outputStream << count(group2.begin(), group2.end(), 8) << ",";
        outputStream << accumulate(group2.begin(), group2.end(), 0) << ",";
        outputStream << group2.size() << endl;

        outputStream << "Group3" << ",";
        outputStream << count(group3.begin(), group3.end(), 2) << ",";
        outputStream << count(group3.begin(), group3.end(), 4) << ",";
        outputStream << count(group3.begin(), group3.end(), 6) << ",";
        outputStream << count(group3.begin(), group3.end(), 8) << ",";
        outputStream << accumulate(group3.begin(), group3.end(), 0) << ",";
        outputStream << group3.size() << ",";
        outputStream << assignednumberofstations << endl;

        outputStream << "Group4" << ",";
        outputStream << count(group4.begin(), group4.end(), 2) << ",";
        outputStream << count(group4.begin(), group4.end(), 4) << ",";
        outputStream << count(group4.begin(), group4.end(), 6) << ",";
        outputStream << count(group4.begin(), group4.end(), 8) << ",";
        outputStream << accumulate(group4.begin(), group4.end(), 0) << ",";
        outputStream << group4.size() << endl;
return 0;
}
```

Appendix B

Source Code (Maple) of Analytical Model

$> restart:$

Load packages "properly" and check Maple

#version

$with(DirectSearch):$

$with(LinearAlgebra):$

$kernelopts(version):$

$> AIFSN := 2:$

$> framebody := 8 \cdot 256:$ # 256 bytes

$> alpha := 6 \cdot 10^{-6}:$ # 6 microseconds

$> t_{sifs} := 160 \cdot 10^{-6}:$ # 160 microseconds

$> t_{slot} := 52 \cdot 10^{-6}:$ #52 microseconds

$> h_{phy} := 156:$ # 156 bits

$> h_{mac} := 112:$ # MAC Header 14 bytes

$> r_{data} := 7800 \cdot 10^{3}:$ # 7800 kbps (can be changed and depands on MCS value)

$> r_{basicdata} := 650 \cdot 10^{3}:$

$> l_{bitpersymbol(basicrate)} := 26:$

$> t_{symbol} := 40 \cdot 10^{-6}:$ # 40 microseconds

$> t_{AIFS} := AIFSN \cdot t_{slot} + t_{sifs}:$

$> t_{phy} := \frac{h_{phy}}{r_{basicdata}}:$

$> t_{data} := ceil\left(\frac{framebody+h_{mac}}{\frac{r_{data}}{r_{basicdata}} \cdot l_{bitpersymbol(basicrate)}}\right) \cdot t_{symbol} + t_{phy}:$

$> t_{framebody} := ceil\left(\frac{framebody+h_{mac}}{\frac{r_{data}}{r_{basicdata}} \cdot l_{bitpersymbol(basicrate)}}\right) \cdot t_{symbol}:$

$> t_{pspoll} := \frac{h_{phy}}{r_{basicdata}}:$

$> t_{pspollack} := \frac{h_{phy}}{r_{basicdata}}$:

$> t_{ack} := \frac{h_{phy}}{r_{basicdata}}$:

$> t_{succ} := t_{AIFS} + t_{pspoll} + t_{pspollack} + t_{data} + t_{ack} + 3 \cdot t_{sifs} + 4 \cdot alpha$:

$> t_{coll} := t_{AIFS} + t_{pspoll} + t_{pspollack} + t_{sifs} + 2 \cdot alpha$:

$> t_{RAW} := 1$: # duration of RAW

$> n_{RAWslot} := 4$: # number of RAW slot

$> t_{RAWslot} := \frac{t_{RAW}}{n_{RAWslot}}$:

$> L_{RAWslot} := \frac{t_{RAWslot}}{t_{slot}}$:

$> p_{last} := \frac{1}{L_{RAWslot}}$:

$> L_{succ} := \frac{t_{succ}}{t_{slot}}$:

$> p_{1,lock} := \frac{L_{succ}}{L_{RAWslot}}$:

$> p_{2,lock} := \frac{L_{succ}}{L_{RAWslot}}$:

$> p_{3,lock} := \frac{L_{succ}}{L_{RAWslot}}$:

$> p_{4,lock} := \frac{L_{succ}}{L_{RAWslot}}$:

$> p_{tx} := 204 \cdot 10^{-3}$:

$> p_{rx} := 92 \cdot 10^{-3}$:

$> p_{idle} := 20 \cdot 10^{-3}$:

$> p_{1,cont} := \frac{t_{RAWslot}}{t_{RAW}}$:

$> p_{2,cont} := \frac{t_{RAWslot}}{t_{RAW}}$:

$> p_{3,cont} := \frac{t_{RAWslot}}{t_{RAW}}$:

$> p_{4,cont} := \frac{t_{RAWslot}}{t_{RAW}}$:

$> cw_{min} := 7$:

$> cw_{max} := 31$:

$> R := 7$: # retry limit

$> m := log_2\left(\frac{cw_{max}+1}{cw_{min}+1}\right)$

$> x := R - m$:

$$> w = \begin{cases} 2^{j1} \times (cw_{min} + 1) - 1 & 0 \le j1 \le m \\ cw_{max} & m + 1 \le j1 \le m + x \end{cases}$$

$> nodetype := 4$: # node type for heterogeneous traffic

$> \lambda_1 := 2$:

$> \lambda_2 := 4$:

$> \lambda_3 := 6$:

$> \lambda_4 := 8$:

$> fname :=$ "F:/IEEE802.11ah/Final(Journal)/UTDG/utdg52.xlsx"

$> n1 := convert(ExcelTools:-Import(fname,$ "Sheet1", "B2:B5"$), Vector):$

$> n2 := convert(ExcelTools:-Import(fname,$ "Sheet1", "C2:C5"$), Vector):$

$> n3 := convert(ExcelTools:-Import(fname,$ "Sheet1", "D2:D5"$), Vector):$

$> n4 := convert(ExcelTools:-Import(fname,$ "Sheet1", "E2:E5"$), Vector):$

$>$ **for** a **from** 1 **by** 1 **to** $n_{RAWslot}$ **do**

$n_1 := n1[a]:$

$n_2 := n2[a]:$

$n_3 := n3[a]:$

$n_4 := n4[a]:$

$e1 := p_{busy} = 1 - (1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}:$

$e2 := p_{1,idle} = \frac{(1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_1)}:$

$e3 := p_{2,idle} = \frac{(1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_2)}:$

$e4 := p_{3,idle} = \frac{(1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_3)}:$

$e5 := p_{4,idle} = \frac{(1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_4)}:$

$e6 := p_{1,succ} = \frac{n_1 \cdot \tau_1 \cdot (1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_1)}:$

$e7 := p_{2,succ} = \frac{n_2 \cdot \tau_2 \cdot (1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_2)}:$

$e8 := p_{3,succ} = \frac{n_3 \cdot \tau_3 \cdot (1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_3)}:$

$e9 := p_{4,succ} = \frac{n_4 \cdot \tau_4 \cdot (1-\tau_1)^{n_1} \cdot (1-\tau_2)^{n_2} \cdot (1-\tau_3)^{n_3} \cdot (1-\tau_4)^{n_4}}{(1-\tau_4)}:$

$e10 := p_{succ} = n_1 \cdot p_{1,succ} + n_2 \cdot p_{2,succ} + n_3 \cdot p_{3,succ} + n_4 \cdot p_{4,succ}:$

$e11 := C_1 = \frac{p_{1,idle} \cdot (1-p_{last})}{1-(1-p_{1,idle}) \cdot (1-p_{last})}:$

$e12 := C_2 = \frac{p_{2,idle} \cdot (1-p_{last})}{1-(1-p_{2,idle}) \cdot (1-p_{last})}:$

$e13 := C_3 = \frac{p_{3,idle} \cdot (1-p_{last})}{1-(1-p_{3,idle}) \cdot (1-p_{last})}:$

$e14 := C_4 = \frac{p_{4,idle} \cdot (1-p_{last})}{1-(1-p_{4,idle}) \cdot (1-p_{last})}:$

$e15 := b_{1,empty} = \frac{(1-\rho_1)}{q_1} \cdot \left((1-p_{1,lock}) \cdot p_{1,succ} \cdot \left(1 + \sum_{j=1}^{m+x} \left(\prod_{j2=1}^{j} \left(\frac{(1-p_{1,lock}) \cdot (1-p_{1,succ})}{(eval(w,j1=j2)+1)}\right.\right.\right.\right.$
$\left.\left.\left.\left.\left(\sum_{k2=0}^{eval(w,j1=j2)} (C_1)^{k2}\right)\right)\right)\right)\right) + (1-p_{1,lock}) \cdot (1-p_{1,succ}) \cdot \left(\prod_{j=1}^{m+x} \left(\frac{(1-p_{1,lock}) \cdot (1-p_{1,succ})}{(eval(w,j1=j)+1)} \cdot\right.\right.$
$\left.\left.\left.\left(\sum_{k2=0}^{eval(w,j1=j)} (C_1)^{k2}\right)\right)\right)\right) \cdot b_1:$

$e16 := b_{2,empty} = \frac{(1-\rho_2)}{q_2} \cdot \left((1-p_{2,lock}) \cdot p_{2,succ} \cdot \left(1 + \sum_{j=1}^{m+x} \left(\prod_{j2=1}^{j} \left(\frac{(1-p_{2,lock}) \cdot (1-p_{2,succ})}{(eval(w,j1=j2)+1)}\right.\right.\right.\right.$
$\left.\left.\left.\left.\left(\sum_{k2=0}^{eval(w,j1=j2)} (C_2)^{k2}\right)\right)\right)\right)\right) + (1-p_{2,lock}) \cdot (1-p_{2,succ}) \cdot \left(\prod_{j=1}^{m+x} \left(\frac{(1-p_{2,lock}) \cdot (1-p_{2,succ})}{(eval(w,j1=j)+1)} \cdot\right.\right.$
$\left.\left.\left.\left(\sum_{k2=0}^{eval(w,j1=j)} (C_2)^{k2}\right)\right)\right)\right) \cdot b_2:$

$e17 := b_{3,empty} = \frac{(1-\rho_3)}{q_3} \cdot \left((1-p_{3,lock}) \cdot p_{3,succ} \cdot \left(1 + \sum_{j=1}^{m+x} \left(\prod_{j2=1}^{j} \left(\frac{(1-p_{3,lock}) \cdot (1-p_{3,succ})}{(eval(w,j1=j2)+1)}\right.\right.\right.\right.$
$\left.\left.\left.\left.\left(\sum_{k2=0}^{eval(w,j1=j2)} (C_3)^{k2}\right)\right)\right)\right)\right) + (1-p_{3,lock}) \cdot (1-p_{3,succ}) \cdot \left(\prod_{j=1}^{m+x} \left(\frac{(1-p_{3,lock}) \cdot (1-p_{3,succ})}{(eval(w,j1=j)+1)} \cdot\right.\right.$

$\left(\sum_{k2=0}^{eval(w,j1=j)}(C_3)^{k2}\right)\Bigg)\Bigg)\Bigg) \cdot b_3$:

$e18 := b_{4,empty} = \frac{(1-\rho_4)}{q_4} \cdot \Bigg((1-p_{4,lock}) \cdot p_{4,succ} \cdot \Bigg(1 + \sum_{j=1}^{m+x}\Bigg(\prod_{j2=1}^{j}\Bigg(\frac{(1-p_{4,lock})\cdot(1-p_{4,succ})}{(eval(w,j1=j2)+1)} \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_4)^{k2}\right)\Bigg)\Bigg)\Bigg) + (1-p_{4,lock}) \cdot (1-p_{4,succ}) \cdot \Bigg(\prod_{j=1}^{m+x}\Bigg(\frac{(1-p_{4,lock})\cdot(1-p_{4,succ})}{(eval(w,j1=j)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j)}(C_4)^{k2}\right)\Bigg)\Bigg)\Bigg) \cdot b_4$:

$e19 := q_1 = 1 - e^{\left(-\lambda_1\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{1,lock})\cdot p_{1,succ}\cdot t_{succ}+(1-p_{1,lock})\cdot(p_{busy}-p_{1,succ})\cdot t_{coll})\right)}$:

$e20 := q_2 = 1 - e^{\left(-\lambda_2\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{2,lock})\cdot p_{2,succ}\cdot t_{succ}+(1-p_{2,lock})\cdot(p_{busy}-p_{2,succ})\cdot t_{coll})\right)}$:

$e21 := q_3 = 1 - e^{\left(-\lambda_3\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{3,lock})\cdot p_{3,succ}\cdot t_{succ}+(1-p_{3,lock})\cdot(p_{busy}-p_{3,succ})\cdot t_{coll})\right)}$:

$e22 := q_4 = 1 - e^{\left(-\lambda_4\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{4,lock})\cdot p_{4,succ}\cdot t_{succ}+(1-p_{4,lock})\cdot(p_{busy}-p_{4,succ})\cdot t_{coll})\right)}$:

$e23 := b_{1,syn} = \frac{1}{\left(1-\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{1,idle})\cdot(1-p_{last}))}\left(\sum_{k=1}^{eval(w,j1=0)}\left(k\cdot(C_1)^{eval(w,j1=0)-k}\right)\right)\right)\cdot p_{1,cont}} \Bigg(q_1 \cdot b_{1,empty} + p_{last}\Bigg(\sum_{j=1}^{m+x}\Bigg(\sum_{k=1}^{eval(w,j1=j)}\Bigg(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)\cdot(1-(1-p_{1,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k1=0}^{eval(w,j1=j)-k}(C_1)^{k1}\right) \cdot \Bigg(\prod_{j2=1}^{j-1}\Bigg(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{eval(w,j1=j2)+1} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_1)^{k2}\right)\Bigg)\Bigg)\Bigg)\Bigg)\Bigg) \cdot b_1 + p_{1,lock} \cdot \Bigg(1 + \sum_{j=1}^{m+x}\Bigg(\prod_{j2=1}^{j}\Bigg(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_1)^{k2}\right)\Bigg)\Bigg)\Bigg) \cdot b_1 + \Bigg(\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{1,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)}\left(k\cdot(C_1)^{eval(w,j1=0)-k}\right)\right)\Bigg) \cdot \Bigg(\rho_1 \cdot (1-p_{1,lock}) \cdot p_{1,idle} \cdot \Bigg(1+\sum_{j=1}^{m+x}\Bigg(\prod_{j2=1}^{j}\Bigg(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_1)^{k2}\right)\Bigg)\Bigg)\Bigg) + \rho_1 \cdot (1-p_{1,lock}) \cdot (1-p_{1,idle}) \cdot \Bigg(\prod_{j2=1}^{m+x}\Bigg(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j)}(C_1)^{k2}\right)\Bigg)\Bigg) \cdot b_1\Bigg)$:

$e24 := b_{2,syn} = \frac{1}{\left(1-\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{2,idle})\cdot(1-p_{last}))}\left(\sum_{k=1}^{eval(w,j1=0)}\left(k\cdot(C_2)^{eval(w,j1=0)-k}\right)\right)\right)\cdot p_{2,cont}} \Bigg(q_2 \cdot b_{2,empty} + p_{last}\Bigg(\sum_{j=1}^{m+x}\Bigg(\sum_{k=1}^{eval(w,j1=j)}\Bigg(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)\cdot(1-(1-p_{2,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k1=0}^{eval(w,j1=j)-k}(C_2)^{k1}\right) \cdot \Bigg(\prod_{j2=1}^{j-1}\Bigg(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{eval(w,j1=j2)+1} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_2)^{k2}\right)\Bigg)\Bigg)\Bigg)\Bigg)\Bigg) \cdot b_2 + p_{2,lock} \cdot \Bigg(1 + \sum_{j=1}^{m+x}\Bigg(\prod_{j2=1}^{j}\Bigg(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_2)^{k2}\right)\Bigg)\Bigg)\Bigg) \cdot b_2 + \Bigg(\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{2,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)}\left(k\cdot(C_2)^{eval(w,j1=0)-k}\right)\right)\Bigg) \cdot \Bigg(\rho_2 \cdot (1-p_{2,lock}) \cdot p_{2,idle} \cdot \Bigg(1+\sum_{j=1}^{m+x}\Bigg(\prod_{j2=1}^{j}\Bigg(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_2)^{k2}\right)\Bigg)\Bigg)\Bigg) + \rho_2 \cdot (1-p_{2,lock}) \cdot (1-p_{2,idle}) \cdot \Bigg(\prod_{j2=1}^{m+x}\Bigg(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j)}(C_2)^{k2}\right)\Bigg)\Bigg) \cdot b_2\Bigg)$:

$e25 := b_{3,syn} = \frac{1}{\left(1-\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{3,idle})\cdot(1-p_{last}))}\left(\sum_{k=1}^{eval(w,j1=0)}\left(k\cdot(C_3)^{eval(w,j1=0)-k}\right)\right)\right)\cdot p_{3,cont}} \Bigg(q_3 \cdot b_{3,empty} + p_{last}\Bigg(\sum_{j=1}^{m+x}\Bigg(\sum_{k=1}^{eval(w,j1=j)}\Bigg(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)\cdot(1-(1-p_{3,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k1=0}^{eval(w,j1=j)-k}(C_3)^{k1}\right) \cdot \Bigg(\prod_{j2=1}^{j-1}\Bigg(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{eval(w,j1=j2)+1} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_3)^{k2}\right)\Bigg)\Bigg)\Bigg)\Bigg)\Bigg) \cdot b_3 + p_{3,lock} \cdot \Bigg(1 + \sum_{j=1}^{m+x}\Bigg(\prod_{j2=1}^{j}\Bigg(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_3)^{k2}\right)\Bigg)\Bigg)\Bigg) \cdot b_3 + \Bigg(\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{3,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)}\left(k\cdot(C_3)^{eval(w,j1=0)-k}\right)\right)\Bigg) \cdot \Bigg(\rho_3 \cdot (1-p_{3,lock}) \cdot$

$$p_{3,idle}\cdot\Bigg(1+\sum_{j=1}^{m+x}\bigg(\prod_{j2=1}^{j}\Big(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j2)}(C_3)^{k2}\Big)\Big)\bigg)\Bigg)+\rho_3\cdot(1-p_{3,lock})\cdot(1-p_{3,idle})\cdot\Bigg(\prod_{j2=1}^{m+x}\Big(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j)}(C_3)^{k2}\Big)\Big)\Bigg)\cdot b_3\Bigg):$$

$$e26 := b_{4,syn} = \frac{1}{\Big(1-\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{4,idle})\cdot(1-p_{last}))}\Big(\sum_{k=1}^{eval(w,j1=0)}\big(k\cdot(C_4)^{eval(w,j1=0)-k}\big)\Big)\Big)\cdot p_{4,cont}}$$
$$\Bigg(q_4\cdot b_{4,empty}+p_{last}\Bigg(\sum_{j=1}^{m+x}\Bigg(\sum_{k=1}^{eval(w,j1=j)}\Bigg(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)\cdot(1-(1-p_{4,idle})\cdot(1-p_{last}))}\cdot\Big(\sum_{k1=0}^{eval(w,j1=j)-k}(C_4)^{k1}\Big)\cdot\Big(\prod_{j2=1}^{j-1}\Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{eval(w,j1=j2)+1}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j2)}(C_4)^{k2}\Big)\Big)\Big)\Bigg)\Bigg)\Bigg)\cdot b_3+p_{4,lock}\cdot\Bigg(1+\sum_{j=1}^{m+x}\Big(\prod_{j2=1}^{j}\Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j2)}(C_4)^{k2}\Big)\Big)\Big)\Bigg)\cdot b_4+\Bigg(\frac{p_{last}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{4,idle})\cdot(1-p_{last}))}\cdot\Big(\sum_{k=1}^{eval(w,j1=0)}\big(k\cdot(C_4)^{eval(w,j1=0)-k}\big)\Big)\Bigg)\cdot\Bigg(\rho_4\cdot(1-p_{4,lock})\cdot p_{4,idle}\cdot\Bigg(1+\sum_{j=1}^{m+x}\Big(\prod_{j2=1}^{j}\Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j2)}(C_4)^{k2}\Big)\Big)\Big)\Bigg)+\rho_4\cdot(1-p_{4,lock})\cdot(1-p_{4,idle})\cdot\Bigg(\prod_{j2=1}^{m+x}\Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j)}(C_4)^{k2}\Big)\Big)\Bigg)\cdot b_4\Bigg):$$

$$e27 := \rho_1 = \lambda_1\cdot\Bigg(\sum_{k=0}^{m+x}\Bigg(\Bigg(\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{1,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{1,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+k\cdot t_{coll}+t_{succ}\Bigg)\cdot((1-p_{1,lock})\cdot(1-p_{1,idle}))^{K}\cdot(1-p_{1,lock})\cdot p_{1,idle}\Bigg)+\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{1,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{1,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+(m+x+1)\cdot t_{coll}\cdot((1-p_{1,lock})\cdot(1-p_{1,idle}))^{m+x+1}\Bigg):$$

$$e28 := \rho_2 = \lambda_2\cdot\Bigg(\sum_{k=0}^{m+x}\Bigg(\Bigg(\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{2,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{2,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+k\cdot t_{coll}+t_{succ}\Bigg)\cdot((1-p_{2,lock})\cdot(1-p_{2,idle}))^{K}\cdot(1-p_{2,lock})\cdot p_{2,idle}\Bigg)+\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{2,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{2,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+(m+x+1)\cdot t_{coll}\cdot((1-p_{2,lock})\cdot(1-p_{2,idle}))^{m+x+1}\Bigg):$$

$$e29 := \rho_3 = \lambda_3\cdot\Bigg(\sum_{k=0}^{m+x}\Bigg(\Bigg(\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{3,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{3,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+k\cdot t_{coll}+t_{succ}\Bigg)\cdot((1-p_{3,lock})\cdot(1-p_{3,idle}))^{K}\cdot(1-p_{3,lock})\cdot p_{3,idle}\Bigg)+\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{3,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{3,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+(m+x+1)\cdot t_{coll}\cdot((1-p_{3,lock})\cdot(1-p_{3,idle}))^{m+x+1}\Bigg):$$

$$e30 := \rho_4 = \lambda_4\cdot\Bigg(\sum_{k=0}^{m+x}\Bigg(\Bigg(\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{4,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{4,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+k\cdot t_{coll}+t_{succ}\Bigg)\cdot((1-p_{4,lock})\cdot(1-p_{4,idle}))^{K}\cdot(1-p_{4,lock})\cdot p_{4,idle}\Bigg)+\sum_{l=0}^{k}\frac{eval(w,j1=l)}{2}\cdot((1-p_{busy})\cdot t_{slot}+(1-p_{4,lock})\cdot p_{succ}\cdot t_{succ}+(1-p_{4,lock})\cdot(p_{busy}-p_{succ})\cdot t_{coll})+(m+x+1)\cdot t_{coll}\cdot((1-p_{4,lock})\cdot(1-p_{4,idle}))^{m+x+1}\Bigg):$$

$$e31 := \tau_1 = \Bigg(1+\sum_{j=1}^{m+x}\Big(\prod_{j2=1}^{j}\Big(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)}\cdot\Big(\sum_{k2=0}^{eval(w,j1=j2)}(C_1)^{k2}\Big)\Big)\Big)\Bigg)\cdot b_1+p_{1,idle}\cdot$$

$p_{1,cont} \cdot b_{1,syn}$:

$$e32 := \tau_2 = \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_2)^{k2}\right)\right)\right)\right) \cdot b_2 + p_{2,idle} \cdot p_{2,cont} \cdot b_{2,syn} :$$

$$e33 := \tau_3 = \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_3)^{k2}\right)\right)\right)\right) \cdot b_3 + p_{3,idle} \cdot p_{3,cont} \cdot b_{3,syn} :$$

$$e34 := \tau_4 = \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_4)^{k2}\right)\right)\right)\right) \cdot b_4 + p_{4,idle} \cdot p_{4,cont} \cdot b_{4,syn} :$$

$$e35 := b_1 = \left(1 - b_{1,empty} - b_{1,syn} \cdot \left(1 + \frac{p_{1,cont}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{1,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)} (k \cdot (C_1)^{(eval(w,j1=0)-k)}\right)\right)\right) / \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2} (C_1)^{k2}\right)\right)\right) + \sum_{j=1}^{m+x}\left(\sum_{k=1}^{eval(w,j1=j)}\left(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{((eval(w,j1=j)+1)\cdot(1-(1-p_{1,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k1=0}^{eval(w,j1=j)-k}(C_1)^{k1}\right) \cdot \left(\prod_{j2=1}^{j-1}\left(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{((eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_1)^{k2}\right)\right)\right)\right)\right) + \left(\frac{1}{(eval(w,j1=0)+1)\cdot(1-(1-p_{1,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)}(k \cdot (C_1)^(eval(w, j1 = 0) - k)\right)\right) \cdot \left(\rho_1 \cdot (1 - p_{1,lock}) \cdot p_{1,idle} \cdot \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_1)^{k2}\right)\right)\right)\right) + \rho_1 \cdot (1 - p_{1,lock}) \cdot (1 - p_{1,idle}) \cdot \left(\prod_{j=1}^{m+x}\left(\frac{(1-p_{1,lock})\cdot(1-p_{1,idle})}{(eval(w,j1=j)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j)}(C_1)^{k2}\right)\right)\right)\right)\right):$$

$$e36 := b_2 = \left(1 - b_{2,empty} - b_{2,syn} \cdot \left(1 + \frac{p_{2,cont}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{2,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)} (k \cdot (C_2)^{(eval(w,j1=0)-k)}\right)\right)\right) / \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2} (C_2)^{k2}\right)\right)\right) + \sum_{j=1}^{m+x}\left(\sum_{k=1}^{eval(w,j1=j)}\left(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{((eval(w,j1=j)+1)\cdot(1-(1-p_{2,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k1=0}^{eval(w,j1=j)-k}(C_2)^{k1}\right) \cdot \left(\prod_{j2=1}^{j-1}\left(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{((eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_2)^{k2}\right)\right)\right)\right)\right) + \left(\frac{1}{(eval(w,j1=0)+1)\cdot(1-(1-p_{2,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)}(k \cdot (C_2)^(eval(w, j1 = 0) - k)\right)\right) \cdot \left(\rho_2 \cdot (1 - p_{2,lock}) \cdot p_{2,idle} \cdot \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_2)^{k2}\right)\right)\right)\right) + \rho_2 \cdot (1 - p_{2,lock}) \cdot (1 - p_{2,idle}) \cdot \left(\prod_{j=1}^{m+x}\left(\frac{(1-p_{2,lock})\cdot(1-p_{2,idle})}{(eval(w,j1=j)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j)}(C_2)^{k2}\right)\right)\right)\right)\right):$$

$$e37 := b_3 = \left(1 - b_{3,empty} - b_{3,syn} \cdot \left(1 + \frac{p_{3,cont}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{3,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)} (k \cdot (C_3)^{(eval(w,j1=0)-k)}\right)\right)\right) / \left(1 + \sum_{j=1}^{m+x}\left(\prod_{j2=1}^{j}\left(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2} (C_3)^{k2}\right)\right)\right) + \sum_{j=1}^{m+x}\left(\sum_{k=1}^{eval(w,j1=j)}\left(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{((eval(w,j1=j)+1)\cdot(1-(1-p_{3,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k1=0}^{eval(w,j1=j)-k}(C_3)^{k1}\right) \cdot \left(\prod_{j2=1}^{j-1}\left(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{((eval(w,j1=j2)+1)} \cdot \left(\sum_{k2=0}^{eval(w,j1=j2)}(C_3)^{k2}\right)\right)\right)\right)\right) + \left(\frac{1}{(eval(w,j1=0)+1)\cdot(1-(1-p_{3,idle})\cdot(1-p_{last}))} \cdot \left(\sum_{k=1}^{eval(w,j1=0)}(k \cdot (C_3)^(eval(w, j1 = 0) - k)\right)\right) \cdot$$

$\Big(\rho_3 \cdot (1-p_{3,lock}) \cdot p_{3,idle} \cdot \Big(1 + \sum_{j=1}^{m+x} \Big(\prod_{j2=1}^{j} \Big(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j2)+1)} \cdot \Big(\sum_{k2=0}^{eval(w,j1=j2)} (C_3)^{k2} \Big)\Big)\Big)\Big)+$
$\rho_3 \cdot (1-p_{3,lock}) \cdot (1-p_{3,idle}) \cdot \Big(\prod_{j=1}^{m+x} \Big(\frac{(1-p_{3,lock})\cdot(1-p_{3,idle})}{(eval(w,j1=j)+1)} \cdot \Big(\sum_{k2=0}^{eval(w,j1=j)} (C_3)^{k2} \Big)\Big)\Big)\Big):$

$e38 := b_4 = \Big(1 - b_{4,empty} - b_{4,syn} \cdot \Big(1 + \frac{p_{4,cont}}{(eval(w,j1=0)+1)\cdot(1-(1-p_{4,idle})\cdot(1-p_{last}))} \cdot \Big(\sum_{k=1}^{eval(w,j1=0)}$
$(k \cdot (C_4)^{(eval(w,j1=0)-k)}\Big)\Big)\Big)/\Big(1 + \sum_{j=1}^{m+x} \Big(\prod_{j2=1}^{j} \Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)} \cdot \Big(\sum_{k2=0}^{eval(w,j1=j2}$
$(C_4)^{k2}\Big)\Big)\Big) + \sum_{j=1}^{m+x} \Big(\sum_{k=1}^{eval(w,j1=j)} \Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{((eval(w,j1=j)+1)\cdot(1-(1-p_{4,idle})\cdot(1-p_{last}))} \cdot$
$\Big(\sum_{k1=0}^{eval(w,j1=j)-k} (C_4)^{k1} \Big) \cdot \Big(\prod_{j2=1}^{j-1} \Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{((eval(w,j1=j2)+1)} \cdot \Big(\sum_{k2=0}^{eval(w,j1=j2)} (C_4)^{k2} \Big)\Big)\Big)\Big)\Big)+$
$\Big(\frac{1}{(eval(w,j1=0)+1)\cdot(1-(1-p_{4,idle})\cdot(1-p_{last}))} \cdot \Big(\sum_{k=1}^{eval(w,j1=0)} (k \cdot (C_4)^{(}eval(w,j1=0)-k)\Big)\Big) \cdot$
$\Big(\rho_4 \cdot (1-p_{4,lock}) \cdot p_{4,idle} \cdot \Big(1 + \sum_{j=1}^{m+x} \Big(\prod_{j2=1}^{j} \Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j2)+1)} \cdot \Big(\sum_{k2=0}^{eval(w,j1=j2)} (C_4)^{k2} \Big)\Big)\Big)\Big)+$
$\rho_4 \cdot (1-p_{4,lock}) \cdot (1-p_{4,idle}) \cdot \Big(\prod_{j=1}^{m+x} \Big(\frac{(1-p_{4,lock})\cdot(1-p_{4,idle})}{(eval(w,j1=j)+1)} \cdot \Big(\sum_{k2=0}^{eval(w,j1=j)} (C_4)^{k2} \Big)\Big)\Big)\Big):$

$CSTR := \{p[busy], p[1, idle], p[2, idle], p[3, idle], p[4, idle], p[1, succ], p[2, succ], p[3, succ],$
$p[4, succ], p[succ], C[1], C[2], C[3], C[4], b[1, empty], b[2, empty], b[3, empty], b[4, empty], q[1],$
$q[2], q[3], q[4], b[1, syn], b[2, syn], b[3, syn], b[4, syn], \rho[1], \rho[2], \rho[3], \rho[4], \tau[1], \tau[2], \tau[3], \tau[4],$
$b[1], b[2], b[3], b[4]\} =\sim (0..1);$

$residuals := (lhs - rhs) \sim ([e1, e2, e3, e4, e5, e6, e7, e8, e9, e10, e11, e12, e13, e14, e15, e16,$
$e17, e18, e19, e20, e21, e22, e23, e24, e25, e26, e27, e28, e29, e30, e31, e32, e33, e34, e35, e36,$
$e37, e38];$

$ansLS[a] := Optimization : -LSSolve(residuals, op(CSTR), iterationlimit = 1000;$

$ansDS[a] := DirectSearch : -SolveEquations(residuals, CSTR, initialpoint = ansLS[a][2];$

end do

$Matrix(3, 38, [seq(ansDS[j][3], j = 1..38)]):$

$Matrix(3, 38, [seq(ansLS[j][3], j = 1..38)]):$

$LSMat := Matrix(max([indices(ansLS,' nolist')]) + 1, numelems(ansLS[1][2] + 1):$

$LSMat[1, 1] :=$ "a":

$LSMat[1, 2.. - 1] := convert \sin(\ (lhs \sin(ansLS[1][2])[]), string):$

$LSMat[2.. - 1, 1] := (seq(j.j = 1..a - 1)):$

$LSMat[2.. - 1, 2.. - 1] := (seq(Transpose(\ (rhs \sin(ansLS[j][2]) \ ) \ ), j = 1..a - 1)):$

$DSMat := Matrix(max([indices(ansDS,' nolist')]) + 1, \ numelems(ansDS[1][3]) + 1):$

$DSMat[1, 1] :=$ "a":

$DSMat[1, 2.. - 1] := convert \sim (\ (lhs \sim (ansDS[1][3])[]), string:$

$DSMat[2..-1,1] := (seq(j, j=1..a-1))$:

$DSMat[2..-1,2..-1] := (seq(\ Transpose(\ (rhs \sim (ansDS[j][3]))), j=1..a-1))$:

$LSMat$:

$DSMat$:

$> mi := max[index](DSMat - LSMat)$:

$(DSMat - LSMat)[mi]$:

$> ExcelTools:-Export(LSMat,\ cat(frame), 1,$ "A9"):

$> p_{busy} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "R10:R13")), $Vector)$:

$> p_{succ} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "S10:S13")), $Vector)$:

$> p_{1,succ} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "U10:U13")), $Vector)$:

$> p_{2,succ} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "W10:W13")), $Vector)$:

$> p_{3,succ} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "Y10:Y13")), $Vector)$:

$> p_{4,succ} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "AA10:AA13")), $Vector)$:

$> p_{1,idle} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "T10:T13")), $Vector)$:

$> p_{2,idle} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "V10:V13")), $Vector)$:

$> p_{3,idle} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "X10:X13")), $Vector)$:

$> p_{4,idle} := convert((ExcelTools:-Impot(frame,$ "Sheet1", "Z10:Z13")), $Vector)$:

$> \tau_1 := convert((ExcelTools:-Impot(frame,$ "Sheet1", "AJ10:AJ13")), $Vector)$:

$> \tau_2 := convert((ExcelTools:-Impot(frame,$ "Sheet1", "AK10:AK13")), $Vector)$:

$> \tau_3 := convert((ExcelTools:-Impot(frame,$ "Sheet1", "AL10:AL13")), $Vector)$:

$> \tau_4 := convert((ExcelTools:-Impot(frame,$ "Sheet1", "AM10:AM13")), $Vector)$:

$>$ **for** i **from** 1 **by** 1 **to** *nodetype* **do**

$n_1 := n1[i]$:

$n_2 := n2[i]$:

$n_3 := n3[i]$:

$n_4 := n4[i]$:

$U_1[i] := \frac{n_1 \cdot p_{1,succ}[i] \cdot t_{framebody}}{(1-p_{busy}[i]) \cdot t_{slot} + p_{succ}[i] \cdot t_{succ} + (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}}$:

$U_2[i] := \frac{n_2 \cdot p_{2,succ}[i] \cdot t_{framebody}}{(1-p_{busy}[i]) \cdot t_{slot} + p_{succ}[i] \cdot t_{succ} + (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}}$:

$U_3[i] := \frac{n_3 \cdot p_{3,succ}[i] \cdot t_{framebody}}{(1-p_{busy}[i]) \cdot t_{slot} + p_{succ}[i] \cdot t_{succ} + (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}}$:

$U_4[i] := \frac{n_4 \cdot p_{4,succ}[i] \cdot t_{framebody}}{(1-p_{busy}[i]) \cdot t_{slot} + p_{succ}[i] \cdot t_{succ} + (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}}$:

$H[i] := U_1[i] + U_2[i] + U_3[i] + U_4[i]$:

$p_{1,coll} := \tau_1[i] \cdot \left(1 - \frac{(1-\tau_1[i])^{n_1} \cdot (1-\tau_2[i])^{n_2} \cdot (1-\tau_3[i])^{n_3} \cdot (1-\tau_4[i])^{n_4}}{(1-\tau_1[i])}\right)$:

$p_{2,coll} := \tau_2[i] \cdot \left(1 - \frac{(1-\tau_1[i])^{n_1} \cdot (1-\tau_2[i])^{n_2} \cdot (1-\tau_3[i])^{n_3} \cdot (1-\tau_4[i])^{n_4}}{(1-\tau_2[i])}\right)$:

$p_{3,coll} := \tau_3[i] \cdot \left(1 - \frac{(1-\tau_1[i])^{n_1} \cdot (1-\tau_2[i])^{n_2} \cdot (1-\tau_3[i])^{n_3} \cdot (1-\tau_4[i])^{n_4}}{(1-\tau_3[i])}\right)$:

$p_{4,coll} := \tau_4[i] \cdot \left(1 - \frac{(1-\tau_1[i])^{n_1} \cdot (1-\tau_2[i])^{n_2} \cdot (1-\tau_3[i])^{n_3} \cdot (1-\tau_4[i])^{n_4}}{(1-\tau_4[i])}\right)$:

$t_{1,delay}[i] := \sum_{k=0}^{m+x} \Bigg(\Bigg(\sum_{l=0}^{k} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{1,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{1,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + k \cdot t_{coll} + t_{succ} \Bigg) \cdot ((1 - p_{1,lock}) \cdot (1 - p_{1,idle}[i]))^K \cdot (1 - p_{1,lock}) \cdot p_{1,idle}[i] \Bigg) + \sum_{l=0}^{m+x} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{1,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{1,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + (m + x + 1) \cdot t_{coll} \cdot ((1 - p_{1,lock}) \cdot (1 - p_{1,idle}[i]))^{m+x+1}$:

$t_{2,delay}[i] := \sum_{k=0}^{m+x} \Bigg(\Bigg(\sum_{l=0}^{k} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{2,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{2,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + k \cdot t_{coll} + t_{succ} \Bigg) \cdot ((1 - p_{2,lock}) \cdot (1 - p_{2,idle}[i]))^K \cdot (1 - p_{2,lock}) \cdot p_{2,idle}[i] \Bigg) + \sum_{l=0}^{m+x} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{2,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{2,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + (m + x + 1) \cdot t_{coll} \cdot ((1 - p_{2,lock}) \cdot (1 - p_{2,idle}[i]))^{m+x+1}$:

$t_{3,delay}[i] := \sum_{k=0}^{m+x} \Bigg(\Bigg(\sum_{l=0}^{k} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{3,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{3,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + k \cdot t_{coll} + t_{succ} \Bigg) \cdot ((1 - p_{3,lock}) \cdot (1 - p_{3,idle}[i]))^K \cdot (1 - p_{3,lock}) \cdot p_{3,idle}[i] \Bigg) + \sum_{l=0}^{m+x} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{3,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{3,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + (m + x + 1) \cdot t_{coll} \cdot ((1 - p_{3,lock}) \cdot (1 - p_{3,idle}[i]))^{m+x+1}$:

$t_{4,delay}[i] := \sum_{k=0}^{m+x} \Bigg(\Bigg(\sum_{l=0}^{k} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{4,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{4,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + k \cdot t_{coll} + t_{succ} \Bigg) \cdot ((1 - p_{4,lock}) \cdot (1 - p_{4,idle}[i]))^K \cdot (1 - p_{4,lock}) \cdot p_{4,idle}[i] \Bigg) + \sum_{l=0}^{m+x} \frac{eval(w,j1=l)}{2} \cdot ((1 - p_{busy}[i]) \cdot t_{slot} + (1 - p_{4,lock}) \cdot p_{succ}[i] \cdot t_{succ} + (1 - p_{4,lock}) \cdot (p_{busy}[i] - p_{succ}[i]) \cdot t_{coll}) + (m + x + 1) \cdot t_{coll} \cdot ((1 - p_{4,lock}) \cdot (1 - p_{4,idle}[i]))^{m+x+1}$:

$t_{delay}[i] := \frac{t_{1,delay}[i] + t_{2,delay}[i] + t_{3,delay}[i] + t_{4,delay}[i]}{nodetype}$:

$r_1[i] := 1 - (1 - p_{1,idle}[i])^{m+x+1}$:

$r_2[i] := 1 - (1 - p_{2,idle}[i])^{m+x+1}$:

$r_3[i] := 1 - (1 - p_{3,idle}[i])^{m+x+1}$:

$r_4[i] := 1 - (1 - p_{4,idle}[i])^{m+x+1}$:

$re[i] := \frac{r_1[i] + r_2[i] + r_3[i] + r_4[i]}{nodetype}$:

$E_{1,succ}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{data} \cdot p_{tx} + t_{ack} \cdot p_{rx} + 3 \cdot t_{sifs} \cdot p_{idle}) \cdot p_{1,succ}[i]$:

$E_{2,succ}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{data} \cdot p_{tx} + t_{ack} \cdot p_{rx} + 3 \cdot t_{sifs} \cdot p_{idle}) \cdot p_{2,succ}[i]$:

$E_{3,succ}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{data} \cdot p_{tx} + t_{ack} \cdot p_{rx} + 3 \cdot t_{sifs} \cdot p_{idle}) \cdot p_{3,succ}[i]$:

$E_{4,succ}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{data} \cdot p_{tx} + t_{ack} \cdot p_{rx} + 3 \cdot t_{sifs} \cdot p_{idle}) \cdot p_{4,succ}[i]$:

$E_{1,coll}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{sifs} \cdot p_{idle}) \cdot p_{1,coll}[i]$:

$E_{2,coll}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{sifs} \cdot p_{idle}) \cdot p_{2,coll}[i]$:

$E_{3,coll}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{sifs} \cdot p_{idle}) \cdot p_{3,coll}[i]$:

$E_{4,coll}[i] := (t_{pspoll} \cdot p_{tx} + t_{pspollack} \cdot p_{rx} + t_{sifs} \cdot p_{idle}) \cdot p_{4,coll}[i]$:

$E_{1,idle}[i] := p_{idle} \cdot t_{slot} \cdot p_{1,idle}[i]$:

$E_{2,idle}[i] := p_{idle} \cdot t_{slot} \cdot p_{2,idle}[i]$:

$E_{3,idle}[i] := p_{idle} \cdot t_{slot} \cdot p_{3,idle}[i]$:

$E_{4,idle}[i] := p_{idle} \cdot t_{slot} \cdot p_{4,idle}[i]$:

$En_1[i] := (E_{1,idle}[i] + E_{1,succ}[i] + E_{1,coll}[i]) \cdot 1000$:

$En_2[i] := (E_{2,idle}[i] + E_{2,succ}[i] + E_{2,coll}[i]) \cdot 1000$:

$En_3[i] := (E_{3,idle}[i] + E_{3,succ}[i] + E_{3,coll}[i]) \cdot 1000$:

$En_4[i] := (E_{4,idle}[i] + E_{4,succ}[i] + E_{4,coll}[i]) \cdot 1000$:

$Energy[i] := \frac{n_1 \cdot En_1[i] + n_2 \cdot En_2[i] + n_3 \cdot En_3[i] + n_4 \cdot En_4[i]}{nodetype}$:

end do

$> ExcelTools : -Export(Groups, cat(frame), 1,$ "A21"):

$> ExcelTools : -Export(Group1, cat(frame), 1,$ "A22"):

$> ExcelTools : -Export(Group2, cat(frame), 1,$ "A23"):

$> ExcelTools : -Export(Group3, cat(frame), 1,$ "A24"):

$> ExcelTools : -Export(Group4, cat(frame), 1,$ "A25"):

$> ExcelTools : -Export(T - C1, cat(frame), 1,$ "B21"):

$> b := Matrix(4, 1, [seq(U_1[j], j = 1..4)])$:

$> ExcelTools : -Expost(b, cat(frame), 1,$ "B22"):

$> ExcelTools : -Export(T - C2, cat(frame), 1,$ "C21"):

$> c := Matrix(4, 1, [seq(U_2[j], j = 1..4)])$:

$> ExcelTools : -Expost(c, cat(frame), 1,$ "C22"):

$> ExcelTools : -Export(T - C3, cat(frame), 1,$ "D21"):

$> d := Matrix(4, 1, [seq(U_3[j], j = 1..4)])$:

$> ExcelTools : -Expost(d, cat(frame), 1,$ "D22"):

$> ExcelTools:-Export(T-C4, cat(frame), 1, \texttt{"E21"})$:

$> e := Matrix(4, 1, [seq(U_4[j], j = 1..4)])$:

$> ExcelTools:-Expost(e, cat(frame), 1, \texttt{"E22"})$:

$> ExcelTools:-Export(T-RAWslot, cat(frame), 1, \texttt{"G21"})$:

$> g := Matrix(4, 1, [seq(H[j], j = 1..4)])$:

$> ExcelTools:-Expost(g, cat(frame), 1, \texttt{"G22"})$:

$> H := convert((ExcelTools:-Import(frame, \texttt{"Sheet1"}, \texttt{"G22:G25"})), Vector)$:

$> S_{agg} := \frac{H[1]\cdot t_{RAWslot}+H[2]\cdot t_{RAWslot}+H[3]\cdot t_{RAWslot}+H[4]\cdot t_{RAWslot}}{t_{RAW}}$:

$> ExcelTools:-Export(T[agg], cat(frame), 1, \texttt{"I21"})$:

$> ExcelTools:-Export(S[agg], cat(frame), 1, \texttt{"I22"})$:

$> F := \frac{(H[1]+H[2]+H[3]+H[4])^2}{n_{RAWslot}\cdot((H[1]^2)+(H[2]^2)+(H[3]^2)+(H[4]^2))}$:

$> ExcelTools:-Export(Fairness, cat(frame), 1, \texttt{"J21"})$:

$> ExcelTools:-Export(F, cat(frame), 1, \texttt{"J22"})$:

$> ExcelTools:-Export(Groups, cat(frame), 1, \texttt{"A28"})$:

$> ExcelTools:-Export(Group1, cat(frame), 1, \texttt{"A29"})$:

$> ExcelTools:-Export(Group2, cat(frame), 1, \texttt{"A30"})$:

$> ExcelTools:-Export(Group3, cat(frame), 1, \texttt{"A31"})$:

$> ExcelTools:-Export(Group4, cat(frame), 1, \texttt{"A32"})$:

$> ExcelTools:-Export(D-C1, cat(frame), 1, \texttt{"B28"})$:

$> d1 := Matrix(4, 1, [seq(t_{1,delay}[j], j = 1..4)])$:

$> ExcelTools:-Expost(d1, cat(frame), 1, \texttt{"B29"})$:

$> ExcelTools:-Export(D-C2, cat(frame), 1, \texttt{"C28"})$:

$> d2 := Matrix(4, 1, [seq(t_{2,delay}[j], j = 1..4)])$:

$> ExcelTools:-Expost(d2, cat(frame), 1, \texttt{"C29"})$:

$> ExcelTools:-Export(D-C3, cat(frame), 1, \texttt{"D28"})$:

$> d3 := Matrix(4, 1, [seq(t_{3,delay}[j], j = 1..4)])$:

$> ExcelTools:-Expost(d3, cat(frame), 1, \texttt{"D29"})$:

$> ExcelTools:-Export(D-C4, cat(frame), 1, \texttt{"E28"})$:

$> d4 := Matrix(4, 1, [seq(t_{4,delay}[j], j = 1..4)])$:

$> ExcelTools:-Expost(d4, cat(frame), 1, \texttt{"E29"})$:

$> ExcelTools:-Export(D-RAWslot, cat(frame), 1, \texttt{"G28"})$:

$> dg := Matrix(4, 1, [seq(t_{delay}[j], j = 1..4)])$:

$> ExcelTools : -Expost(dg, cat(frame), 1,$ "G29"):

$> t_{delay} := convert((ExcelTools : -Import(frame,$ "Sheet1", "G29:G32")), $Vector)$:

$> t_{delayagg} := \frac{t_{delay}[1]+t_{delay}[2]+t_{delay}[3]+t_{delay}[4]}{n_{RAWslot}}$:

$> ExcelTools : -Export(T[delayagg], cat(frame), 1,$ "I28"):

$> ExcelTools : -Export(t[delayagg], cat(frame), 1,$ "Sheet1""I30"):

$> ExcelTools : -Export(Groups, cat(frame), 1,$ "A35"):

$> ExcelTools : -Export(Group1, cat(frame), 1,$ "A36"):

$> ExcelTools : -Export(Group2, cat(frame), 1,$ "A37"):

$> ExcelTools : -Export(Group3, cat(frame), 1,$ "A38"):

$> ExcelTools : -Export(Group4, cat(frame), 1,$ "A39"):

$> ExcelTools : -Export(RE - C1, cat(frame), 1,$ "B35"):

$> re1 := Matrix(4, 1, [seq(r_1[j], j = 1..4)])$:

$> ExcelTools : -Expost(re1, cat(frame), 1,$ "B36"):

$> ExcelTools : -Export(RE - C2, cat(frame), 1,$ "C35"):

$> re2 := Matrix(4, 1, [seq(r_2[j], j = 1..4)])$:

$> ExcelTools : -Expost(re2, cat(frame), 1,$ "C36"):

$> ExcelTools : -Export(RE - C3, cat(frame), 1,$ "D35"):

$> re3 := Matrix(4, 1, [seq(r_3[j], j = 1..4)])$:

$> ExcelTools : -Expost(re3, cat(frame), 1,$ "D36"):

$> ExcelTools : -Export(RE - C4, cat(frame), 1,$ "E35"):

$> re4 := Matrix(4, 1, [seq(r_4[j], j = 1..4)])$:

$> ExcelTools : -Expost(re4, cat(frame), 1,$ "E36"):

$> ExcelTools : -Export(RE - RAWslot, cat(frame), 1,$ "G35"):

$> reg := Matrix(4, 1, [seq(re[j], j = 1..4)])$:

$> ExcelTools : -Expost(reg, cat(frame), 1,$ "G36"):

$> re := convert((ExcelTools : -Import(frame,$ "Sheet1", "G36:G39")), $Vector)$:

$> reagg := \frac{re[1]+re[2]+re[3]+re[4]}{n_{RAWslot}}$:

$> ExcelTools : -Export(REagg, cat(frame), 1,$ "I35"):

$> ExcelTools : -Export(reagg, cat(frame), 1,$ "I37"):

$> ExcelTools : -Export(Groups, cat(frame), 1,$ "A42"):

$> ExcelTools : -Export(Group1, cat(frame), 1,$ "A43"):

$> ExcelTools : -Export(Group2, cat(frame), 1,$ "A44"):

$> ExcelTools : -Export(Group3, cat(frame), 1, \texttt{"A45"})$:

$> ExcelTools : -Export(Group4, cat(frame), 1, \texttt{"A46"})$:

$> ExcelTools : -Export(E - C1, cat(frame), 1, \texttt{"B42"})$:

$> en1 := Matrix(4, 1, [seq(En_1[j], j = 1..4)])$:

$> ExcelTools : -Expost(en1, cat(frame), 1, \texttt{"B43"})$:

$> ExcelTools : -Export(E - C2, cat(frame), 1, \texttt{"C42"})$:

$> en2 := Matrix(4, 1, [seq(En_2[j], j = 1..4)])$:

$> ExcelTools : -Expost(en2, cat(frame), 1, \texttt{"C43"})$:

$> ExcelTools : -Export(E - C3, cat(frame), 1, \texttt{"D42"})$:

$> en3 := Matrix(4, 1, [seq(En_3[j], j = 1..4)])$:

$> ExcelTools : -Expost(en3, cat(frame), 1, \texttt{"D43"})$:

$> ExcelTools : -Export(E - C4, cat(frame), 1, \texttt{"E42"})$:

$> en4 := Matrix(4, 1, [seq(En_4[j], j = 1..4)])$:

$> ExcelTools : -Expost(en4, cat(frame), 1, \texttt{"E43"})$:

$> ExcelTools : -Export(E - RAWslot, cat(frame), 1, \texttt{"G42"})$:

$> eg := Matrix(4, 1, [seq(Energy[j], j = 1..4)])$:

$> ExcelTools : -Expost(eg, cat(frame), 1, \texttt{"G43"})$:

$> Ener := convert((ExcelTools : -Import(frame, \texttt{"G43:G46"},)), Vector)$:

$> E_{agg} := \frac{Ener[1]+Ener[2]+Ener[3]+Ener[4]}{n_{RAWslot}}$:

$> ExcelTools : -Export(Eagg, cat(frame), 1, \texttt{"I42"})$:

$> ExcelTools : -Export(E[agg], cat(frame), 1, \texttt{"I44"})$:

List of Publications

[1] Most. Anju Ara Hasi, Md. Dulal Haque and Md. Abubakar Siddik, "Traffic Demand-based Grouping for Fairness among the RAW Groups of Heterogeneous Stations in IEEE 802.11ah IoT Networks," in *2022 International Conference on Advancement in Electrical and Electronic Engineering (ICAEEE), DUET, Gazipur, Bangladesh*, pp. 1-6, 2022.