DESIGNING IEEE 802.11ah-BASED SCALABLE NETWORK FOR INTERNET OF THINGS

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR AWARD OF THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

INFORMATION TECHNOLOGY

NURZAMAN AHMED

Registration No: 2693 of 26.08.2016

DEPARTMENT OF INFORMATION TECHNOLOGY

NORTH-EASTERN HILL UNIVERSITY, SHILLONG

MEGHALAYA - 793 022

Declaration

I, Nurzaman Ahmed, hereby declare that the thesis entitled "Designing IEEE 802.11ah-based scalable network for Internet of Things" submitted to the Department of Information Technology under the School of Technology, North-Eastern Hill University, in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Information Technology is based on bonafide work carried out by me. The results embodied in this thesis have not been submitted in part or in full to any other university or institute for award of any degree or diploma.

(Nurzaman Ahmed)

Countersigned by:

Head of the Department | Supervisor

DEPARTMENT OF INFORMATION TECHNOLOGY

NORTH-EASTERN HILL UNIVERSITY

SHILLONG, MEGHALAYA-793 022

Certificate

This is to certify that the thesis entitled "Designing IEEE 802.11ah-based scalable network for Internet of Things" submitted to the North-Eastern Hill University in the Department of Information Technology under the School of Technology in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Information Technology is a record of research work carried out by Mr. Nurzaman Ahmed under my personal supervision and guidance.

All helps received by him from various sources have been duly acknowledged.

No part of this thesis has been reproduced elsewhere for award of any other degree.

Signature of the Supervisor

(Dr. Md. Iftekhar Hussain)

Designation: Associate Professor

School: Technology

Department: Information Technology

Institute: North-Eastern Hill University

DEPARTMENT OF INFORMATION TECHNOLOGY

NORTH-EASTERN HILL UNIVERSITY

SHILLONG, MEGHALAYA-793022

Certificate

This is to certify that the thesis entitled “Designing IEEE 802.11ah-based scalable network for Internet of Things” submitted by Mr. Nurzaman Ahmed to the North-Eastern Hill University in the Department of Information Technology under the School of Technology in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Information Technology has been examined by us on ____________ and found to be satisfactory.

The Committee recommends for award of the degree of Doctor of Philosophy.

Signature of

Supervisor External Examiner

Date:

Acknowledgments

Words are often less to express one's deep regard. An understanding of work like this may not be the outcome of the efforts of a single person. I take this opportunity to express my keen sense of gratitude and thanks to all who matter in achieving this tough and the most important goal of my life.

As a matter of first importance, I would like to thank my supervisor, Dr. Md. Iftekhar Hussain of North-Eastern Hill University for giving me an opportunity to work under him on this burning but challenging topic and providing me ample guidance and support throughout the course of this research. I am grateful for his guidance, encouragement and support throughout my doctoral research work at North-Eastern Hill University and also in my life. This thesis comes from his helpful discussions, supervision and meticulous attention to details.

I take this opportunity to express my appreciations to all my respected teachers in the Department and all the Research Scholars for their constructive suggestions throughout the research. I am grateful to all the technical and non-technical staff of the Department for their support. I am thankful to Ministry of Electronics and Information Technology (MeitY), Government of India for supporting this research through the project entitled "QoS Provisioning in Internet of Things (IoT)" (Ref. No. 13 (7) /2015-CC&BT dated: 28/09/2015).

I want to express my greatest gratitude to my family for their endless love, constant support, encouragement, and patients throughout my research without which I would not have reached this position.

Last but not least I would like to thank almighty for everything.

NURZAMAN AHMED

North-Eastern Hill University

Abstract

IEEE 802.11ah is considered as a promising solution for massive-scale IoT device connectivity in Internet of Things (IoT). The heterogeneous and large-scale networks of resource-constraint devices in IoT pose some unique and daunting challenges. While addressing those challenges, 802.11ah has come up with some unique features. With the use of sub-1 GHz channel bands and various Modulation and Coding Schemes (MCSs), 802.11ah can achieve up to 1 Km of coverage in a single hop with a minimum of 100 Kbps data rate. It allows up to 8,191 devices to be associated with an Access Point (AP) by using a new hierarchical Association IDentification (AID) scheme.

Different IoT applications have their own requirements while achieving scalability, power efficiency, larger coverage range, and supporting heterogeneity. Although IEEE 802.11ah with all its innovative features solves many of these, it leaves out many important and interesting issues too. Addressing those issues in order to facilitate communication over smart scalable IoT system provides motivation for this research. In this thesis, we propose four schemes which can be easily integrated with the existing features of 802.11ah. The proposed solutions and enhancements mainly address the issues related to Restricted Access Window (RAW), node grouping, relay, sectorization, and Quality of Service (QoS). In the first contribution, we propose a dynamic RAW configuration scheme for multi-hop IoT networks. A network having heterogeneous traffic loads and MCSs is considered for this protocol. The AP and relay nodes optimally adjust their RAW sizes over such scenarios. The relay nodes also use a dedicated time frame for communication with AP and other relay nodes. The new time frame is adjusted based on the optimally calculated RAW size and its own traffic load. Further, we model the optimal RAW size from an optimal backoff window measured using 2D Markov Chain method. The simulation and analytical results show significant throughput improvements in comparison to the traditional scheme.

Event-driven traffic which are generated for taking some actions in IoT ecosystem needs some sort of QoS guarantees from the networks. In our second contribution, we propose a QoS-aware MAC layer solution to increase network reliability and reduce critical traffic latency by employing a priority scheduling and an adaptive node grouping scheme. The proposed grouping scheme calculates the current traffic load and distributes them among different RAW groups considering the requirements of different stations. The RAW scheduling scheme further provides priority slot access using a backoff scheme. The proposed protocol shows significant delay improvement and better reliability for priority traffic without compromising throughput performance.

Single channel based centralized channel access mechanism employed in IEEE 802.11ah may not scale well in a large multi-hop network leading to poor quality of data reception. In the third contribution, we propose a solution to dynamically adjust MCSs in relay nodes for supporting a massive number of devices with different traffic requirements. However, to support this, the AP node has to handle the congestion occurring due to higher traffic load in it. Therefore, to improve the bandwidth capacity of the AP, a multi-band sectorization scheme is proposed. Utilizing the available channels, the proposed protocol facilitates multi-hop communication in an efficient manner. The performance results show that the proposed protocol significantly improves average throughput and packet delay over the existing 802.11ah-based protocols.

Efficient channel access mechanism for periodic stations in a large-scale 802.11ah network is still a challenging problem. In our final contribution, we propose a novel channel access mechanism for IEEE 802.11ah to reduce delay and energy consumption in large-scale networks. The proposed protocol predicts the service interval of a monitoring application and schedules its subsequent frames before their arrivals without requiring any further contention. By doing so, the proposed protocol reduces access delay and unnecessary wake-ups to a certain extent. The proposed protocol shows throughput improvement, and reduces average packet latency and energy consumption as compared to the traditional scheme.

Keywords: IEEE 802.11ah, Restricted Access Window (RAW), Internet of Things (IoT), Scalability, Heterogeneity, Quality of Service (QoS), Node Grouping, and Sectorization.

Contents

List of Figures

List of Tables

List of Abbreviations

IoT	Internet of Things
MAC	Medium Access Control
RAW	Restricted Access Window
PRAW	Periodic RAW
ACK	Acknowledgement
DCF	Distributed Coordination Function
PCF	Point Coordination Function
HCF	Hybrid Coordination Function
HCCA	HCF Controlled Channel Access
EDCA	Enhanced Distributed Channel Access
DIFS	DCF Interframe Space
RA	Resource Allocation
PS-Poll	Power Save Poll
RPS	RAW Parameter Set
MCS	Modulation and Coding Scheme
PHY	Physical
AID	Association Identifier
CBS	Cross-Slot Boundary
M2M	Machine-to-Machine

AP	Access Point
STA	Station
RAP	Relay AP
TIM	Traffic Indication Map
DTIM	Delivery TIM
SST	Channel Selective Transmission
Tx/Rx	Transmission/Reception
NDP	Null Data Packet
TXOP	Transmission Opportunity
TXOP RD	TXOP Reverse Direction
BDT	Bi-Directional TXOP
TWT	Target Wakeup Time
TBTT	Target Beacon Transmission Time
TGah	IEEE 802.11ah Task Group
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ITU	International Telecommunications Union
ISM	Industrial, Scientific and Medical
RFID	Radio-Frequency IDentification
BLE	Bluetooth Low Energy
LTE	Long Term Evolution
WiMAX	Worldwide Interoperability for Microwave Access
WiFi	Wireless Fidelity
LPWAN	Low Power Wide Area Network
T/FDM	Time/Frequency Division Multiplexing
TDMA	Time-division Multiple Access

GPRS	General Packet Radio Service
RTS/CTS	Request to Send/ Clear to Send
CSMA (/CA)	Carrier Sense Multiple Access (/with Collision Avoidance)
OFDM	Orthogonal Frequency-Division Multiplexing
AIFS/SIFS	Arbitration/Short Inter Frame Space
CAC/DAC	Centralized/Distributed Authentication Control
PSMP	Power Save Multi-Poll
CPF	Cell Polling Frame
PS-OLi	Power Save with OffsetListenInterval
RID	Response Indication Deferral
QoS	Quality of Service
BSS	Basic Service Set
MPDU	MAC Protocol Data Unit
RSS (I)	Received Signal Strength (Indicator)
UDP	User Datagram Protocol
PRR	Packet Received Ratio
NS-3	Network Simulator-3

List of Notations

$\mathbb{A}$	Access window for Relay or AP node
$\mathsf{s(t)}$	Backoff stages in 2D Markov Chain Model
$\mathsf{c(t)}$	Backoff counter in 2D Markov Chain Model
$P_{i,k}$	State transition probability of state (i,k)
$b_{i,k}$	Steady state probability that a system is in state (i,k)
τ	Probability that a station transmits a packet
τ_{opt}	Optimal transmission probability
ρ_{opt}	Optimal RAW size
$SLOT_{time}$	Total time frame duration of TDMA frame
W_i	Backoff window size at stage i
$f(c, i, j)$	Probability density function distributed over backoff stage i and backoff window j for class c
Γ_{G_i}	Ease of transmission for group G_i
φ_c	A real number, which gives the increase and decrease of the distribution for class c
$f(d)$	Probability density function for an event d
μ^d	Expected rate of occurrence of an event d
τ_c	Probability of successful transmission of a station from class c
$P_{c,i,k}$	State transition probability of (i,k) for class c

$\mathsf{E(D_c)}$	Average saturation delay for class c in a group
$\mathsf{Th_c}$	Average saturation throughput for class c in a group
$\mathsf{T_{assoc}}$	Total association time
$\mathsf{L(d)}$	Propagation loss
$\Delta\theta$	Angular separation
$\mathsf{P_r}$	Received signal power
$\mathsf{P_t}$	Transmit signal power
$\mathsf{G_r}$	Reception gain
$\mathsf{G_t}$	Transmission gain
X_σ	Shadowing effect distributed over σ
L_γ	Avg. Traffic load, calculated over γ duration
B_γ	Available bandwidth of a node, calculated over γ duration
$\mathsf{T_{FRAME}}$	Complete time frame allocated to all the associated stations
$\mathsf{T_{CON}}$	Time required contention in RAW group
$\mathsf{T_{TDATA}}$	Total time required for transmitting a data frame

Chapter 1

Introduction

The vision for Smart World brings fast growth in research, development, and deployment of Internet of Things (IoT). Things in IoT are not only connected computers, and mobiles phones, but also sensors/actuators and day to day objects such as books, medicines, vehicles, TVs, and refrigerators [1, 2]. The future of IoT lies in the success of Machine-to-Machine (M2M) communication where billions to the trillions of objects, sensors/actuators in the surrounding environments are connected and operated through a set of electronic devices supported by communication networks, and one or more cloud-based servers [3]. In different IoT-based applications such as smart healthcare, agricultural automation, electric grids, and transportation systems, the M2M network is expected to be widely utilized. The projected number of connected devices worldwide for the period 2015 to 2025 [4] is shown in Figure 1.1. Wireless network technology is the ultimate solution for connecting such a massive quantity of devices seamlessly without

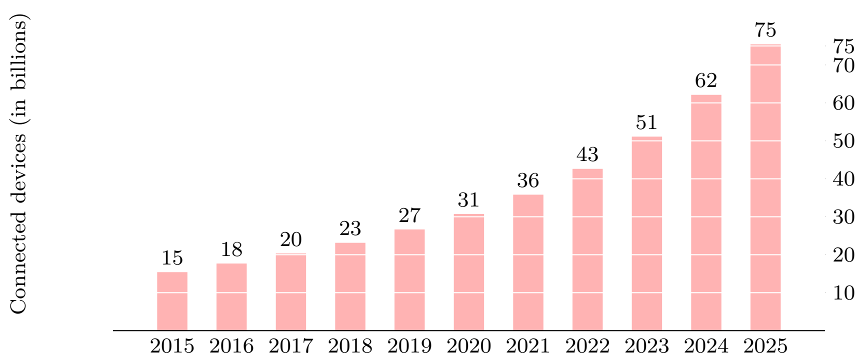


Figure 1.1: Number of connected devices installed worldwide

bothering about their geographical locations [5].

M2M communication is characterized by a large number of devices, covering a wide range, and having different requirements in terms of network and services. For example – smart lighting, smart grid, smart environment, and healthcare deploy thousands of devices, and all of these are part of a single network [6]. Traffic patterns in such a network are also not the same. In smart parking application, based on the arrival and departure events created by a car, the packet generation rate varies [7]. Monitoring applications like smart environment monitoring and smart grid mostly generate traffic periodically. These devices are restricted by—processing, storing, and energy saving capabilities. These applications use different wireless standards considering their known benefits. As a result, many heterogeneous wireless networks are competing for the same frequency in the same coverage area [8]. Again, chances of interference due to the coexistence of multiple types of networks are also high.

1.1 Research Motivation

For supporting seamless performance in M2M network having a massive number of IoT devices, a Medium Access Control (MAC) protocol holds the most important role [9, 10]. Compared to traditional ones, the MAC protocol for IoT demands features like low-power, low-cost, adaptive, cognitive, and large-scale operation [11]. The most critical MAC layer challenge in M2M communication is to enable channel access among a massive number of devices supporting their various service requirements. Additionally, the connection needs to be efficient in terms of power consumption, data-rate, latency, and cost. In these scenarios, channel access has the potential to become a bottleneck, as foreseen by many industries and standardization bodies [12]. Consequently, designing a MAC layer protocol for M2M communication has emerged as an essential area of considerable work to both researchers and practitioners. In summary, the following are the challenges that a MAC protocol needs to handle for supporting scalable M2M communication.

- The MAC protocol should be able to control huge contention and collisions to enable stable performances in a shared wireless medium with an increasing number of IoT devices.

- For enabling communication features in tiny objects, energy efficiency is one of the most important design parameter.
- With the recent technological advancements for increasing physical layer capacity, MAC layer throughput should also need to be scaled up for better performance.
- It should minimize the protocol overhead when a large number of nodes communicate over a wide coverage area.
- The solution should be able to adapt itself along with the changing nature of IoT and its traffic.
- Need to deal with the unusual but mission-critical application traffic.
- It should reduce interference when multiple networks coexist in a service area, and all of them use the same Industrial, Scientific and Medical (ISM) band.

Various standardization bodies such as the Institute of Electrical and Electronics Engineers (IEEE), Internet Engineering Task Force (IETF), and International Telecommunications Union (ITU), are working hard to make low-cost communication feasible. Among them, IEEE 802.11 and IEEE 802.15.4 standards have continuously tried to add new technologies and functionalists, and several amendments [13]. These technologies have been used widely in current IoT testbeds available worldwide as well as expanded over a wide application area, including business, mobile, and automotive [14].

There are three critical reasons for such considerable acceptance:

- Use of Industrial, Scientific and Medical (ISM) band for the communication channel
- Low-cost hardware
- Adaptation of MAC protocol called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which enables communication of multiple STAs

To meet the requirements of M2M communication such as scalability, heterogeneity, and low power consumption, 802.11ah Task Group (TGah) [15] extends the features of current 802.11-based MAC scheme with some new innovative ideas [16, 17, 18, 19].

The existing networks for smart city, smart grid, and smart agriculture operate in both sensor and backhaul scenarios. Standards such as IEEE 802.15.4, Radio-Frequency IDentification (RFID), or Bluetooth Low Energy (BLE) work over relatively shorter coverage range (1-100 meters) supporting low data-rates (bytes to megabytes) and low-power consumption. Backhaul network standards like Wireless Fidelity (WiFi), World-wide Interoperability for Microwave Access (WiMAX), General Packet Radio Services (GPRS), and Long-Term Evolution (LTE) work over relatively long distances (100 meters to kilometres) and higher data-rates (kilobytes to gigabytes) with the infrastructure of base stations demanding a proper line of sights [20, 21]. These solutions can provide high throughput (kilobytes to gigabytes) but at the cost of more energy consumption. Some recent testbeds like JEJU Testbed [22], Telefonica Ubiquitous Sensor Networks (USN) Platform [23], SmartGridLab [24], Birmingham Urban Climate Laboratory (BUCL) [25], SmartSantander [26], and OpenTestBed [27] follow this approach for communication. These procedures open spaces while connecting the sensor devices smoothly in different conditions. Further, their capabilities are limited by the—number of devices, throughput, and coverage range, and hence scalability is less.

IEEE 802.15.4 provides low-rate and low-power Wireless Personal Area Network (WPAN) that has been commercially used for a diverse range of embedded wireless sensing and control applications. It is noticed that most of the testbeds [23, 22, 26] use 802.15.4-based technology for constructing a large-scale network. However, the scalability of 802.15.4 protocol is found to be very poor in dense deployments due to a steep reduction in throughput and an increase in energy consumption with an enhancement of network sizes [28]. Due to the low-rate and use of contention-based CSMA/CA MAC protocol, it shows abysmal throughput and energy performance with a large number of nodes. It justifies the need to enhance the MAC protocol for supporting a large number of low-power devices to communicate.

The latest IEEE 802.11ah standard fills the space up to a great extent by exploiting the edge of both WiFi and low-power sensor network communication technologies[29]. Figure 1.2 shows an IEEE 802.11ah-based multi-hop network. It uses sub-1 GHz channel band to achieve coverage range up to 1 km of distance in single hop. Further, it extends the connectivity beyond the coverage range by a new relay node concept between the Access Point (AP) and stations manifold and thereby reduces power consumption by allowing shorter transmission [30].

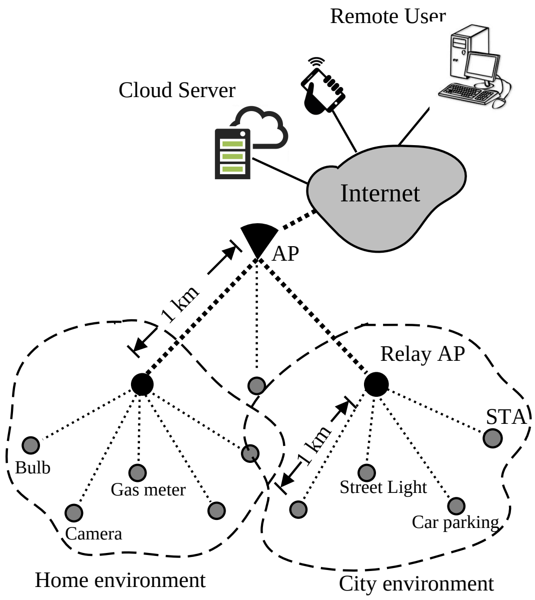


Figure 1.2: IEEE 802.11ah-based multi-hop IoT network structure

To provide support for energy efficiency and scalability in 802.11ah, TGah has been working on the Physical (PHY) and MAC layers. With the use of sub-1GHz and different Modulation and Coding Sachems (MCSs), 802.11ah can achieve longer coverage range with various data-rates (100Kbps - 78Mbps). It allows up to 8,191 devices to be associated with an AP using a hierarchical Association Identifier (AID) scheme. The use of newly proposed short MAC header, management frame, and Null Data Packet (NDP) MAC frames reduce Tx/Rx time up to a large amount. It supports very low energy consumption by adopting strategies like Target Wake Time (TWT), Traffic Indication Map (TIM) and Segmentation. To reduce collisions due to contention, 802.11ah uses Bi-Directional Transmission opportunity (BDT), and Restricted Access Window (RAW), and slotted channel access with synchronization frame. For efficient channel access and power saving, STAs are divided into non-TIM (for periodic low-traffic), TIM (for high-traffic), and unscheduled (for very low-traffic). Relay and sectorization operation allows the network to extend and organize accurately.

Use-cases of IEEE 802.11ah

Utilization of sub-1GHz band and various MCSs support over 802.11ah allows configuring different IoT applications easily. The varying data rates ranging from 100 Kbps to 78 Mbps has proved to be suitable for low-powered and resource-constraint IoT ([31] and [32]). With short and burst transmissions, the sensors of IoT devices need to be in wake-up mode only for a short time thereby conserving battery and energy. Along with IoT use-cases adopted by 802.11ah, there are backhaul networking, extended WLAN range, cellular traffic offloading, and rural communications. IEEE 802.11ah allows developing technology for sensor networks with the required throughput and coverage range. Various automation and remote control applications can be run over 802.11ah-based access network. A list of smart applications enabled by sensors, meters, and their traffic types are discussed in Table 1.1 ([33] and [34]).

An AP or Relay of 802.11ah covers thousands of sensor/actuators which are connected to the Internet. The devices like a camera for a surveillance system or WiFi node of the Internet require significant amount of bandwidth to transmit. On the other hand, devices like lights or alarms, send a very short packet with a very low data-rate. As 802.11ah has different MCSs with the various data rates, it is more suitable for complex

Use-case	Traffic flow	Data rate	Traffic types
Smart grid	Bi-Directional	100Kbps	Continuous/Periodic /Burst
Environment /Agriculture Monitoring	Mostly Uplink	100Kbps	Periodic, Event-driven
Industrial process automation	Bi-Directional	< 1Mbps	Periodic, Burst
Indoor healthcare system	Mostly Uplink	100Kbps	Periodic, Event-driven
Healthcare /Fitness	Bi-Directional	100Kbps	Periodic, Event-driven
Backhaul Network	Bi-Directional	>200Kbps	Continuous, Periodic, Burst, Event-driven

Table 1.1: IoT use-cases of 802.11ah

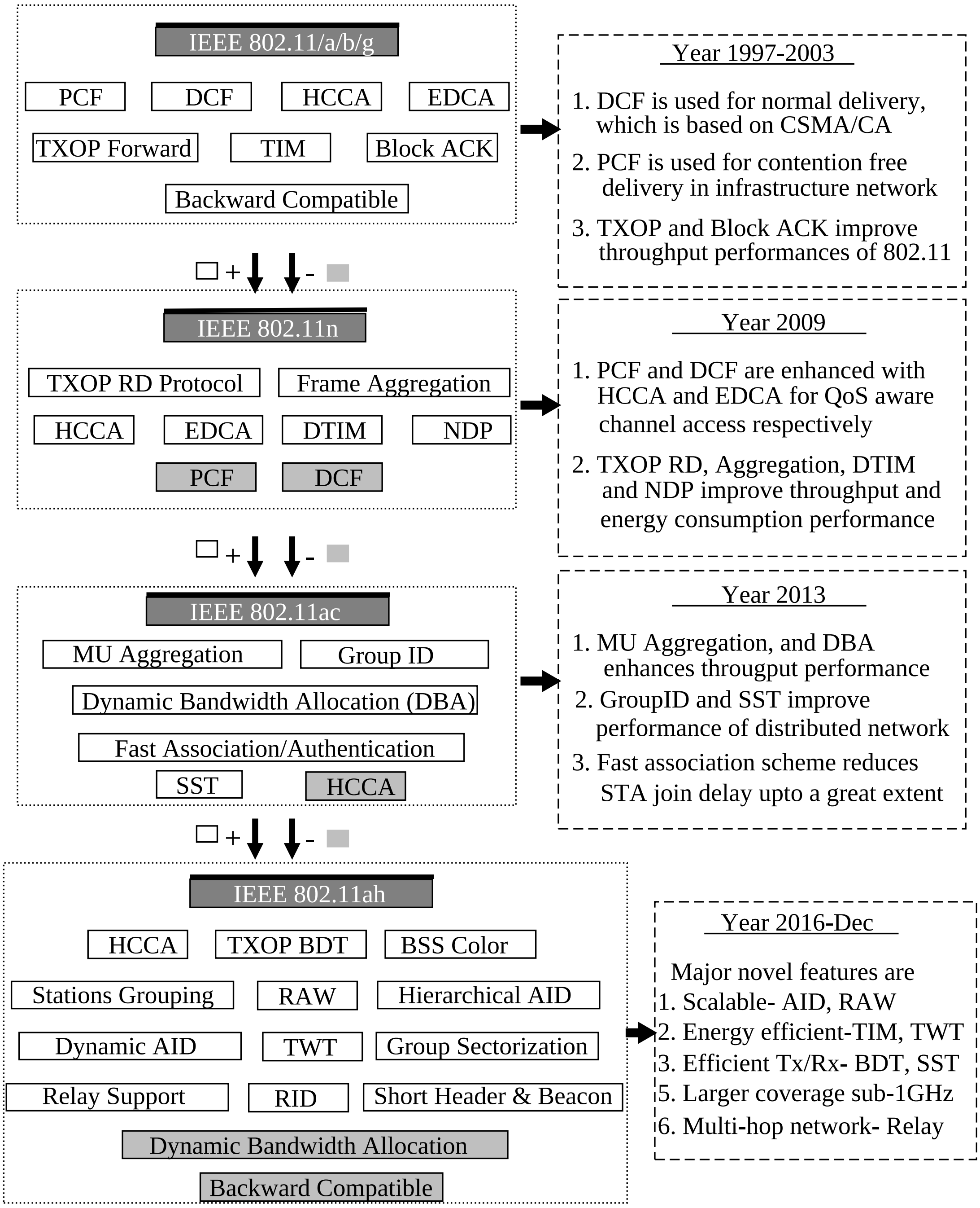


Figure 1.3: Evolution of different MAC layer features from the most relevant 802.11 standards to 802.11ah

network applications such as smart home, and smart campus ([16] and [32]). Again, when a large numbers of STAs try to communicate simultaneously, collision increases. Long transmission range leads to higher IFS duration, and smaller packets increase overhead caused by a large header size. Hence, 802.11ah use different novel schemes to cope with these issues and solves many.

Key Features of IEEE 802.11ah

The 802.1ah standard primarily inherits the basic features from the 802.11ac which is further inherited from the traditional 802.11. IEEE 802.11ah standard is powered by a set of new and novel concepts. The evolution of those features is shown in Figure 1.3. After the first WiFi standard, IEEE 802.11, was proposed in 1997, a series of advancements have been done. Standards such as 802.11n and 802.11ac mainly tried to improve network throughput. In IEEE 802.11ah, the new features such as RAW, AID, and TIM and Segmentation mechanisms, help to connect thousands of STAs in a single network which is very important in IoT. Some of the key features of it are discussed below:

Hierarchical Station Organization

The legacy 802.11 can only associate 2007 numbers of STAs per AP due to the limitation in AID field size. On the other hand, as shown in Figure 1.4, 802.11ah uses a hierarchical structure using a 13bit AID, assigned to each of the associated STAs. The new AID/TIM structure is organized into pages, blocks, sub-blocks, and finally to STAs (can be seen in Figure 1.5). A set of STAs having AIDs within a specific range is kept in the same TIM block. In this way, a single AP can support up to 8191 ($2^{13} - 1$) to associate in a single AP.

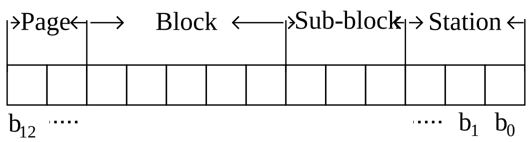


Figure 1.4: Hierarchical AID structure

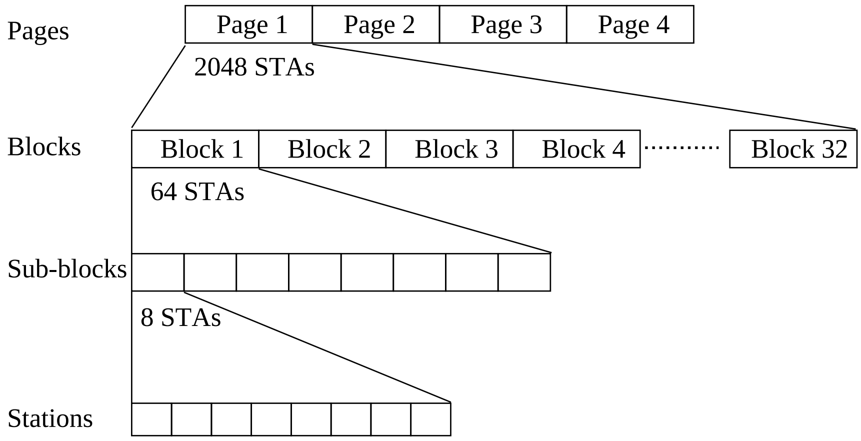


Figure 1.5: Hierarchical AID organization

TIM and Segmentation

IEEE 802.11ah proposes new power saving schemes to reduce the energy consumption of sensor devices. These schemes use the types of STAs while scheduling their radio on/off duration. This mechanism reduces the waiting time for channel access and increases sleep duration of STAs. Here, time is divided into pages, pages into Delivery TIM (DTIM) periods, DTIM into TIM periods, and TIM into slots in a hierarchical manner. The duration of DTIM and TIM for a STA starts on receipt of DTIM and TIM beacon from the AP. The AP sends DTIM beacon informing about the pending data to the TIM groups within. Then, TIM beacon carries in the information of which STA has pending data at AP. Figure 1.6 shows an example of TIM and DTIM structure. In the DTIM mapping, among 8 TIMs, STA for TIM5 only have data pending at AP. Similarly, TIM mapping needs to create for STAs like 770, 773, etc. If there is no pending data at AP, it will keep itself in power saving state by following two conditions:

- DTIM beacon notifies the STA of TIM group that there is no pending data at AP
- STA knows about pending data at AP but is not explicitly aware of the TIM beacon

As compared to the traditional power saving scheme of 802.11, the following are the advantages in 802.11ah which can be highlighted as:

- It reduces the energy consumption of STAs not having data at AP

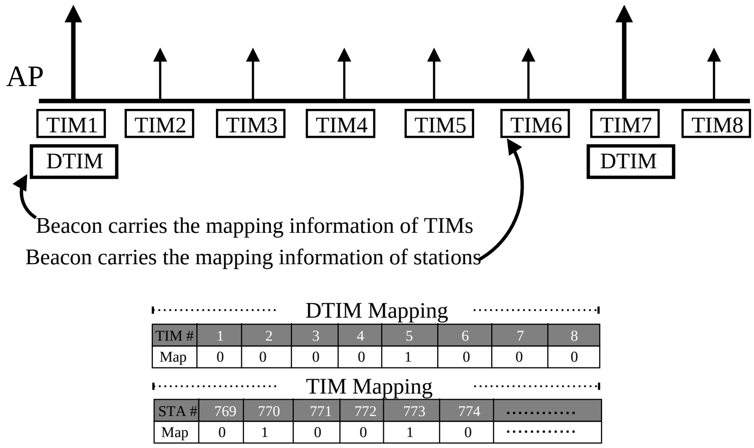


Figure 1.6: Example of TIM and DTIM mapping

- It reduces the traffic indication map size in TIM beacon

- It is allowed to customize the size of DTIM for better energy efficiency

IEEE 802.11ah provides more freedom to a STA so that it can negotiate with AP about its next wake-up time in TWT mechanism, and accordingly, it can stay in the sleeping mode to save energy. However, for a network like IoT, a huge number of STAs may unnecessarily wake-up due to its paging in the TIM group.

Channel Access Mechanism

Using the existing channel access mechanism, communication among thousands of STAs increases the chance of collision by a large extent. To this problem, 802.11ah promises to increase throughput and energy consumption using a RAW mechanism. It divides the STAs into different RAW groups which spread the channel access over a long period of time. The RAW is further divided into slots, a STA can only run its Transmission/Reception (Tx/Rx) mechanism in the dedicated slot. The STAs belonging to a RAW group are allowed for contention within the assigned slot duration. Figure 1.7 shows a RAW frame structure. Getting a slot is dependent on a mapping function as mentioned below:

$$\mathsf{x} = (\mathsf{i} + \mathsf{offset})\%\mathsf{S}_{\mathsf{RAW}} \quad (1.1)$$

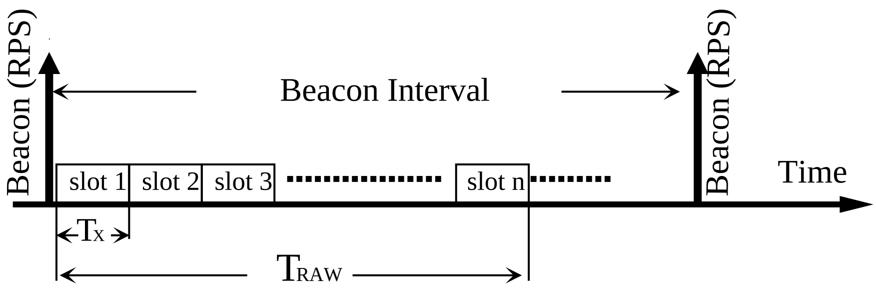


Figure 1.7: RAW frame structure in IEEE 802.11ah

Where, x is the slot number in a RAW frame of size S_{RAW}, the offset value is for improving fairness among the STAs in a RAW, and i is the position index or AID of the STA. If STA is already paged, it uses AID, otherwise position index is used. If the RAW is restricted to STAs with AID bits in the TIM element set to 1.

Once a slot is identified using Eq. (1.1), the STA can start its contention for transmission in the slot. Figure 1.8 illustrates the working of channel access in 802.11ah. A TIM period can be divided into a RAW frame for uplink and downlink transmission, a Periodic RAW (PRAW) frame for non-TIM STAs, and a frame for unscheduled STAs. A STA that wants to initiate a transmission, needs to send a Power Save Poll (PS-Poll) frame after successful backoff. If the AP acknowledges the PS-Poll, then the STA can send the data frame. For the downlink, AP informs about the buffered data through TIM-mapping, and then the STA needs to send a PS-Poll frame like before. If succeeded, then AP can send data in the allocated slot. At the beginning of RAW, AP broadcasts a synchronization (SYNC) frame. The STAs can detect the availability of the channel and can initiate its transmission. Hence, the STAs do not need to wait for an allocated time frame called ProbeDelay timeout [35]. Additionally, other key features of 802.11ah are mentioned as below.

- EDCA: Enhanced Distributed Channel Access (EDCA) is adopted by 802.11ah for service category based access [36]. It provides traffic-aware channel access employing different inter-frame spaces for each category. A flexible time duration named as Arbitration Inter-Frame Space (AIFS) is used just before the backoff period. Accordingly, the contention period is not the same for different types of traffic classes.

- PRAW: In IoT, a huge number of STAs may be deployed for monitoring purposes. The STAs mostly follow periodic traffic patterns. To reduce overhead for such traffic, 802.11ah proposes a PRAW as a part of the existing RAW frame. If the periodicity is known, STAs can be scheduled in the PRAW phase without requiring multiple times of contentions. These reduce overall access time which further increases the efficiency of the network. The PRAW allocation may be indicated by the RPS. The allocated indication is further broadcasted by AP such that all other PRAW STAs can know about the scheduled details.

- Cross-slot boundary: If a STA is transmitting or counting down in backoff over EDCA, there is an option for AP to allow the transmission over the cross-slot boundary (CSB). The CBS indication is sent using RPS with 1bit filed. If the CSB field is “0”, a STA can cross the slot boundary, otherwise (i.e., CSB field “1”) there is not enough space in the RAW, which is called non-cross boundary case.

Relay Node Support

IEEE 802.11ah standard provides RAP support which works as a relay between AP and STAs. It extends connectivity for an STA located outside the coverage of AP. IEEE 802.11ah implements RAP consisting of an AP and an STA module in it [29]. A Relay function is responsible for connecting AP entity with STA entity. Figure 1.9 shows network architecture with relay nodes. Frames coming from AP are received by Relay STA and forwarded to STA3 via Relay AP.

Overall, IEEE 802.11ah is a true IoT-enabling solution for seamless communication among a massive number of devices. The channel bandwidths – 1 MHz and 2 MHz and coding schemes–MCS0 and MCS10 are widely used in IoT and M2M communication for short burst data-rates and long-range communication ([32] and [37]). This new standard is of interest for both industry and research communities. A list of organizations such [38], [39], and [40], are trying to implement the features in their 802.11ah-based products. The specifications of 802.11ah are mostly discussed with reference to a list of

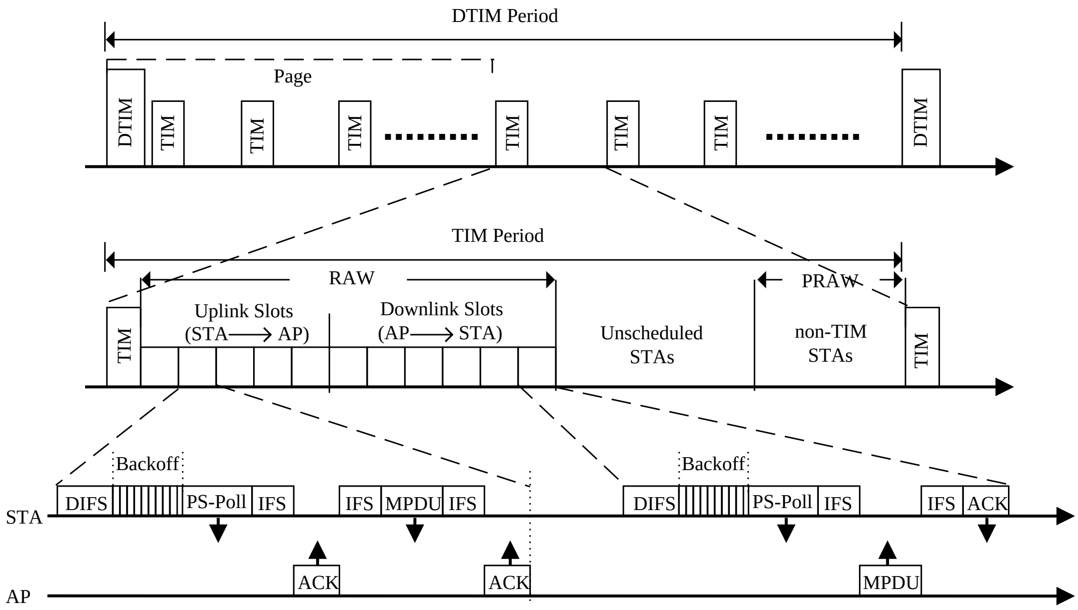


Figure 1.8: Hierarchical TIM and RAW based channel access mechanism in 802.11ah

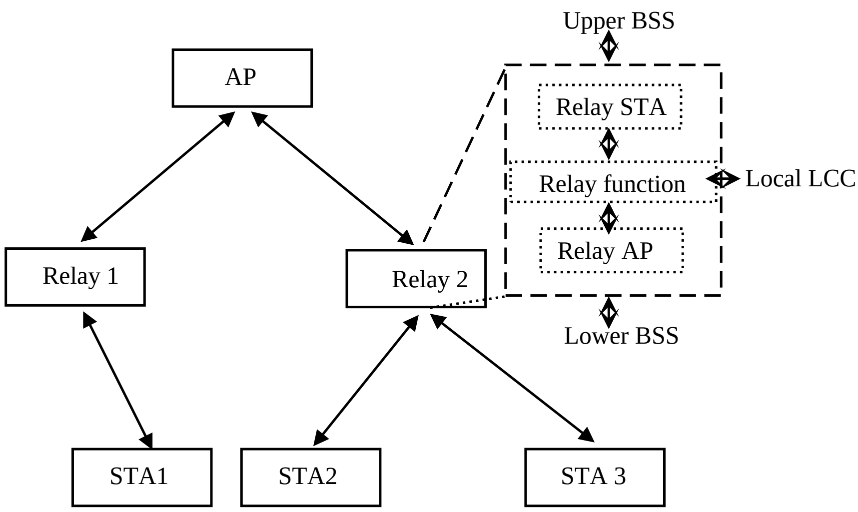


Figure 1.9: IEEE 802.11ah relay architecture

published literature. Apart from this, there are dozens of research papers which discuss the idea of MAC and PHY layer concepts in details. However, for making smart and scalable IoT, many exciting and salient issues are still not considered. In summary, the primary MAC issues and challenges – dense network operation, power efficiency of sensor devices, presence of a large number of hidden nodes, distributed and synchronized access, dynamic association and grouping, and massive overhead due to multi-hop forwarding, are to be resolved.

1.2 Overall Objectives

The broad objectives of this research are to design protocols and schemes in order to support scalability in 802.11ah based networks. Following are the primary objectives of this work:

i. Estimation of RAW size for large, dynamic, and heterogeneous IoT environments.

ii. QoS-aware scheduling and node-grouping for RAW-based channel access mechanism employed large scale IoT.

iii. Channel allocation and load balancing scheme in Relay-based networks for improving scalability.

iv. Reducing delay and energy consumption in periodic RAW-based MAC schemes for a large-scale network.

In this research, we address these issues and proposed mechanisms to improve the scalability for IoT networks.

1.3 Thesis Contributions

To fulfill the above objectives, we contributes a few protocols and schemes particularly in MAC layer of IEEE 802.11ah. The main contributions of this thesis can be divided into four parts, which are outlined in the following subsections in brief.

1.3.1 Dynamic RAW Configuration for Heterogeneous and Multi-hop Networks

Enabling channel access among a large-scale IoT devices for initiating uplink transmission is an intricate issue. The centralized channel access and unknown RAW figure in 802.11ah are not fully suitable for such heterogeneous network scenarios. Without the absence of a RAW size adjustment technique, it fails to optimally utilize the resources in a dynamic network environment. The contribution of this work is threefold. First of all, a distributed channel access mechanism is designed for relay based multi-hop IoT. Secondly, an enhancement to the RAW mechanism of 802.11ah is proposed in order to support heterogeneous loads over different RAW groups. A RAW size is dynamically adjusted based on the current backoff stage of the STAs in a group. Similarly, to achieve a better frame at AP and Relay node, the calculated RAW size further helps in achieving an optimal frame size over dynamic and heterogeneous network conditions. Finally, an analytical model is developed to optimize the RAW performance over dynamic traffic load condition.

1.3.2 QoS-aware Scheduling and Node-grouping Scheme for IoT

Event-driven and query-driven traffic are rare and important in IoT. They deserve special processing over RAW frame. A MAC layer scheduling scheme for provisioning QoS in such network is essential. Further, a dynamic grouping scheme can help to efficiently utilize network performance. Unfortunately, the MAC solution for IEEE 802.11ah does not consider these requirements. In this work, we propose a QoS-aware MAC layer solution to increase network reliability and reduce critical traffic latency by an adaptive grouping and a priority scheduling scheme respectively. The proposed grouping scheme calculates the current traffic load and distributed them among different RAW groups if needed considering different requirements of stations (STAs). The RAW scheduling scheme further provides priority slot access using a novel backoff distribution. Finally, a fairness scheme is proposed for critical traffic, those have failed to transmit during last tries.

1.3.3 Dynamic Load Balancing Scheme for Relay-based Networks

Single channel based centralized channel access mechanism employed in 802.11ah may not scale well in a large network and hence lead to poor quality of data reception. In this contribution, initially, we propose a relay node planning scheme for large-scale and multi-hop 802.11ah network. Secondly, a distributed association scheme is proposed for such relay networks. Thirdly, we propose a multi-band sectorization scheme to increase network capacity. Fourthly, we propose a solution to dynamically adjust MCSs in relay nodes for supporting different traffic requirements. Utilizing the available channels the proposed protocol facilitates multi-hop communication in an efficient manner. Finally, a Transmission Opportunity (TXOP) based efficient transmission scheduling scheme for Relay and AP is proposed. Performance results show that the proposed protocol significantly improves scalability of 802.11ah network.

1.3.4 Periodic Traffic Scheduling Scheme for IoT Applications

In IoT, applications such as smart-healthcare, smart-agriculture, smart-home, and smart-grid transmit packets in a periodic manner for the monitoring purposes. A very less effort is given for scheduling such non-TIM periodic STAs in 802.11ah. Identifying the scenarios in which the use of such STAs is beneficial and further investigating how they negotiate over periodic RAW with a large number of STAs is an issue. In this work, we propose a RAW scheme for 802.11ah to reduce access delay in such a large-scale network for monitoring application. The contribution of this work is threefold. Firstly, a hybrid MAC protocol is designed to appropriately predict the number of STAs and allocate slots for transmission accordingly. Secondly, an efficient RAW scheme is proposed for the periodic STAs to reduce contention over the time frame. Finally, a service interval prediction algorithm is developed to appropriately adjust the next slot for transmission. We analyze the proposed scheme and compare with the 802.11ah.

1.4 Organization of the Thesis

The rest of the thesis is organized as follows:

- Chapter 2 presents the traffic load-aware dynamic RAW configuration scheme for heterogeneous, and multi-hop network.
- A QoS-aware mechanism in terms of latency and reliability for large-scale 802.11ah-based IoT is discussed in Chapter 3.
- Chapter 4 gives the details of a channel allocation and dynamic bandwidth allocation scheme proposed for a relay and sectorized 802.11ah network.

- Chapter 5 presents a MAC layer solution of 802.11ah to improve throughput and energy efficiency for large-scale monitoring applications generating periodic traffic.
- Finally, Chapter 6 concludes the thesis by summarizing the overall contributions and suggesting some future directions of research in this area.

Chapter 2

Dynamic RAW Configuration for Heterogeneous and Multi-hop Networks

This chapter discusses an IEEE 802.11-based MAC protocol – HL-MAC, which is proposed to solve dynamic and heterogeneous load conditions among different RAW groups of a network. The proposed scheme dynamically sets the RAW size of AP and Relay nodes for better utilization of the channel. HL-MAC improves the throughput and delay performance significantly as compared to the existing relevant schemes.

2.1 Introduction

IoT combines different applications consisting of a large number of domains with diverse concepts. Long-range and infrequent M2M communication support by Low-Power Wide Area Network (LPWAN) technologies (e.g., LoRa [41], SigFox [42], and NB-IoT [43]) solve many problems as they can cover a larger area. However, due to their very low data rate support, these are not very suitable for many applications. High scalability and wide coverage range are the key requirements for many IoT applications. Provisioning support for dynamicity and heterogeneity are also considered as the primary factors in IoT [21]. Dynamicity and heterogeneity in IoT are caused by the following reasons:

1. Heterogeneous communication networks and technologies

2. Diversity of application protocols and data formats to support various services
3. Nodes in the network generate traffic at different intervals, enter and leave, and switch between active and inactive states.

A large number of IoT devices that need to be deployed in the targeted environment for larger coverage, may create interference from neighbor networks. Moreover, the use of the same ISM bands by such a large number of networks and nodes will be the bottleneck in performance. In such a case, an efficient MAC layer protocol considering the above requirements can improve the performance of a network. To reduce collisions in such a large-scale network with thousands of devices and thus to improve power efficiency, 802.11ah group has developed a RAW mechanism. The RAW schemes should be able to handle the traffic heterogeneity for efficient utilization of the network that operates in the ISM band.

The default RAW-based channel access mechanism is discussed in Section 1.1. The RPS in the beacon carries the related information like the size of RAW, size of the slot, etc. The RAW size parameter is the key entity to decide the performance of a network. The number of RAWs in a group affects the performance of the channel access scheme. If there are few numbers of RAW groups, contention will be less and throughput will be increased. However, there will be high latency due to the larger contention. Similarly, if there are many RAW groups, contention will be high and throughput will be less for a massive number of devices. However, a lesser delay is required due to low contention. Performance of RAW is measured and analyzed in existing literature such as [44], [19], [16], [45] and more. When the number of nodes is very high, the RAW with larger size performs better to send packets for a particular range of time. IoT is being characterized by heterogeneous traffic patterns and dynamic nodes. The unknown RAW size of 802.11ah is not very suitable for such network scenarios. Secondly, IoT requires a wide range of coverage (beyond 1km distance), hence, 802.11ah needs to establish multi-hop communication with the help of relay nodes. However, proper channel access and high overhead in such a relay network is still an issue.

As shown in Figure 2.1, a network with two groups of nodes – group 1 and group

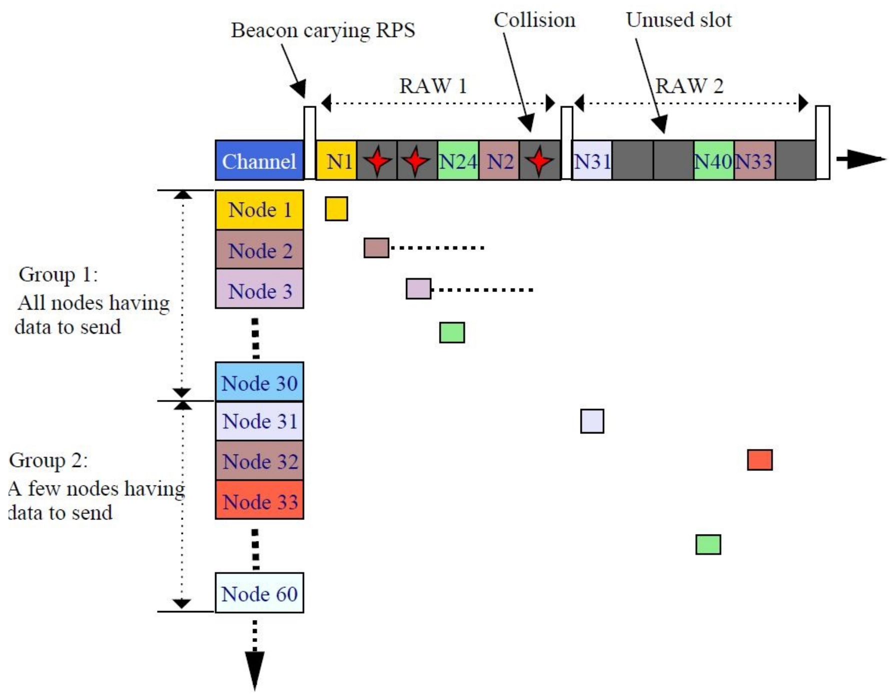


Figure 2.1: An illustration of RAW operation in 802.11ah over heterogeneous traffic scenarios

2, are allocated RAW1 and RAW2 respectively for transmission. Accordingly, a STA having data to transmit and receive can contend in the mapped slot from its RAW as discussed in Sec. 1.1. As group 1 contains a large number of STAs with their data to transmit, collision probability in RAW1 is high. However, RAW2, which is assigned to group 2, many slots will remain unused due to the less number of requests for a slot.

Considering heterogeneous requirements of IoT, this work proposed a load-aware multi-hop MAC protocol named, HL-MAC. The contribution of this work is threefold:

- We measure the suitability of 802.11ah based networks in covering a larger region. The dynamicity and heterogeneity of IoT are discussed and various issues in such networks are pointed out.

- An enhancement to the existing RAW mechanism to support node dynamicity and traffic heterogeneity in IoT is provided. An analytical model is developed to optimize the RAW performance over the saturated and dynamic load condition of a network.

- We incorporate the concept of Relay AP (RAP) to enable support for different

MCSs in STAs and extend connectivity to longer distances. These enhancements improve scalability and perform well over dynamic environments.

The rest of this chapter is organized as follows. The related works concerning the proposed scheme are presented in Section 2.2. The network model and assumptions of this protocol are discussed in Section 2.3. Section 2.4 presents a detail discussion of the proposed solution. Simulation and theoretical analysis of the proposed scheme are presented in Section 2.5. Finally, Section 2.6 concludes this work.

2.2 Related Works

To solve the issues such as collisions, traffic load and heterogeneity in RAW, different enhancements are proposed. Bel et al. [46] talks about the division of RAW time into equal time slots and allowing a STA to randomly select a slot for further contention. Collisions can occur if more than one devices select the same slot. Park et al. [47] proposes to allocate the RAWs according to the number of devices, which can be estimated by a mathematical model. This scheme improved throughput performance as compared to the traditional RAW. But, this enhancement does not touch problems like energy consumption and network dynamics. Also, it assumes that all the devices generate a uniform load. Wang et al. [48] proposes an adaptive RAW mechanism based on total energy consumption. The size of the RAW determines the energy consumption for transmitting overhead. Tian et al. [49] proposes a real-time grouping scheme, which optimizes RAW parameters by analyzing the current traffic load conditions. However, it only considers homogeneous and saturated network conditions. With the use of more data field of the header, a better traffic-aware RAW estimation technique is proposed in [50]. Further, the author in [51] enhances it to support heterogeneous MCSs in STAs.

Lei et al. [52] proposes a RAW grouping approach based on the Tx request received by the AP node. A similar approach considers the report activities from alarm based application in [53]. Based on the reporting activity, the RAW size is dynamically tuned. However, in a heterogeneous traffic scenario where a STA may transmit any time, at any rate, the protocol fails to meet the requirements. Considering the current backoff stage of the STAs, Hamzi et al. [54] estimates the RAW size at AP. To provide guaranteed QoS for delay-sensitive STAs, Charaniya et al. [55] categorized RAW operation into slot reservation-based access for Delay Sensitive Machine type Devices (DSMDs) and conventional 802.11ah-based access for non-Delay Sensitive Machine type Devices (nonDSMDs). In [56], RAW slots are allocated to the STAs based on their requirements. But, RAW issues due to the network dynamicity and heterogeneity still need to be resolved. A brief comparison of related works is presented in Table 2.1. The general limitation of the existing literature also mentioned in the table.

Considering the heterogeneous and dynamic behaviors, where STAs may transmit traffic at any interval and leave or join at any time, the existing 802.11ah based multi-hop network fails to support the changes. Most of the works are carried out on RAW and grouping mechanisms considering the single-hop scenario. Further works are required to solve the RAW and grouping problem for IoT-based heterogeneous, dynamic, and multi-hop networks.

Protocol	Year	Description	Limitation	Multi-hop support	Energy efficient	Heterogeneity support	Scalability support
[47]	2014	Estimates the size of RAW based on probability of successful transmission	A full buffer approach, i.e., the network is always considered to be fully connected,	✗	✗	✗	✓
[54]	2015	Considers STA's backoff stage for adjusting RAW duration	The enhancement shows suitability only to homogeneous traffic	✗	✗	✗	✓
[48]	2015	Optimizes RAW size is estimated based on energy consumption	It does not consider the traffic heterogeneity and network dynamicity	✗	✓	✗	✗
[57]	2017	Optimal RAW size based on energy consumption and data-rate	It does not consider the heterogeneous traffic scenario	✗	✓	✗	✗
[53]	2016	Size of the RAW is adjusted based on periodic reporting of alarms	It is not easy to accurately set the threshold for alarm event detection. Also, it requires the number of RAW to be changed dynamically	✗	✗	✗	✓
[52]	2017	Predicts the RAW size based on the number of PS-Poll messages in a hybrid access manner	The proposed protocol does not consider dynamic traffic patterns and intensities	✗	✗	✗	✓
[49]	2017	Adjusts the RAW parameter set based on the real-time uplink traffic nature	The adjustment is done by only considering available information at AP and RAW grouping is not efficient for long time performance	✗	✗	✓	✓
[50]	2017	In addition to [49], it uses more data field in header to estimate traffic load	RAW grouping is not efficient for long time performance and it considers only homogeneous STAs	✗	✗	✓	✓
[58]	2018	The RAW slot size is set based on group size to improve throughput	Does not consider the traffic and collisions in the network	✗	✗	✓	✓
[51]	2018	Considers heterogeneous MCSs in the network to improve RAW performance	However, it does not consider heterogeneous STAs (i.e., different MCSs) within a RAW group	✗	✗	✓	✓
[59]	2018	Holds regression and greedy approach while proposing a traffic aware grouping scheme	It does not consider the requirements of applications	✗	✗	✓	✓
[60]	2018	A mathematical performance model is developed to allow cross slot boundary transmission	The proposed solution may increase more energy consumption	✗	✗	✓	✓
[56]	2019	Allocates RAW slots to applications based on their requirements	RAW issues due to the network dynamicity and heterogeneity are still need to be resolved	✗	✗	✓	✓

Table 2.1: Attempts to improve RAW performance

2.3 Network Model and Assumption

A typical network architecture with many components is assumed for explaining the proposed scheme (as shown in Figure 1.2). It contains AP node (A), a set of RAP nodes $\mathsf{R} = \mathsf{R}_1, \mathsf{R}_2, \mathsf{R}_3$, ..., and set of sensor/end nodes $\mathsf{S} = \mathsf{S}_1, \mathsf{S}_2, \mathsf{S}_3, ...$ The AP node is responsible for initialization, synchronization, association, and channel allocation. The R node allows STAs to use different MCSs. The A and R nodes dynamically allocate bandwidth to support heterogeneous MCSs.

The AP node transmits RPS which contains time and RAW information. All the relay and STA nodes synchronize themselves with the AP node. Initially, the protocol follows the existing RAW based channel allocation scheme. STAs listen to the RPS to find $\mathsf{RAW} \in \{\mathsf{RAW}_1, \mathsf{RAW}_2, \mathsf{RAW}_3, \ ....\}$, to which it belong to and start contention in the mapped slot. Again, RAW is divided into ρ number of slots as–($\mathsf{s} = \mathsf{s}_1, \mathsf{s}_2, ..., \mathsf{s}_\rho$). The communication between RAP to the RAP, RAP to AP, and vise-versa are accomplished using dedicated Time Division Multiple Access (TDMA), which is termed as SLOT. Therefore, the overall frame maintained by the AP or RAP can be defined as $\mathsf{Frame} = \mathsf{RAW} + \mathsf{SLOT}$, where SLOT ($\mathsf{SLOT} = \mathsf{slot}_1, \mathsf{slot}_2, \mathsf{slot}_3, ...$) is the set of TDMA slots for AP and RAP node. Figure 2.2 shows the structure of the proposed time frame.

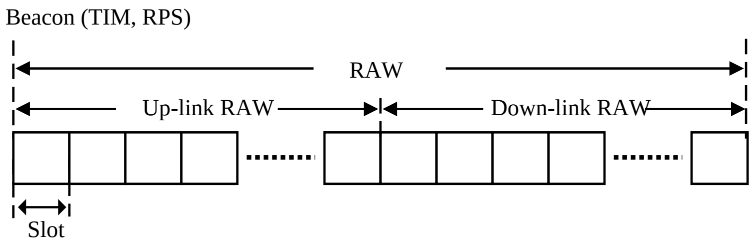


Figure 2.2: IEEE 802.11ah based RAW structure with Up-link and Down-link slots

A RAW is comprised of an uplink and a down-link RAW. Finding the appropriate size of an up-link RAW is an important but challenging issue. Hence, we only focus on the Up-link transmission. The STAs in the network are divided into two groups, viz., Relay group ($\mathsf{R} = \mathsf{R}_{\mathsf{h}1}, \mathsf{R}_{\mathsf{h}2}, \mathsf{R}_{\mathsf{h}3}, ...$) and RAW group ($\mathsf{g} = \mathsf{g}_1, \mathsf{g}_2, \mathsf{g}_3, ...$). A Relay group head is responsible for enabling channel access among other Relays associated with itself. A Relay group may contain multiple RAW groups, therefore $\mathsf{g}_\mathsf{i} \subseteq \mathsf{R}_{\mathsf{hj}}$.

2.4 The Proposed Protocol

Different RAW groups in a network face various load conditions due to the heterogeneous traffic intervals and the number of actives nodes in the network. To improve the efficiency of RAW performance, we propose a backoff based RAW adjustment scheme. The proposed protocol dynamically configure the RPS based on the current load in a RAW. The AP node collects the current backoff stage of STAs within a group and adjusts RAW sizes. Optimal RAW size is measured from the optimal backoff window in each of the PS-Poll frames. Further, to improve the performance of a multi-hop IoT network, the proposed scheme dynamically adjusts the overall time frame size at AP and RAP node. Additionally, a dynamic RAP allocation scheme supporting heterogeneous MCSs is also proposed.

2.4.1 Distributed Channel Access

A distributed channel access scheme is incorporated for the AP (A) and Relay group head ($\mathsf{R_h}$). They use resultant Frame in allocating channels to the STAs (by RAPs) and RAPs (by AP). Figure 2.3 shows the structure of a distributed time frame used by AP and RAPs in different levels of the network. The STAs are allowed to transmit in the RAW frame of AP/RAP. The RAP or AP uses a dedicated TDMA slot, which reduces control overhead for such a multi-hop network. For example, STAs under group $\mathsf{R_{h1}}$ will use RAW_{h1} and relay will use $\mathsf{SLOT_1}$ or $\mathsf{SLOT_2}$ of the same frame. We propose a RAW and SLOT adjustment scheme to handle dynamic traffic load at A and $\mathsf{R_h}$ nodes. Sec. 2.4.2 discusses the proposed scheme in detail. As there are multiple channels available (depending on the country's channel usage regulation) under sub-1 GHz of IEEE 802.11ah, the proposed protocol has an option to use available channels at RAPS for simultaneous transmissions. If available, channels are allocated to the different $\mathsf{R_h}$s in a sequence. The RAP, which is successful in getting a new channel, can transmit in an interfering time frame. However, when the number of channels is higher, nodes need to use the same and non-interfering time frame.

Algorithm 1 presents the proposed channel access mechanism. Considering the issues

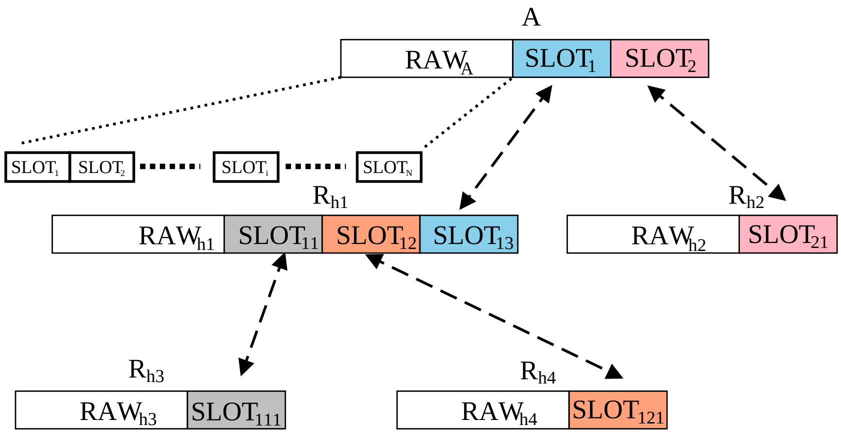


Figure 2.3: The architecture of distributed and hierarchical channel access

Algorithm 1 Distributed Channel Access

Initialize:
$\mathbb{A} \leftarrow$ access frame window
$h \leq 3 \leftarrow$ maximum number of hops
$k \leftarrow$ Total number of children RAPs of a Parent AP/RAP

1: **for** $i = 1$ to h **do**
2:     **if** $\mathsf{R}_{\mathsf{h}_{i+1}} == parent(\mathsf{R}_{\mathsf{h}_i})$ **then** ▷ children relay node finds its parent relay/AP
3:         Create TDMA frame with k number of sub SLOTs
4:         Assign SLOT_i to $\mathsf{R}_{\mathsf{h}_i}$ and $\mathsf{R}_{\mathsf{lh}_{i+1}}$ ▷ same slot is assigned to parent and children node for dedicated communication
5:         $\mathbb{A}_{\mathsf{h}_i} \leftarrow \mathsf{RAW} + \mathsf{SLOT}_i$ ▷ the resultant access window
6:     **else**
7:         $\mathbb{A}_{\mathsf{h}_i} \leftarrow \mathsf{RAW}$
8:         **if** RAW **then**
9:             **if** STA **then**
10:                 Transmit PS-Poll message to send frame
11:                 Allow slot access in Uplink-RAW as discussed in Sec.1.1 using mapping Eq. (1.1)
12:             **else**
13:                 Allow slot access in Downlink-RAW as discussed in Sec.1.1 using mapping Eq. (1.1)

with multi-hop transmissions like poor quality of data reception, protocol overhead, etc., we are limiting the maximum number of hops up to 3. Line #2-6 finds the parent node of a relay and allocates RAW and SLOT for communication with STAs and AP/RAPs respectively. After that, based on the frame type, i.e., SLOT or RAW, channel allocation is carried out (as described in line #6-13).

2.4.2 Dynamic RAW and SLOT Adjustment Scheme

The proposed adjustment scheme works in two phases: RAW and SLOT phases in AP and RAP nodes respectively.

2.4.2.1 RAW Adjustment

We propose a backoff-based RAW adjustment scheme for improving efficiency in the network. IEEE 802.11ah devices time into differed RAWs, and each of them is assigned to different groups of STAs. Further, a STA starts its transmission within the mapped slot using the PS-Poll frame. For a successful PS-Poll transmission, the AP node acknowledges by an ACK frame. Once, all the requirements from STAs are collected, the AP node broadcasts their schedule using a Resource Allocation (RA) frame. Not destined STAs from the same and other groups to keep themselves in sleep mode for saving energy, until the next TDIM beacon.

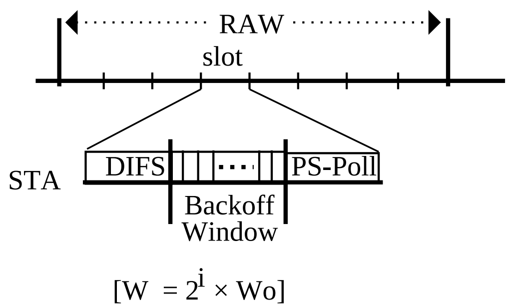


Figure 2.4: Contention resolution in 802.11ah

To provide priority access for different service categories, IEEE 802.11ah adopted the Enhanced Distributed Channel Access (EDCA) [29]. However, IoT traffic is mostly short and burst nature and mainly follows periodic or event-driven traffic patterns. In such a case, DCF is more suitable for the scalability of the scheme. In DCF, before transmitting a frame, a STA needs to wait for DCF Interframe Space (DIFS) time. For an idle channel condition, it chooses a random number of backoff slots from the range $[0 - W]$ (where W is the size of contention window). If the backoff is successful, a STA can start its transmission.

The contention resolution of 802.11 can be seen in Figure 2.4. Initially, the size of the contention window is W_0, which is the minimum one. The size of W_0 depends on the success and failure in the transmission of PS-Poll message. For every PS-Poll frame, the STA waits for an ACK. If the STA does not receive any ACK within a given time, the frame is treated as lost. Thereafter, the PS-Poll message is re-transmitted again with doubling the Window size on each attempt until it reaches W_m, which is the maximum size. Finally, once the transmission is successful, W is reset to W_0. There may a collision if more than one STAs try to send PS-Poll simultaneously.

Bianchi et al. [61] uses the discrete-time 2-Dimensional (2D) Markov-chain model to find the probability of successful transmission in a slot. A diagrammatic representation of 2D markov chain model is shown in Figure 2.5. The network with N STAs are divided into different RAW groups of n STAs. A random 2D process $(s(t), c(t))$ where s(t) is the backoff stages in $\{0, m\}$ and c(t) is the backoff counter in $\{0, W_m - 1\}$ is represented by (i, k). The transition probability for state (i,k) is denoted as $P_{i,k}$. Different backoff transition probabilities can be described as below:

1. If channel is found to be idle, state (i, k+1) moves to state (i,k), decrementing the k value by 1

$$P\{i, k|i, k+1\} = 1; \in [0, W_i - 2], i \in [0, m]]$$

2. At state (i,k), if the channel is busy, backoff counter stays at the same state with probability, p

$$P\{i, k|i, k\} = p; k \in [1, W_i - 1], i \in [0, m]$$

3. If the transmission is successful, initialize i=0 to the minimum contention window W_0 with probability, $(1 - p)$

$$P\{0, k|i, 0\} = (1 - p)/W_0;\ k \in [0, W_i - 1], i \in [0, 2]$$

4. STA at stage i-1 moves to stage i with probability p for an unsuccessful transmis-

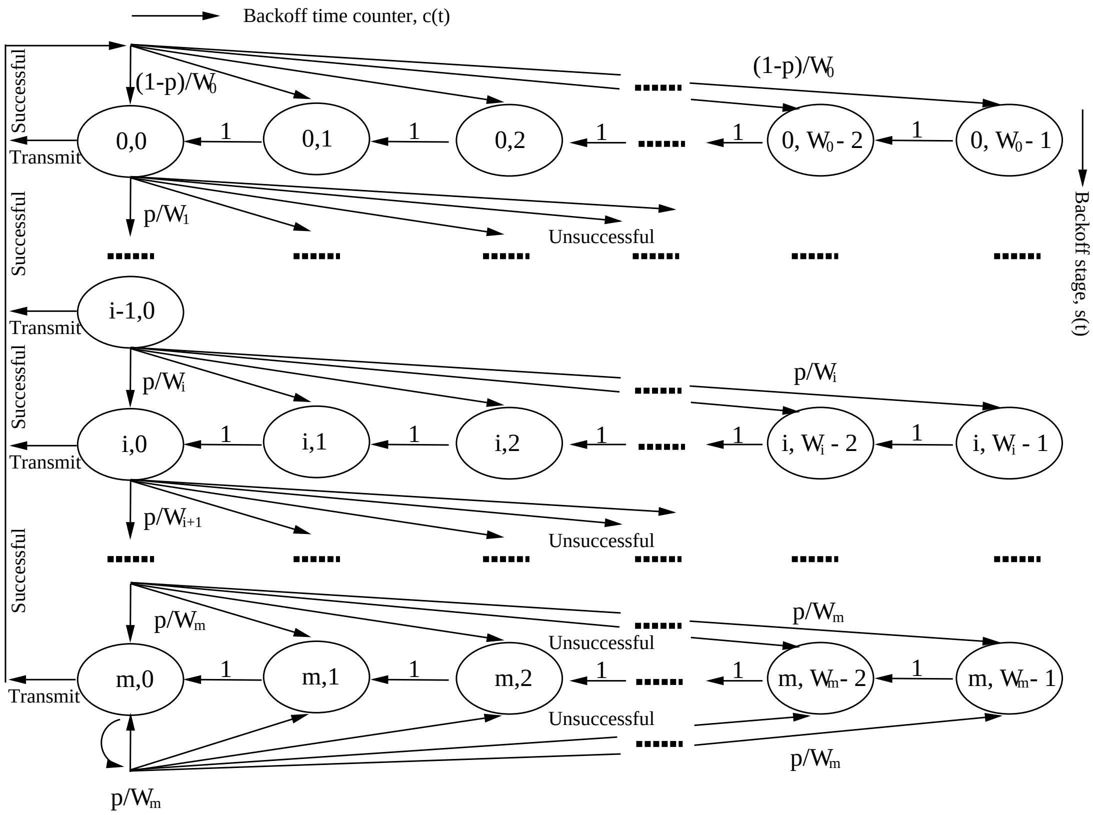


Figure 2.5: Diagrammatic representation of 2D Markov Chain Model

sion, and selects its backoff counter value from $(0,W_i - 1)$,

$$\mathsf{P}\{\mathsf{i},\mathsf{k}|\mathsf{i}-1,0\} = \mathsf{p}/\mathsf{W_i};\ \ \mathsf{k} \in [0,\mathsf{W_i}-1], \mathsf{i} \in [1,\mathsf{m}]$$

5. The STA reaches to last stage, m, if all the transmissions are failed at all its previous stages, and stays at the same state with probability p until successful,

$$\mathsf{P}\{\mathsf{m},\mathsf{k}|\mathsf{m},0\} = \mathsf{p}/\mathsf{W_m}, \mathsf{k} \in (0,\mathsf{W_m}-1)$$

The steady state probability that the system is in state $(\mathsf{i}_0,\mathsf{k}_0)$

$$\mathsf{b_{i,k}} = \lim_{\mathsf{i}\to\infty} \mathsf{P}(\mathsf{s}(\mathsf{t}) = \mathsf{i}, \mathsf{c}(\mathsf{t}) = \mathsf{k})$$

The normalization equation and the resulting steady state probability of being in state (0,0) is calculated as:

$$b_{0,0} = \frac{1(1-2p)(1-p)}{(1-2p)(W_0+1)+pW(1-(2p)^m)} \tag{2.1}$$

Therefore, the probability that a STA transmits a packet is equal to:

$$\tau = b_{0,0} + b_{1,0} + ... + b_{m,0} \tag{2.2}$$

A STA transmits when the backoff counter becomes zero regardless of the backoff stage, and if τ is the probability that the STA transmits in a randomly chosen slot within the RAW, then,

$$\tau = \sum_{i=0}^{m} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW(1-(2p)^m)} \tag{2.3}$$

In 802.11ah-based channel access duration, the following events may occur during the transmission of frame:

1. Channel may be idle, probability that no STA is currently contending for a RAW slot

$$P_{idl} = (1-\tau)^n$$

2. Probability that at least one STA get access to a slot for transmission

$$P_{txn} = 1-(1-\tau)^n \tag{2.4}$$

3. Probability that exactly one STA get access and transmit successfully

$$P_{suc} = \frac{n\tau(1-\tau)^{n-1}}{P_{txn}}$$

4. If more that one STAs try for a single slot at a time, collision occurs with proba-

bility

$$\begin{aligned}\mathsf{P_{col}} &= 1 - (\mathsf{P_{idl}} + \mathsf{P_{txn}} + \mathsf{P_{suc}}) \\ &= \mathsf{P_{txn}}(1 - \mathsf{P_{suc}})\end{aligned}$$

Throughout (Th) is defined as the successful transmission of a frame bits for a given time

$$\begin{aligned}\mathsf{Th} &= \frac{\mathsf{E}[\text{Payload size transmitted in a slot}]}{\mathsf{E}[\text{Length of slot time}]} \\ &= \frac{\mathsf{P_{txn}P_{suc}E[Payload]}}{(1-\mathsf{P_{txn}})\sigma + \mathsf{P_{txn}P_{suc}T_{suc}} + \mathsf{P_{col}T_{col}}}\end{aligned} \tag{2.5}$$

where $\mathsf{T_{suc}}$ is the busy time for successful transmission, σ is the average duration of a slot, and $\mathsf{T_{col}}$ is the busy time when a collision occurs. For 802.11ah, it can be calculated as below:

$$\begin{aligned}\mathsf{T_{suc}} &= \mathsf{T_{FH}} + \mathsf{T_{DATA}} + \mathsf{T_{SIFS}} + \mathsf{T_{P}} + \mathsf{T_{ACK}} + \mathsf{T_{DIFS}} + \mathsf{T_{P}} \\ \mathsf{T_{col}} &= \mathsf{T_{FH}} + \mathsf{T_{DATA}} + \mathsf{T_{DIFS}} + \mathsf{T_{P}}\end{aligned} \tag{2.6}$$

where $\mathsf{T_{FH}} = \mathsf{T_{PHY}} + \mathsf{T_{MAC}}$ is the frame header duration, and $\mathsf{T_{DATA}}, \mathsf{T_{SIFS}}, \mathsf{T_{P}}, \mathsf{T_{ACK}}$, $\mathsf{T_{DIFS}}$ are the data, Short Interframe Space (SIFS), propagation, ACK and DIFS duration respectively.

As in Eq. 2.4 and 2.3, the value of τ depends on the network size and parameters such as W and m. As τ is not a directly controllable variable, so, we need to consider an adaptive a way to tune the values. Consequently, on the basis of that, an optimal transmission probability (τ_{opt}) can be calculated [61]. Anouar et al. [62] calculated τ_{opt} by differentiating Eq. (2.5) as:

$$\tau_{\mathsf{opt}} = \frac{\gamma - (1-\tau_{\mathsf{opt}})^{\mathsf{n}}}{\gamma \mathsf{n}} \tag{2.7}$$

where $\gamma = \frac{\mathsf{T_{col}}}{\mathsf{T_{col}} - \sigma}$. Below τ_{opt} channel is misused due to idle slots and above which performance is reduced due to high collision probability. However, collision is the primary issue in the assumed use cases. As n and γ is known, we can calculate the value of τ_{opt}.

An optimal backoff window (W_{opt}) can bee seen from an optimal transmission probability (τ_{opt}). The value below τ_{opt} signifies that the channel is under-utilized due to idle slots and above which performance is reduced as collision probability is high. At network saturation condition, τ_s can be calculated as [62]:

$$\tau_s = \frac{2(1-\tau)^{n-1}}{W_0 - 1 + 2(1-\tau)^{n-1}} \tag{2.8}$$

Where W_0 is the initial backoff window size. From Eq. (2.7) and (2.8), the optimal backoff window at saturated condition is

$$W^s_{opt} = 1 + \frac{2(1-\tau_{opt})^n}{\tau_s} \tag{2.9}$$

The STAs wake up and listen to the beacon to know whether the bitmap for itself is set in TIM or not. If the bit is set to"1", STAs use 10-bit additional field (to represent window size with 1023 as a maximum value) in the PS-Poll frame to send W^s_{opt}. This way, AP collects the backoff window size of a particular group of nodes. The AP calculates optimal RAW size as:

$$\rho_{opt} = \frac{W^s_{opt}(\rho_{max} - \rho_{min})}{W_{max} - W_{min}} \tag{2.10}$$

RPS is updated with the latest RAW information in the contention phase and transmitted in the next beacon frame. Smaller RAW size results in higher overhead as well as energy consumption due to the scheduling information which needs to be transmitted several times in a short interval. Hence, a minimum RAW size is maintained.

2.4.2.2 SLOT Adjustment

A Relay node follows the Time Division Multiple Access (TDMA)-based data transmission approach. The TDMA approach reduces control overhead while communication among AP and a few Relay nodes around. As a Relay group (R) contains multiple RAW groups (gs), the RAP nodes predict total bandwidth by adding optimal RAW size, ρ_{opt}

as in Eq. 2.10 of all its RAW groups in terms of time duration. The RAP calculates TDMA frame time as:

$$\mathsf{SLOT_{time}} = (\sum_{\hat{s}=1}^{\rho_{opt}} \mathsf{t}_{\hat{s}}) + (\sum_{\hat{k}=1}^{\rho_{opt}} \mathsf{t}_{\hat{k}})$$

Where $\mathsf{t}_{\hat{s}}$ and $\mathsf{t}_{\hat{k}}$ are RAW slot and guard time respectively. If the TDMA slot size and guard time are $\mathsf{T_{slot}}$ and $\mathsf{t_{slot}}$ respectively, then the number of slots can be calculated as:

$$\mathsf{n_{slots}} = \mathsf{SLOT_{time}}/(\mathsf{T_{slot}} + \mathsf{t_{slot}})$$

To increase throughput at RAPs and to increase the network efficiency, we use a larger slot size for TDMA-based communication. The larger slot is capable of sending multiple frames together. A new frame is allocated to the TDMA slot based on availability. In this way, with the use of optimal RAW-powered Access Frame Window ($\mathbb{A}$) and multiple frame transmission, the efficiency of the network is enhanced.

2.5 Performance Evaluation

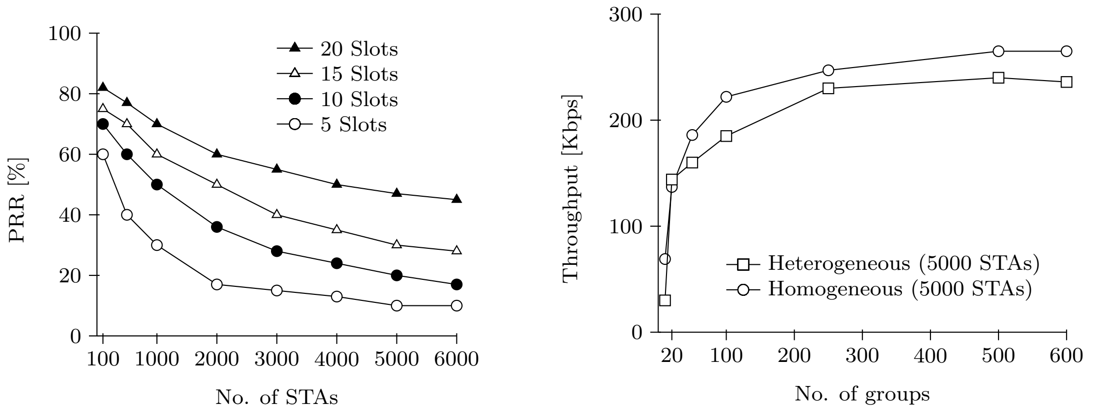
We use Network Simulator-3 (NS-3) [64] for analyzing the performance of the proposed protocol. Table 4.3 shows the parameters used for simulation and theoretical analysis in various network scenarios. We extend the network simulator capacity to support multiple relay nodes in the network. The considered topology uses three RAPs in different random locations between the STAs and the AP. Therefore, the simulation network scenario has three relay groups as well. The RAP nodes work over different MCSs to provide support for various IoT applications. For example- MCS2 is applied to run applications with higher bandwidth requirements like video surveillance. We use HET-T and HET-H notation to indicate heterogeneous and homogeneous traffic scenarios respectively. For heterogeneity, traffic is generated by sending packets in 0.1, 0.5, 1, 5 Second(s) of intervals. The proposed protocol, HL-MAC is compared with the traditional 802.11ah MAC protocol and TAROA [49] (a traffic-adaptive RAW optimization scheme, which is found to be most relevant with the proposed protocol).

Table 2.2: System and other parameters used in simulation and theoretical analysis

Parameter	Value
Bandwidth	2 MHz
Modulation and Coding Schemes	MCS0, MCS1, and MCS2
Data rate	650, 1300, and 1950 Kbps
Payload size	256 bytes
Radio propagation model	Outdoor (macro [63])
Backoff window size (W)	15 (Min.), and 1023 (Max.)
Orthogonal Frequency Division Multiplexing (OFDM) symbols time ($\mathsf{T}_{\mathsf{sym}}$)	40 μs
MAC header	14 bytes
PHY header	6 x $\mathsf{T}_{\mathsf{sym}}$
SIFS	16 μs
DIFS	120 μs
Backoff slot size	52 μs
Initial backoff window	64
Types of traffic	UDP
Beacon size	25 bytes
ACK size	14 bytes
Simulation area	2000m $\times$ 2000m Flat-grid
No. of nodes (Max.)	6000
TIM	200 ms
DTIM	1000 ms
RAW size	5 (Min.), and 20 (Max.)
Default RAW size	10
RAW slot duration	3 ms
TDMA slot duration	5 ms
No. of Relay nodes	3

2.5.1 Throughput and Packet Received Ratio

Initially, we analyze the performance of RAW size with the increasing number of STAs in the traditional 802.11ah scheme. As shown in Figure 2.6a, PRR (%) decreases with increasing STAs. With the same RAW size, when more number of STAs tries for contention, collisions are higher. However, PRR (%) is higher for larger RAW size, because the chances of getting a slot are better in this case. Also, we analyze the throughput performance over heterogeneous traffic scenarios. Figure 2.6b shows the throughput achieved in traditional RAW with an increasing number of groups over homogeneous and heterogeneous scenarios. For 5000 numbers of STAs, a higher number of groups reduces contention in the case of a single group. However, when heterogeneous traffic is transmitted (i.e., at different intervals) throughput performance starts deteriorating. As a STA may or may not have traffic to transmit within its group, for fixed-size RAW, throughput performance degrades. Moreover, when the number of groups goes beyond



(a) Packet Received Ratio (PRR) (b) Throughput achieved

Figure 2.6: Packet Received Ratio (PRR) and throughput results in traditional 802.11ah-MAC protocol

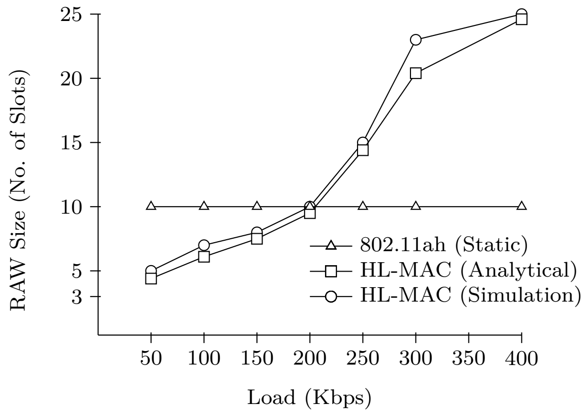
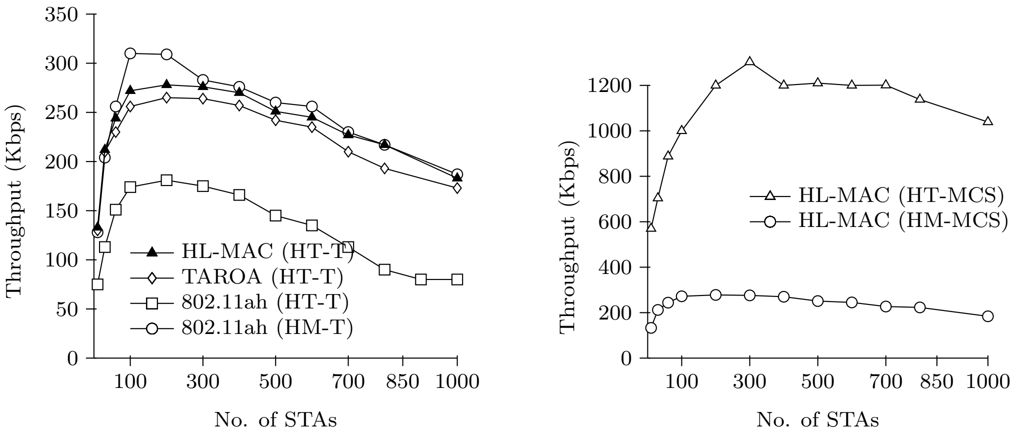


Figure 2.7: Dynamic RAW adjustment with varying load conditions

500, the throughput performance remains almost the same. Therefore, throughput results are affected by the total number of STAs, traffic types, RAW size, and the total number of groups in a network. The performance of the proposed protocol is discussed below.

2.5.2 Dynamic RAW Configuration

In heterogeneous traffic conditions, with an increasing number of nodes, traffic load may not increase proportionally. Instead of this, the proposed protocol considers dynamic traffic load as a parameter for adjusting the RAW size. The RAW size estimated by the proposed scheme over different traffic load scenarios is compared in Figure 2.7. The proposed scheme adjusts it considering the current traffic load within the group. As



(a) HL-MAC Vs. TAROA Vs. 802.11ah-RAW (b) HL-MAC

Figure 2.8: Average throughput achieved at AP node over heterogeneous traffic and MCSs

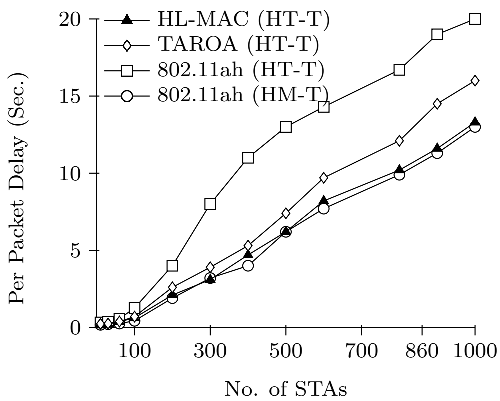


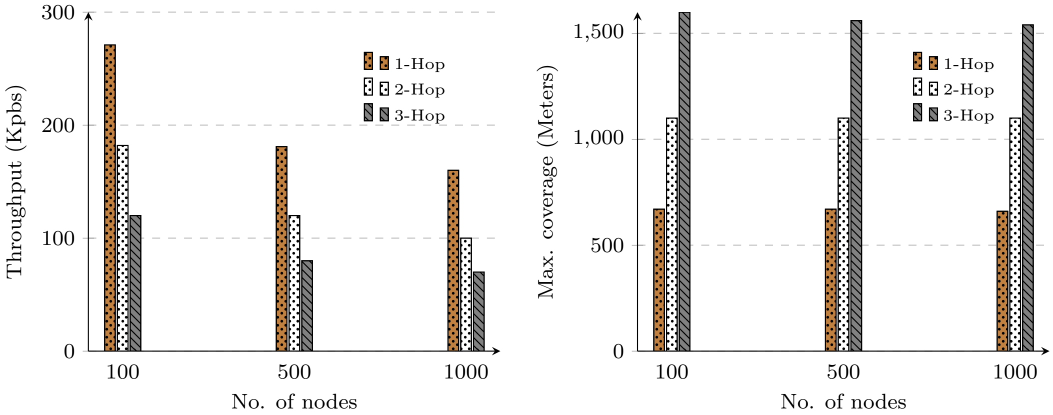
Figure 2.9: Average end-to-end delay incurred using MCS0

the proposed scheme finds the best RAW size over different traffic load conditions, it enhances with increasing loads. However, in the traditional scheme, irrespective of the varying traffic loads, the size of RAW remains constant (static) over time.

We theoretically calculate the RAW size with increasing load conditions, the results show almost similar trends as compared to the simulation results.

2.5.3 Throughput Characteristics

As shown in Figure 2.8a, the throughput performance of 802.11ah in the heterogeneous environment has been improved by the proposed protocol. In these circumstances, throughput decreases with an increasing number of STAs. Considering the heterogeneous traffic conditions, the proposed scheme improves throughput up to 54%. The rea-



(a) Average throughput (b) Average network coverage

Figure 2.10: Throughput achieved and distance covered using multiple hops

son behind this is that the proposed protocol utilizes all the RAW slots among different groups optimally. It is clear from Figure 2.8a that the proposed protocol in heterogeneous traffic scenario shows almost similar throughput as RAW at homogeneous traffic scenario. TAROA protocol optimizes RAW size based on the predicted service interval of uplink traffic. However, the proposed protocol uses the current backoff stages of STAs, consequently, not more specific to the periodicity of traffic. In heterogeneous traffic conditions, the proposed protocol achieves up to 7% higher throughput than TAROA.

With the use of heterogeneous MCSs (MCS0, MCS1, and MCS2) applied over different Relay groups, the proposed protocol achieved higher throughput performances. This is because of the higher bandwidth capacity supported by MCS1 and MCS2 (can be seen in Figure 2.8b). The proposed RAW mechanism adjusts the RAW size based on the traffic rate and collision probability. It is obvious that considering only MCS0 in HM-MCS will give lesser throughput as compared to HT-MCS.

2.5.4 Delay Characteristics

The channel access time is greatly reduced in the proposed protocol by dynamically changing RAW size based on the number of nodes and traffic loads. The overflow of loads in terms of traffic and number of nodes while accessing within a group in a RAW scheme is balanced by the proposed scheme. Figure 2.9 depicts delay performance of the proposed protocol. Although, TAROA protocol optimizes the RAW size based on the AP predicted traffic intervals, the expected traffic intervals always may not be accurate due to the uneven nature of heterogeneous traffic and network conditions. Delay is significantly reduced in the proposed protocol. With deployed network traffic, 100 STAs are sufficient to saturate the network, beyond that, the delay increases drastically, especially in the case of traditional 802.11ah.

2.5.5 Multi-hop Performance

In addition to the RAW performances of the proposed RAP based 802.11ah network, we explicitly analyze the multi-hop results in terms of throughput and coverage range. For successful transmission of a frame, it requires at least one and two TDMA slots in case of 2-hops and 3-hops scenarios respectively. Therefore, throughput decreases with the increasing number of hops as shown in Figure 2.10a. Moreover, due to collisions, throughput decreases with the increasing number of STAs (as discussed above). Provisioning multi-hops support in the network allows us to transmit frames beyond 1 Km distance. We validate the coverage range of the proposed enhancement through simulation. The average maximum distance covered in the proposed solution is presented in Figure 2.10b. This distance is measured by calculating the packet error rate which is considered to be 100% while increasing the coverage range.

2.6 Conclusion

In this work, we presented a RAW and Relay solution for 802.11ah-based IoT networks. The proposed scheme, HL-MAC significantly improved the performances of the RAW mechanism with the use of an optimal backoff window solution. In a dynamic and saturation environment, the proposed protocol showed a performance close to the network with homogeneous nodes. With the support of heterogeneous MCSs and dynamic bandwidth allocation schemes, the proposed protocol improved scalability over IoT to a great extent. The dedicated slot based communication among AP and RAPs provides efficiency in multi-hop and large-scale networks. We can highlight the achievements of the proposed work as follows:

- Dynamic configuration of RAW size over heterogeneous traffic showed suitability for better utilization of channels in a large scale 802.11ah network.
- In the current network scenarios, to 350 Kbps of load, the proposed protocol dynamically increases RAW size for allowing more transmission to occur.
- The proposed protocol dynamically sets RAW size for different groups of STAs with heterogeneous traffic loads and reduces channel access delay, which further reduces the average frame delay up to 38%.
- The proposed protocol improves throughput performance up to 44% and 14% as compared to the traditional and TAROA protocol, respectively.
- The proposed protocol can dynamically use MCSs with higher data-rate to support the current throughput requirements (i.e., up to 350%) in the network.
- Multi-hop support with proper channel access mechanism shows better end-to-end results in terms of coverage range (i.e., up to 1500 m) and throughput (i.e., up to 280 Kbps) in a large scale IoT network.

While supporting the requirements of different IoT applications, QoS is another important parameter that needed to be considered. In the next chapter, we propose a QoS-aware MAC layer solution to increase network reliability and reduce critical traffic latency by an adaptive node grouping and a priority scheduling scheme.

Chapter 3

QoS-aware Scheduling and Node-grouping Scheme for IoT

In this chapter, we propose a scheduling and grouping scheme – QS-MAC for provisioning QoS in an IEEE 802.11ah network. The proposed scheme uses dynamic STA grouping and fairness mechanisms to enable priority scheduling among needy nodes. QS-MAC ensures QoS in terms of delay, throughput, and reliability over a large-scale network having various types of STAs.

3.1 Introduction

In IoT, data flows are mainly of three types – event-driven, query-driven, and continuous [65]. Event-driven and query-driven traffic flows are generated only when there is an event or query respectively. While supporting communication in an IEEE 802.11ah network with 8191 STAs which is more for multiple Basic Service Sets (BSSs), such traffic diversity is obvious. Furthermore, there are IoT applications such as health-care and fire-alarm, where data are sensitive in terms of reliability and delay, so provisioning QoS is important but challenging. Also, real-time audio or graphics data streaming are delay-sensitive and has a certain requirement of bandwidth. As shown in Figure 3.1, the overall IoT control loop may take a huge delay. Unfortunately, the design of 802.11ah does not specifically consider these dynamic behaviors.

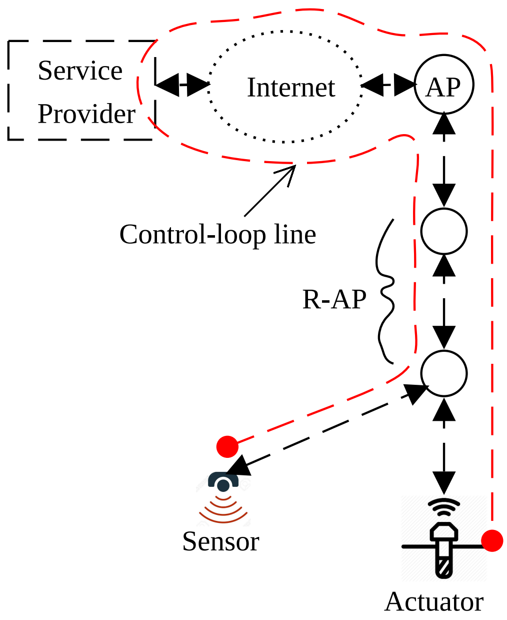


Figure 3.1: An example of IoT action control loop considering an IEEE 802.11ah network

The RAW mechanism of IEEE 802.11ah divides the time frame and allows a particular group of STAs for transmission. Several issues evolve while dealing with such a massive number of STAs with heterogeneous traffic flow. The grouping of STAs is dependent on the AID, which is assigned according to their association time. After the association, STAs are grouped in a sequence. Therefore, in the case of STAs with higher AID, it may differ a possible transmission. Further, critical and rare traffic demand special processing over continuous data flows to meet different requirements. The current research works are primarily focused on estimating the RAW size based on the number of STAs or traffic loads for a particular group. However, the solutions do not consider traffic types, QoS requirements, and distribution of traffic loads among the groups. In such a case, dynamic and priority-based RAW allocation and adaptive grouping mechanisms can help a network to achieve better performance.

A QoS-aware priority RAW scheduling and adaptive load aware node grouping scheme, named QS-MAC are proposed. The proposed solution can optimize channel access among different groups in a highly dense network. Contributions of this chapter can be summarized as:

- A QoS-aware RAW slot assignment and fairness method to handle the traffic flow of critical applications.
- A load balancing scheme among different RAW groups using dynamic AID allocation to improve network reliability.

The rest of the Chapter is organized into four sections. Background and related works are discussed in Section 3.2. Section 3.3 presents the proposed QS-MAC protocol for IEEE 802.11ah. Section 3.4 describes the performance evaluation and analysis of the proposed protocol. Finally, Section 3.5, concludes this chapter.

3.2 Background and Related Works

This section discusses the different QoS requirements of various IoT applications and their support in 802.11ah. We discuss some of the related solutions while provisioning different QoS supports. Finally, we provide an analysis of the existing RAW scheme.

3.2.1 QoS Provisioning in IoT Networks

The QoS is defined as a set of quality criteria for a particular service [66]. QoS in IoT depends on the characteristics of the objects and applications. Different rules/criteria need to set due to their various characteristics. Looking at the traffic in IoT applications, there can be event-driven, query-driven, and continuous flows. Low rate traffic are usually generated by the alarms/commands from the control center to the corresponding authorities/actuators. For example, there may be a huge amount of on-demand reporting type of traffic from thousands of smart-grid STAs [53]. In the power outage situation, a huge number of STA simultaneously tries to report the failure before the battery dies [67]. Prior scheduling is important for improving reliability for such even-driven traffic. Also, many critical applications need to be processed within a given time-bound. Expecting the behavior of event-driven and query-driven traffic, scheduling MAC protocol accordingly can improve the performance up to a great extent. Further, a dynamic node grouping scheme can help to efficiently utilize network resources. The

MAC solution for 802.11ah does not consider these requirements.

3.2.2 Related Works

The current research works are primarily focusing on estimating RAW size in different network conditions. For example, Park et al. [47] estimated the number of uplink STAs to determine the size of RAW. Zhao et al. [68] optimized the performance of the RAW-mechanism in terms of power consumption, and showed that energy efficiency in the sensor nodes improves with the increasing number of RAW groups. In [69], based on the delay requirements of STAs, RAW is divided and allocated. Tian et al. [49] suggested an optimization algorithm to judicially define the grouping parameters based on real-time traffic and improved network efficiency. Šljivo et al. [19] proposed an immediate reply scheme for 802.11ah AP to reduce downlink latency.

The above mechanisms improve RAW performance to achieve a better result in terms of success rate. Tian et al. [49] and Šljivo et al. [19] improve delay performance considering real-time nature of traffic. Seferagic et al. [70] enhances QoS by considering the overall control loop frame. It considers delay and reliability for sensitive and periodic traffic over the RAW frame. Further, Kia et al. [71] improves energy-efficiency with the help of a load-aware grouping scheme without considering the QoS requirements of an application.

Table 3.1 shows a comparison of QoS-aware IEEE 802.11ah based schemes. However, for real IoT scenarios, traffic classification and priority scheduling for delay-sensitive applications according to their requirements are needed to be considered. Furthermore, load balancing among the complete network is important to optimally utilize the available bandwidth. The analysis of state-of-art makes out a research space on provisioning QoS for real-time priority traffic over limited channel bandwidth in 802.11ah. To address this issue we propose RAW scheduling and load-aware node grouping scheme for 802.11ah called, QS-MAC.

Protocol	Year	Description	QoS Support	Priority Scheduling	Adaptive Grouping	Fairness Support
[48]	2015	Optimize RAW size based on delay and energy	✓	✗	✗	✗
[55]	2017	Divides RAW frames into delay and non-delay sensitive applications	✓	✗	✗	✗
[72]	2017	Reduces delay by new association scheme	✓	✗	✗	✗
[19]	2018	An immediate reply scheme is proposed for downlink traffic,which reduces the extra RTT delay	✓	✓	✗	✗
[59]	2018	It holds regression and greedy approach while proposing a traffic aware grouping scheme	✗	✗	✓	✗
[73]	2018	It proposes a grouping algorithm using association process to prevent hidden node collision	✗	✗	✓	✗
[70]	2019	Analyzes latency requirements over RAW frame cycle	✓	✓	✗	✗

Table 3.1: QoS provisioning in IEEE 802.11ah by RAW adjustment

3.2.3 Problem Formulation

The AP node in IEEE 802.11ah transmits beacon which also broadcast RAW Parameter Set (RPS) information in the preceding. In the interval, there may be one or more number of RAW for a group of STAs. The STAs belonging to a RAW group are allowed for contention within the assigned slot duration (can be seen in Figure 1.7). To get a slot from RAW is decided based on a mapping function as shown in Eq. (1.1). The slot duration ($\mathsf{T_x}$) is calculated from slot duration count (S_c) specified in RPS as:

$$\mathsf{T_x} = 500\mu\mathsf{s} + \mathsf{S_c} \times 120\mu\mathsf{s}$$

Where, $\mathsf{S_c}$ depends on the value of k ($\mathsf{S_c} = 2^{\mathsf{k}} - 1$), which is the number of bits in sub-filed. If the slot format field is set to 0, $k = 11$ otherwise for 1, $k = 8$.

(i) For $k = 11$, the minimum value of $\mathsf{T_x} = 500\mu s$ when $\mathsf{S_c} = 0$, whereas the maximum of $\mathsf{T_x}$ is $500\mu\mathsf{s} + (2^{11} - 1).120\mu s = 246.14ms$

(ii) For $k = 8$, the maximum value of $\mathsf{T_x}$ is 31.1ms.

Again, size of $\mathsf{S_{RAW}}$ is calculated as $2^{14-\mathsf{y}}$ from a 14 bit field, hence the maximum number of slots in a RAW is 8 for $k = 11$, and 64 for $k = 8$. In this way, group size will be $\mathsf{T_{RAW}} = \mathsf{T_x} \times \mathsf{S_{RAW}}$, and maximum time frame size of group for $k = 11$ is 1.96s and 1.99s for $k = 8$. The complete time frame ($\mathsf{T_{FRAME}}$) for a network with all associated STAs can be calculated as:

$$T_{FRAME} = N_{RAW} \times T_{RAW}$$

Where, N_{RAW} is the total number of RAW groups in the network. If we consider $N_{RAW} = 10$, a STA may need to wait for $T_{wait} = 19.9 - T_x$ Second for its transmission. However, such delay is not tolerable for critical and rare traffic flows. Once STA finds its RAW slot, it uses a DCF based contention mechanism. The second approach needs T_{ac} access time to get its slot for transmission. Access delay in the DCF scheme depends on the probability of successful transmission in a slot. An increase in the number of groups results in the reduction of a collision, hence throughput improves beyond a threshold number of groups. Again, the latency of a STA will be very high if the number of groups is high, as it may need to wait for T_{wait} time till assigned RAW and slot. In such a case, the primary concern in a network is to find the optimal RAW and group size based on throughput, delay, and energy consumption. Also, for uplink traffic, the main issue in a large-scale network is to reduce collisions due to contention.

Further, event-driven traffic is generated randomly which can create congestion in the network. This is considered as a bottleneck of the existing RAW mechanism. For any event, if a STA is not in the current RAW, it is not allowed to transmit. Although, predicting the patterns of such traffic is challenging, but proposing a suitable priority scheduling and adaptive grouping scheme may solve the problem up to a certain extent. As shown in Figure 3.2, although an event has occurred in Group 5 for a STA, it can not transmit because Group 1 is currently transmitting.

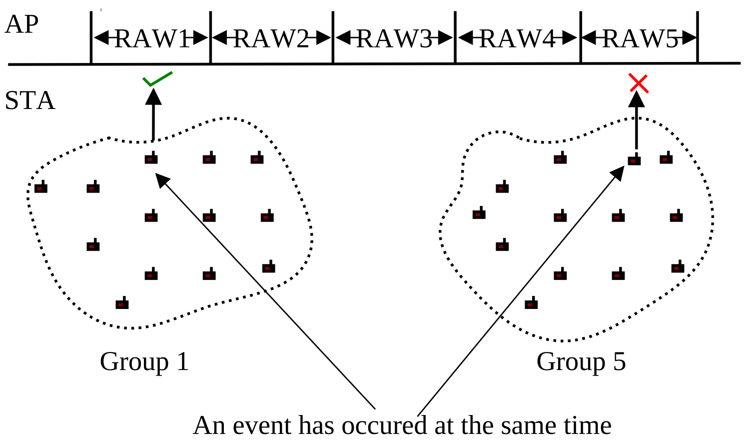


Figure 3.2: An illustration of RAW operation for real-time application

3.3 The Proposed Protocol

The proposed protocol provides QoS in terms of delay and reliability in large-scale 802.11ah network. Considering the requirements of critical IoT applications, the proposed scheme dynamically schedules and regroups STAs. It works primarily in two phases: i) Priority slot scheduling within a RAW group, and ii) Adaptive grouping within the network.

3.3.1 Network Model

The 802.11ah technology operates in sub-1 GHz band which extends connectivity over distances upto 1Km in single hop. Relay node support may increase this distance further. The 802.11ah network can be represented as $\mathsf{N}(\mathsf{A},\mathsf{S})$ is a combination of an AP (A) node and a set of groups $\mathsf{S} = \{\mathsf{G}_1, \mathsf{G}_2, ..., \mathsf{G}_{\mathsf{N}_{\mathsf{RAW}}}\}$, where $\mathsf{G}_\mathsf{i} = \{\mathsf{S}_1, \mathsf{S}_2, ..., \mathsf{S}_\mathsf{R}\}$ is a set of STAs. For a network with n associated STAs, the total number of groups will be $\lceil \mathsf{n}/\mathsf{R} \rceil$. These STAs are categorized into C priority classes, $\mathsf{c} \in [0, \mathsf{C}-1]$ where, $\mathsf{c}_\mathsf{i} > \mathsf{c}_{\mathsf{i}+1}$, based on different QoS performance metrics used in IoT (discussed in Sec. 3.2.1). Each of the priority classes are assigned with a contention window W with successful transmission probability p. The AP node is responsible for assigning a lower W to higher priority class to ensure better probability of successful transmission. For example, a critical traffic may acquire an initial value from a list of c. Due to the heterogeneity and

QoS restrictions, there are different loads $\{L_1, L_2, L_3, ..., L_{N_{RAW}}\}$ and $L_{G_i} \neq L_{G_j}$. Hence, AP adaptively balances loads and if required, it increases the number of groups for additional AID or swaps an unused AID j with i from an existing group. Considering α be the Latency and β be the Reliability as the primary QoS requirements, traffic are classified as follows:

1. QoS Traffic: $C_1 \in \{\alpha, \beta\}, C_2 \in \{\alpha, -\}, C_3 \in \{-, \beta\}$

2. Non-QoS Traffic: $C_4 \in \{-, -\}$

where, '-' indicates no QoS requirement. The binary and decimal representation of the classified traffic can be seen in Table 3.2.

3.3.2 A QoS-aware RAW Scheduling Scheme

A slot scheduling scheme is run for uplink and downlink traffic from STA and AP respectively. The scheme starts with Target Beacon Transmission Time (TBTT) carrying RPS information from AP. Although, most of the IoT application periodically generates traffic, however, other types of traffic as discussed above may be present in a single network. The AP collects transmission behavior from the different received information and predict their next transmission time. We identify the traffic in the network mostly into two types – periodic and non-periodic, based on their transmission behavior. The past information is stored in a database to predict the expected next packet arriving. AP can easily find the periodic traffic by monitoring the initial transmissions from a STA. However, finding the next transmission for non-periodic STA is challenging. To find the next transmission for non-periodic (i.e., event-based) traffic, poison distribution

Class	$\alpha\beta$	Value
1	11	3
2	10	2
3	01	1
4	00	0

Table 3.2: Binary and decimal representation of traffic classes

is commonly used, where probability mass function $\mathsf{f(d)}$ can be calculated as [74]:

$$\mathsf{f(d)} = \frac{\mu^{\mathsf{d}}\mathsf{e}^{-\mu}}{\mathsf{d!}}$$

Here, $\mathsf{f(d)}$ is the probability for d events that occur in a time-bound, and μ is the expected rate of occurrence of an event. Probability of several packets arrived in range (between a and b, where $\mathsf{a} < \mathsf{b}$) is given as:

$$\mathsf{f(a \leq d \leq b)} = \sum_{t=a}^{\mathsf{b}} \mathsf{f(t); t \in I} \tag{3.1}$$

Where I is the average service interval of traffic. Value of I is dependent on the requirements of IoT applications. We store flow rates associated with different links from STAs in an event database. A prediction model decides the expected service interval using Eq. (3.1). If a STA is ready to transmit, the AP node finds an available slot over the RAW frame. The AP node checks priority class C_j and their priority value j for scheduling. Meanwhile, the proposed protocol ensures earlier slot for low priority STAs if higher priority STAs are currently not requesting. Then, a smaller backoff window is assigned to a higher priority STA so that it can win an earlier slot. Instead of uniform random backoff time selection, we use a non-uniform random backoff time selection using a truncated distribution defined in [0, $\mathsf{W_i}$-1] where i is the actual backoff stage. Most of the existing mechanisms use continuous distribution to model the backoff process. But, due to the discrete nature of slots, we need a discrete backoff distribution technique for different classes. Therefore, we use a random time selection scheme that utilizes all the slots at any backoff stage. For any backoff stage i, window size, W_i is calculated as [75]:

$$\mathsf{W_i} = \begin{cases} \mathsf{2^i W_0} & \text{for} \quad \mathsf{i \in [0, m' - 1]} \\ \mathsf{2^{m'} W_0} & \text{for} \quad \mathsf{i \in [m', m]} \end{cases}$$

where m is the maximum retry limits and m' is the backoff stage after which the window size remains constant. From n number of classes, a STA chooses a backoff time from distribution with parameter φ_c defined over $[0, \mathsf{W_i} - 1]$. The probability density function,

Algorithm 2 Priority-based RAW scheduling scheme

Initialize: $\mathsf{uRPS} \leftarrow$ modified RPS, $\alpha \leftarrow$ Latency, $\beta \leftarrow$ Reliability

1: **while** TBTT **do**
2: Transmit BEACON (uRPS)
3: Collect and update information on past transmission
4: Predict STAs time interval and next transmission time
5: Classify STAs into QoS (Q) and non-QoS (nQ)
6: **if** Q **then**
7: $\mathsf{c}_0 \in \{\alpha, \beta\}, \mathsf{c}_1 \in \{\alpha, -\}, \mathsf{c}_2 \in \{-, \beta\}$ ▷ QoS STAs
8: **else**
9: $\mathsf{c}_3 \in \{-, -\}$ ▷ Non-QoS STAs
10: Distribute backoff window into using truncated probability distribution, f(c) over class c ▷ Eq. (3.2) and (3.3)
11: **if** $\mathrm{f}(c_1) > \mathrm{f}(c_2)$ **then**
12: c_1 has more chance to win an earlier slot than c_2
13: **else**
14: c_2 has more chance to win an earlier slot than c_1
15: **for** $\mathsf{i} = 0$ & $\mathsf{i} < 4$ **do** ▷ Allocation of backoff window sizes for different traffic classes
16: Allocate $\mathsf{W_i} \rightarrow \mathsf{c_i}$
17: $\mathsf{i} = \mathsf{i} + 1$
18: **if** Ready to transmit **then**
19: Calculate $\mathsf{T_{FRAME}}, \mathsf{N_{RAW}}, \mathsf{T_{RAW}}$
20: Allow $\mathsf{G_i}$ to transmit in $\mathsf{T_{RAW}}$
21: **else**
22: Go to Step (1)

$\mathsf{f(x)}$ of the mentioned geometric distribution can be calculated as [76]:

$$\mathsf{f(c, i, j)} = \varphi_{\mathsf{c}}^{\mathsf{j}} \frac{1 - \varphi_{\mathsf{c}}}{1 - \varphi_{\mathsf{c}}^{\mathsf{W_i}}} \tag{3.2}$$

Where, $\mathsf{i} \in [0, \mathsf{m}], \mathsf{j} \in [0, \mathsf{W_i} - 1], \tau \in [0, \mathsf{C} - 1]$ and $\varphi_c \in \mathbb{R}$ gives the increase and decrease of the distribution for a given class c. The variation of $\mathsf{f(c, i, j)}$ gives different W value which further defines the priority of class c. For example, if $\varphi_{\mathsf{c_1}} < \varphi_{\mathsf{c_2}}$ then priority of class c_1 is higher than c_2.

$$\varphi_{\mathsf{c_1}} < \varphi_{\mathsf{c_2}} \Rightarrow \left\{ \begin{array}{ll} \mathsf{f(c_1, i, j)} > \mathsf{f(c_2, i, j)}; & \mathsf{j} \in [0, \mathsf{I_j}] \\ \mathsf{f(c_1, i, j)} < \mathsf{f(c_2, i, j)}; & \mathsf{j} \in [\mathsf{I_j}, \mathsf{W_i} - 1] \end{array} \right\} \tag{3.3}$$

where, $\mathsf{I_j}$ is the point of intersection for the density function. Eq. (3.3) says that c_1

has more chance to win an earlier slot $\in [0, \mathsf{I_j}]$ with respect to c_2 in the range $[\mathsf{I_j}, \mathsf{W_i} - 1]$. The value of $\varphi_\mathsf{c} \in \mathsf{f(c, i, j)}$ generates various priority classes. Algorithm 2 describes the proposed traffic classification and priority scheduling scheme. Line #5-14 classifies the traffic into different categories. Once the STAs are classified, RAW scheduling is carried out in line #15-22.

Algorithm 3 Fairness for Critical Applications

Initialize: $\mathsf{W_a^c} \leftarrow$ average window size for class C, $\mathsf{S} \leftarrow$ a set of STAs, $\mathsf{T_c} \leftarrow$ is the failure count

1: **if** Ready to transmit **then**
2:     **for** $(\mathsf{S} \in \mathsf{C_i})$ **do**
3:         **for** Every failure **do**
4:             $\mathsf{T_c} = \mathsf{T_c} + 1$ ▷ Increases failure counts
5:             **if** $(\mathsf{W_a}(\mathsf{C_{i-1}}) < \mathsf{W_m^{i-1}})$ **then**
6:                 Promote $\mathsf{S} \rightarrow \mathsf{C_{i-1}}$ with highest $\mathsf{T_c}$ ▷ QoS class promotion for STA S
7: **else**
8:     Wait for the next beacon

To provide fairness among critical traffic which has failed in recent attempts, the proposed scheme keeps track of transmission count $\mathsf{T_c}$. On every failure, this count value is incremented by 1. Higher the value of $\mathsf{T_c}$, higher is the chance of getting a slot in the near future. Algorithm 3 describes a QoS class promotion scheme. A STA with higher transmission count is promoted to higher priority class if the current RAW is not saturated as discussed from line #2-6.

3.3.3 Adaptive Load-aware Grouping

The proposed grouping algorithm starts whenever any request arrives from the previous phase of the protocol. Meanwhile, the AP periodically collects all the load information of RAWs for both types of traffic. For all received frames, the AP node keeps records of the window (W) and timestamp (t_s), which they have piggybacked. A circular queue is used to store this information for every node in a group. Whenever the queue becomes full, the oldest entry is automatically removed to allow the latest frame to enter. For maximum permissible window sizes $\mathsf{W_m} = \{\mathsf{W_1}, \mathsf{W_2}, \mathsf{W_3}, \mathsf{W_4}\}$, AP finds a set of X, where $\mathsf{X_m}$ is the number of counts for same type of entries in the queue. Enhancing PigWin [77], the ease of transmission (Γ) which is the reciprocal of the average W size. The Γ

is calculated as:

$$\Gamma_{G_i} = \frac{\sum_{m=1}^{4} X_m}{\sum_{m=1}^{4} W_m X_m}$$

The value of a large and small Γ indicates that the STAs are currently using a small and large W respectively. Consequently, the transmission failure is low and high for a large and small W respectively. Therefore, we define the load in the network is the reciprocal of Γ. This can further define the difficulty of transmission. Hence, the average W size considering the recent past transmission is important for understanding the current network load.

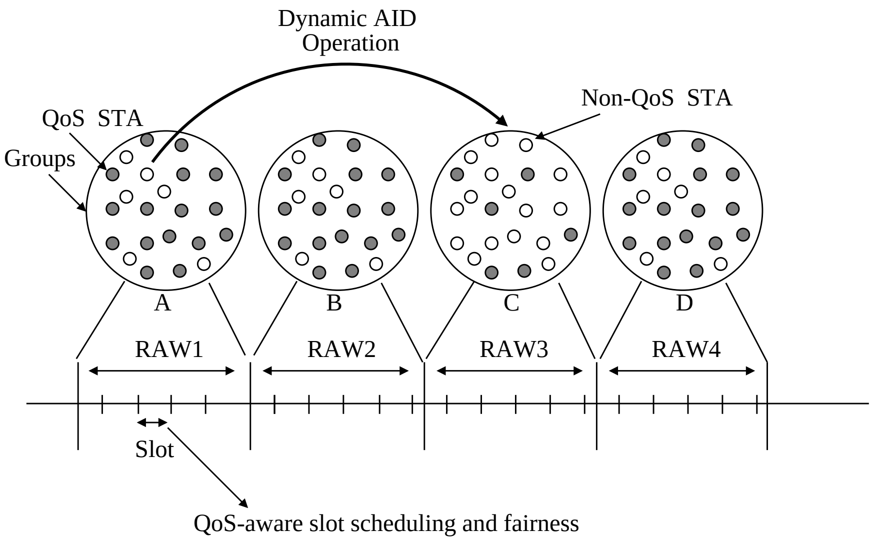


Figure 3.3: An example scenario of the proposed scheme

The theoretical maximum value of the load is W_m, whereas, the minimum permission value of it is W_0 if the frames are being transmitted successfully. Similarly, loads of other groups are also monitored. However, according to the current network condition, a threshold value ($\Gamma^t_{G_i}$) is decided. For example, value of $\Gamma^t_{G_i}$) is calculated considering all the saturated window sizes received only once, i.e., $X = \{1, 1, 1, 1\}$. So, $\Gamma^t_{G_i}$ is calculated with $C = \{1, 2, 3, 4\}$ and $W_m = \{16, 64, 256, 1024\}$ as:

$$\Gamma^t_{G_i} = \frac{1 + 1 + 1 + 1}{16\text{x}1 + 64\text{x}1 + 256\text{x}1 + 1024\text{x}1} = \frac{4}{560} = 0.00294$$

- Case 1: $\mathsf{X} = \{1, 1, 2, 3\}$, $\Gamma^1_{G_i} = 0.0019; \Gamma^1_{G_i} < \Gamma^t_{G_i}$ hence, group is heavily loaded
- Case 2: $\mathsf{X} = \{1, 1, 0, 0\}$, $\Gamma^2_{G_i} = 0.025; \Gamma^2_{G_i} > \Gamma^t_{G_i}$ hence, group is lightly loaded

In general, dynamic AID allocation is initiated by a non-AP node by sending an AID switch request. To enable this, STAs are programmed with dot11DynamicAIDActivated equal to true. The proposed adaptive grouping scheme is discussed in Algorithm 4. In our scheme, an AID switch frame is sent to a particular STA from a heavy loaded group with a new, unused, or AID from the lesser loaded group. Most of the major operations are carried out by AP node which further reduces the load of resource constraint STAs. Figure 3.3 shows an example scenario of the proposed QoS scheme. RAW1, RAW2, RAW3, and RAW4 are allocated for groups– A, B, C, and D, respectively. We consider the CSB type of slots. As discussed, the QoS aware scheduling happens within a slot. However, as group A has more number of QoS STAs, there is a chance of congestion in the slot. In such a case, a non-QoS STA may need to follow different AID, preferably from a group with lesser number of QoS-STAs. This allows the scheme to automatically reduce the load in group A by transferring the STA to group C.

Algorithm 4 Adaptive load balancing for different groups

Initialize: Associated STAs are grouped as: $\mathsf{G}_1, \mathsf{G}_2 ... \mathsf{G}_\mathsf{N}$

1: for $\mathsf{G} = 1$ to N do
2:     Calculate ease of load $\Gamma^{\mathsf{C}}_{\mathsf{G}_\mathsf{i}}$ ▷ For class C in group G_i
3: for $\mathsf{C} = 4$ to 1 do
4:     if $\Gamma^{\mathsf{C}}_{\mathsf{i}} < \Gamma^{\mathsf{C}}_{\mathsf{t}}$ then ▷ $\Gamma^{\mathsf{t}}_{\mathsf{C}}$ is the threshold value for ease of load
5:         Find $\mathsf{G}^{\mathsf{C}}_{\mathsf{j}}$ with highest $\Gamma^{\mathsf{C}}_{\mathsf{j}}$
6:         if $\Gamma^{\mathsf{C}}_{\mathsf{j}}$ then
7:             Swap $(\mathsf{ID}_{\mathsf{STA}}(\mathsf{L}^{\mathsf{C}}_{\mathsf{i}}), \mathsf{ID}_{\mathsf{STA}}(\mathsf{L}^{\mathsf{C}}_{\mathsf{j}}))$ ▷ Exchanging AID values with a STA from low load group
8:         else
9:             Create new group G_k
10:     else
11:         Goto Step (3)
12:     if Transmission failed then
13:         Goto Step (3)
14:     else
15:         Initiate priority slot scheduling ▷ As described in Algorithm 2

3.4 Performance Evaluation

The performance of the proposed priority RAW and grouping scheme is measured using analysis and simulation and compared with the relevant traditional schemes. Although, the existing solutions consider delay, energy consumption, and throughput as the QoS parameters in their proposed architecture. For example, optimise RAW size based on delay and energy consumption [48], reduce association delay [72], and control loop latency [70]. To the best of our knowledge, this work comes as the first for proposing a traffic class-based QoS with dynamic grouping in 802.11ah. Therefore, the proposed protocol is compared with traditional 802.11ah.

3.4.1 Analytical Model

The 2-Dimensional (2D) discrete Markov Chain model (proposed by Bianchi [61]) is used to analyze the performance of the proposed protocol. The probability of transition to a next state is only dependent on the current state without any regard for the past states. The probabilistic picture for a possible transition is dependent on two stochastic functions: s(t) and c(t) at time slot t. The 2D-Markov chain model is represented as shown in Figure 2.5.

3.4.1.1 Probability of successful transmission for priority classes

The network with n STAs are divided into C classes with class $\mathsf{c} \in [0, \mathsf{C}-1]$ having n_g STAs in each group. A random 2D process $(\mathsf{s(t)}, \mathsf{c(t)})$ where s(t) is the backoff stages in $[0, m]$ and c(t) is the backoff counter in $[0, \mathsf{W}-1]$ is represented by (i, k). The state transition probability of (i, k) for class c is denoted as $\mathsf{P_{c,i,k}}$. Different backoff transition probabilities can be described as:

1. From state (i, k+1), if channel is found to be idle, k is decremented by 1 and moves to state (i, k)

$$\mathsf{P}\{\mathsf{i},\mathsf{k}|\mathsf{i},\mathsf{k}+1\} = 1; \mathsf{k} \in [0, \mathsf{W_i}-2], \mathsf{i} \in [0, \mathsf{m}]$$

2. At state (i,k), if the channel is busy, backoff counter stays at the same state with probability, p_c

$$\mathsf{P}\{\mathsf{i},\mathsf{k}|\mathsf{i},\mathsf{k}\} = \mathsf{p_c}; \mathsf{k} \in [1, \mathsf{W_i}-1], \mathsf{i} \in [0, \mathsf{m}]$$

3. If the transmission is successful, initialize i=0 to the minimum contention window W_0 with probability, $1 - p_c$

$$\mathsf{P}\{0,\mathsf{k}|\mathsf{i},0\} = (1-\mathsf{p_c})\mathsf{f}(\mathsf{c},0,\mathsf{k});\ \ \mathsf{k} \in [0, \mathsf{W_i}-1], \mathsf{i} \in [0, 2]$$

4. After an unsuccessful transmission attempts at stage i-1, the STA selects its backoff counter value from the range (0,$W_i - 1$) in the next stage i with the probability p_c

$$\mathsf{P}\{\mathsf{i},\mathsf{k}|\mathsf{i}-1,0\} = \mathsf{p_c}\mathsf{f}(\mathsf{c},0,\mathsf{k}); \mathsf{k} \in [0, \mathsf{W_i}-1], \mathsf{i} \in [1, \mathsf{m}]$$

5. After being unsuccessful is transmission attempts at all the stages, the STA reaches the last stage m, and it remains in the same stage with the probability p until the transmission succeeds.

$$\mathsf{P}\{\mathsf{m},\mathsf{k}|\mathsf{m},0\} = \mathsf{p_c}\mathsf{f}(\mathsf{c},0,\mathsf{k}), \mathsf{k} \in (0, \mathsf{W_m}-1)$$

The steady distribution of the Markov Chain model can be calculated as:

$$b_{c,i,k} = \lim_{i\to\infty} P_c(s(t) = i, c(t) = k)$$

For class c, $b_{c,i,0} = b_{c,i-1,0}; i \in [1, m] \implies b_{c,i,0} = p_c^i b_{c,0,0}; i \in [0, m]$ and $b_{c,0,0} = (1 - p_c)\sum_{i=0}^{m-1} b_{c,i,0} + b_{c,m,0}$. Finally, once STA's backoff counter reaches zero (k=0), probability τ_c that STA can transmit in the randomly chosen slot can be calculated as:

$$\tau_c = \sum_{i=0}^{m} b_{c,i,0} = b_{c,0,0}\frac{1 - p_c^{m+1}}{1 - p_c}; i \in [0, m] \tag{3.4}$$

3.4.1.2 Throughput Analysis

Let $n \subset N$ be the total number STA of class c, so during allocated RAW slot duration, the following events may occur [78]:

1. Channel may be idle, so probability that no STA is currently contending for a RAW slot is given by
$$P_{idl} = (1 - \tau_c)^n$$
2. Probability that at least one STA gets access to a slot for transmission
$$P_{txn} = 1 - (1 - \tau_c)^n$$
3. Probability that exactly one STA gets access and transmits successfully can be written as
$$P_{suc} = \frac{n\tau_c(1 - \tau_c)^{n-1}}{P_{txn}}$$
4. If more than one STAs try to transmit in a single slot at the same time, collision occurs with probability,
$$\begin{aligned} P_{col} &= 1 - (P_{idl} + P_{txn} + P_{suc}) \\ &= P_{txn}(1 - P_{suc}) \end{aligned}$$

Throughout ($\mathsf{Th_c}$) is defined as the successful transmission of a frame bits for a given time for class c (calculated in Eq. (2.5))

$$\begin{aligned}\mathsf{Th_c} &= \frac{\mathsf{E}[\text{Payload size transmitted in a slot}]}{\mathsf{E}[\text{Length of slot time}]} \\ &= \frac{\mathsf{P_{txn}P_{suc}E[Payload]}}{(1-\mathsf{P_{txn}})\mathsf{t_{slot}} + \mathsf{P_{txn}P_{suc}T_{suc}} + \mathsf{P_{col}T_{col}}}\end{aligned}$$

Where, $\mathsf{T_{suc}}$ is the busy time for successful transmission, $\mathsf{t_{slot}}$ is the average duration of a slot, and $\mathsf{T_{col}}$ is the busy time when a collision occurs. In 802.11ah, it can be calculated as below:

$$\begin{aligned}\mathsf{T_{suc}} &= \mathsf{T_{FH}} + \mathsf{T_{DATA}} + \mathsf{T_{SIFS}} + \mathsf{T_P} + \mathsf{T_{ACK}} + \mathsf{T_{DIFS}} + \mathsf{T_P} \\ \mathsf{T_{col}} &= \mathsf{T_{FH}} + \mathsf{T_{DATA}} + \mathsf{T_{DIFS}} + \mathsf{T_P}\end{aligned}$$

Where, $\mathsf{T_{FH}} = \mathsf{T_{PHY}} + \mathsf{T_{MAC}}$ is the frame header duration, and $\mathsf{T_{DATA}}, \mathsf{T_{SIFS}}, \mathsf{T_P}, \mathsf{T_{ACK}},$ and $\mathsf{T_{DIFS}}$ are the data, SIFS, propagation, ACK and DIFS duration respectively. Again, the system throughput (Th) is the summation of throughput for all classes of STAs, i.e.,

$$\mathsf{Th} = \sum_{\mathsf{c}=0}^{\mathsf{C}-1} \mathsf{Th_c}; \mathsf{c} \in [0, \mathsf{C}-1]$$

3.4.1.3 Delay Analysis

We calculate the average delay as discussed in [79]. If $\mathsf{E(D_b)}$, $\mathsf{E(D_s)}$, and $\mathsf{E(D_r)}$ are the delays due to backoff, number slots before the backoff counter freezes, and retries respectively, then the average delay for class c can be calculated as:

$$\mathsf{E(D_c)} = \mathsf{E(D_b)}\sigma + \mathsf{E(D_s)T_1} + \mathsf{E(D_r)T_2} + \mathsf{T_{suc}}$$

where,$\mathsf{T_2} = \mathsf{T_{col}} + \mathsf{T_{DIFS}} + \mathsf{T_{ACKtimeout}}$, $T_{ACKtimeout}$ is the ACK time out, and $\mathsf{T_1} = \mathsf{P_{suc}T_{suc}} + \mathsf{P_{col}T_{col}}$. So, the average delay including all classes is

$$\mathsf{E(D)} = \frac{1}{\mathsf{C}} \sum_{\mathsf{c}=0}^{\mathsf{C}-1} \mathsf{E(D_c)}; \mathsf{c} \in [0, \mathsf{C}-1]$$

3.4.2 Analytical Results and Validation

We analyze the RAW performance considering traffic classes- C_1, C_2, C_3, and C_4, where priority of $C_i > C_{i+1}$; $1 \leq i \leq 4$.We compare the results of the proposed QoS-aware MAC protocol (QS-MAC) with the DCF mechanism of 802.11ah. Further, a simulation analysis is carried out in the same environment. The values of different parameters are mentioned in Table 3.5. The duration of the data frame for MCSs used in 802.11ah can be calculated by the equation mentioned in [45] as:

$$T_{DATA} = \lceil \frac{8 \times (L + m_h)}{\frac{R}{D_r} \times L^{D_{rs}}} \rceil \times T_{sym} + T_{PHY} \tag{3.5}$$

where, $m_h, R, D_r, L^{D_{rs}}, T_{sym}$ and T_{PHY} are MAC header size, basic data rate, number of bits in one OFDM, symbol duration of OFDM, and PHY header size respectively. For 256 bytes (MCS0, 2MHz), T_{DATA}=4.56 ms. To see the saturation throughput in a condition where the number of STAs from different classes is not the same (among 1000 STAs), we use tabular data representation. We consider 4, 6, and 10 as the maximum backoff stages for C1, C2, and C4 classes respectively. Otherwise, a graphical representation is used for common case scenarios. Initially, we analyze the throughput and delay performance of the proposed scheme in analytical (A) and simulation (S) environments and compare the results with traditional 802.11ah. Considering the theoretical analysis from Sec. 3.4.1.2, the calculated saturation throughput can be seen as presented in Table 3.3. Throughput achieved by the QoS scheme is much higher than the conventional DCF used in 802.11ah. The required bandwidth is optimally utilized for more reliabil-

Table 3.3: Saturation throughput: analytical vs. simulation

Traffic Class	Protocol	A/S	N_{C_1}=100 N_{C_2}=100 (Kbps)	N_{C_1}=100 N_{C_2}=150 (Kbps)	N_{C_1}=150 N_{C_2}=200 (Kbps)	N_{C_1}=250 N_{C_2}=300 (Kbps)
C1	QS-MAC	A	104.9	111.7	116.3	121.4
		S	101.4	107.2	113.4	120.5
C2	QS-MAC	A	102.3	100.1	97.1	100.7
		S	91.0	93.2	94.9	92.7
Default	802.11ah	A	60.3	63.9	66.1	70.9
		S	56.0	58.2	59.8	61.8

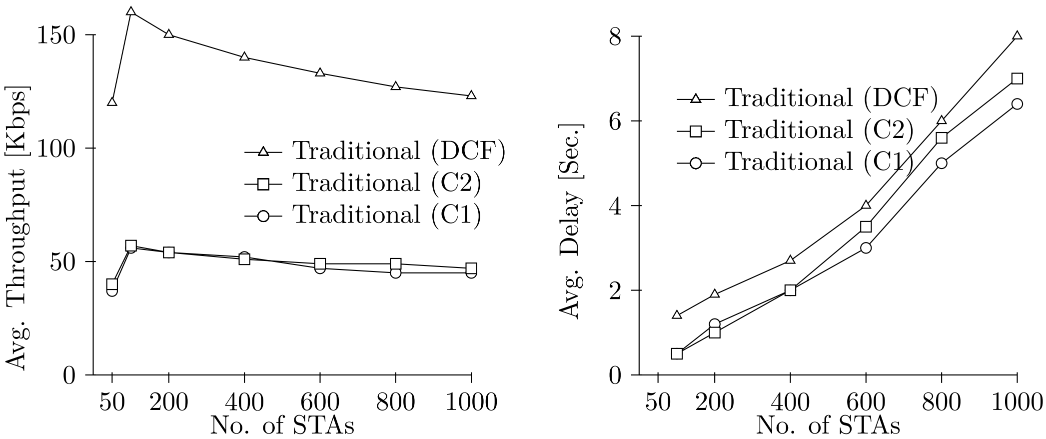
Table 3.4: Saturation delay: analytical vs. simulation

Traffic Class	Protocol	A/S	N_{C_1}=100 N_{C_2}=100 (Sec.)	N_{C_1}=100 N_{C_2}=150 (Sec.)	N_{C_1}=150 N_{C_2}=200 (Sec.)	N_{C_1}=250 N_{C_2}=300 (Sec.)
C1	QS-MAC	A	1.902	1.954	2.077	2.167
		S	1.941	2.105	2.167	2.311
C2	QS-MAC	A	3.101	3.201	3.658	3.814
		S	3.112	3.402	3.756	3.987
Default	802.11ah	A	9.081	11.102	12.982	14.088
		S	9.120	11.201	13.321	14.568

ity and low latency in priority traffic. Further, a saturation delay is calculated from both types of traffic, which can be seen in Table 3.4. The saturation delay is greatly improved in the proposed protocol. About 700% and 500% (on average) lesser latency can be noticed in C1 and C2 respectively as compared to the default DCF scheme.

Table 3.5: Default parameters used for simulation and analysis

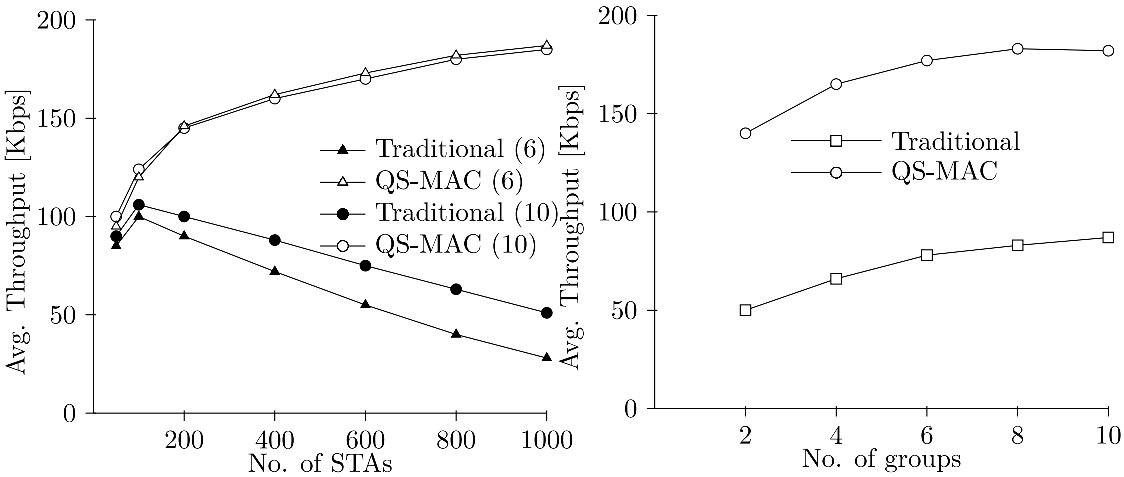
Parameters	Value
Bandwidth	2MHz (MCS0)
Data rate (D_r)	650 Kbps
Payload size (L)	256 bytes
CWmin/ CWmax	15/1023
Slot time	52 μs
SIFS	160 μs
DIFS	SIFS+2 *Slot time (μs)
RTS/CTS	Not enabled
STA distribution	Random
Beacon Interval	0.1s
Number of STA	1000
No. of data bits in one OFDM ($L^{D_{rs}}$)	26 bits
Symbol duration (T_{sym})	40 μs
Coding rate for Binary Phase Shift Keying (BPSK)-MCS0 (R)	0.5
PHY header	6 * symbol duration (μs)
MAC header (m_h)	14 B
Number of slot in each RAW	10
RAW slot duration	15 ms
Queue size	100 packets
No. of QoS STAs	50%
No. of groups	2-10
Simulation area	1000×1000 m^2
Simulation time	5 min



(a) Throughput

(b) Delay

Figure 3.4: Throughput and delay characteristics with increasing number of STAs in traditional scheme



(a) With increasing number of STAs

(b) With increasing number of groups

Figure 3.5: Throughput characteristics with increasing number of STAs and groups

3.4.3 Simulation Analysis

We use NS-3 [64] for simulation analyses of the proposed protocol. Initially, the effect on throughput and delay are analyzed for different priority classes with 50% of QoS traffic in the traditional scheme. Other simulation parameters are mentioned in Table 3.5. The following throughput and delay analysis are carried out to portray the essence of the proposed scheme:

- QoS in the traditional scheme: Throughput and delay results are analyzed.
- QoS in proposed and traditional scheme: Throughout results are compared in the

proposed and traditional scheme.

- QoS of Different Traffic Categories: Throughput and delay of the proposed scheme considering different classes of traffic are measured.
- Overall QoS performance in the proposed and traditional scheme: Throughput performance are measured to see the efficiency of QS-MAC for dynamic grouping.

3.4.3.1 QoS in Traditional Scheme

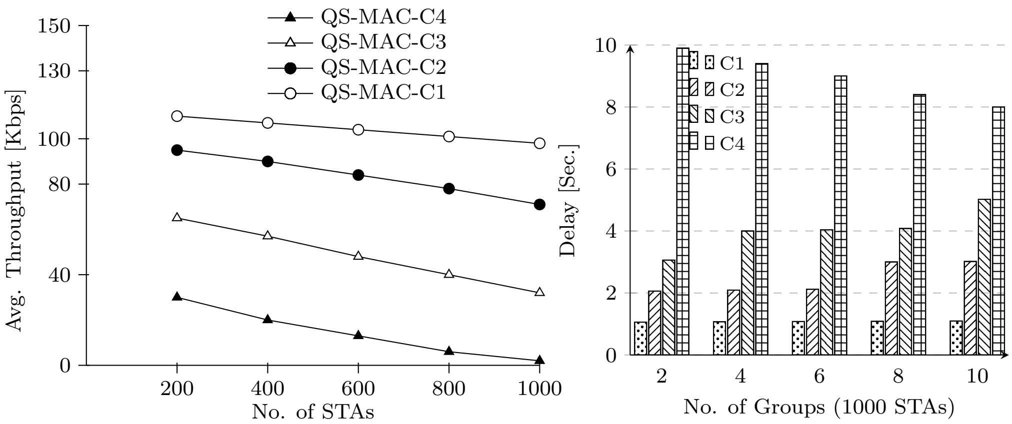
Before applying the proposed scheme, we measure the performance of the traditional 802.11ah MAC protocol with the considered traffic classes. As shown in Figure 3.4a, the tradition scheme with more number of non-QoS STAs show higher throughput due to the higher possibility of transmission. Similarly, the delay is not reduced for the QoS traffic as shown in Figure 3.4b.

3.4.3.2 QoS in Proposed Vs. Traditional Scheme

We compare the performance of QS-MAC with the traditional scheme. We measure the effect on the priority of traffic over non-priority traffic is measured. In Figure 3.5a, considering a number of groups like 6 and 10, with an increasing number of STAs, throughput decreases for the DCF scheme. However, in the case of the priority scheme, saturation throughput increases. With an increasing number of STAs, a higher number of priority STAs try for channel access. Hence, the probability of getting a channel for the non-QoS STA is lesser. Secondly, without any priority scheduling, chances of collisions are higher in case of a higher number of STAs in DCF. The remaining bandwidth can be utilized to support the requirements of class STAs, which is done by the proposed adaptive grouping scheme. Again, the DCF mechanism performs better in case of a higher number of groups. This is because of the reduction in collisions (due to contention). Figure 3.5b considers all the traffic classes for analysis. Throughput is measured with an increasing number of groups considering QoS bound traffic. For the only group in the DCF mechanism, throughput decreases drastically. However, using 6 groups a better result can be seen especially in a case for a large number of STAs.

3.4.3.3 QoS of Different Traffic Categories

Throughput achieved over increasing number of STAs considering all classes C1, C2, C3, and C4 of traffic at the same time. If we consider only class-based traffic in the same scenarios, throughput achieved by the higher priority class is better. Also, a small decline in throughput is observed as compared to DCF scheme. Also, in addition to all the priority classes, throughput shows 125% of higher than the tradition DCF scheme. Further, throughput performance for class STAs is also measured against different groups sizes. The proposed protocol shows similar results in almost all the group sizes (can be seen in Figure 3.6a). Throughput achieved over increasing number of STAs considering all classes C1, C2, C3, and C4 of traffic at the same time. This is due to the adaptive grouping scheme, which balances the available bandwidth among all the groups. The proposed scheme reduces the simultaneous channel access by early priority scheduling. Finally, Figure 3.6b shows the saturation delay performance. The proposed scheme reduces delay up to a huge margin. It applies RAW scheduling and adaptive grouping to provide QoS for the critical STAs. The preliminary delay in a large-scale network is the channel access delay, which is reduced in this scheme. However, non-class STAs incur higher delay in-spite of relief for more number of groups.

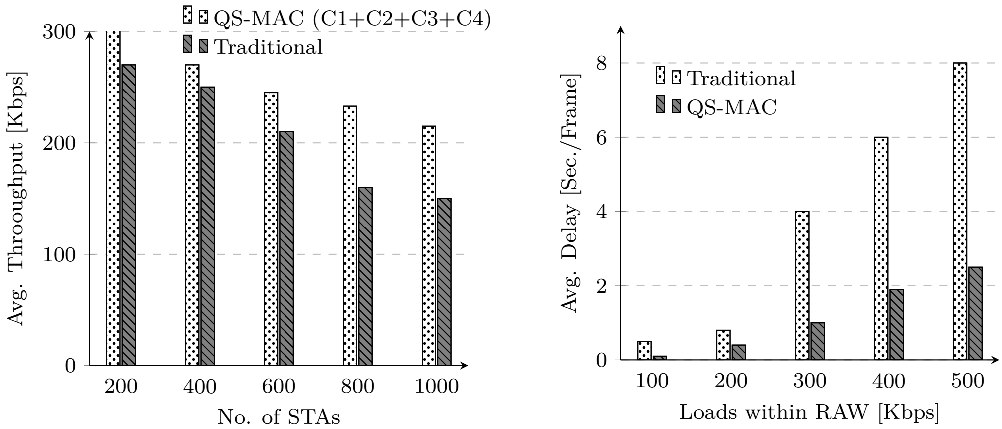


(a) Throughput (b) Delay

Figure 3.6: Average throughput and delay for different network and node group sizes respectively

3.4.3.4 Effect of Grouping in Proposed Vs. Traditional Scheme

We analyze the overall delay improvement in the proposed scheme and compared with the traditional scheme. As shown in Figure 3.7a, the average throughout is measured with the increasing number of STAs. Our solution efficiently utilizes the available channel bandwidth, which is distributed among different RAW groups. Due to this, the total throughput (C1+C2+C3+C4) in the proposed scheme is higher than the traditional scheme. Figure 3.7b shows the average delay performance of the proposed scheme with increasing loads in a group. Considering 50% of QoS traffic in a RAW group, we take an average of delays in all the STAs that are initially considered to be in the same group. It may be noted that a STA may not be in the same group for all the duration. Due to the dynamic grouping scheme, the average delay of the STAs is reduced significantly as compared to the traditional scheme. Due to the saturation capacity of the links, the delay drastically changes when the loads increase beyond 300 Kbps.



(a) Effect of grouping in throughput (b) Effect of grouping in delay

Figure 3.7: Average throughput and delay performance

3.5 Conclusion

This work presented a priority scheduling and adaptive grouping scheme for improving QoS performance in terms of latency and throughput over a highly dense network. Applying the proposed scheme, the utilization of a large-scale network is significantly improved over the existing RAW grouping scheme. From the result, we can judge that a higher number of groups give better performance applying the scheme over different requirements of STAs. We can further conclude that it is more advisable to classify all the STAs of the network into different priority classes according to their requirements and then allow them for transmission. The proposed protocol used three algorithms, viz., priority scheduling, fairness scheme, and adaptive grouping to achieve QoS. The algorithms use the same computation on backoff operations for different purposes such as window-based priority setup, load balancing, and achieving fairness. Hence, computational latency is lesser and scalability is higher as compared to the existing related works. The key achivements of the proposed works are as follows:

- IEEE 802.11ah without special scheduling is not suitable for provisioning IoT services with the required quality. In such a case, load from non-QoS traffic may create a burden to achieve QoS for priority traffic.
- Considering all the priority classes in a network, throughput shows 125% of higher than the traditional DCF based schemes.
- In case of delay performance, about 700% and 500% (on average) lesser latency can be noticed in C1 and C2 class of traffic respectively as compared to the default DCF scheme.
- Due to the dynamic grouping scheme, the proposed protocol improved throughput up to 12.7% and delay up to 300% over existing RAW schemes.
- We proposed four traffic classes considering delay and reliability requirements, therefore, the proposed scheme can use both scheduling and grouping schemes to provide QoS in all the scenarios with better efficiency in the network.
- Three algorithms – priority scheduling, fairness scheme, and adaptive grouping use the same computation on backoff operations for different purposes, which ultimately reduced the computational latency in the network.

Although the proposed QoS scheme can ensure guaranteed services for critical application upto a certain extent, with an increasing number of STAs and critical traffics, congestion will be high. In such a case, the total network capacity needs to be increased. In the following chapter, we propose a multi-band sectoring scheme powered by a dynamic bandwidth allocation scheme at the Relay node.

Chapter 4

Dynamic Load Balancing Scheme for Relay-based Networks

This chapter proposes a dynamic load balancing scheme – DL-MAC for large-scale 802.11ah network. Beforehand, a network with a distributed association, Relay node planning, and sectorization scheme is designed for better efficiency. DL-MAC uses current load in Relay or AP and dynamically switches its Modulation and Coding Scheme (MCS) as per the requirements. Further, an efficient TXOP-based channel access mechanism is proposed for improving scalability.

4.1 Introduction

With the technical support from IoT, applications have evolved for provisioning smart technology, smart services, smart industry, smart management, and smart life. However, for holistic operation in the whole network, it requires seamless communication from the sensor/actuator to the gateway. The state of art solutions is not very suitable for supporting communication among a massive number of IoT devices. As discussed above, the latest IEEE 802.11ah standard [29] has emerged as new candidates to solve the above gap problem. This standard proposes some innovative and unique concepts for supporting a large number of low-power devices in smart cities [16]. With the support of the sub-1GHz frequency band, it can cover up to 1km in a hop. Along with the grouping-aware a RAW, it also proposes a Relay AP (RAP) solution, which can increase the coverage beyond 1-hop distance and can support more number of devices in the network ([80] and [81]).

In the 802.11ah-based large-scale network, there is a possibility of poor quality data reception due to long communication range and higher delay in multi-hop transmission. As it uses only a single channel, only one node in the network can transmit at a particular time. Carry on the point a little, this may cause interference on each other or increase the chances of hidden node problems. Also, networks used in IoT solutions need to support heterogeneous traffic requirements. For example, a surveillance application requires a higher data-rate than in a smart lighting system. Severe hidden nodes problem in communication can also arise if we do not group the STAs according to their geographic locations, especially in urban infrastructure. In such a dense network scenario, without spatial reuse of channel, the overall network may lead to performing beggarly. Many IoT applications require some sort of QoS guarantees in terms of parameters like delay and throughput. Further, a better Relay AP (RAP) solution for 802.11ah network to dynamically adjust bandwidth requirements in a different part of IoT is important.

In this work, we propose a dynamic load balancing scheme for the RAP-based 802.11ah network, named, DL-MAC for maximizing overall network efficiency using multiple channels. Before implementing the dynamic load balancing scheme, we propose an 802.11ah based network considering relay and sectorization support. The proposed network enables the nodes to contend and get associated with the AP in a distributed manner. With the use of a dynamic network organization and channel allocation scheme, the proposed protocol improves the scalability of 802.11ah significantly by allowing multiple channels and RAPs with simultaneous transmissions. Later, a MAC protocol for dynamic load balancing and transmission scheduling at RAP and AP is proposed. In summary, the following are the key contributions of this work:

- We propose a large-scale network for IoT, which is distributed over RAPs and different sectors. RAPs use different channels for simultaneous transmissions in different sectors of the network. To achieve this, an efficient RAP planning scheme is proposed with the help of the angular separation of nodes.

- A MAC layer protocol for RAPs or AP, to periodically check its load and adjust bandwidth using multiple MCSs dynamically.
- An efficient transmission scheduling scheme for RAP and AP communication.

The rest of the chapter is organized as follows. A background study on IEEE 802.11ah for IoT concerning their network scalability support and related works are presented in Section 4.2. Section 4.3 gives the detail of the proposed solution. Simulation and performance evaluation of the protocol is presented in Section 4.4. Finally, Section 4.5 concludes this work.

4.2 Background and Related Works

IEEE 802.11ah amendment [29] aims to provide Wireless Local Area Network (WLAN), which can manage and control a large number of heterogeneous, low-powered devices within a BSS. To support the requirements of heterogeneous traffic in IoT, it has proposed different MCSs to be applied in various scenarios. Considering the wide channel of 16 MHz, MCS9 can provide up to 78 Mbps of data rates. IEEE 802.11ah utilizes sub-1 GHz license-exempt bands to provide extended coverage range. It defines 2, 4, 8, and 16 MHz channel bands for data transmission [82].

MCS	Modulation	Coding rate	1 MHz (Mbps)	2 MHz (Mbps)	4 MHz (Mbps)	8 MHz (Mbps)	16 MHz (Mbps)
MCS0	BPSK	1/2	0.3	0.65	1.35	2.925	5.85
MCS1	QPSK	1/2	0.6	1.30	2.70	5.850	11.70
MCS2	QPSK	3/4	0.9	1.95	4.05	8.775	17.55
MCS3	16QAM	1/2	1.2	2.60	5.40	11.700	23.40
MCS4	16QAM	3/4	1.8	3.90	8.10	17.550	35.10
MCS5	64QAM	2/3	2.4	5.20	10.80	23.400	46.80
MCS6	64QAM	3/4	2.7	5.85	12.15	26.325	52.65
MCS7	64QAM	5/6	3.0	6.50	13.50	29.250	58.50
MCS8	256QAM	3/4	3.6	7.80	16.20	35.100	70.20
MCS9	256QAM	5/6	4.0	-	18.00	39.000	78.00
MCS10	BPSK	1/2	0.15	-	-	-	-

Table 4.1: MCSs supported in 802.11ah

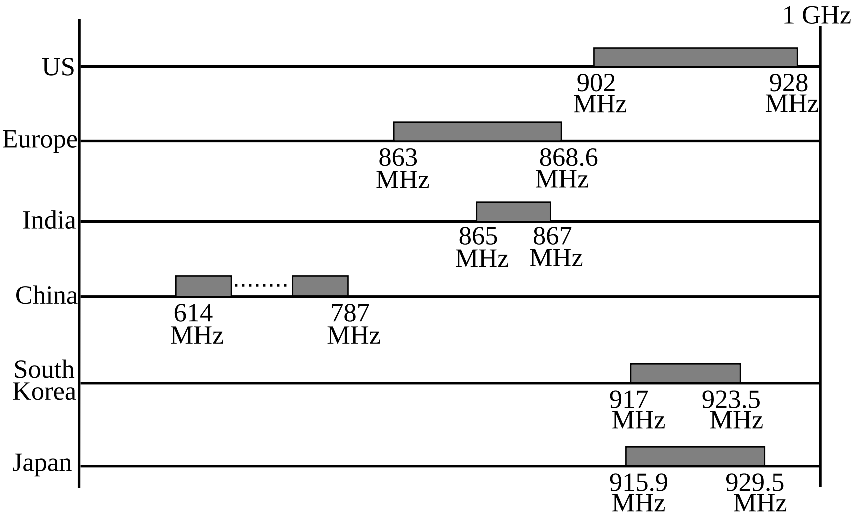


Figure 4.1: Country-wise license-exempt bands in sub-1GHz

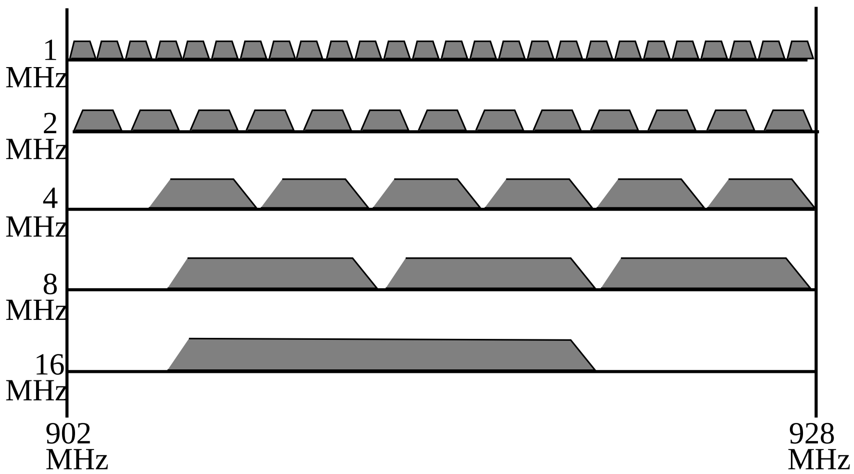


Figure 4.2: Different channels from usable Sub-1 GHz bands in USA

4.2.1 Channelization

The channelization in 802.11ah inherits the PHY layer of 802.11ac. Figure 4.1 shows the available license-exempt channels in sub-1 GHz spectrum for different countries. For example, current availability as: 902-928 MHz (US), 755-787, 614-787 MHz (China), 917-923.5 MHz (South Korea), 863-868.6 MHz (Europe), 865-867 MHz (India), 915.9-929.7 MHz (Japan), 866-869 MHz, 920-925, 866-869 MHz (Singapore) [83]. The channel bandwidth in 802.11ah includes 1, 2, 4, 8 and 16 MHz, whereas 1 and 2 MHz are widely available in many countries and more suitable for low rate traffic scenarios. Possible channel bands for USA can be seen in Figure 4.2. Considering 1 MHz and 2 MHz of bandwidth, there are 26 and 13 channels, respectively.

A MAC protocol proposed by Kumar et al. [84] uses a static channel allocation mechanism for the distributed relay nodes. A dynamic channel allocation and organization approach is proposed in [85] to improve the performance of relay-based large networks. Rao et al. [86] introduces a dual-hop relay to extend the connectivity till STAs, however, the detail deployments in different geographic locations are not considered while placing a relay node. A cooperative relay with a cross-layer design for minimizing the power consumption of an 802.11ah network is proposed by Argyriou et al. [87]. None of these schemes consider the heterogeneous traffic coexisting inelastic and elastic traffic in the same 802.11ah network while efficiently utilizing the bandwidth.

Shafiq et al. [88] proposes a Cognitive Radio (CR) based MAC protocol which regroups STAs based on the probabilistic analysis of collisions. Nabuuma et al. [89] proposes a backoff scheme with AID for reducing collisions in sectorized network. A Received Signal Strength (RSS) based solution to the hidden node problem is proposed in [90]. The protocol senses the neighbors by measuring the RSS and ensures that nodes in the same group are known, which is not always true in dynamic conditions. Enhancing this, Laipeng et al. [91] additionally used several reference nodes according to their location to reduce collision probability. However, collision chains remain in the network due to a large number of sleeping nodes. Further, they assumed that the network is saturated to uplink traffic only. Yu et al. [92] proposes a grouping mechanism based on a list of exposed terminal nodes. The factors like wide coverage range, CSMA/CA mechanism, large power-saving STAs, and uplink traffic, the 802.11ah-based network is severely affected by the hidden terminal node. A comparison of different relay and sectorization schemes are presented in Table 4.2.

A large amount of current research is focusing on RAW protocol design attempting scalability, but in many cases, the possibility of high collisions at the time of slot assignment with the dense network still exists. The centralized access with a single-channel mechanism in 802.11ah affects the performance of such networks considering a huge number of devices trying to access a time slot simultaneously. Further, in a hierarchy based multi-hop network, chances of delay and poor quality data reception are high. However, in heterogeneous traffic and dynamic networking scenarios, a STA may leave and join at any time, may transmit at any rate. So, the RAP or AP node without dynamic load adjustments may perform beggarly.

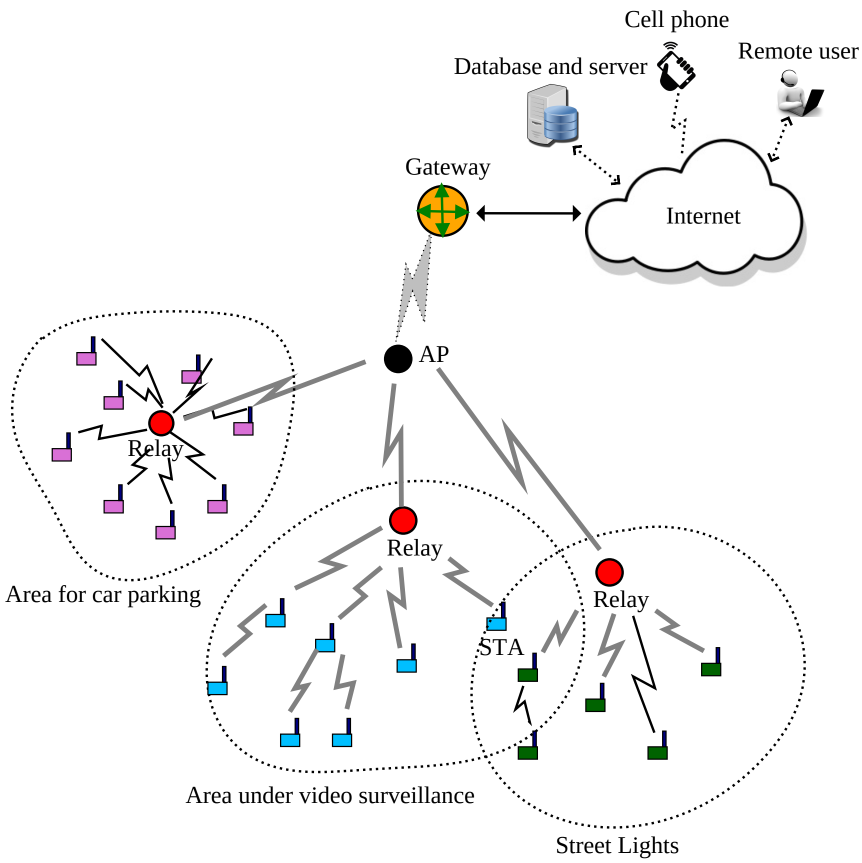


Figure 4.3: IEEE 802.11ah based IoT network spreading over large coverage area

Protocol	Year	Description	Sectorization	Relay Support	Load Adjustment	Multi-channel
[84]	2015	Allows to use different channel at relay	✗	✓	✗	✓
[93]	2015	Discusses the feasibility of 6LoWPAN and mesh support in 802.11ah	-	✓	-	-
[94]	2016	Detects a hidden nodes and regrouped based on geographical location	✓	✗	✗	✗
[95]	2016	Detects a hidden nodes using collision chain	✓	✗	✗	✗
[78]	2016	Uses start time of two STAs to detect a hidden pair	✓	✓	✗	✗
[90]	2017	Avoids hidden nodes using RSSI	✓	✗	✗	✗
[91]	2017	Hidden pairs are detected based on signal strength	✓	✗	✗	✗
[92]	2017	Detect exposed terminal nodes for neighbor transmission	✓	✓	✗	✓
[73]	2018	It proposes a grouping algorithm using association process to prevent hidden node collision	✗	✗	✗	✗
[96]	2018	Uses multiple sector antenna at AP	✓	✗	✗	✓
[86]	2018	Uses dual hop relay node to extend connectivity	✗	✓	✗	✗
[97]	2019	It proposes an Interference-aware Dynamic Frequency Allocation (IDFA) scheme to reduce hidden node problem	✓	✗	✗	✗

Table 4.2: Relay and sectorization schemes

4.3 The Proposed Protocol

The proposed protocol is an 802.11ah-based scheme designed for multi-hop networks. The design is greatly influenced by the multiple available channels of 1 and 2 MHz bandwidth in sub-1 GHz and flexible MCSs proposed for 802.11ah. Further, it maintains a distributed RAW and TXOP mechanism to provide efficient access to a huge number of IoT devices.

The proposed protocol aims to improve the performance of the multi-hop network by distributing the available channel among the nodes spreading over sectors in a larger coverage area. The protocol allows simultaneous channel access in different RAW groups implemented by the sectors.

4.3.1 The Network Topology

The RAP can be connected with the AP using multi-hop distances. Figure 4.3 shows a typical network architecture of IoT using 802.11ah where three IoT networks are connected to the Internet.

IoT is a combination of sensor and backhaul networks. The overall network can be represented as a set of $\mathsf{N}(\mathsf{A},\mathsf{R},\mathsf{E}) = \{\mathsf{B}(\mathsf{A},\mathsf{R}),\mathsf{T}(\mathsf{R},\mathsf{E})\}$, where B and T are the backhaul and sensor network respectively, here A is the AP node, R is the set of RAP nodes ($\mathsf{R} = \mathsf{R}_1, \mathsf{R}_2, ..., \mathsf{R}_n$) and E is the set of sensor/actuator nodes ($\mathsf{E} = \mathsf{E}_1, \mathsf{E}_2, ..., \mathsf{E}_m$). A takes the responsibility of initialization, synchronization, slot assignment and channel allocation of the whole network. The Rs are the owner of channels and hold the responsibility of forwarding data from Es to A and vice versa.

4.3.1.1 Relay Organization

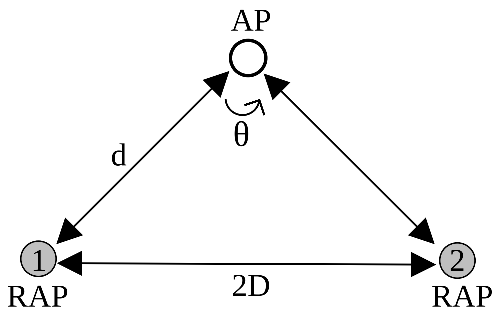


Figure 4.4: Positioning of AP and RAP nodes in a network

The RAP nodes are as powerful as AP node. An RAP node carried out to carry the operations like association, on, and synchronization. Therefore, an organization and planning scheme is important to optimally use as less number of RAP as possible. We can calculate the coverage range of AP or RAP nodes using signal strength of the radio. The 802.11ah standard uses the macro model of propagation [33] for Tx/Rx. Considering an antenna height of 15 meters above a rooftop, the propagation loss (in dB) in this model is calculated as:

$$\mathsf{L(d)} = 8 + 37.6\log_{10}(\mathsf{d}) + 21\log_{10}\left(\frac{\mathsf{f}}{900\mathsf{MHz}}\right)$$

Where d is the wireless distance between sender and receiver node and f is the carrier frequency. The value of d can be calculated as [98]:

$$\mathsf{d} = 10^{(\mathsf{T_{xpower}} - \mathsf{T_{RSSI}})/20}$$

where $\mathsf{T}_{\mathsf{RSSI}}$ is the Received Signal Strength Indicator (RSSI). It depends on gains, loss, sensitivity, fading effect, and carrier frequency band. $\mathsf{T}_{\mathsf{xpower}}$ is the transmission power of an 802.11ah node. For better coverage range, a node at the edge of d coverage maintains its mode of operation as RELAY mode. Enhancing [85], another relay node is selected using angular separation, which can be calculated as:

$$\Delta\theta = \frac{360^0 \times 2D}{2\pi d}$$

where D is the RAP node coverage. As the coverage of RAP and AP are same, the value of d and D are also same, hence $\Delta\theta = \frac{360^0}{\pi}$. So, the required number of RAPs in 1-hop distance can be calculated as:

$$N_n^{1hop} = \lceil \frac{360^0}{\Delta\theta} \rceil$$

Similarly, angular separation for k-hop RAP node is given by $\Delta\theta/k$. We can calculate the number of RAP nodes in i^{th} hop as:

$$N_n^k = \lceil \frac{k \times 360^0}{\Delta\theta} \rceil$$

This procedure gives the lowest number of RAPs to be deployed around the AP. Once, the nodes are organized, the AP or RAP can start association with STAs.

4.3.2 Node Association

To solve the problem of a huge delay in association procedure, 802.11ah has proposed Centralized Authentication Control (CAC) as well as Distributed Authentication Control (DAC) [99]. In CAC, a value called authentication control threshold is set by an AP which is transmitted through the beacon frame. A STA can associate only if the value of it is smaller than the threshold. The DAC scheme divides beacon into different slots of equal duration. It uses two random variables uniformly distributed in beacon and transmission interval, respectively. An authentication request containing the two random variables is sent to the AP using truncated binary exponential backoff. The proposed solutions reduces overall association delay by reducing the number of STAs for sending simultaneous requests.

For the association of a huge number of STAs, we use CAC. The fast association mechanism is initiated by the AP by transmitting an authentication control threshold (θ) value along with the beacon. A STA, S selects a random value (ϑ) within the window range of $[0, 1022]$ and then associates itself with A or R only if $\vartheta < \theta$. Total number of association groups is $n+1$ (n number of distributed active Rs + A's group (g_a)). Then, the total association time can be calculated as:

$$\mathsf{T_{assoc}} = \max\,(\mathsf{T_{g_a}}, \mathsf{T_{g_i}}), \forall \mathsf{i} = 1, 2, ..., \mathsf{n}$$

where T_g is the association time required for all the nodes in a group to get associated with the nearest R.

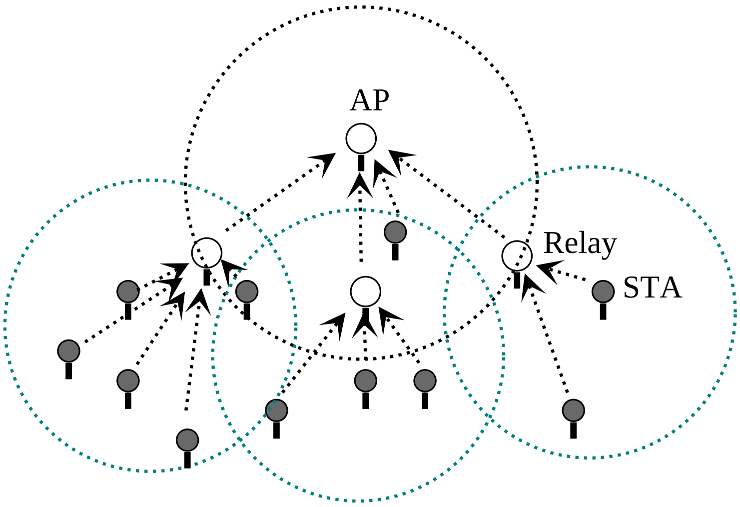


Figure 4.5: Example scenario of node association

4.3.2.1 A Multi-band Sectorization Scheme

IEEE 802.11ah proposes a sectorization scheme to partition the coverage of a BSS into different non-overlapping sectors. The AP uses beacon to inform the timing of which sector should transmit for a particular time frame. The beacon carries sector option element with group ID. Each STA is allocated a group ID to enable transmission in

Algorithm 5 Multi-band sectorization scheme for AP

Initialize: $\{\mathsf{STA}, \mathsf{RELAY}, \mathsf{AP}\} \leftarrow$ modes of STAs
$\mathsf{C} \leftarrow$ a set of available channels
$\mathsf{S} \leftarrow$ a set of sectors to be used around the AP
$\mathsf{S_A} \leftarrow$ a set of sector antennas for transmitting signal to set of regions
$\mathsf{m} \leftarrow$ number of available channels
k $\leftarrow$ total number of sectors

```
if (mode==AP) then
    for i = 1 to k do
        Create sector S_i                    ▷ based on their geographic location
        S_{A_i} → S_i                         ▷ assignment of sector antennas
    Transmit beacon → {RPS, group ID, allowed channel, allowed MCS)}
    Associate STA and Relay
    if (k ≤ m) then    ▷ more number of channels than the sectors to cover areas all around the AP
        Allocate channel C_i → S_i
        Transmit data using allocated slot
    else
        if (m == Even) then ▷ even number of sectors to cover areas all around the AP
            Allocate C_i → S_i, C_{i+1} → S_{i+1}
            Transmit data using allocated slot
        else if (m == Odd and m > 1) then  ▷ odd number of sectors to cover areas all around the AP
            Allocate C_i → S_i, C_{i+1} → S_{i+1}, C_{i+2} → S_{i+2}
            Transmit data using allocated slot
```

different sectors around the AP using Time Division Multiplexing (TDM). With the support of the proposed RAP solution and multiple available channels, we have incorporated two features to the existing group sectiorization scheme. The following are the key enhancements:

- Support for multi-band sectorized transmission using Frequency Division Multiplexing (FDM)
- RAP node is configured with multiple channels and MCSs

The current sectorization schemes proposed for 802.11ah consider TDM-based approaches. These schemes solve hidden node problem up to a certain extent, however, overall network capacity remains the same. The proposed solution allows the AP node to use multiple channels and hence STAs from different sectors can transmit simultaneously using different channels. The number of radios employed an AP depends on the number of available channels. For N number of channels, the same number of radios and sector antennas are required. Due to the limited number of available channels, we restrict the value of N limited to 4. In this case, the angular beam of a sector antenna is $360/N$ degree. However, we consider four sectors by default to cover all around the AP (can be seen in Figure 4.6). Algorithm 5 discusses the proposed sectorization scheme. Lines #1-4 allocates the sector antennas to the radios that are mounted in an AP. Lines #7-15 discusses the allocation of channels and transmission. STAs or RAPs check the received signal strength (P_r) from the AP through a or a list of sectorized beacon and join with a better sector. Considering the fast fading effect, the power received at the receiver (P_r) is given by [89]:

$$P_r = P_t + G_t + G_r - (L(d) + X_\sigma \tag{4.1}$$

where P_t is the received powers, G_t and G_r are the transmitter and receiver gains respectively, and X_σ is the shadowing, which is a zero-mean log random variable with a standard deviation, σ. The STAs or RAPs collect other information like group ID, RPS, and channel information from the beacon.

4.3.3 Dynamic Bandwidth Adjustment

The proposed protocol enables the STAs to use different MCSs according to their data-rate requirements. The RAP nodes check the current load of itself in a periodic manner. The load is proportional to the amount of time wasted in collisions for a time duration (t) [100], which can be calculated as:

$$L_t = \frac{T_{col}}{T_{col} + T_{idl} + T_{bus}} \tag{4.2}$$

where T_{col}, T_{idl}, and T_{bus} are the collision, idle, and busy times respectively.The value of L_t lies between 0 and 1; lower bound 0 says that there is no collision and upper bound 1 means there are collisions in the complete t duration. Considering application's traffic

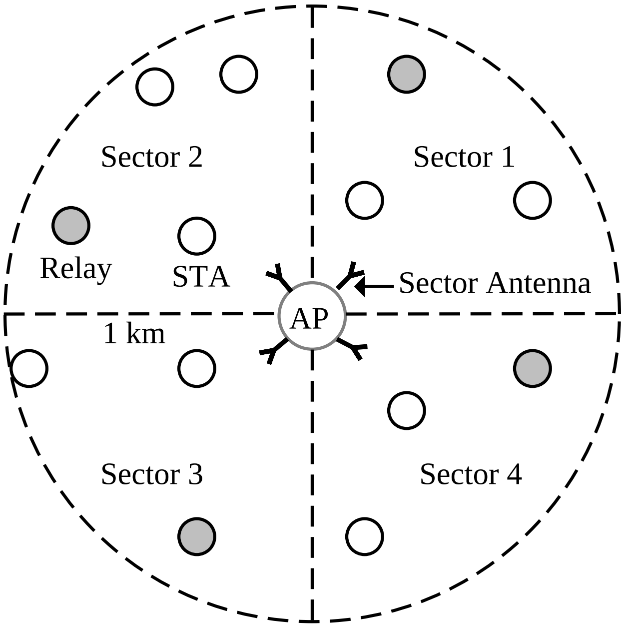


Figure 4.6: Sector configuration around the AP node

requirements, number of STAs, and network conditions, a B_{γ} is chosen. B_{γ} is the current available bandwidth of an RAP, calculated for a duration γ The RAP chooses an MCS with higher data-rate when $\mathsf{L_t} > B_{\gamma}$ and lower MCS for $\mathsf{L_t} < \mathsf{B}_{\gamma}$.

4.3.4 Channel Access Mechanism

In the proposed enhancement, we use the maximum three different levels of RAWs. The AP and RAP nodes broadcast their RPS element with the beacon frame for the child Rs and Es which are connected with AP directly. As shown in Figure 4.7, access frame is divided into number of RAWs and TXOPs. To communicate with STA and RAP or AP, RAW frame and TXOP frame is used respectively. There are two modes of TXOP:

- BlockACK: If the network is having only uplink traffic or downlink traffic.

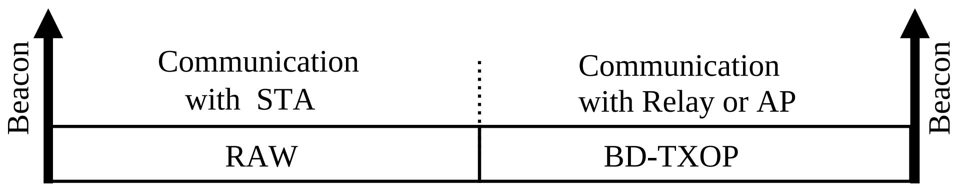


Figure 4.7: Channel access frame for RAP or AP

Algorithm 6 Dynamic bandwidth allocation at Relay Access Point

Initialize:
$\mathsf{D} \leftarrow$ a set of available data rates ▷ this is based on available MCSs configurations
$\{\mathsf{STA}, \mathsf{RELAY}, \mathsf{AP}\} \leftarrow$ modes of STAs

if (mode==RELAY) **then**
  if Multiple Beacons Received **then**
    Join AP or RAP with highest $\mathsf{P_r}$ ▷ calculated using Eq. (4.1)
  else
    Join AP or RAP
  Transmit beacon $\rightarrow$ {RPS, group ID, allowed channel, allowed MCS}
  Associate STA and RAP
  Monitor Load L_τ ▷ calculated using Eq. (4.2)
  if $\gamma < \mathsf{L}_\tau$ **then**
    if D with higher data-rate **then**
      Data rate can be changed as $\mathsf{D_i} \rightarrow \mathsf{D_j}; \mathsf{j} > \mathsf{i}$
      Transmit data using allocated slot
  else
    if D with lesser data-rate **then**
      Data rate can be changed as $\mathsf{D_j} \rightarrow \mathsf{D_i}; \mathsf{j} > \mathsf{i}$
      Transmit data using allocated slot
else if (mode==STA) **then**
  Read beacon $\rightarrow$ {RPS, group ID, allowed channel, allowed MCS}
  if Multiple Beacons Received **then**
    Join AP or RAP with highest $\mathsf{P_r}$
  else
    Join AP or RAP
  Transmit data using allocated slot

- BD-TXOP: Network with bi-directional traffic, the RAP switches its mode to BD-TXOP

DTIM and TIM beacons carry the details scheduling information. If the AP is using multiple channels, simultaneous transmission is possible in two or more sectors. Figure 4.8 shows an example of two sectors sharing the same access frame at the same time. Sector 1 and 2 use two different channels, hence STA1 and STA2 can share the same RAW1 frame of AP. Similarly, Relay 1 and 2 also use the same TXOP1. RAW2 and RAW3 may use same time frame for transmission However, if channels are sufficiently available, RAP further can be use different channel, but to communicate with AP, it needs to switch to its parent AP or RAP's channel (as discussed in Algorithm 6).

After selecting the RAW and TXOP, a STA, or an RAP, or an AP can initiate channel access. If a STA needs to transmit, it sends a PS-Poll frame using DCF as

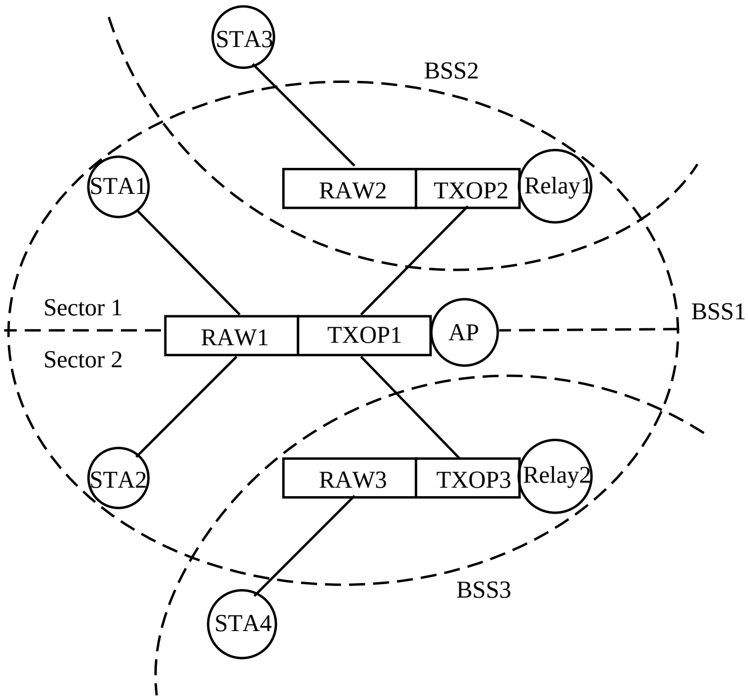


Figure 4.8: Schematic representation of distributed RAW and TXOP

Algorithm 7 Tx/Rx of frames in AP, RAP and STA

Initialize:
TXOP← Transmission mode
BDT ← Bi-Directional traffic flows

```
if DATA to Receive or Transmit then
    if AP then
        Communicate with RAP in TXOP and STA in RAW
        Call proc. USE_TXOP                          ▷ a function to choose TXOP schedule
    else if RELAY then
        If required switch to MCS and channel of parent (AP, RELAY) and child (STA) in IFS time
        Communicate with RAP in TXOP and STA in RAW
        Call proc. USE_TXOP
    else if STA then
        If required switch to MCS and channel of parent (AP, RELAY) in IFS time
        Communicate with RELAY or AP in RAW
procedure USE_TXOP
    if BDT then
        Use BD-TXOP
    else
        Use Block-ACK
```

shown in Figure 4.9. Once successful, a MAC Protocol Data Unit (MPDU) can be transmitted. If AP needs to send a frame, it informs though TIM beacon and then waits for a PS-Poll frame for the STA. AP to RAP or RAP to RAP access mechanism is done using BD-TXOP for better efficiency. As shown in Figure 4.9, BD-TXOP, an MPDU is sent without waiting for ACK. Rather, more data field of the header is used to inform the destination about pending data. The more data field is set to 1 or 0 to notify about more data or no more data pending respectively. The data Tx/Rx procedure of the proposed scheme is discussed in Algorithm 7.

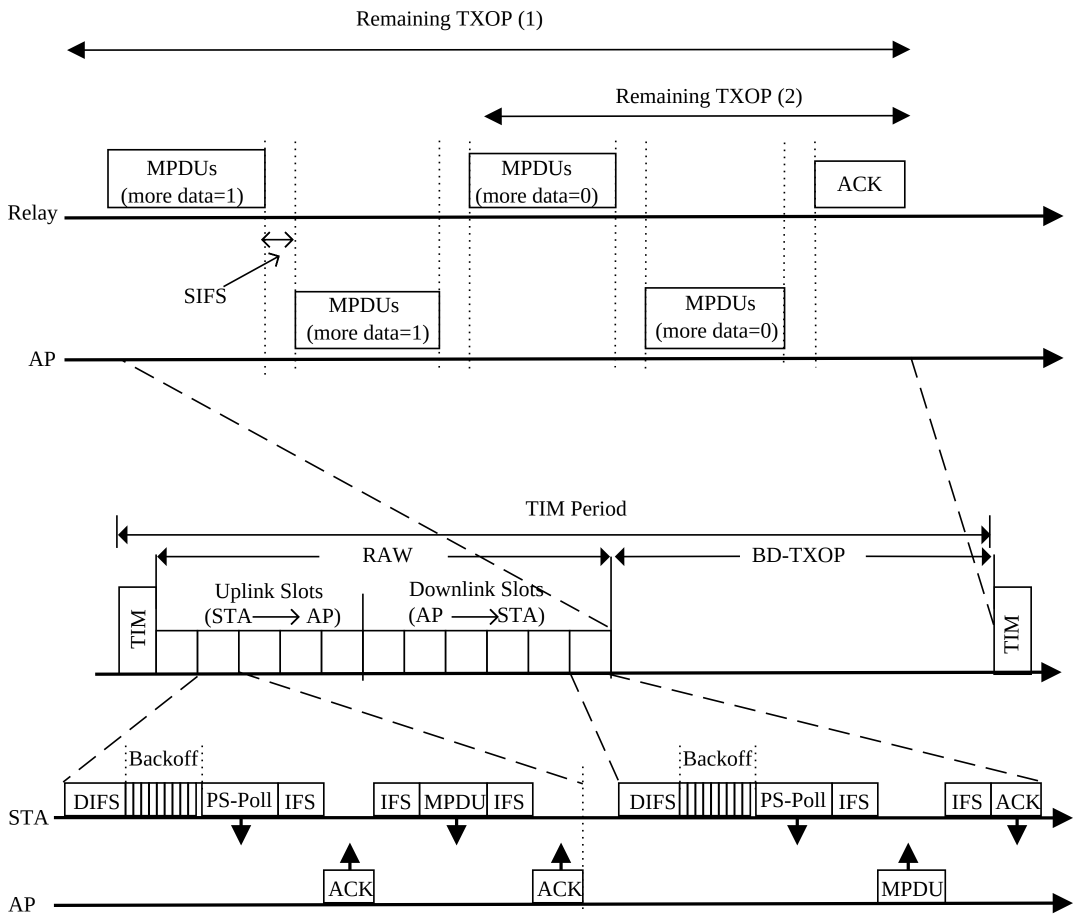


Figure 4.9: RAW and TXOP based access in the proposed multi-hop network

4.4 Performance Evaluation

To validate and analyse the proposed scheme, initially, we present a theoretical analysis to show the throughput enhancements. After that, an extensive analysis with the help of simulation.

4.4.1 Theoretical Analysis

Bianchi et al. [61] defines saturation throughput (Th), which is the average amount of payload bits transmitted successfully in a slot over the average duration of a slot time. The saturation throughput for DCF based channel access can be calculated using Eq. 2.5. The final equation to calculate the saturation throughput is as follows:

$$\mathsf{Th} = \frac{\mathsf{P_{tx}P_{suc}E[Payload]}}{\mathsf{(1-P_{tx})t_{slot} + P_{tx}P_{suc}T_{suc} + P_{col}T_{col}}} \tag{4.3}$$

Where probability $\mathsf{P_{tx}} = 1-(1-\tau)^{\mathsf{n}}$ says that, for a given n number of STAs, at least once transmission in a slot time. $\mathsf{P_{suc}} = \frac{\mathsf{n}\tau(1-\tau)^{\mathsf{n}-1}}{\mathsf{P_{tx}}}$ is the transmission occurring on a slot is successful, s_t is the average duration of a slot, and $\mathsf{P_{col}}(= (1-\mathsf{P_{suc}})\mathsf{P_{tx}})$ is the collision probability. $\mathsf{T_{suc}}$ and $\mathsf{T_{col}}$ are the busy time for successful transmission and collision respectively. For 802.11ah, $\mathsf{T_{suc}}$ and $\mathsf{T_{col}}$ can be calculated as below:

$$\mathsf{T_{suc} = T_{FH} + T_{PS-POLL} + T_{DATA} + T_{ACK} + +T_{SIFS} + T_{DIFS} + 3T_{P}}$$

$$\mathsf{T_{col} = T_{FH} + T_{DATA} + T_{DIFS} + T_{P} + T_{Timeout}}$$

Where, $\mathsf{T_{DATA}, T_{SIFS}, T_{P}, T_{ACK}, T_{timeout}}$ and $\mathsf{T_{DIFS}}$ are the Data, SIFS, Propagation, ACK, ACK-Timeout, and DIFS duration respectively. The values of different parameters are mentioned in Table 4.3. The duration of data and control frame used 802.11ah can be calculated by the Eq. 4.4 and 4.5 respectively [45]:

$$\mathsf{T_{DATA}} = \lceil \frac{\mathsf{8 \times (L + m_h)}}{\mathsf{\frac{R}{D_r} \times L^{D_{rs}}}} \rceil \times \mathsf{T_{sym} + T_{PHY}} \tag{4.4}$$

$$\mathsf{T_{ACK}} = \lceil \frac{\mathsf{8 \times (L_{ctrl})}}{\mathsf{L^{D^{rs}}}} \rceil \times \mathsf{T_{sym} + T_{PHY}} \tag{4.5}$$

Where, $\mathsf{m_h, R, D_r, L^{D_{rs}}, T_{sym}}$, $\mathsf{L_{ctrl}}$, and $\mathsf{T_{PHY}}$ are MAC header size, basic data rate, number of bits in one OFDM, symbol duration of OFDM, size of control frame, and PHY header size respectively. Theoretically, the saturation throughput of the proposed protocol is calculated by multiplying throughout with number of channels (λ):

$$\mathsf{Th}_{\mathsf{prop}} = \lambda \times \mathsf{Th}$$

With the use of TXOP in the proposed protocol, the value of $\mathsf{T}_{\mathsf{suc}}$ can be updated as:

$$\begin{aligned}\mathsf{T}_{\mathsf{suc}}^{\mathsf{txop}} = {} & \mathsf{T}_{\mathsf{PS-POLL}} + \delta \mathsf{T}_{\mathsf{DATA}} + \mathsf{T}_{\mathsf{ACK}} + \\ & (\delta + 1)(\mathsf{T}_{\mathsf{SIFS}} + \mathsf{T}_{\mathsf{DIFS}} + \mathsf{T}_{\mathsf{P}} + \mathsf{T}_{\mathsf{FH}})\end{aligned} \tag{4.6}$$

Where, δ is the number of data frames that we can send in a TXOP. Then, the saturation throughput will be:

$$\mathsf{Th}_{\mathsf{txop}} = \frac{\mathsf{P}_{\mathsf{tx}}\mathsf{P}_{\mathsf{suc}}(\delta \times \mathsf{E}[\mathsf{Payload}])}{(1 - \mathsf{P}_{\mathsf{tx}})\mathsf{t}_{\mathsf{slot}} + \mathsf{P}_{\mathsf{tx}}\mathsf{P}_{\mathsf{suc}}\mathsf{T}_{\mathsf{suc}}^{\mathsf{txop}} + \mathsf{P}_{\mathsf{col}}\mathsf{T}_{\mathsf{col}}} \tag{4.7}$$

As a part of the proposed scheme, we can further implement multiple channels in AP. Then, the saturation throughput will be updated as:

$$\mathsf{Th}_{\mathsf{txop}}^{\lambda} = \lambda \times \mathsf{Th}_{\mathsf{txop}} \tag{4.8}$$

4.4.2 Simulation Analysis

The performance of proposed protocol is evaluated through extensive simulations using NS-3 [64]. Table 4.3 presents different parameters used in the simulation. Results are compared with Traditional access mechanism of 802.11ah. Further, a sectorization scheme (SectorGroup) proposed by Bhandari et al. [96] is compared with the proposed scheme. In SectorGroup, AP broadcasts beacons to the specific locations by utilizing the sectorized beams created with multiple antennas in it. We have analyzed the performance of the proposed protocol as follows:

- Association time in proposed Vs. traditional Scheme
- Throughput performance of the proposed multi-channel and sectorization scheme
- Delay performance of the proposed multi-channel and sectorization scheme

- Analysis of PRR (%) in the proposed load balancing scheme
- Comparison of the proposed channel access mechanism

Table 4.3: System and other parameters used in simulation analysis

Parameter	Value
Basic data rate	650, 300 Kbps
Payload size	256 Bytes
Radio propagation model	Outdoor (macro [17])
OFDM symbol time (T_{sym})	40 μs
MAC header	Legacy
PHY header	6 x T_{sym}
Slot time	52 μs
SIFS	16 μs
DIFS	SIFS + 2 x Slot time
Modulation and Coding	MCS0, MCS1
[CW_{min}, CW_{max}]	[15, 1023]
Backoff time	$(W_{min}/2) \times$ Slot time
Initial backoff window	64
Types of traffic	UDP
Traffic Interval	100 ms
Simulation area	2000 m × 2000 m Flat-grid
Bandwidth	1, 2 MHz
TXOP	BlockACK (Uplink), Bi-Directional
No. of nodes (Max.)	3000
RAW size	15
Group size	8
Beacon interval	100 ms

4.4.2.1 Association Time

The RAPs create different BSSs in the network. Randomly scattered nodes get associated with the AP or RAP in a distributed manner. It is obvious that the association time of the proposed scheme is equal to the time required to associate all STAs from the largest BSS. As shown in Figure 4.10, total association time for 2000 devices in the proposed protocol is about 37 Seconds, whereas, in traditional 802.11ah, it is 42 Seconds. The RAP nodes are further supported with multiple MCSs, where it can choose an MCS with a higher or lower data-rate according to the current requirements of a BSS.

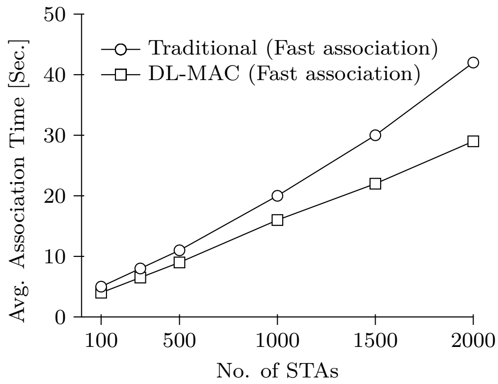
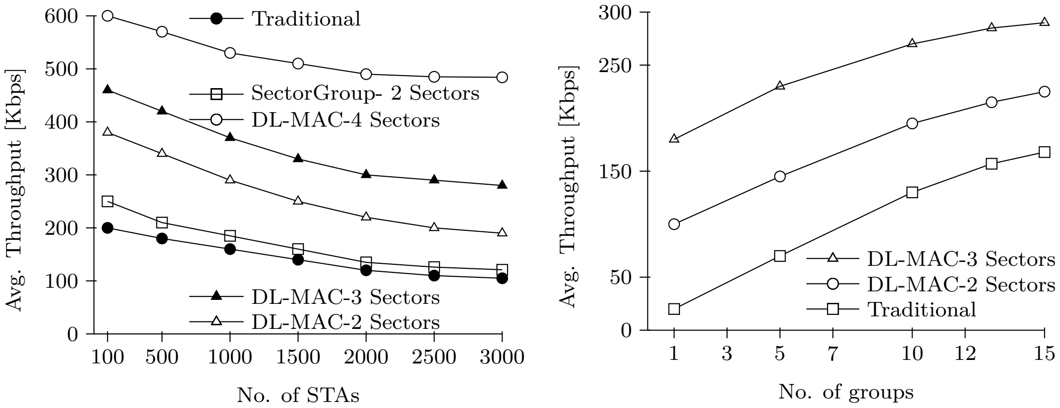


Figure 4.10: Average association time in proposed Vs. traditional Scheme

4.4.2.2 Throughput in Proposed Vs. Existing Schemes

Figure 4.11a shows the performance of the proposed scheme as compared to the traditional scheme with an increasing number of STAs. Along with existing grouping, multi-channel operation and sectorized beacon enhance the throughput performance up to a great extent. As shown in Figure 4.11a, throughput in the proposed scheme is significantly improved considering 2, 3, and 4 sectors for the same number of channels. Generally, multiple channel operation supported in the scheme can multiply the exiting capacity, but due to the limited memory and processing capabilities of AP and RAP, the achieved throughput in the simulation seems lesser. In the case of SectorGroup scheme with 2 sectors, the throughput performance has improved as compared to the traditional scheme. However, due to the lack of FDM support at AP and multi-channel operation, it shows lesser throughput results than the proposed scheme. We have compared the proposed scheme with the traditional scheme considering 2 sectors over a varying number of RAW groups and a larger coverage area. The grouping mechanism in 802.11ah reduces collisions due to contention. For a large number of STAs, throughput performance will be better when group size is higher. However, without a proper RAP organization over a larger coverage area, the hidden terminal problem is a major concern. So, along with the RAW grouping for the STAs, our protocol uses location-aware sectorized beacon from AP. Figure 4.11b shows the throughput achieved at AP node with an increasing number of groups. The proposed scheme achieved superior performance as compared to the traditional one.



(a) Increasing number of STAs (b) Increasing number of groups

Figure 4.11: Throughput characteristics in proposed Vs. existing schemes

To see the throughput performance over normal load conditions, we compare the proposed scheme considering lesser number of STAs in the network. We generate traffic with an interval of 0.5 Sec. As shown in Fig. 4.12, once the saturation point has achieved, the performance of the proposed protocols start deteriorating. The saturation point for the proposed scheme is higher than the existing schemes.

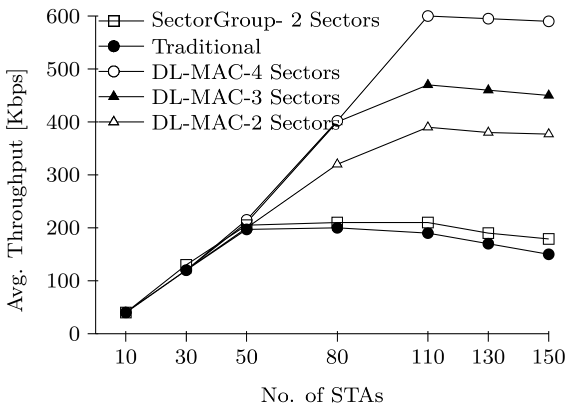


Figure 4.12: Throughput characteristics at normal load condition

4.4.2.3 Delay in Proposed Vs. Existing Schemes

As shown in Figure 4.13, the proposed scheme significantly improved the delay characteristics considering 2 to 4 sectors for the same number of channels. As discussed, the multiple channel operations supported in the scheme allows efficient transmission among different STAs in the network. The delay is reduced by the proposed protocol as shown in Figure 4.13. The proposed protocol allows simultaneous transmission in different sectors by using different channels. The RAPs added in a particular sector also transmit simultaneously as per the allocated channel. Further, when the number of STAs is divided based on the channels, the size of contention is also reduced, hence access delay is less.

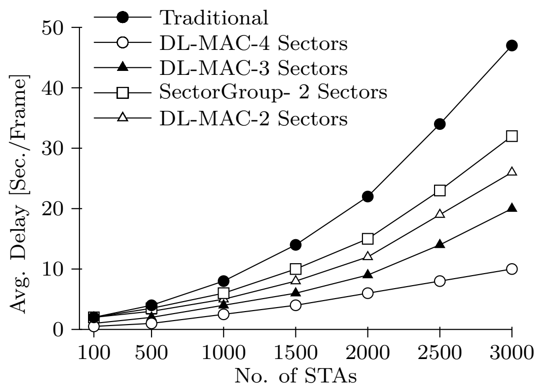


Figure 4.13: Average packet delay

4.4.2.4 Dynamic Load Balancing

We measure the Packet Received Ratio (PRR%) for the traditional scheme with 300Kbps (MCS0, 1MHz) and proposed scheme with 300Kbps (MCS0, 1MHz) and 650Kbps (MCS0, 2MHz). We have introduced varying uplink traffic loads (100-1000Kbps) from different BSS towards AP. The saturation capacity for the traditional scheme is almost 150Kbps, whereas the proposed scheme can carry almost up to 325Kbps. Due to the support of multiple MCSs, at saturation capacity, the RAP in the proposed scheme switches its MCS to another MCSs having a higher data-rate. Therefore, as shown in Figure 4.14, the proposed scheme performs almost 25% better than the traditional one.

4.4.2.5 Channel Access Mechanism

Finally, we have measured the efficiency of the BD-TXOP scheme used in the proposed protocol as compared to the BlockACK mechanism. In BlockACK, once a list of buffered frames has been sent, the sender node sends a request frame (BlockAckReq) containing the sequence numbers frames. In response to BlockAckReq, a BlockAck frame is further sent by the receiver node. For long-distance and multi-hop networks, high control

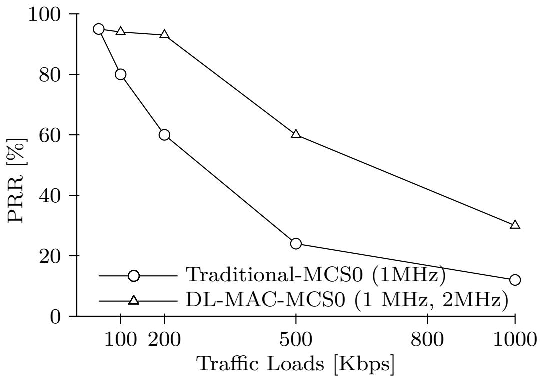


Figure 4.14: Average Packet Received Ratio (PRR)

overhead is another challenge. The BD-TXOP of 802.11ah has solved the issues by not sending an ACK for all received packets, rather the data packet itself is used. As shown in Figure 4.15, a significant improvement can be seen in the BD-TXOP-based solution considering bi-directional traffic. We analyze the saturation throughput of the proposed

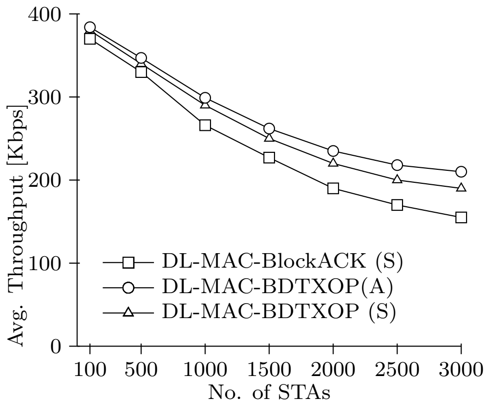


Figure 4.15: Throughput performance with increasing number of STAs

protocol using the Markov Chain model. With the help of equations 4.8, 4.4, and 4.5, throughput is calculated with increasing number of STAs. Figure 4.15 shows the trends of analytically calculated results. Results are shown for analytical (A) and simulation (S) configured with 2 channels. The theoretical results show almost similar throughput as compared to the simulation performance considering the same configuration.

4.5 Conclusion

This work presented a distributed, multi-channel, and load-aware MAC protocol for multi-hop networks. It showed significant performance improvement over the 802.11ah MAC protocol. The proposed protocol achieves a higher success rate, larger coverage range, and lesser delay than 802.11ah. The sectorization scheme increases the network capacity and achieves superior performance over a large-scale distributed network. It can dynamically adjust bandwidth with the use of MCS with a higher data-rate. From the performance results, it is evident that the proposed scheme is a suitable solution for large-scale IoT networks. Following are the key achievements of the proposed work:

- The proposed distributed association mechanism powered relay placement scheme achieved lesser association time (i.e., 11%) than the traditional fast association scheme.
- The proposed sectorized network with multiple antennas and four channels improves throughput performance up to almost three times as compared to the traditional and two and half times than the existing scheme (i.e., SectorGroup).
- Delay performance also improved up to three and two times as compared to the traditional 802.11ah and SectorGroup scheme respectively.
- Traffic congestion issues at AP node have been resolved up to a great extent by allowing simultaneous transmission using multiple channels and sectors.
- Dynamic load balancing and TXOP operation at RAP node increase the efficiency of the proposed large scale IoT network.
- From the analysis, we found that a network with a higher number of STAs requires higher grouping for better performance.

In IoT, most of the implementations deploy a huge number of periodic STAs for monitoring purposes. A channel access mechanism can be redesign to achieve better efficiency in terms of throughput and power consumption. In the next chapter, we discuss a new channel access mechanism considering a large-scale periodic STAs in the existing RAW scheme.

Chapter 5

Periodic Traffic Scheduling Scheme for IoT

In this chapter, we propose a MAC protocol – PS-MAC, for periodic traffic in IoT. The proposed protocol is seamlessly assimilated with the existing RAW mechanism of an 802.11ah-based large-scale network. Considering the periodicity of traffic, the proposed scheme schedules RAW slots for better performance in terms of throughput, delay, and energy consumption.

5.1 Introduction

In IoT, traffic direction maybe uplink (from sensors) or downlink (from actuators) according to the requirements of the applications. Most of the deployment of devices is to monitor the current situation. The applications including smart-healthcare, smart-agriculture, smart-home, smart-grid, etc., require a large-scale nodes to be deployed for the purpose of monitoring ([101], [102], and [103]). Due to the resource-constraint nature, the devices are programmed to transmit a packet periodically in most of the cases. This periodicity varies from application to application. For example, in smart-precision agriculture, the devices may send a packet in a day or a device in the intrusion detection system may send a packet in a second. The channel access mechanism of 802.11ah can solve such diverse requirements of an application.

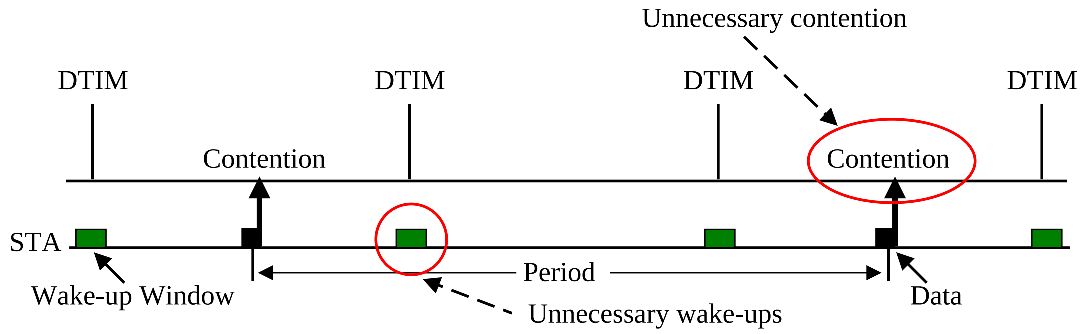


Figure 5.1: An example showing unnecessary wakes-up and contention for nodes with periodic traffic

The RAW mechanism of IEEE 802.11ah divides the time frame and allows a particular group of STAs for transmission. Several issues evolve while dealing with such a massive number of STAs with heterogeneous traffic flow characteristics. The grouping of STAs is dependent on the AID value. The STAs from a particular group can transmit only in the allocated RAW. For uplink transmission, a STA needs to contend for channel to transmit a packet resulting in a huge access delay in the default 802.11ah. The average access delay increases drastically with the increasing number of STAs in a group.

To get a slot for transmission, a STA needs to continuously monitor the DTIM beacon from AP in-spite of its service interval. This consumes a huge amount of energy considering large-scale resource constraint STAs. Similarly, in RAW, a STA needs to content every time for its transmission causing a huge access delay. As shown in Figure 5.1, due to the longer periodicity of traffic, a STA needs to go through extra wake-up time and contention. The current research works primarily focus on estimating the RAW size based on the number of STAs or traffic loads for a particular group. However, these solutions do not consider the contentions and collisions in a RAW group.

This work proposes a MAC protocol – PS-MAC, for better scheduling of periodic traffic in IoT. A service interval prediction scheme is proposed to properly schedule the next-frame coming from the same STA. Based on the achieved service interval, a STA is scheduled in its RAW for transmission without contention. The proposed hybrid channel access mechanism allows the AP node to appropriately predict the network load and reduces the contention time when large-scale nodes simultaneously try for transmission. While provisioning efficient channel access in such scenarios, we propose the following contributions:

- A hybrid MAC protocol to appropriately predict the number of STAs and allocate slots for transmission accordingly.
- An efficient scheduling scheme for periodic traffic to reduce contention and unnecessary wake-ups.
- A service interval prediction algorithm is developed to allocate the next slot more accurately.

The rest of the chapter is organized as follows. Background and related works are presented in Section 5.2. Section 5.3 gives the detail of the proposed traffic scheduling and energy saving scheme. Simulation and performance evaluation of the protocol is presented in Section 5.4. Finally, Section 5.5 concludes this work.

5.2 Background and Related Works

This section discusses the different IoT applications and their service interval characteristics. We also compared some of the most relevant works proposed for increasing efficiency in large-scale IEEE 802.11ah network.

5.2.1 A Study on Monitoring Applications in IoT

Along with the number of devices, network traffic is also increasing exponentially in IoT. For such low-power, battery-operated devices that send and receive messages over constrained networks, we must understand the traffic pattern for better efficiency. Mocnej et al. [104] discusses different network requirements of IoT applications including regular (mostly periodic) and irregular (other types like- event-driven and query-driven) types of traffic. Similarly, other works like [105], and [106] analyses the traffic characteristics of IoT traffic. From their analyses, it is clear that for wide-spread deployments with a large number of devices, the most common purpose is for monitoring some regions.

In this procedure, traffic is mostly periodic. Table 5.1 shows a list of IoT applications along with, their periodicity, and network requirements.

Applications	Periodicity	Energy constraints	Criticality
Air pollution monitoring	15 min.	Very high	Very high
Agriculture monitoring	30 min.	Very high	Moderate
Wildlife tracking	30 min.	Very high	Very high
Personal health monitoring	$\leq$ 10 sec.	Moderate	Very high
Personal assistance	$\leq$ 10 sec.	Moderate	Very high
Building condition monitoring	2 hr.	Moderate	Moderate

Table 5.1: Different monitoring applications and their network requirements

5.2.2 Related Works

Madueno et al. [53] considers the periodicity of traffic for scheduling over RAW; however, it assumes only known traffic parameters. Seferagic et al. [70] evaluated the RAW frame cycle for critical and periodic traffic. Considering the inter-packet delay of traffic, it proposes a scheduling scheme with the help of a beacon interval to improve network performance. In PS-OLi [107], the AP node sets a calculated offset to STAs for controlling their initial wake-up time. This allows the STAs to avoid wake-up time alignment and as a result, the network collision probability is reduced. However, this mechanism considers the only collision reduction scheme to improve energy efficiency for such a network. Moreover, this work shows suitability for periodic traffic, but in many cases, traffic is unscheduled. Ogawa et al. [36] enhances the power saving in 802.11ah when the network is congested. The STAs are classified into contending and non-contending to reduce contention. Based on the number of idle states a STA can go to sleep mode. Zhao et al. [68] proposes a method to save energy for uplink transmitting nodes. It allows a STA to sleep mode for a random amount of time when the channel is busy.

Che et al. [108] proposes a new mechanism using Cell Polling Frame (CPF) which schedules the STAs within one community or one cell. This mechanism improves the Power Save Multi-Poll (PSMP) power-saving scheme by reducing the overall overhead in the network while reducing power consumption. The STA information field size decreased with the use of existing hierarchical AID mechanisms. However, power saving for unscheduled and non-TIM STAs is still challenging. A hybrid MAC protocol proposed by Beltramelli et al. [109] considers both RAW and TWT based power saving in the contention phase. Detail scenarios of the strategies are informed using short control frames and slots are only assigned to the STAs having data to send or receive. Bel et al. [110] develops an analytic model to predict energy consumption and lifetime for an 802.11ah STA. The computation considers beacon, the density of STAs, transmission period, TIM and segmentation STAs. While resolving the unnecessary wakeup problem in TIM and DTIM grouping, Kim et al. [111] propose a temporary membership and traffic scheduling scheme. Wang et al. [57] optimizes the size of RAW based on energy consumption. Considering the overall energy consumption and data-rate, optimal RAW size is measured analytically. Some of the related MAC protocols are compared in Table 5.2.

Protocol	Year	Description	Periodic Traffic	Unnecessary Contention	Unnecessary Wake-ups	Energy Saving
[107]	2013	Adding offset in STA's sleep time, wake-up time of STAs are nonaligned to reduces collisions	✓	✗	✗	✓
[68]	2015	The author proposed new energy saving scheme called Further Energy-saving Mode (FESM) for uplink traffic	✗	✗	✗	✓
[53]	2016	Size of the RAW is adjusted based on periodic reporting of alarms based on known parameters	✓	✗	✗	✗
[109]	2017	Considers both RAW and TWT based power saving in their scheme at the same time to reduce uplink traffic congestion	✗	✓	✗	✓
[111]	2017	Saves unnecessary power consumption by increasing sleeping duration of STAs	✗	✓	✗	✓
[112]	2017	It proposes a mathematical method to accurately calculate throughput and energy consumption in a heterogeneous network	✗	✗	✗	✗
[113]	2018	Discusses the TWT based low-consumption mode with low traffic requirements	✗	✗	✗	✓
[114]	2019	A surrogate model is developed considering energy and throughput to optimize RAW	✗	✗	✓	✓
[19]	2018	An immediate reply scheme is proposed for downlink traffic, which reduces the extra RTT delay	✗	✓	✗	✗
[70]	2019	Analyzes latency requirements over RAW frame cycle	✓	✓	✗	✗

Table 5.2: A survey on periodic traffic scheduling schemes

For a large-scale network like IoT, channel access due to high contention is still a big challenge. Although IEEE 802.11ah-based RAW scheme reduces the collision domain by allowing group-based access for periodic STAs, it may not be required to contend every-time for its transmission. Similarly, these type stations need to wake-up for every DTIM causing huge energy consumption for stations with higher periodicity. The current solutions do not consider the contentions, collisions, and unnecessary wake-ups in a RAW group.

5.3 The Proposed Protocol

The proposed protocol is an 802.11ah-based MAC protocol for supporting large-scale monitoring STAs. The RAW-based channel access mechanism works in a hybrid manner by adopting contention and reservation-based policies. As shown in Figure 5.2, the RAW is a combination of uplink Periodic RAW (PRAW) and Normal RAW. The Uplink PRAW is further divided into contention and reservation phases. The STAs transmitting for the first time need to send a Power Save Poll (PS-Poll) frame using Distributed Coordination Function (DCF) in the contention phase (also called as PS-Poll phase). If the contention and periodicity test (as discussed in Sec. 5.3.1) of a STA is successful, a slot $\in [\mathsf{Slot}_1, \mathsf{Slot}_2, ..., \mathsf{Slot}_\mathsf{N}]$ is assigned from the reservation period for the earliest Tx. Otherwise, the STA is allocated a slot in the Normal RAW, where, channel access is done in a traditional way. Initially, normal RAW takes almost the complete frame by only excluding the PS-Poll Phase. Later, for identified periodic STAs, the PRAW phase starts taking the share. For better performance, in the later phase, normal RAW size determined by counting the number of STAs which failed the test at any given time. The beacon message is broadcasted after the contention period to inform the STAs about their Tx schedule in the reserved period. The proposed protocol dynamically adjusts the RAW size based on the active number of STAs. Initially, the size of the PS-Poll phase is kept as large as possible so that all the STAs get a chance to contend. Further, the proposed protocol reduces unnecessary wake-ups by allowing a STA to sleep according to its periodicity. This feature is implemented by using intervals of TIMs and DTIMs as discussed in Sec. 5.3.1.

5.3.1 Prediction of Frame Interval

AP node reduces the contention by predicting the next packet generated from a periodic STA more accurately. Service intervals of periodic STAs are predicted by monitoring their transmission timing behaviors. For a RAW group, a separate Circular Queue (CQ) is maintained to keep track of the recent traffic intervals of different STAs. The packets originated from the same STA are numbered in a sequence with increasing values. The AP calculates packet interval (I) value for each of the STAs from the times of recently received two consecutive frames. If $\mathsf{T}_{\mathsf{P}_1}, \mathsf{T}_{\mathsf{P}_2}, ..., \mathsf{T}_{\mathsf{P}_{k-1}}, \mathsf{T}_{\mathsf{P}_k}$ are the times at which packets are received consecutively from a STA, I-value can be calculated as:

$$\mathsf{I} = \frac{(\mathsf{T}_{\mathsf{P}_2} - \mathsf{T}_{\mathsf{P}_1}) + ... + (\mathsf{T}_{\mathsf{P}_k} - \mathsf{T}_{\mathsf{P}_{k-1}})}{\mathsf{k}}$$

For higher variation in the interval ($\sigma \leq \sigma_{\mathsf{max}}$, where σ_{max} is the maximum value of allowed variance), we may need to set a higher value of k for better accuracy. If the variation in traffic interval is higher we may need to set a higher value of it for better accuracy, otherwise smaller k is chosen. Once the I-value is available, AP generates an $\mathsf{ACK(I)}$ (with Interval value). The AP informs about skipping the number of Delivery TIM (DTIM) beacons for the STAs having longer periodicity. Algo. 8 is used by an AP to find the next DTIM as mentioned in lines #6-11.

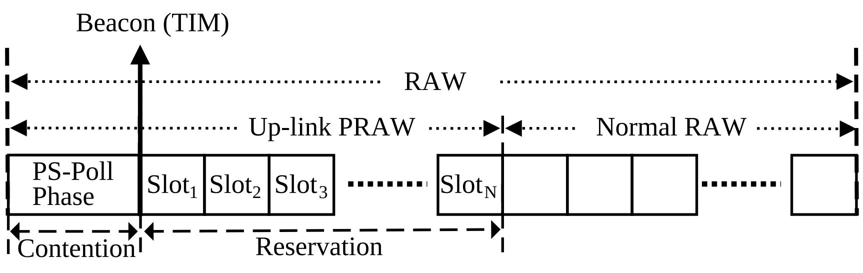


Figure 5.2: The RAW structure used in the proposed scheme

5.3.2 Scheduling of Periodic Traffic

AP schedules the respective RAW and slot index through the beacon. If an appropriate RAW is identified, a procedure namely ALLOCATION (lines #12-18) is called in Algorithm 8. This procedure allocates a slot in the RAW and keeps a record of available slots. For any collision/failure of Tx, a counter value is incremented which is used later for scheduling with fairness. When more number of STAs arrive than the available number of slots in a DTIM period, AP schedules a STA with higher counter value.

After checking the ACK, if a STA finds a positive I-value, it can extract wake-up time for the next DTIM. Following DTIM and TIM, it can transmit a packet in the allocated time frame and stop its contention procedure like before. As shown in Figure 5.3, after its last contention, a STA does not need to wake-up for all DTIMs and contend again. Meanwhile, the AP also keeps track of $\sigma_1, \sigma_2, \sigma_3, ..., \sigma_k$ values for a STA. If $\sigma_i \leq \sigma_{max}$ fails for more than $\lceil k/2 \rceil$ times, then the ACK is modified as ACK(0) considering the associated STA is not periodic. If the STA needs to transmit again, it requires to start contention procedure in the Normal RAW in the traditional manner. We call this approach a periodicity test. A STA which has successfully completed the periodicity test is scheduled in the PRAW phase for future Tx. Thus, periodic STAs are categorised into– new, under-identification and identified based on their phases.

The proposed protocol is illustrated in Figure 5.4. Group 1 contains STAs that want to transmit for the first time (white), under-identification (cross), and already successfully contented and identified (grey). We consider the CQ size as 10 in this example. The new STAs need to continue the same in the next FRAME as it has not

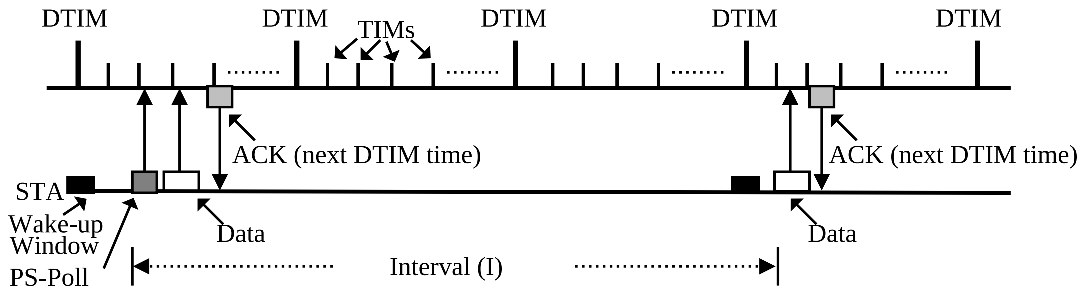


Figure 5.3: An illustration of DTIM-aware scheduling in the proposed scheme

finished the 10^{th} contention yet. As a cross marked STA finishes its contention period, it is scheduled in the next FRAME without further wait. The grey STAs can directly transmit in their dedicated slots. Note that the size of the PS-Poll phase is reduced in the next frame as there are fewer new STAs available. In Group X, as all the STAs are grey, they can transmit during their allocated slots. Here, although a STA fails in the first FRAME, it wins a slot in the next FRAME as the failure count (C) is higher in this case, i.e., $x > y$.

The AP node can decide the dedicated slot time for Tx by finding T_{DATA} based on the Modulation and Coding Scheme (MCS) and payload size (L). The duration of the data frame for MCSs used in 802.11ah can be calculated as [45] as mentioned in Eq. (3.5).

5.3.2.1 Frame Size Calculation

In the traditional scheme, the RAW slot duration (T_x) is calculated from slot duration count (S_c) specified in RPS as:

$$T_x = 500\mu s + S_c \times 120\mu s$$

where S_c is dependent on the value of i ($S_c = 2^i - 1$), which is the number of bits in the sub-field. The slot duration count sub-field is specified in RPS for setting the size of a slot.The sub-field value with 8-11bits are used to vary the slot size if required. i=8 and 11 give the maximum of slot size. In this way, RAW time will be $T_{RAW} = T_x \times S_{RAW}$, where S_{RAW} is the RAW size. The complete time frame (T_{FRAME}) for a network with all associated STAs can be calculated as:

$$T_{FRAME} = N_{RAW} \times T_{RAW}$$

where $\mathsf{N_{RAW}}$ is the total number of RAW groups in the network. In dedicated slot based Tx, total time required for transmitting a data frame is:

$$\mathsf{T_{TDATA} = T_{FH} + T_{DATA} + T_{ACK} + 2T_{P}}$$

where $\mathsf{T_{FH}}(= \mathsf{T_{PHY} + T_{MAC}})$ is the frame header duration.

Algorithm 8 Finding DTIM, RAW group and transmission slot

Initialize:
$\mathsf{T^{j}_{PERIOD}} \leftarrow$ I-value of STA j,
$\mathsf{T_{DTIM}} \leftarrow$ DTIM period,
$\mathsf{N_{SCON}} \leftarrow$ Number of contended STAs,
$\mathsf{N_{SPRAW}} \leftarrow$ Number of slots in PRAW,
$\mathsf{C} \leftarrow$ Number of Tx failure

```
if (T_DTIM > T^j_PERIOD) then
    Call proc. FIND_RAW
else
    STA_j avoids next ⌊T^j_PERIOD / T_DTIM⌋ DTIMs
    Call proc. FIND_RAW
procedure Find_RAW                                        ▷ Finding RAW
    if ((T_RAW − T_TDATA) > T^j_PERIOD then
        Call proc. ALLOCATION
    else
        Find the immediate RAW_i after T^j_PERIOD over T_FRAME
        Call proc. ALLOCATION
procedure Allocation                          ▷ Slot allocation and fairness
    if N_SPRAW ≥ N_SCON then
        Allocate T_TDATA after T^j_PERIOD in RAW_i
        N_SPRAW = N_SPRAW − 1
    else
        Schedule STA with highest N_FAIL among multiple requested STAs for same slot
        C = C + 1
```

5.3.2.2 Sizes of PS-Poll and PRAW phases

The contention time frame is calculated to estimate the size of PS-Poll phase and allow all the requested STA for Tx. Let $\mathsf{T_{CON}}$ be the contention time for requesting the AP node for Tx, then:

$$\mathsf{T_{CON} = T_{PS-POLL} + T_{ACK} + 2T_{P} + T_{BO}}$$

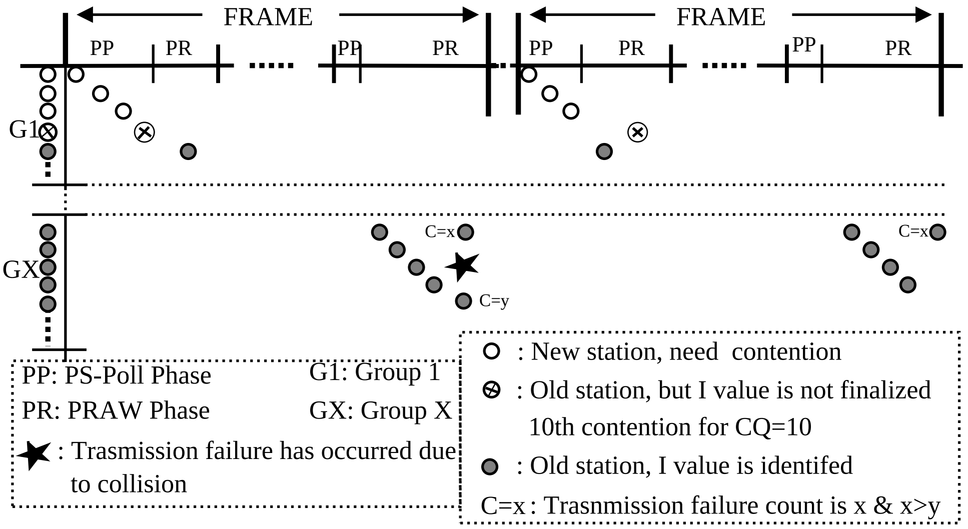


Figure 5.4: An illustration of the proposed RAW-based hybrid access mechanism

where $\mathsf{T_{PS-POLL}}, \mathsf{T_{ACK}}, \mathsf{T_{BO}}$, and $\mathsf{T_P}$ are the time required to send a PS-Poll, an ACK, for Backoff, and Propagation respectively. If there are $\mathsf{N_{RAW}}$ number of STAs in a group, the maximum time required for the first phase is calculated as:

$$\mathsf{T_{PS-PollPhase}} = \mathsf{N_{RAW}} \times \mathsf{T_{CON}}$$

The size of $\mathsf{T_{PS-PollPhase}}$ is reduced based on the number of STAs which have not joined in the PS-Poll Phase yet, which is calculated as:

$$\mathsf{N_{NCON}} = \mathsf{N_{RAW}} - \mathsf{N_{CON}}$$

After the contention procedure, the size of reservation phase depends on the periodicity based scheduling as discussed in Algorithm 8.

5.4 Performance Evaluation

We analyze the proposed protocol using simulation, which is further followed by a theoretical analysis.

5.4.1 Mathematical Analysis

In DCF scheme, a STA can transmit when the backoff counter is zero and the event has occurred in the current state decides the probability of going to the next state. This mechanism is modeled using a two-dimensional discrete Markov Chain Model [61]. Let p be the probability of a collision encountered by a frame being transmitted on the channel, then the probability (τ) that a STA transmits in a slot can be calculated as:

$$\tau = \frac{2}{1 + W + pW_0 \sum_{i=0}^{m-1} (2p)^i}$$
$$\tau = 1 - (1 - p)^{1/(n-1)}$$

where W_0 and $m = \log \frac{W}{W_0}$ are the minimum backoff window and maximum backoff stages respectively. The probability of at least one Tx within RAW having n STAs is given by:

$$P_{tx} = 1 - (1 - \tau)^n$$

Now, let P_{suc} be probability of successful Tx in a slot, which can be calculated as:

$$P_{suc} = \frac{n\tau(1-\tau)^{n-1}}{P_{tx}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}$$

The saturation throughput (Th) using the traditional protocol can be calculated as:

$$Th = \frac{E[\text{Payload size transmitted in a slot}]}{E[\text{Length of slot time}]}$$

$$Th(Traditional) = \frac{P_{tx} P_{suc} E[Payload]}{(1 - P_{tx}) t_{slot} + P_{tx} P_{suc} T_{suc} + P_{col} T_{col}} \tag{5.1}$$

where t_{slot} is the average duration of a slot, and $P_{col} (= (1 - P_{suc}) P_{tx})$ is the collision probability. T_{suc} and T_{col} are the busy times for successful Tx and when a collision occurs respectively. For 802.11ah, these values can be calculated as below:

$$T_{suc} = T_{FH} + T_{PS-POLL} + T_{DATA} + T_{ACK} + +T_{SIFS} + T_{DIFS} + 3T_P$$

$$T_{col} = T_{FH} + T_{DATA} + T_{DIFS} + T_P + T_{Timeout}$$

where $T_{DATA}, T_{SIFS}, T_P, T_{ACK}, T_{timeout}$ and T_{DIFS} are the Data, SIFS, Propagation, ACK, ACK-Timeout, and DIFS duration respectively. For long durable periodic STA, we can neglect the initial contention time. Then, saturation throughput in the proposed scheme can be calculated as:

$$\mathsf{Th(Proposed)} = \frac{\mathsf{E[Payload]}}{\mathsf{T_{TDATA}}} \tag{5.2}$$

For successfully transmitting a frame in the traditional scheme, $\mathsf{T_{suc}}$ additionally includes $\mathsf{T_{PS-POLL}}, \mathsf{T_{DIFS}}$, and $\mathsf{T_{SIFS}}$. Furthermore, the performance is measured under uncertainty. From Eq. 5.1, and 5.2, it is clear that the throughput of the proposed scheme will be higher. Again, an 802.11ah transceiver may be in receiving, transmitting, idle, and sleeping mode for the duration, $\mathsf{T_{rx}}, \mathsf{T_{tx}}, \mathsf{T_{id}}$, and $\mathsf{T_{sl}}$ within a DTIM respectively. Total energy consumption by a STA within a DTIM can be calculated by multiplying these operations duration with their respective power consumptions as [115]:

$$\mathsf{E} = \mathsf{T_{rx}P_{rx}} + \mathsf{T_{tx}P_{tx}} + \mathsf{T_{id}P_{id}} + \mathsf{T_{sl}P_{sl}}$$

where $\mathsf{P_{tx}}, \mathsf{P_{rx}}, \mathsf{P_{id}}$, and $\mathsf{P_{sl}}$ are the power consumption required in Tx, Rx, Idle, and sleep mode, respectively.

5.4.2 Experimental Analysis

We compare the performance of the proposed protocol with the traditional 802.11ah protocol. Table 5.3 gives the required parameters used in the analysis. We generate traffic at different intervals– {1,0.5, 2, and 5} Sec., are maintained equally for the same number of STAs in the network. For example, in a group with 1000 STAs, 25 number of them will follow the same traffic pattern.

The proposed protocol is tested with the following experiments:

- Average throughput achieved with an increasing number of STAs.
- Average per frame energy consumption with an increasing number of STAs.
- Average per frame delay with an increasing number of STAs.
- Throughput achieved over simulation time.
- Effect of frame delay with varying number of groups.

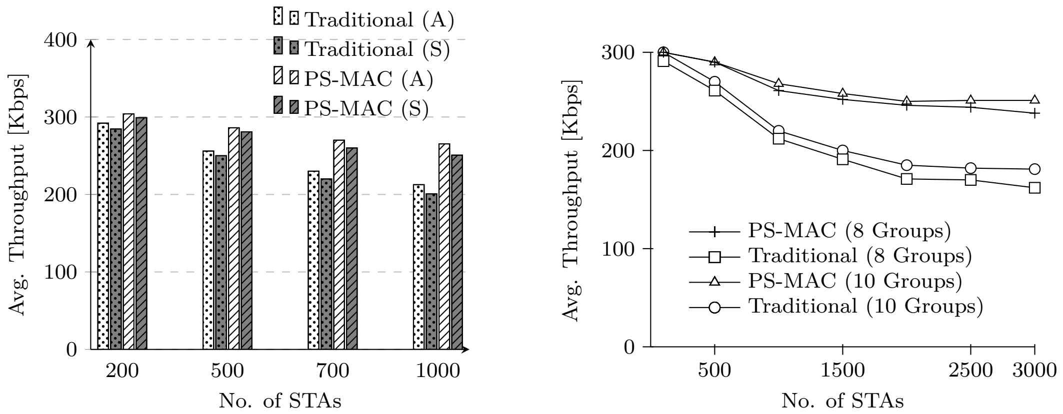
Table 5.3: Parameters used in simulation and analysis

Parameters	Value
Bandwidth	2MHz (MCS0)
Data rate	650Kbps
Payload size (L) /Traffic type	256Bytes/UDP
Avg. Traffic rate	≈2Kbps
Traffic type	UDP
CWmin/ CWmax	15/ 1023
Backoff slot time	52 μs
SIFS time	160 μs
DIFS time	SIFS+2*slot time μs
Distribution / Path loss model	Random /Macro
T_{PHY}	6 * symbol duration (μs)
MAC (m_h) header	14Bytes
Queue	100
CQ size	10
Group size	2-10
RAW size	15
No. of STAs (Max.)	3000
$P_{tx}/P_{rx}/P_{id}/P_{sl}$	255 /135/135 /1.5mW [45]
Simulator	NS-3 [64]
Simulation area	1000×1000 m^2
Simulation Time	5 min

5.4.2.1 Throughput Performance

In the theoretical analysis, contention happens among the STAs within a RAW. Once contention is over, the AP node predicts the service interval from incoming frames. The proposed protocol reduces access delay of STAs by allowing contention up to k times. The throughput achieved in Analytic (A) and Simulation (S) considering 10 groups are shown in Figure 5.5a. The proposed protocol achieves higher throughput than the traditional scheme by an average improvement of 10.24%. It becomes 25% when the number of STAs reaches to 1000 and goes beyond. In the conventional DCF-based access scheme, the Tx of every packet requires a huge access delay due to high contention. Although contention is not an issue for a lesser number of STAs, when the number increases, the problem starts cropping up. In the simulation study, initially, we observe the throughput with more number of nodes.

For half-duplex link, maximum achievable throughput in 802.11ah (in the considered scenarios) is approximately 300Kbps. By sending traffic with 2 Kbps rate, a maximum



(a) Simulation and analytical results

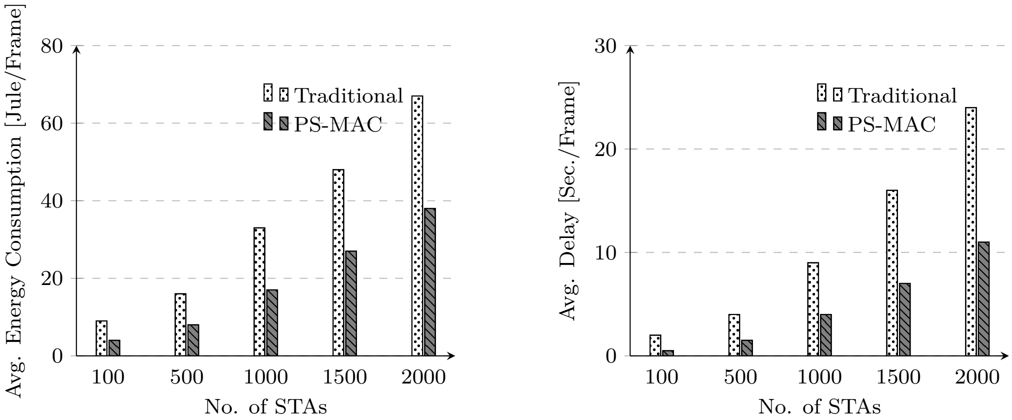
(b) Extensive simulation analysis

Figure 5.5: Throughput achieved with increasing number of STAs

of 150 STAs can be supported if they transmit almost at the same time. However, if the number of STAs are increased even beyond, throughput is observed to be diminishing due to collisions. Further, an extensive simulation analysis with more number of devices (i.e., 3000) with 8 and 10 groups are shown in Figure 5.5b. Figure 5.5b shows the throughput performance with an increasing number of STAs. In the traditional scheme, due to high contention, throughput decreases linearly. Among them, a higher number of groups (i.e., 10) shows better average throughput than the lesser number of groups (i.e., 8). The proposed protocol improves throughput performance up to a good extent. As periodic STAs are scheduled beforehand for dedicated slot-based Tx, the group size hardly affects the performance.

5.4.2.2 Energy and Delay Analysis

We measure the average per-packet energy consumption and delay with the increasing number of STAs (can be seen in Figure 5.6a and 5.6b respectively). The energy required to transmit a frame is calculated by multiplying the power required in different states (can be seen in Table 5.3) with their respective timing parameters. The primary energy consumption and delay in a large network are due to unnecessary wake-ups, and channel access respectively. The proposed protocol reduces unnecessary wake-ups (due to short TIMs) by allowing the STAs to sleep approximately according to its periodic duration. The traditional DCF incurs a significant delay as simultaneous contention causes failures



(a) Average energy consumption

(b) Average delay incurred

Figure 5.6: Average energy consumption and delay incurred

and re-transmissions. This value further increases drastically with an increasing number of STAs. As the proposed protocol reduces delay by removing per-frame contention over time, the average delay is improved. For delay and energy consumption, the proposed protocol improves performance up to 55.5% and 48.4% respectively oversaturated conditions.

5.4.2.3 Throughput Vs. Simulation Time

Along with the contention, association time also impacts on the performance of the proposed protocol. We observe the throughput behavior with increasing simulation time keeping the number of STAs as constant (i.e., 1000) which is shown in Figure 5.7. As both protocols need to go through an association and contention mechanisms, the throughput performance seems to be not up to the mark. After this phase, the proposed protocol provides stable performances. Otherwise, after the association, contention continues over simulation resulting in poorer performance in the traditional scheme.

5.4.2.4 Throughput with Periodic Vs. Non-Periodic Traffic

The proposed PS-MAC protocol takes additional time in the periodicity test before scheduling a STA in the RAW frame However, if the traffic is non-periodic, the periodicity test will fail. In this analysis, we generate traffic with random intervals throughout the simulation time. A shown in Figure 5.8, throughput performances are measured

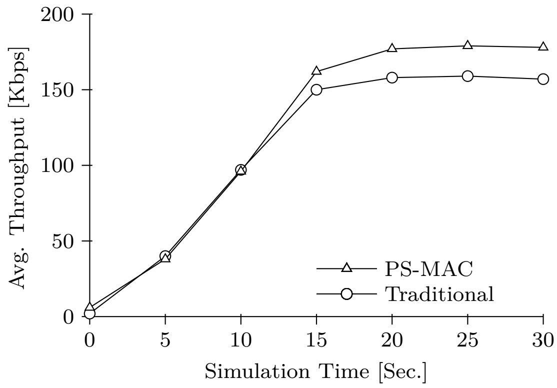


Figure 5.7: Average throughput achieved over simulation time

considering periodic and non-periodic traffic in the proposed protocol. Note that the traditional scheme is not aware of the periodicity of traffic. The proposed protocol with periodic traffic shows the highest throughput performance. Due to the hybrid channel access, throughput results with non-periodic traffic in the proposed protocol shows almost similar results with the traditional scheme.

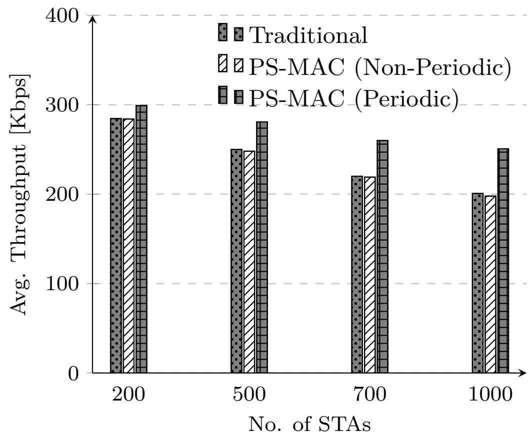


Figure 5.8: Throughput achieved using periodic and non-periodic traffic

5.4.2.5 Delay Vs. Group Sizes

To see the effects with increasing number groups, we monitor average per-packet latency as shown in Figure 5.9. The delay is significantly reduced in the proposed scheme. As the scheduling is done based on the DTIM interval, the waiting time is lessened for a smaller interval, consequently minimizing the delay. The proposed protocol reduces latency close to 52.3% (on average) considering 1000 STAs.

The existing hybrid mechanisms are based on traditional DCF based channel access without grouping. However, to create a scenario for a similar environment with large-scale periodic STAs, an 802.11ah based network having a single group in the proposed protocol is considered. In addition to the existing analysis on group sizes as shown in Figure 5.9, we have shown extensive results considering a single group. The performance results for one group are further compared with the traditional non-hybrid scheme.

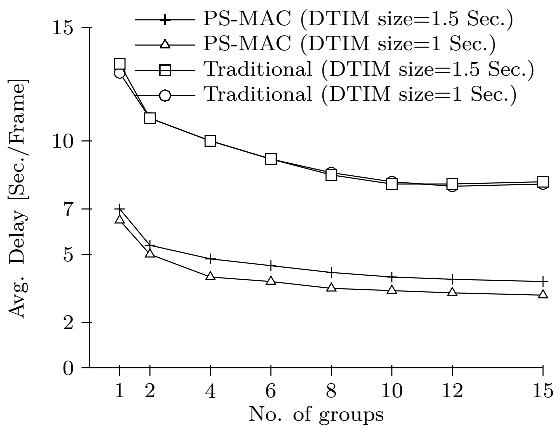


Figure 5.9: Average delay incurred with increasing number of RAW groups

We consider single-hop network where all the STAs are directly associated with the AP node. However, the same channel access mechanism can be seamlessly extended over the Relay-based multi-hop 802.11ah network.

5.5 Conclusion

This work presented an efficient RAW scheme for IEEE 802.11ah to reduce access delay and energy consumption. Considering the periodicity of traffic arrival in IoT, the proposed protocol accurately predicted the traffic interval and created the transmission schedule effectively. In saturation network conditions, the proposed protocol improves throughput performance as compared to the conventional access mechanism. From the results, it is clear that the proposed protocol suits for large-scale, energy-efficient, and latency-aware networks. In summary, the following are the key achievements of the presented work:

- The proposed protocol showed suitability in achieving better throughput and delay performance in a network having periodic and uplink traffic.

- With the help of a hybrid MAC scheme and RAW slot scheduling for periodic traffic, PS-MAC reduces the average transmission latency up to 55.5%.
- The total energy consumption in the network is improved by up to 48.4% by reducing unnecessary wake-ups.
- The proposed protocol achieves higher throughput than the traditional scheme by an average improvement of 10.24%, which is further increased to 25% when the number of STAs reaches to 1000 and beyond.
- The proposed hybrid MAC protocol with periodic traffic improves throughput performance up to 12.4% than the performance with non-periodic traffic.
- The waiting time is reduced for the STAs with smaller traffic interval, consequently minimizing the delay.
- As most of the IoT deployment (e.g., sensors) use periodic traffic patterns for uplink data transmission, the proposed periodicity test based traffic scheduling will be used for better performance.

In this work, we assumed that all the traffic in a monitoring application is uplink nature, however, in some cases, we may need to deploy some devices for actuation purposes, eventually creating downlink traffic. In the future, we plan to enhance this work to identify such traffic and STAs to enable proper scheduling over the same network.

Chapter 6

Conclusion and Future Works

Looking at the growing popularity and its rapid expansion and recent development of IoT, it can be expected that the novel IEEE 802.11ah technology will emerge more and more in the near future. Various IoT applications have their own requirements such as scalability, heterogeneity, and power inefficiency, for their smooth functioning. The MAC layer protocols in IEEE 802.11ah carries a significant responsibility to support these requirements. We have studied the MAC features of IEEE 802.11ah and analyzed them relating to IoT application scenarios, emphasizing on what is being discussed in the IEEE 802.11ah standard and what are the issues that require further research. While solving some of the problems, four enhancements/solutions have been proposed in this thesis to provide better scalability in IoT network. In this chapter, we summarize the main contributions made. Further, we discuss the limitations of the proposed schemes and suggest some future directions for research on this field.

6.1 Conclusion

In this thesis, initially, we discussed the key features of IEEE 802.11ah concerning communication issues in IoT. However, for more scalability, a list of issues (including standardization and implementation) needs to be resolved. To solve some of them, we proposed four schemes, which are highlighted below:

- HL-MAC: We proposed a RAW optimization scheme considering heterogeneous load conditions among different groups of STAs. Markov Chain Model is used to calculate the optimal RAW performance in terms of efficiently utilizing the channel bandwidth and collisions in saturated network conditions. The proposed RAW scheme is found to be achieved better performances over various traffic conditions. In a heterogeneous traffic environment, the proposed protocol showed a performance close to the network with homogeneous nodes. Moreover, multi-hop support with proper channel access mechanism shows better end-to-end results in terms of coverage range and throughput.

- QS-MAC: A priority RAW and dynamic node re-grouping scheme is proposed for provisioning QoS in IoT. For the STAs, which are responsible for carrying critical application traffic, a priority slot scheduling algorithm is used. However, this solution may create congestion when more number of priority STAs try to access within a RAW group. In such a case, a backoff based balancing scheme is proposed to distribute the load among different RAW groups. With the combination of both the algorithms, a network with different QoS requirements can efficiently utilize the available channel bandwidth.

- DL-MAC: The total network capacity is increased with the support of a relay and sectorization scheme. The proposed scheme can further utilize the available channels in different sectors and relays. After provisioning support for multiple MCSs, a dynamic load adjustment mechanism is presented for the relay nodes. The traffic congestion issues at the AP node have been resolved up to a great extend by allowing simultaneous transmission using multiple channels and sectors. Performance results of the proposed network found to be scalable for large-scale IoT.

- PS-MAC: Finally, we presented a RAW and sleep scheduling scheme for periodic traffic. The proposed scheme is effectively integrated with the existing RAW and TIM solution of 802.11ah to identify periodic STAs and scheduled them without competing over high contention. Also, based on the periodicity, a STA is kept in sleep mode for some DTIM beacons. The waiting time is reduced for the STAs with smaller traffic interval, consequently minimizing the delay. The proposed scheme showed better performance in terms of throughput and energy consumption for up-link periodic traffic scenarios.

The proposed protocols have proven their suitability in provisioning channel access for large scale IoT, however, some limitations can be noted. Also, as IEEE 802.11ah is a relatively new standard, many of the features and issues are not yet been explored, especially in the case of using it in IoT. These provide the opportunity of research for improving performance. We discuss the limitations and future works below.

6.2 Future Works

Below, we discuss the limitations of the proposed schemes, which are presented in this thesis and highlight some of the future works in this domain.

6.2.1 Limitations of the Proposed Schemes

- HL-MAC: The proposed RAW optimization scheme considers only the traffic load of the network, however, other parameters such as delay, and energy consumption also need to be calculated for maintaining a minimum performance balance. In IoT, the network condition is mostly saturated. However, a suitable number of RAW groups is needed to be measured dynamically in case of unsaturated network conditions.

- QS-MAC: Identification of QoS traffic and classify them into different categories is still challenging. Also, a further solution is required to predict the nature of event-driven traffic and measure its criticality and priority.

- DL-MAC: Although the proposed scheme considers multiple channels and MCSs to increase the network capacity, very less bandwidth of sub-1 GHz is currently available freely in a world-wide context. Also, we assumed that the STAs from different RAPs are static in terms of their locations.

- PS-MAC: In IoT, traffic heterogeneity is one of the most important parameters. There may be periodic, event-driven, and query-driven traffic in a network. Although the proposed scheme can improve performance for most of the monitoring applications, accurately predicting the periodicity of the STA is still a challenge.

6.2.2 Future Directions of Research

Further works are required to solve different problems for IoT-based heterogeneous, dynamic, and multi-hop networks. We highlight some of the future directions as follows:

- Power saving issues on a large-scale and multi-hop network: A STA needs to wake up in a TIM if any other STA in the same TIM group pages. But, this causes wastes of excess energy consumption. In terms of the entire network, such individual energy cost creates huge degradation for the whole network. Similarly, relay nodes should be scheduled in such a way so that re-transmission can be reduced as low as possible. Power saving of relay node is also another challenge of such a network.

- Issues of time synchronization in TWT based power saving based schemes for large network: For TWT mechanism followed by STAs, other than time synchronization issue, if a STA stays in doze state for a long time, timer error is very high [16]. Also, the channel may be busy with other STAs for transmission or other cases. In such a case, the transmission of the TWT STA may lead to collisions and wastage of energy and bandwidth.

- Ensuring harmonious coexistence with other standards operating in sub-1GHz channel band: The IEEE 802.11ah and 802.15.4-based networks are likely to coexist in different IoT deployments. It is obvious that for longer coverage range 802.15.4 will use the sub-1 GHz band. A scalable and energy-efficient cognitive MAC protocol solution will improve the performance of 802.11ah in such a network.

- Securing IEEE 802.11ah-based large-scale and resource-constraint IoT: Due to the use of sub-1 GHz channel band, 802.11ah is anticipated to extend the distance from which stations can be attacked from. The 802.11ah standard only specifies the PHY and MAC layers, thus leaving out the network and transport layers. These leaves room to the various IoT vendors to implement their versions, thus possibly introducing risky security functionalities. Further, the use of relay stations creates more things to worry about.

- Mobility facilities and handoff among different relay-enabled BSSs: In a typical IoT application, the STA may be mobile. Efficient hand-off and dynamic channel switching for mobile nodes are kept as the future extension of this work.

List of Publications

1. Ahmed, N., Rahman, H., & Hussain, M.I.: Scalability Analysis of Medium Access Control Protocols for Internet of Things. In book: Advances in Intelligent Systems and Computing, Edition: Modi, Nilesh K., Verma, Pramode, Trivedi, Bhushan (Eds.), Chapter: Proceedings of International Conference on Communication and Networks, Publisher: Springer, 508, (2017), 601-611 (Scopus Indexed)

2. Ahmed, N. , Rahman, H., & Hussain, M.I.: A Comparison of 802.11ah and 802.15.4 for IoT. Information & Communications Technology Express (ICT Express), 2(3), (2016) 100-103 (ESCI Indexed).

3. Ahmed, N. , De, D., & Hussain, M.I. (2018): Internet of Things (IoT) for Smart Precision Agriculture and Farming in Rural Areas . IEEE Internet of Things Journal, 5(6), 4890 - 4899, (SCI Indexed).

4. Ahmed, N. , Rahman, H., & Hussain, M.I. : An IEEE 802.11ah-based scalable network architecture for Internet of Things. Annals of Telecommunications, 73(7-8), (2018) 499-509 (SCI Indexed, IF: 1.6).

5. Ahmed, N. & Hussain, M.I.: Periodic Traffic Scheduling for IEEE 802.11ah Networks. IEEE Communications Letters,
Available at: https://doi.org/10.1109/LCOMM.2020.2981087 (2020) (SCI Indexed, IF: 3.46, Early Access).

6. Ahmed, N., De, D., & Hussain, M.I. : A QoS-aware MAC protocol for IEEE 802.11ah-based Internet of Things. In: 15th International Conference on Wireless

and Optical Communications Networks (WOCN), Kolkata, India, IEEE (2018), 1-6.

7. Ahmed, N. & Hussain, M.I.: Relay-based IEEE 802.11ah network: A Smart City Solution. In: IEEE International Conference on Cloudification of Internet of Things (CIoT), Paris, France, IEEE (2016), 1-6.

8. Ahmed, N. & Hussain, M.I.: A Distributed Channel Access Mechanism for IEEE 802.11 ah. In: IEEE 3rd World Forum on Internet of Things (WF-IoT), Reston, VA, USA, IEEE (2016), 1-6.

9. Ahmed, N. & Hussain, M.I.: Improving Scalability for IEEE 802.11ah-based Smart City Network. Communicated to IEEE Internet of Things Journal (Under Revision), (2020).

10. Ahmed, N., De, D., & Hussain, M.I.: MAC protocols for IEEE 802.11ah-based Internet of Things: A Survey. Communicated to IEEE Internet of Things Journal (Under Review), (2020).

11. Ahmed, N. & Hussain, M.I.: A Prioritized RAW and Load-aware Grouping Scheme for Critical IoT Application. Communicated to IEEE Transactions on Wireless Communications (Under Review), (2020).

Bibliography

[1] Lee, G.M., Park, J., Kong, N., Crespi, N.: The Internet of Things: Concept and Problem statement: 01. Internet Engineering Task Force, Institut TELECOM, Draft (2011) Available at: https://tools.ietf.org/id/draft-lee-iot-problem-statement-00.txt.

[2] Tschofenig, H., Arkko, J., Thaler, D., McPherson, D.: Architectural Considerations in Smart Object Networking. Internet Engineering Task Force, RFC-7452 (2015) Available at: https://tools.ietf.org/html/rfc7452.

[3] Wu, G., Talwar, S., Johnsson, K., Himayat, N., Johnson, K.D.: M2M: From mobile to embedded Internet. IEEE Communications Magazine 49(4) (2011) 36–43

[4] Statista: (IoT- connected devices installed base worldwide from 2015 to 2025 (in billions). (https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/) Last Accessed: 4th March, 2020.

[5] Want, R., Schilit, B.N., Jenson, S.: Enabling the Internet of Things. Computer 48(1) (2015) 28–35

[6] Dandelski, C., Wenning, B.L., Perez, D.V., Pesch, D., Linnartz, J.P.M.: Scalability of dense wireless lighting control networks. IEEE Communications Magazine 53(1) (2015) 157–165

[7] Lin, T., Rivano, H., Le Mouël, F.: How to choose the relevant MAC protocol for wireless smart parking urban networks? In: 11th ACM symposium on Performance evaluation of wireless Adhoc, Sensor, & Ubiquitous Networks, ACM (2014) 1–8

[8] Winter, J.M., Muller, I., Soatti, G., Savazzi, S., Nicoli, M., Becker, L.B., Netto, J.C., Pereira, C.E.: Wireless Coexistence and Spectrum Sensing in Industrial Internet of Things: An Experimental Study. International Journal of Distributed Sensor Networks 11(11) (2015) 1–12

[9] Huang, J., Xing, C.C., Shin, S.Y., Hou, F., Hsu, C.H.: Optimizing M2M communications and quality of services in the IoT for sustainable Smart Cities. IEEE Transactions on Sustainable Computing 3(1) (2018) 4–15

[10] Chen, M., Wan, J., Liao, X., Leung, V.C.: A Survey of Recent Developments in Home M2M Networks. IEEE Communications Surveys and Tutorials 16(1) (2014) 98–114

[11] Rajandekar, A., Sikdar, B.: A survey of MAC layer issues and protocols for machine-to-machine communications. IEEE Internet of Things Journal 2(2) (2015) 175–186

[12] Furht, B., Ahson, S.A.: Long Term Evolution: 3GPP LTE radio and cellular technology. CRC Press (2016) ISBN: 9781420072105.

[13] Bellalta, B., Bononi, L., Bruno, R., Kassler, A.: Next generation IEEE 802.11 Wireless Local Area Networks: Current status, future directions and open challenges. Computer Communications 75 (2016) 1–25

[14] Hiertz, G.R., Denteneer, D., Stibor, L., Zang, Y., Costa, X.P., Walke, B.: The IEEE 802.11 universe. IEEE Communications Magazine 48(1) (2010)

[15] TGah: IEEE P802.11 Sub 1GHz Study Group - IEEE 802. (http://www.ieee802.org/11/Reports/tgah_update.htm) Last Accessed: 4th March, 2020.

[16] Khorov, E., Lyakhov, A., Krotov, A., Guschin, A.: A survey on IEEE 802.11ah: An enabling networking technology for smart cities. Computer Communications 58 (2015) 53–69

[17] Aust, S., Prasad, R.V., Niemegeers, I.G.: Outdoor long-range WLANs: A lesson for IEEE 802.11ah. IEEE Communications Surveys & Tutorials 17(3) (2015) 1761–1775

[18] Ahmed, N., Rahman, H., Hussain, M.I.: A comparison of 802.11ah and 802.15.4 for IoT. ICT Express 2(3) (2016) 100–102

[19] Šljivo, A., Kerkhove, D., Tian, L., Famaey, J., Munteanu, A., Moerman, I., Hoebeke, J., De Poorter, E.: Performance Evaluation of IEEE 802.11ah Networks With High-Throughput Bidirectional Traffic. Sensors 18(2) (2018) 325

[20] Lee, I.G., Kim, M.: Interference-aware Self-optimizing Wi-Fi for high Efficiency Internet of Things in dense Networks. Computer Communications 89 (2016) 60–74

[21] Javed, F., Afzal, M.K., Sharif, M., Kim, B.S.: Internet of things (IoT) operating systems support, networking technologies, applications, and challenges: A comparative review. IEEE Communications Surveys & Tutorials 20(3) (2018) 2062–2100

[22] Mah, D.N.y., van der Vleuten, J.M., Ip, J.C.m., Hills, P.R.: Governing the transition of socio-technical systems: A case study of the development of smart grids in Korea. Energy Policy 45 (2012) 133–141

[23] Hernández-Muñoz, J.M., Vercher, J.B., Muñoz, L., Galache, J.A., Presser, M., Gómez, L.A.H., Pettersson, J.: Smart Cities at the forefront of the future Internet. In: The Future Internet Assembly, Springer (2011) 447–462

[24] Lu, G., De, D., Song, W.Z.: Smartgridlab: A laboratory-based smart grid testbed. In: IEEE International Conference on Smart Grid Communications (SmartGridComm), IEEE (2010) 143–148

[25] Chapman, L., Muller, C.L., Young, D.T., Warren, E.L., Grimmond, C., Cai, X.M., Ferranti, E.J.: The Birmingham urban climate laboratory: An open meteorological test bed and challenges of the Smart City. Bulletin of the American Meteorological Society 96(9) (2015) 1545–1560

[26] Sanchez, L., Muñoz, L., Galache, J.A., Sotres, P., Santana, J.R., Gutierrez, V., Ramdhany, R., Gluhak, A., Krco, S., Theodoridis, E., Pfisterer, D.: SmartSantander: IoT experimentation over a Smart City testbed. Computer Networks 61 (2014) 217–238

[27] Munoz, J., Rincon, F., Chang, T., Vilajosana, X., Vermeulen, B., Walcarius, T., Van de Meerssche, W., Watteyne, T.: OpenTestBed: Poor Man's IoT Testbed. In: Conference on Computer Communications Workshops (INFOCOM WKSHPS), IEEE (2019) 467–471

[28] Yedavalli, K., Krishnamachari, B.: Enhancement of the IEEE 802.15. 4 MAC protocol for scalable data collection in dense sensor networks. In: Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks and Workshops, 2008. WiOPT 2008. 6th International Symposium on, IEEE (2008) 152–161

[29] IEEE: Approved Draft 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. IEEE P802.11ah/D10.0, Sep 2016 (2016) 1–660

[30] Lloyd, E.L., Xue, G.: Relay node placement in wireless sensor networks. IEEE Transactions on Computers 56(1) (2007) 134–138

[31] Akpakwu, G.A., Silva, B.J., Hancke, G.P., Abu-Mahfouz, A.M.: A survey on 5G networks for the Internet of Things: Communication technologies and challenges. IEEE Access 6 (2017) 3619–3647

[32] Park, M.: IEEE 802.11ah: sub-1-GHz license-exempt operation for the Internet of Things. IEEE Communications Magazine 53(9) (2015) 145–151

[33] Hazmi, A., Rinne, J., Valkama, M.: Feasibility study of IEEE 802.11ah radio technology for IoT and M2M use cases. In: IEEE GlOBECOM WORKSHOPS, IEEE (2012) 1687–1692

[34] Sun, W., Choi, M., Choi, S.: IEEE 802.11ah: A long range 802.11 WLAN at sub 1 GHz. Journal of ICT Standardization 1(1) (2013) 83–108

[35] Park, M.: IEEE 802.11ah: Energy efficient MAC protocols for long range wireless LAN. In: International conference on communications (ICC), IEEE (2014) 2388–2393

[36] Ogawa, K., Morikura, M., Yamamoto, K., Sugihara, T.: IEEE 802.11ah based M2M networks employing virtual grouping and power saving methods. IEICE Transactions on Communications 96(12) (2013) 2976–2985

[37] Oliveira, L., Rodrigues, J.J., Kozlov, S.A., Rabêlo, R.A., Albuquerque, V.H.C.d.: MAC layer protocols for internet of things: A survey. Future Internet 11(1) (2019) 16

[38] NEWRACOM: Ultra-low power & Long-range Wi-Fi by Wi-Fi 802.11ah. (http://newracom.com/products/) Last Accessed: 4th March, 2020.

[39] AGILEIP: IEEE 802.11ah WiFi HaLow. (http://www.aegis-ip.com/wifi-halow.html) Last Accessed: 4th March, 2020.

[40] MorseMicro: Morse Micro: Wi-Fi HaLow for IoT – 802.11ah chips. (https://www.morsemicro.com/) Last Accessed: 4th March, 2020.

[41] LoRa: LoRa Alliance. (https://www.lora-alliance.org/) Last Accessed: 4th March, 2020.

[42] SIGFOX: SIGFOX - The Global Communications Service Provider. (https://www.sigfox.com/) Last Accessed: 4th March, 2020.

[43] Wang, Y.P.E., Lin, X., Adhikary, A., Grövlen, A., Sui, Y., Blankenship, Y., Bergman, J., Razaghi, H.S.: A Primer on 3GPP Narrowband Internet of Things (NB-IoT). arXiv preprint arXiv:1606.04171 (2016)

[44] Tian, L., Deronne, S., Latré, S., Famaey, J.: Implementation and Validation of an IEEE 802.11ah Module for NS-3. In: Proceedings of the Workshop on ns-3, ACM (2016) 49–56

[45] Raeesi, O., Pirskanen, J., Hazmi, A., Levanen, T., Valkama, M.: Performance evaluation of IEEE 802.11ah and its restricted access window mechanism. In: International Conference on Communications Workshops (ICC), IEEE (2014) 460–466

[46] Bel, A., Adame, T., Bellalta, B., Barcelo, J., Gonzalez, J., Oliver, M.: CAS-based channel access protocol for IEEE 802.11ah WLANs. In: 20th European Wireless Conference, VDE (2014) 1–6

[47] Park, C.W., Hwang, D., Lee, T.J.: Enhancement of IEEE 802.11ah MAC for M2M Communications. IEEE Communications Letters 18(7) (2014) 1151–1154

[48] Wang, Y., Li, Y., Chai, K.K., Chen, Y., Schormans, J.: Energy-aware adaptive restricted access window for IEEE 802.11ah based Smart Grid networks. In: International Conference on Smart Grid Communications (SmartGridComm), IEEE (2015) 581–586

[49] Tian, L., Khorov, E., Latré, S., Famaey, J.: Real-time station grouping under dynamic traffic for ieee 802.11ah. Sensors 17(7) (2017) 1–24

[50] Tian, L., Santi, S., Latré, S., Famaey, J.: Accurate sensor traffic estimation for station grouping in highly dense IEEE 802.11ah networks. In: Proceedings of the First ACM International Workshop on the Engineering of Reliable, Robust, and Secure Embedded Wireless Sensing Systems, ACM (2017) 1–9

[51] Tian, L., Mehari, M., Santi, S., Latré, S., De Poorter, E., Famaey, J.: IEEE 802.11ah Restricted Access Window Surrogate Model for Real-Time Station Grouping. In: 19th International Symposium on" A World of Wireless, Mobile and Multimedia Networks"(WoWMoM), IEEE (2018) 14–22

[52] Lei, X., Rhee, S.H.: Performance Improvement of Sub-1 GHz WLANs for Future IoT Environments. Wireless Personal Communications 93(4) (2017) 933–947

[53] Madueño, G.C., Stefanović, Č., Popovski, P.: Reliable and efficient access for alarm-initiated and regular M2M traffic in IEEE 802.11ah Systems. IEEE Internet of Things Journal 3(5) (2016) 673–682

[54] Hazmi, A., Badihi, B., Larmo, A., Torsner, J., Valkama, M., et al.: Performance analysis of IoT-enabling IEEE 802.11ah technology and its RAW mechanism with

non-cross slot boundary holding schemes. In: International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), IEEE (2015) 1–6

[55] Charania, N.: Delay and Energy Aware RAW Formation Scheme to Support Delay Sensitive M2M Traffic in IEEE 802.11ah Networks. PhD thesis, Indian Institute of Technology Hyderabad (2017)

[56] Mahesh, M., Harigovindan, V.: Restricted access window based novel service differentiation scheme for group-synchronized dcf. IEEE Communications Letters 23(5) (2019)

[57] Wang, Y., Liu, C., Chai, K.K., Chen, Y., Loo, J.: Optimized energy-aware window control for IEEE 802.11ah based networks in smart grid enabled cities. In: Smart Grid Inspired Future Technologies. Springer (2017) 165–173

[58] Nawaz, N., Hafeez, M., Zaidi, S.A.R., McLernon, D.C., Ghogho, M.: Throughput enhancement of restricted access window for uniform grouping scheme in IEEE 802.11ah. In: IEEE International Conference on Communications (ICC), IEEE (2017) 1–7

[59] Chang, T.C., Lin, C.H., Lin, K.C.J., Chen, W.T.: Traffic-Aware Sensor Grouping for IEEE 802.11ah Networks: Regression Based Analysis and Design. IEEE Transactions on Mobile Computing (2018) DOI: 10.1109/TMC.2018.2840692.

[60] Khorov, E., Lyakhov, A., Yusupov, R.: Two-Slot Based Model of the IEEE 802.11ah Restricted Access Window with Enabled Transmissions Crossing Slot Boundaries. In: 19th International Symposium on" A World of Wireless, Mobile and Multimedia Networks(WoWMoM), IEEE (2018) 1–9

[61] Bianchi, G.: Performance analysis of the IEEE 802.11 distributed coordination function. IEEE Journal on selected areas in communications 18(3) (2000) 535–547

[62] Anouar, H., Bonnet, C.: Optimal constant-window backoff scheme for IEEE 802.11 DCF in single-hop wireless networks under finite load conditions. Wireless Personal Communications 43(4) (2007) 1583–1602

[63] Bellekens, B., Tian, L., Boer, P., Weyn, M., Famaey, J.: Outdoor IEEE 802.11 ah range characterization using validated propagation models. In: GLOBECOM 2017-2017 IEEE Global Communications Conference, IEEE (2017) 1–6

[64] NSNAM: What is NS-3. (https://www.nsnam.org/overview/what-is-ns-3/) Last Accessed: 4th March, 2020.

[65] Ming, Z., Yan, M.: A Modeling and Computational Method for QoS in IOT. In: International Conference on Software Engineering and Service Science (ICSESS), IEEE (2012) 275–279

[66] Ali, M.Z., Mišić, J., Mišić, V.B.: Performance Evaluation of Heterogeneous IoT Nodes With Differentiated QoS in IEEE 802.11ah RAW Mechanism. IEEE Transactions on Vehicular Technology 68(4) (2019) 3905–3918

[67] IEEE802.16p: IEEE 802.16p Machine to Machine (M2M) Evaluation Methodology Document (EMD). IEEE 802.16 Broadband Wireless Access Working Group (802.16p) (2011) EMD 11/0005.

[68] Zhao, Y., Yilmaz, O.N., Larmo, A.: Optimizing m2m energy efficiency in ieee 802.11ah. In: Globecom Workshops (GC Wkshps), IEEE (2015) 1–6

[69] Charania, N.F., Giluka, M.K., Tamma, B.R., Franklin, A.: DEARF: Delay and energy aware raw formation scheme to support delay sensitive M2M traffic in IEEE 802.11ah networks. arXiv preprint arXiv:1709.03723 (2017)

[70] Seferagić, A., Moerman, I., De Poorter, E., Hoebeke, J.: Evaluating the suitability of IEEE 802.11ah for low-latency time-critical control loops. IEEE Internet of Things Journal (2019) Available at- https://doi.org/10.1109/JIOT.2019.2916579.

[71] Kai, C., Zhang, J., Zhang, X., Huang, W.: Energy-Efficient Sensor Grouping for IEEE 802.11ah Networks With Max-Min Fairness Guarantees. IEEE Access 7 (2019) 102284–102294

[72] Sthapit, P., Pyun, J.Y.: Station grouping strategy for minimizing association delay in IEEE 802.11ah. IEICE Transactions on Communications 100(8) (2017) 1419–1427

[73] Wang, R., Lin, M.: Restricted Access Window Based Hidden Node Problem Mitigating Algorithm in IEEE 802.11ah Networks. IEICE Transactions on Communications (2018) 2017EBP3462

[74] Adas, A.: Traffic models in broadband networks. IEEE communications Magazine 35(7) (1997) 82–89

[75] Dehbi, Y., Benaboud, H., Mikou, N.: A Geometric Backoff Time Distribution of IEEE 802.11 DCF: An Analytical Study. International Journal of Communication Networks and Information Security (IJCNIS) 5(3) (2013)

[76] Malone, D., Duffy, K., Leith, D.: Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions. IEEE/ACM Transactions on Networking (TON) 15(1) (2007) 159–172

[77] Dhananjay, A., Ruan, L.: PigWin: Meaningful load estimation in ieee 802.11 based wireless lans. In: IEEE International Conference on Communications, IEEE (2008) 2541–2546

[78] Yoon, S.G., Seo, J.O., Bahk, S.: Regrouping algorithm to alleviate the hidden node problem in 802.11ah networks. Computer Networks 105 (2016) 22–32

[79] Xiao, Y.: Backoff-based priority schemes for IEEE 802.11. In: IEEE International Conference on Communications. Volume 3., IEEE (2003) 1568–1572

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

[81] Madueño, G.C., Stefanović, Č., Popovski, P.: Reliable and efficient access for alarm-initiated and regular M2M traffic in IEEE 802.11ah systems. IEEE Internet of Things Journal 3(5) (2015) 673–682

[82] Baños-Gonzalez, V., Afaqui, M.S., Lopez-Aguilera, E., Garcia-Villegas, E.: Throughput and Range characterization of IEEE 802.11ah. ArXiv e-prints (2016)

[83] Kocan, E., Domazetovic, B., Pejanovic-Djurisic, M.: Range extension in IEEE 802.11ah systems through relaying. Wireless Personal Communications 97(2) (2017) 1889–1910

[84] Kumar, S., Lim, H., Kim, H.: Hierarchical MAC protocol with Multi-channel allocation for enhancing IEEE 802.11ah Relay Networks. In: Wireless Communications and Mobile Computing Conference (IWCMC), IEEE (2015) 1458–1463

[85] Ahmed, N., Rahman, H., Hussain, M.I.: An IEEE 802.11ah-based scalable network architecture for Internet of Things. Annals of Telecommunications 73(7-8) (2018) 499–509

[86] Rao, S.N., Akhil, P., Kumaravelu, V.B., Arthi, M.: Dual—Hop Relaying for Quality of Service Improvement in IEEE 802.11ah-Downlink. In: 2018 Interna-

tional Conference on Communication and Signal Processing (ICCSP), IEEE (2018) 0249–0253

[87] Argyriou, A.: Power-efficient estimation in IEEE 802.11ah wireless sensor networks with a cooperative relay. In: International Conference on Communications (ICC), IEEE (2015) 6755–6760

[88] Shafiq, M., Ahmad, M., Irshad, A., Gohar, M., Usman, M., Khalil Afzal, M., Choi, J.G., Yu, H.: Multiple Access Control for Cognitive Radio-Based IEEE 802.11ah Networks. Sensors 18(7) (2018) 2043

[89] Nabuuma, H., Alsusa, E., Baidas, M.W.: AID-based backoff for throughput enhancement in 802.11ah networks. International Journal of Communication Systems 32(7) (2019) e3923

[90] Ghasemiahmadi, M., Li, Y., Cai, L.: RSS-based grouping strategy for avoiding hidden terminals with GS-DCF MAC protocol. In: Wireless Communications and Networking Conference (WCNC), IEEE (2017) 1–6

[91] Zhang, L., Li, H., Guo, Z., Ding, L., Yang, F., Qian, L.: Signal strength assistant grouping for lower hidden node collision probability in 802.11ah. In: 19th International Conference on Wireless Communications and Signal Processing (WCSP), IEEE (2017) 1–6

[92] Yu, T.H., Liang, S.T.: Grouping Method Based on Exposed Terminal Detection in IEEE 802.11ah. In: International Conference on E-Society, E-Education and E-Technology, ACM (2017) 37–41

[93] Carpio, L., Robles, M., Morabito, R.: IPv6 over 802.11ah. Internet-Draft, IETF (2015) Available at: https://tools.ietf.org/html/draft-delcarpio-6lo-wlanah-00.

[94] Dong, M., Wu, Z., Gao, X., Zhao, H.: An efficient spatial group restricted access window scheme for IEEE 802.11ah networks. In: 6th International Conference on Information Science and Technology (ICIST), IEEE (2016) 168–173

[95] Damayanti, W., Kim, S., Yun, J.H.: Collision chain mitigation and hidden device-aware grouping in large-scale IEEE 802.11ah networks. Computer Networks 108 (2016) 296–306

[96] Bhandari, S., Sharma, S.K., Wang, X.: Device Grouping for Fast and Efficient Channel Access in IEEE 802.11ah based IoT Networks. In: IEEE International Conference on Communications Workshops (ICC Workshops), IEEE (2018) 1–6

[97] Pandya, B., Chiueh, T.D.: Interference aware coordinated multiuser access in multi-band WLAN for next generation low power applications. Wireless Networks 25(4) (2019) 1965–1981

[98] Dong, Q., Dargie, W.: Evaluation of the reliability of RSSI for indoor localization. In: 2012 International Conference on Wireless Communications in Underground and Confined Areas, IEEE (2012) 1–6

[99] Bankov, D., Khorov, E., Lyakhov, A., Stepanova, E.: Fast centralized authentication in Wi-Fi HaLow networks. In: 2017 IEEE International Conference on Communications (ICC), IEEE (2017) 1–6

[100] Dhananjay, A.V.: Load estimation in IEEE 802.11 wireless networks. (2008) Published at: Digital Repository Iowa State University, http://lib. dr. iastate. edu/.

[101] Sridharan, M., Devi, R., Dharshini, C., Bhavadarani, M.: IoT based performance monitoring and control in counter flow double pipe heat exchanger. Internet of Things 5 (2019) 34–40

[102] Shipman, R., Gillott, M.: SCENe Things: IoT-based Monitoring of a Community Energy Scheme. Future Cities and Environment 5(1) (2019)

[103] Moreno, C., Aquino, R., Ibarreche, J., Pérez, I., Castellanos, E., Álvarez, E., Rentería, R., Anguiano, L., Edwards, A., Lepper, P., et al.: RiverCore: IoT device for river water level monitoring over cellular communications. Sensors 19(1) (2019) 127

[104] Mocnej, J., Pekar, A., Seah, W.K., Zolotova, I.: Network traffic characteristics of the IoT application use cases. Victoria University of Wellington 20 (2017) 1–20

[105] Sivanathan, A., Sherratt, D., Gharakheili, H.H., Radford, A., Wijenayake, C., Vishwanath, A., Sivaraman, V.: Characterizing and classifying IoT traffic in smart cities and campuses. In: IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), IEEE (2017) 559–564

[106] Sivanathan, A., Gharakheili, H.H., Loi, F., Radford, A., Wijenayake, C., Vishwanath, A., Sivaraman, V.: Classifying IoT devices in smart environments using network traffic characteristics. IEEE Transactions on Mobile Computing 18(8) (2018)

[107] Liu, R.P., Sutton, G.J., Collings, I.B.: Power save with offset listen interval for IEEE 802.11ah smart grid communications. In: International Conference on Communications (ICC), IEEE (2013) 4488–4492

[108] Chen, C., Zhao, H., Qiu, T., Hu, M., Han, H., Ren, Z.: An efficient power saving polling scheme in the internet of energy. Journal of Network and Computer Applications (2017) https://doi.org/10.1016/j.jnca.2017.01.002.

[109] Beltramelli, L., Österberg, P., Jennehag, U., Gidlund, M.: Hybrid MAC mechanism for energy efficient communication in IEEE 802.11ah. In: International Conference on Industrial Technology (ICIT), IEEE (2017) 1295–1300

[110] Bel, A., Adame, T., Bellalta, B.: An energy consumption model for IEEE 802.11ah WLANs. Ad Hoc Networks 72 (2018) 14–26

[111] Kim, T., Chang, J.M.: Enhanced power saving mechanism for large-scale 802.11ah wireless sensor networks. IEEE Transactions on Green Communications and Networking 1(4) (2017) 516–527

[112] Kureev, A., Bankov, D., Khorov, E., Lyakhov, A.: Improving efficiency of heterogeneous Wi-Fi networks with joint usage of TIM segmentation and restricted access window. In: 18th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), IEEE (2017) 1–5

[113] Nurchis, M., Bellalta, B.: Target Wake Time: Scheduled access in IEEE 802.11 ax WLANs. arXiv preprint arXiv:1804.07717 (2018)

[114] Tian, L., Mehari, M., Santi, S., Latré, S., De Poorter, E., Famaey, J.: Multi-objective surrogate modeling for real-time energy-efficient station grouping in IEEE 802.11ah. Pervasive and Mobile Computing (2019) Available at: https://doi.org/10.1016/j.pmcj.2019.04.007.

[115] Fan, Q., Fan, J., Li, J., Wang, X.: A multi-hop energy-efficient sleeping MAC protocol based on TDMA scheduling for wireless mesh sensor networks. Journal of Networks 7(9) (2012) 1355