TAMPERE UNIVERSITY OF TECHNOLOGY

OROD RAEESI

SYSTEM-LEVEL PERFORMANCE ANALYSIS AND OPTIMIZATION OF IEEE 802.11AH – THE NEW SUB-1 GHz WI-FI

Master of Science Thesis

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ABSTRACT

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Internet of Things (IoT) is a concept which will have major effects on our future lives. It will introduce a novel dimension to the world of information and communication technology where connectivity will be available anytime, anywhere for anything. This will implicitly introduce billions of devices and stations that need to communicate within the IoT network. Consequently, it is necessary to design new wireless technologies to support them. IEEE 802.11ah is one of these technologies which exploit IEEE 802.11 standard advantages while benefiting from certain changes specifically made to satisfy IoT requirements like being able to handle this amount of devices and being power efficient. IEEE 802.11ah which operates in sub-1 GHz band is expected to assure 1 km coverage with at least 100 Kbps data rate and it should support beyond 2000 stations.

This thesis evaluates the performance of IEEE 802.11ah and some of its features in various scenarios using a system-level simulator developed in this research work. Comparing the developed simulator's results with two analytical models, one introduced in the literatures and one developed in this thesis, proves the high accuracy of the simulator in modeling the IEEE 802.11ah network.

The performance analysis shows that for IoT use cases with relatively low packet size (256 bytes), it is better not to use RTS/CTS access scheme. Based on the presented results, it is concluded that frequency management mechanisms, link adaptation algorithms and Restricted Access Window (RAW) mechanism, should be used in most of the practical cases to have higher energy efficiency and improve the general system performance.

PREFACE

The research work related to this Master of Science Thesis is conducted in the Internet of Things program of TiViT (Finnish Strategic Center for Science, Technology and Innovation in ICT), funded by the Finnish Funding Agency for Technology and Innovation (Tekes). The work is also financially supported by Renesas Mobile Europe Ltd. The research work was carried out during the year 2012-2013 at the Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere, Finland.

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Finally, I would like to express my deepest gratitude and respect to my family, especially my parents to whom I owe everything I have achieved, for their love and invaluable support in every possible way they could.

Tampere, September 2013

Orod Raeesi

CONTENTS

LIST OF FIGURES

TERMS AND DEFINITIONS OR LIST OF SYMBOLS AND ABBREVIATIONS

IEEE	Institute of Electrical and Electronics Engineers
WLAN	Wireless Local Area Network
Wi-Fi	Any WLAN product which is based on IEEE 802.11 standard
MAC	Medium Access Control
PHY	Physical Layer
OFDM	Orthogonal Frequency Division Multiplexing
MIMO	Multiple Input Multiple Output
LAN	Local Area Network
STA	Station
AP	Access Point
QoS	Quality of Service
ACK	Acknowledgment
RTS	Request to Send
CTS	Clear to Send
MCS	Modulation and Coding Scheme
BW	Bandwidth
OBSS	Overlapping Basic Service Sets
RAW	Restricted Access Window

1. INTRODUCTION

In the past three decades, the Internet has evolved from a network consisting of a few hundreds users to a network linking billions of users to each other. This evolution not only increased the number of users, but also introduced new ways of communications and new concepts. In the new network, there would be interconnection between diverse objects in the physical world, such as computers, healthcare devices, home appliances, vehicles and etcetera. This new concept, called the Internet of Things (IoT), will introduce a novel dimension to the world of information and communication technology where connectivity will be available anytime, anywhere for anything. IoT will have major effects on our future lives by addressing the challenges that individuals and organizations face. For example, the traffic congestion can be solved by monitoring of vehicles and pedestrian levels to optimize driving and walking routes; detection of forest fire by monitoring of combustion gases and preemptive fire conditions to define alert zones; intelligent shopping applications by getting advices in the point of sale according to customer habits, preferences, presence of allergic components for them or expiring dates and so on. [1]

To make this huge amount of connectivity possible, IoT utilizes a huge number of information gathering and dissemination devices, such as sensors and RFID tags. The Wireless World Research Forum predicts that by 2017, there will be 7 trillion wireless devices serving 7 billion people [2]. Therefore, one of the main requirements for IoT networks is being able to handle this number of devices. On the other hand, IoT devices need to report data periodically over a long time which makes power efficiency an important factor in the network performance. There are many existing wireless technologies being shaped for IoT use case and many others which are being introduced mainly for this purpose.

One of these technologies is based on IEEE 802.11 standard. This standard was originally targeting high throughput applications. However, being able to have IP connectivity and the fact that Wi-Fi have already spread in every corner of the world, make this standard one of the most suitable technologies for IoT purpose. IEEE 802.11ah [3] which operates in sub-1 GHz band is introduced mainly to satisfy IoT requirements [4].

The basics of an IEEE 802.11ah network is discussed in Chapter 2. In addition, Chapter 2 summarizes the use cases of IEEE 802.11ah and the requirements which should be followed by this amendment. The MAC and the PHY of IEEE 802.11ah which have some common parts with IEEE 802.11 baseline standard are described in the last two sections of Chapter 2.

IEEE 802.11ah amendment is currently being developed and is expected to be finalized by 2014. Therefore, in this stage it is vital to evaluate the performance of IEEE 802.11ah in general and the new proposed features in particular. For this purpose, a system-level simulator is developed in this research work. The software platform employed to develop the simulator and the simulation model's settings are discussed in the Chapter 3.

To evaluate the reliability of the simulation model, it is compared to two different analytical models, one introduced in the literatures and one developed in this thesis, considering some basic assumptions. This comparison is reported in Chapter 4. The first analytical model, calculates the maximum achievable throughput in IEEE 802.11ah network when there is no error neither due to the collisions nor because of channel effects. The second one analyzes the saturation throughput and the energy efficiency of IEEE 802.11ah with the assumption of known collision and packet error probabilities. These analytic models are followed by the evaluation of the basic performance of IEEE 802.11ah using the system-level simulator. Here the above assumptions were relaxed and more practical and basic scenarios were considered. This basic evaluation is reported in the last section of Chapter 4.

In addition to the basic performance evaluation, the performance of the IEEE 802.11ah should be examined in more complex scenarios. First part of Chapter 5 studies the effect of having more than one AP in the network which is referred to as OBSS problem. Furthermore, two link adaptation algorithms which are trying to dynamically switch data rate to match the channel conditions are studied in Chapter 5. In the last part of Chapter 5, RAW mechanism that has been introduced in IEEE 802.11ah amendment and tries to cope with collision problem is also evaluated.

Chapter 6 concludes the work. The publications related to this research work are also presented in Chapter 6.

2. IEEE 802.11AH

IEEE 802.11$^{\text{TM}}$ is a standard developed by IEEE Standards Association (IEEE-SA) which is a leading organization that designs, develops and advances global technologies and standards, through IEEE [5]. The purpose of this standard is to provide wireless connectivity for fixed, portable and moving stations within a local area (WLAN). The scope is to define one MAC and several PHY specifications for the mentioned purpose. [6]

The standard is updated by means of amendments, each of which is defined by a set of features that relate to performance, frequency and bandwidth. Some of the amendments and their respective description are as follows:

- *IEEE 802.11a*: High-speed (54 Mbps) Physical Layer in the 5 GHz Band (using OFDM) [7]
- *IEEE 802.11n*: Enhancements for Higher Throughput (up to 600 Mbps, using MIMO, 40 MHz channels) [8]
- *IEEE 802.11ac*: Very High Throughput (beyond 1 Gbps), less than 6 GHz bands (in progress) [9]
- *IEEE 802.11ah*: Sub-1 GHz license-exempt operation (in progress) [10]

IEEE 802.11ah as defined in [3, p. iii] "defines modifications to both the IEEE 802.11 physical layer (PHY) and the medium access control (MAC) sublayer to enable operation of license-exempt 802.11 wireless networks in frequency bands below 1 GHz excluding the TV White Space bands, with a transmission range up to 1 km and a minimum data rate of at least 100 Kbps". IEEE 802.11ah is currently being developed by IEEE 802.11ah task group which is the committee that is assigned by the IEEE 802.11 working group as the author of this amendment.

Altogether, IEEE 802.11ah has dozens of features which make it impossible to go through all of them. The features which are discussed in this chapter are mostly the ones used throughout this thesis.

In this chapter some basics, use cases, requirements and different layers of IEEE 802.11ah are briefly discussed.

2.1 The Basics

This section introduces the main components that form the IEEE 802.11ah network and the basic architectures.

2.1.1 Main Components of the Network

The elements used in the wireless LANs are one of the fundamental characteristics which differ in wired LANs.

Wireless station (STA)

STAs are the addressable units in IEEE 802.11. In other words, a STA is the source or destination of a message [6].

Access Point (AP)

The entity which provides access to distribution service for associated STAs through the wireless medium is called AP. The APs also implement the functionalities of STA. [6]

If an AP is present in the network, STAs cannot communicate with each other directly. They should send their messages to the AP and the AP will take care of delivering the message to the corresponding destination. APs are also responsible for exchanging frames between the network and the rest of the world by converting the frames to other types [11].

Relay

An AP and STAs can exchange frames with one another through a relay. A Relay is an entity that logically consists of a Relay AP and a Relay STA as illustrated in Figure 2.1.

Relays enable STAs to use higher data rates which improves the energy consumption. They can be used also to extend the coverage of an AP. The relaying function is bi-directional and limited to two hops in order not to cause high overhead and complexity. [3]

2.1.2 The Architecture

The basic building block of an IEEE 802.11 LAN is the Basic Service Set (BSS). It means no more than some STAs communicating to each other. The coverage area within which the member STAs of a BSS may remain in communication is called Basic Service Area (BSA). There are mainly two different BSSs which are shown in Figure 2.2. [11]

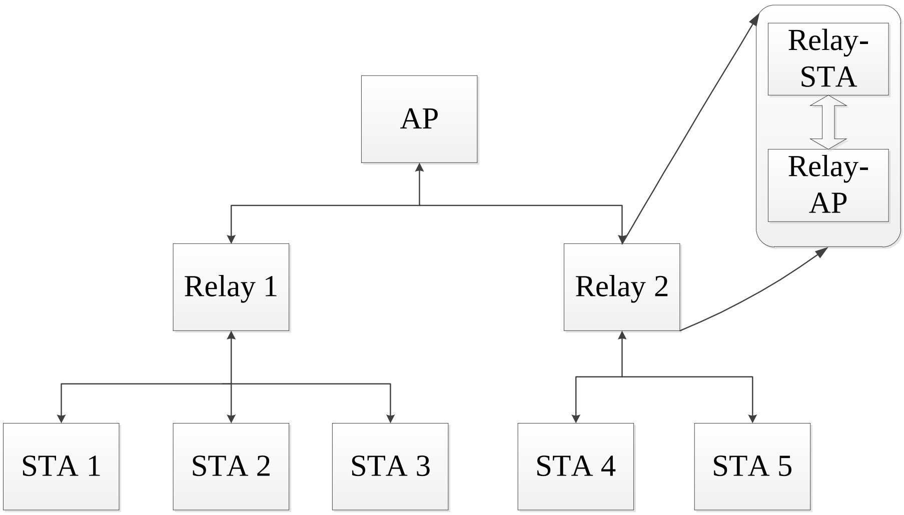

Figure 2.1. *an example of having Relays in the network*

Independent BSS (IBSS)

IBSS is the most basic type of IEEE 802.11 LAN. In IBSSs, as it can be seen in the right side of Figure 2.2, STAs are communicating directly to each other. Typically, IBSSs are set up for specific purposes and a short period of time and are composed of small number of STAs.

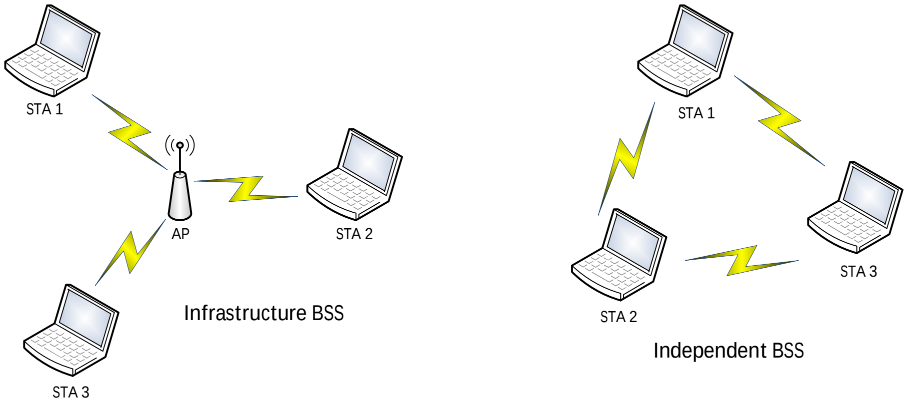

Figure 2.2. *Infrastructure and Independent BSSs*

Infrastructure BSS

An infrastructure BSSs is illustrated in the left side of Figure 2.2. This kind of networks are distinguished by the use of an AP. As it is said earlier, all the communications in the network should go through the AP. It means that even if STAs are trying to communicate with each other, the communication must take two hops.

Forcing all the transmissions to go through the AP takes higher transmission capacity compared to the case in which all the STAs can communicate with each other directly. However, there are two major advantages in having infrastructure BSSs:

1. In independent BSSs, STAs need to maintain a neighbor relationship with all other STAs. However, in infrastructure networks, there is no restriction on the distance between the STAs. STAs only need to be in the basic service area which is defined by the distance in which the transmission with AP can take place.
2. APs in infrastructure BSSs can assist STAs to save power. STAs can turn their transceivers off while the AP buffers frames for them. The AP can send the buffered frames to their corresponding STAs when they are awake.

These two advantages makes infrastructure BSS the perfect option for IEEE 802.11ah use cases which will be discussed in section 2.2.

Extended Service Set (ESS)

IEEE 802.11 networks with arbitrary size and complexity can be created by linking different BSSs. This new topology is called Extended Service Set. The backbone used to interconnect infrastructure BSSs in an ESS is the **Distribution System (DS)**. An example of an ESS and the DS is illustrated in Figure 2.3.

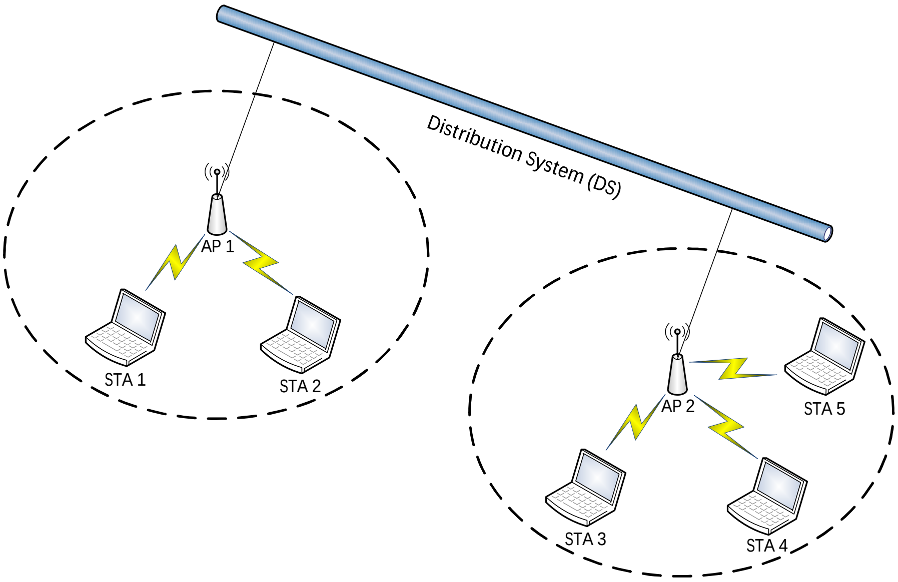

Figure 2.3. *Extended Service Set (ESS)*

STAs within the same ESS can communicate with each other, even if they are located in different basic service areas. Data moves between a BSS and the DS through an AP.

2.2 Use Cases

There are several use cases defined for IEEE 802.11ah by its task group. Each use case has its own requirements. These use cases are categorized in three major groups, namely sensors and meters, backhaul sensor/meter data and extended range Wi-Fi [12].

2.2.1 Sensors and Meters

For sensing and metering purposes, when the large amount of battery operated sensors/meters are needed, users and manufacturers want to extend the battery life of end devices as long as possible. Those sensors/meters only need to perform essential functions. IEEE 802.11ah devices are going to be used in the aforementioned cases by providing the wireless communication needed for sensors/meters.

There are different scenarios defined for IEEE 802.11ah devices to work as a sensor/meter device which are briefly discussed in the following.

Smart Grid - Meter to Pole

The electric industry is making the transformation from a centralized, producer-controlled network to a less centralized and more consumer-interactive one. The smart grid will make an entire change to all consumers of electric power. [13]

Wireless senor networks enable smart grid utilities and customers to transfer, monitor, predict, and manage energy usage effectively. They are widely applied in wireless automatic meter reading system. Based on those sensors, energy usage information such as frequency, phase angle and voltage values can be read in real-time. Therefore, managing electricity demand can be done by utility companies efficiently. [14]

The same method can be applied to manage other resources such as water and gas. The proposed infrastructure to use IEEE 802.11ah for the following purposes can be seen in Figure 2.4.

Environmental/Agricultural Monitoring

This use case is one of the outdoor use cases of this amendment. Monitoring data includes temperature, humidity, wind speed/direction, water level, pollution information, soil condition, plant/crop or animal/livestock condition and location and disaster detection information (forest fire, flood and etcetera). [16]

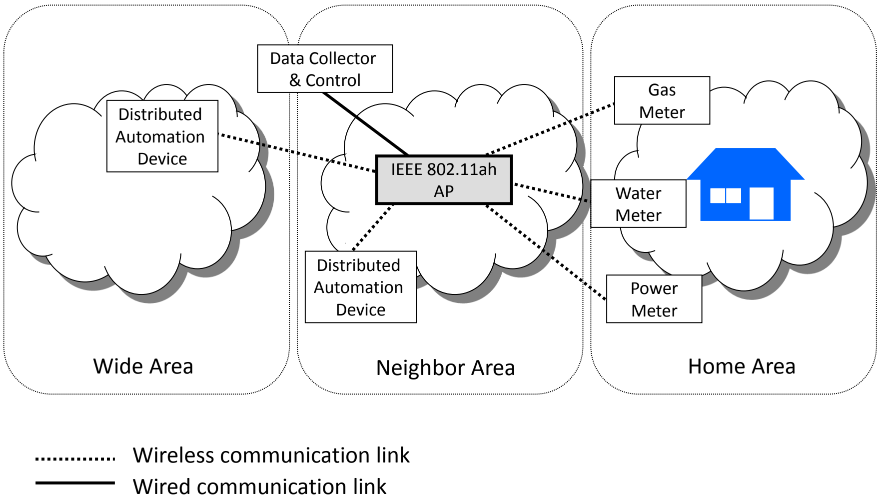

Figure 2.4. *Proposed infrastructure for Smart Grid and Meter to Pole applications using IEEE 802.11ah [15]*

Industrial Process Sensors

Industrial processes make the production of a rare material cheaper and economically feasible. It also increases the quality and productivity. There are up to thousands of Input/Output points where the sensors are needed in the automation of industrial processes like petroleum refinement, iron and steel, pharmacy and etcetera. [17]

Healthcare/Fitness

This use case is divided into three major parts, namely hospital/clinic, elderly-care/independent living and personal fitness [18].

In hospital/clinic cases, body monitoring can be done by having different sensors for example for heart rate, blood pressure (sphygmomanometer), oxygen in blood (SPO2), airflow (breathing), body temperature, electrocardiogram (ECG), glucometer, galvanic skin response (GSR - sweating) and patient position (accelerometer). The information provided by the sensors can be used to monitor the state of a patient in real time or to get sensitive data in order to be subsequently analyzed for medical diagnosis.

For elderly-care purposes, sensors can help for ambient (temperature, humidity and CO2) and elderly people monitoring, emergency and urgent event notification and communication and as a reminder for important items and medicaments usage [19].

Information about weight, heart rate and other related factors which have effect on fitness can be gathered over time. They can be analyzed periodically to help each person control and improve his/her own lifestyle.

Home/Building Automation/Control

Sensors can be used in home automation as light control, presence detection, temperature/humidity monitor and security/safety such as door/windows lock/unlock detection, intrusion detection and smoke/gas detection [12].

2.2.2 Backhaul Sensor/Meter Data

While some sensors are using IEEE802.15.4 and IEEE802.15.4g to provide a link for lower traffic leaf sensors with battery power constraints, IEEE802.11ah is going to co-exist with those standards and provide an appropriate feature as a backhaul link. IEEE 802.11ah works as an aggregator of those leaf sensors. The information of sensors need to be collected by IEEE 802.11ah STA and reported to IEEE 802.11ah AP for network management purposes and being able to get accessed through the Internet. The IEEE802.11ah should perform without degradation of throughput and reliability when co-existing with other standards. [20]

2.2.3 Extended Range Wi-Fi

This use case is an extension of traditional Wi-Fi. Operators need to operate and manage both IEEE 802.11 AP and IEEE 802.11 STA by the proxy of IEEE 802.11 AP.

One of the scenarios is extended range hotspots which are sites that offer Internet access over a WLAN. Wi-Fi is being increasingly used for hotspot applications around the world. These applications can benefit from extended range enabled by use of lower frequency bands in IEEE 802.11ah. Typical scenarios in which the extended range hotspot can be used are extended home coverage, campus wide coverage, shopping malls and so on. [21]

Other than hotspots, having extended range Wi-Fi can also help on cellular traffic offloading. IEEE 802.11 WLAN is considered as a good candidate for traffic offloading which is a solution to mobile traffic explosion. However, current IEEE 802.11 amendments have short coverage and mostly assume indoor environment. IEEE 802.11ah has large coverage (around 1 km), so it can be used for mobile traffic offloading in outdoor environments. [22]

2.3 Requirements

Functional requirements defined for IEEE 802.11ah are mandatory. It means that all proposals submitted to the IEEE 802.11ah task group must address these functional requirements.

IEEE 802.11ah should define an OFDM physical layer operating in the license-exempt bands below 1 GHz. It should have enhancements to the IEEE 802.11 Medium Access Control (MAC) to support this PHY, and provide mechanisms that enable coexistence with other systems in the bands including IEEE 802.15.4 and IEEE 802.15.4g. [10]

IEEE 802.11ah should support a mode of operation in which at least 100 Kbps PHY data rate is provided with coverage of 1 km. It also should have at least one mode of operation capable of achieving a maximum aggregate Multi-Station data rate of 20 Mbps as measured at the PHY data service access point (SAP) in sub-1 GHz band. The data rates defined in the amendment should optimize the rate vs range performance of the specific channelization in a given band. Regardless of the mode of operation and data rate, IEEE 802.11ah should maintain the network architecture of the IEEE 802.11 system for fixed, outdoor and point-to-multi-point applications and support compatibility to IEEE 802.11 management plane. [23]

Another requirement for IEEE 802.11ah is that it should support beyond 2007 stations for outdoor applications. It should also provide an enhanced power saving mechanism to support battery-powered operation with long replacement cycle. [23]

2.4 Medium Access Control Layer

The Medium Access Control (MAC) in IEEE 802.11 family is the second sublayer in Layer 2 of the network architecture based on the Open System Interconnection (OSI) model. The MAC layer provides coordinate access to the medium by controlling addressing and channel access.

When a unicast packet is sent from PHY to other stations, it will be like a boradcast message, meaning that the packet is heard by all the receivers within range. It is MAC which makes it possible for the destination device to be the only one decoding the packet. This is done by the IEEE 802 48-bit global address space which is used in whole IEEE 802 LAN family [24].

The MAC layer in each single device controls packets sent from that same device. It cannot directly control sending packets from other devices. Therefore, there are certain set of rules which should be followed by all the devices that are trying to communicate in a network. This set of rules is called MAC protocol. A MAC protocol is standardized to be used in IEEE 802.11 family networks and there are some modifications and enhancements which are introduced in IEEE 802.11ah.

2.4.1 MAC Frame Types

There are three main types of frames:

1. *Control Frames*: assist in the delivery of data frames. They are used for

addressing some wireless communication phenomena and controlling medium access of STAs in order to reduce collisions.

2. *Data Frames*: carry higher-level protocol data in the frame body. They have the responsibility of hauling data from one STA to another.

3. *Management Frames*: are used to exchange management information, but they do not belong to the upper layers.

2.4.2 MAC Frame Format

MAC frame consists of a set of fields that occur in a fixed order. The general MAC frame format is depicted in Figure 2.5. The first three fields (Frame Control, Duration/ID, and Address 1) and the last field (FCS) are present in all frames. The other fields are present only in certain frame types and subtypes.

Bytes: 2	2	6	0 or 6	0 or 6	0 or 2	0 or 6	0 or 2	0 or 4	0-7959	4
Frame Control	Duration /ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	QoS Conrol	HT Control	Frame Body	FCS

Figure 2.5. *IEEE 802.11ah generic MAC frame format [25]*

Each frame is divided into three parts: a MAC header, a variable length frame body and a Frame Check Sequence (FCS) which contains an IEEE 32-bit CRC for error detection. The MAC header comprises several fields:

- *Frame Control*: consists of several subfields. Type of a frame defines which subfields should be included in frame control. Frame control contains information about the frame type, fragmentation, power management and etcetera.

- *Duration/ID*: varies with frame type, but it is usually set to the time (in micro seconds) required to complete the current transmission. It can also carry the association identifier (AID) of the STA that transmitted the frame [3].

- *Address Fields*: used to identify the basic service set identifier (BSSID), source address (SA), destination address (DA), transmitting STA address (TA) and receiving STA address (RA).

- *Sequence Control*: indicates the sequence number of the frame. Sequence numbers are used for duplicate detection and recovery.

- *QoS Control*: determines the QoS policies desired for the corresponding frame transmitted by QoS-enabled STAs.

- *HT Control*: gives information about link adaptation, used MCS, antenna selection in MIMO and etcetera.

2.4.3 MAC Challenges

Wireless network environment has fundamentally different characteristics compared to traditional wired one. Two of this kind of differences which caused trouble in developing MAC layer for IEEE 802.11 are presented in the following. [11]

Unreliability

When wired communication is used, it is safe to assume that a transmitted frame is received correctly. However, in case of wireless communication, this assumption does not hold since transmissions in wireless communication are subject to noise, interference, fading and etcetera. Therefore, communication using a wireless medium is significantly less reliable than wired communications.

In order to compensate this unreliability, IEEE 802.11 standard makes use of positive acknowledgment (ACK) to ensure the correct reception of a transmitted packet as shown in Figure 2.6.

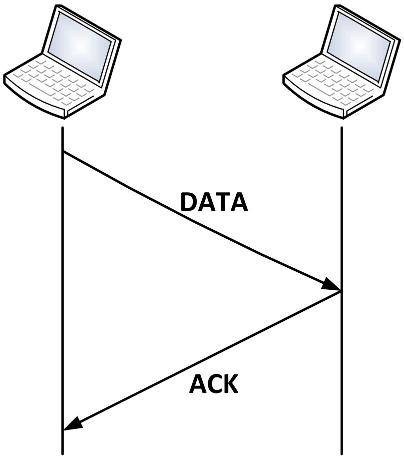

Figure 2.6. *Positive acknowledgment in IEEE 802.11*

The STA who sends the DATA packet must receive a correct ACK. There is no difference in having error in the DATA packet or in the ACK. In both cases, the DATA packet is considered to be lost and it will be retransmitted or dropped.

Hidden Node Problem

In wired communication, when a STA is sending a packet, all the other STAs in the network can sense that. Therefore, STAs do not start their transmissions when there is an ongoing transmission on the network. In wireless networks, each STA has some range defined by its transmission power and path loss. STAs outside this range cannot hear the transmission originated from that particular STA.

The hidden node problem in wireless communication occurs when two STAs not hearing each other, try to send their packets to the STAs placed in their common range. This phenomena is illustrated in Figure 2.7. [26]

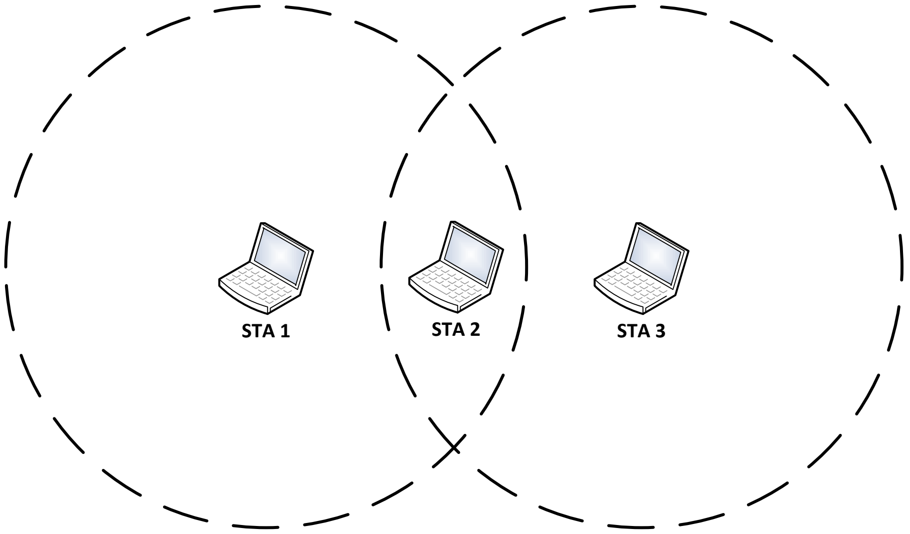

Figure 2.7. *Hidden node problem*

In Figure 2.7, STA 1 and STA 2 are hidden to each other, meaning that they are not in the range of one another. STA 1 is transmitting a packet to STA 2. Meanwhile, STA 3 which cannot detect any ongoing transmission starts sending its packet to STA 2. There will be collision in STA 2 because of simultaneous transmissions.

To prevent the hidden node problem, IEEE 802.11 introduced RTS and CTS. The RTS/CTS mechanism is shown in Figure 2.8.

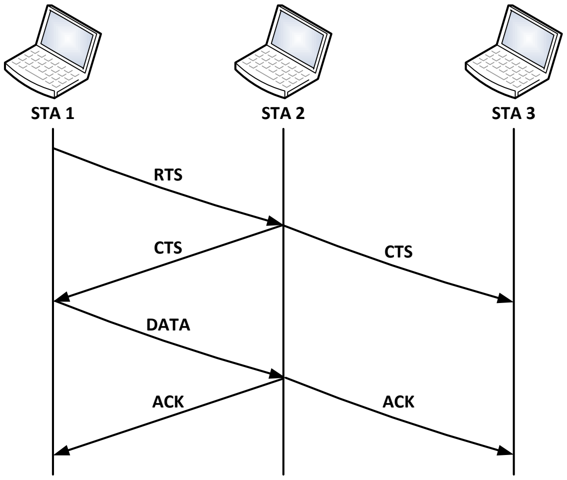

Figure 2.8. *RTS/CTS in IEEE 802.11 to avoid hidden nodes*

In Figure 2.8, STA 1 which is willing to send a DATA packet, starts the process by sending an RTS which reserves the channel for the whole duration of the process including receiving a CTS, sending a DATA packet and receiving an ACK. All the STAs in the range of STA 1 can hear RTS. Hearing RTS forces other STAs not to start any transmission before the whole process is finished. STA 2 which is the target STA responds to RTS with a CTS. CTS also reserves the channel for the whole process. STA 3 which is hidden to STA 1 hears the CTS and halts any possible transmission which results in reducing the number of collisions.

2.4.4 MAC Access Methods

There are several access methods defined in IEEE 802.11 family MAC to control accessing the wireless medium. Each access method uses a particular set of functions called coordination functions. Different coordination functions are shown in Figure 2.9 [6].

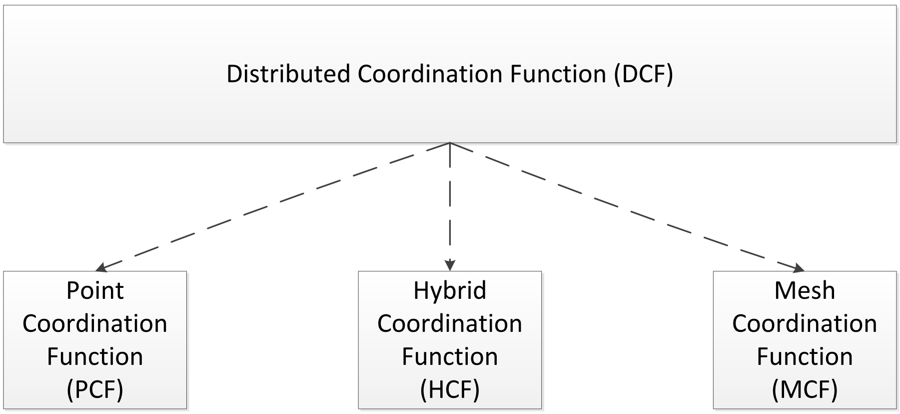

Figure 2.9. *IEEE 802.11 MAC coordination functions*

Distributed Coordination Function (DCF)

In DCF, STAs are contending to access the medium using carrier sense multiple access with collision avoidance (CSMA/CA) which is based on using a random backoff in each STA. It is partially similar to carrier sense multiple access with collision detection (CSMA/CD) which is used in wired communications like Ethernet. CSMA/CD is based on detecting collision while sending the packet and it requires full duplex devices which is currently difficult and too expensive in wireless communications [27].

DCF is the fundamental access method in IEEE 802.11. It means that it should be implemented in all the STAs using IEEE 802.11 standard while all the other coordination functions are optional [28]. For this reason, it is the only access method used in this thesis and discussed in more detail in section 2.4.7.

Point Coordination Function (PCF)

PCF which provides contention free access to the medium is only usable in infrastructure BSSs. In this access method, the access to the channel is determined centrally by the AP, usually referred to as the Point Coordinator (PC). PC which operates as a polling master determines which STA currently has the right to transmit. Therefore, it eliminates contention for a duration called contention free period (CFP). [29]

Hybrid Coordination Function (HCF)

QoS is not available in the previously mentioned coordination functions. HCF which provides this capability in QoS network configurations should be implemented in all QoS STAs except the ones using MCF [30]. HCF can be used in both contention based and contention free periods. Enhanced distributed channel access (EDCA) is referred to the HCF using contention based channel access while HCF controlled channel access (HCCA) for contention free transfer.

Mesh Coordination Function (MCF)

MCF is being used in Mesh BSSs to add mesh facility to these networks. MCF has both modes of contention free and contention based. MCF controlled channel access (MCCA) is referred to as MCF with contention free mechanism.

2.4.5 Interframe Spaces

To prioritize access to the medium, IEEE 802.11 uses time intervals between frames called interframe space (IFS). Each STA should detect the medium as idle for whole duration of its corresponding IFS. There are six different IFSs defined in the IEEE 802.11 which are listed according to their size, from the shortest to the longest in the following.

- *Reduced interframe space (RIFS)*: can be used to separate multiple transmissions from a single transmitter. It is not used in normal cases and it is just introduced to reduce the overhead of the network.

- *Short interframe space (SIFS)*: is the shortest IFS in normal transmissions. SIFS is used prior to sending an ACK and a CTS. It should also be used before sening a DATA packet when RTS/CTS is used. It is used in one transmission cycle to give highest priority to the ongoing transmission.

- *PCF interframe space (PIFS)*: is used by STAs using PCF during contention free operation.

- *DCF interframe space (DIFS)*: is used in DCF mode. A STA trying to initiate a new transmission cycle should wait for the medium to be idle for the whole duration of a DIFS.
- *Arbitration interframe space (AIFS)*: is used by QoS STAs in EDCA. AIFS does not have one particular value. The duration of a AIFS depends on the QoS class of the DATA packet which is going to be transmitted.
- *Extended interframe space (EIFS)*: is used in DCF under certain circumstances. A STA should use EIFS instead of DIFS in DCF if the last received packet was erroneous.

SIFS, DIFS and EIFS are the only IFSs used in this thesis, since DCF is the only coordination function covered. Duration of DIFS and EIFS are dependent on duration of SIFS and two other parameters as follows:

- *SlotTime*: is the main elementary timing parameter which is PHY dependent. SIFS should be able to cover for the hardware processing and propagation time of a packet.
- *ACKTxTime*: is the required time to transmit an ACK at the lowest data rate.

SlotTime, ACKTxTime and SIFS are defined by PHY's characteristics. DIFS and EIFS can be calculated using respectively equation (2.1) and equation (2.2).

$$\text{DIFS} = \text{SIFS} + 2 \times \text{SlotTime} \tag{2.1}$$

$$\text{EIFS} = \text{SIFS} + \text{DIFS} + \text{ACKTxTime} \tag{2.2}$$

2.4.6 Carrier Sensing Mechanisms

Except the time when the STA is transmitting and therefore knowing that the medium is busy, it needs an additional mechanism to check the state of the channel. Carrier sensing is used by each STA to determine whether the medium is busy or not. There are two types of carrier sensing used in IEEE 802.11: physical carrier sensing called Clear Channel Assessment (CCA) provided by PHY and virtual carrier sensing called Network Allocation Vector (NAV) provided by MAC. Medium is considered to be busy if either of these two mechanisms indicates a busy channel.

In physical carrier sensing, a busy indication should be raised when another signal is detected on the medium. However, having powerful noise on the same channel can be as harmful as having another signal. Therefore, PHY provides a busy medium recognition based on the detection of any signal energy above a given threshold called sensitivity or any other energy above 20 dB higher than sensitivity. [6]

By using NAV, STAs can predict the future traffic on the channel without detecting any energy on it. NAV is a counter which shows a busy medium when it is nonzero. RTS and CTS which are sent prior to the actual exchange of DATA contain the needed information in their duration field. Each STA hearing an RTS or a CTS can update its NAV based on those information and can predict the time needed for the whole transmission cycle to be finished. An example of using RTS/CTS information for NAV is illustrated in Figure 2.10.

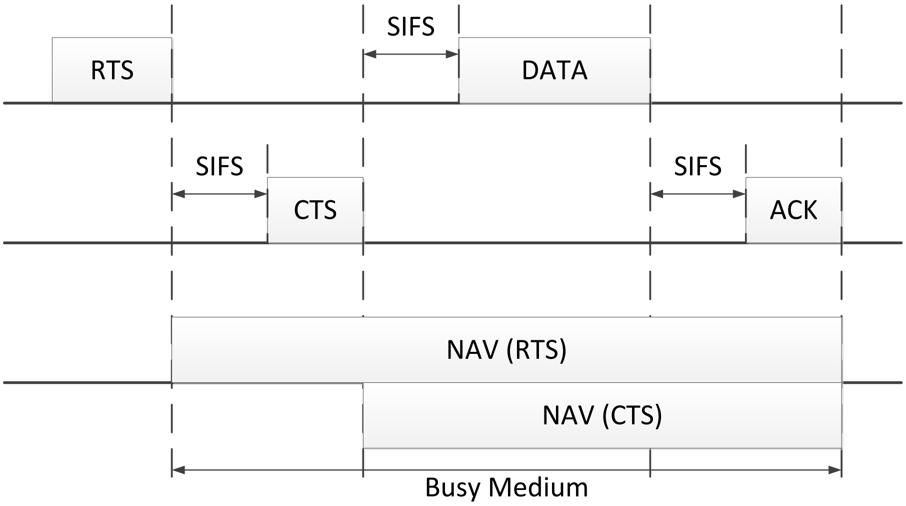

Figure 2.10. *Virtual carrier sensing (NAV) in IEEE 802.11*

If a STA receives a new packet with new NAV information (duration), it should update its NAV if the new value is greater than the previous one. All the NAV values should be in microseconds. Therefore, it should be rounded up to the next higher integer if the calculated duration contains a fractional microsecond.

A STA that updated its NAV based on information in an RTS frame is permitted to reset its NAV if no transmission detected during a period with a certain duration. Let's assume that this permission is not considered and there is an error in RTS, then there will be no CTS and therefore no DATA and ACK. However, the medium is going to be wasted for the whole duration of DATA transmission cycle because of NAV information in RTS.

2.4.7 DCF

DCF which is based on CSMA/CA is the only mandatory coordination function implemented in all the STAs in an IEEE 802.11 network. It is used by the STAs to access the medium when there is no Point Coordinator in the network, or in the contention period of PCF.

There are two different mechanisms to send DATA packets defined in IEEE 802.11 which are introduced earlier. One is called Basic Access scheme (two-way handshake) and the other one is RTS/CTS Access scheme (four-way handshake).

In the basic access, sender of the DATA packet starts the transmission cycle by sending the DATA packet itself. The receiver waits for a SIFS period after completely receiving the DATA packet and then sends an ACK.

To overcome to the hidden node problem and avoid wasting the channel in collisions because of having large DATA packets, IEEE 802.11 uses the RTS/CTS access scheme. In this mechanism, the sender requests for the right to start the DATA packet transmission by sending a Request to Send (RTS). In response, the receiver sends a Clear to Send (CTS) after a SIFS interval. Subsequently, the requesting station is allowed to start the data frame transmission after a SIFS period. The procedure can be seen in Figure 2.10.

Both of the above mentioned access schemes can be started once the sender of the DATA packet gets access to the medium after contending with other STAs. A STA will get the channel and will be able to initiate the transmission cycle if it senses the medium to be idle for greater than or equal to a DIFS period, or an EIFS period if the previous busy medium was caused by detection of a frame that had an error in it. Since DIFS interval is longer than SIFS interval, the ongoing transmission cycle has priority in accessing the channel and it will not be stopped by any of the other transmissions. If the STA senses a busy medium before initiating the transmission cycle or it is not the first attempt to send the DATA packet, the random backoff procedure should be followed for getting access to the channel. Figure 2.11 shows two STAs using basic access scheme accessing the channel, one without backoff procedure and one with it.

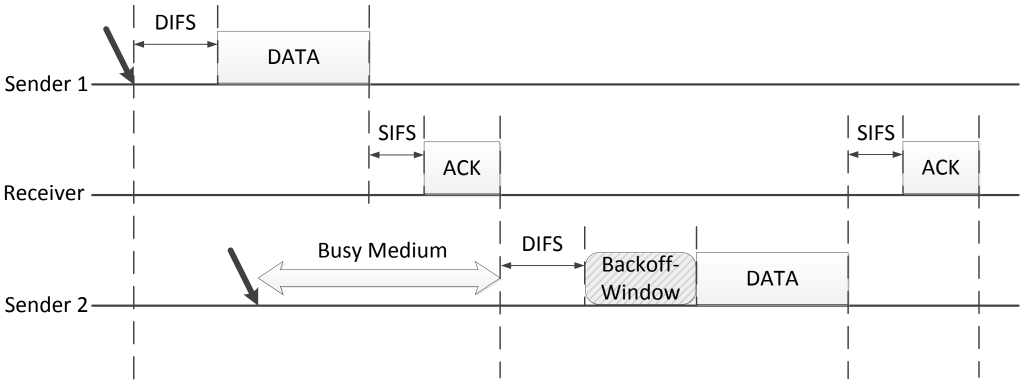

Figure 2.11. *Enabling random backoff procedure in basic access scheme*

Backoff Procedure in DCF

As explained in the previous section, a station operating in DCF must always wait for an idle DIFS interval after a busy channel. However, multiple stations might have been waiting for a particular transmission cycle to be finished. Therefore, they will all start and end their DIFS period together. If no other rule applies, there will certainly be collisions after each transmission cycle. Random backoff procedure is the solution to the mentioned problem.

Random backoff procedure or backoff procedure is the mechanism used in DCF to distribute the access to the channel between the STAs while assuring fairness among them. This is done by forcing the STAs to wait for additional uniformly random duration.

In the certain cases which are discussed in the previous section, a STA is forced to follow backoff procedure. In the first step, if the backoff counter is zero, the STA chooses a random integer from a uniform distribution over the interval [0,CW] and stores it in the backoff counter. CW is an integer from a range of predefined integers defined between CWmin and CWmax which are two PHY characteristics defined in each amendment.

If the STA fails to successfully send the DATA packet, which means regardless of the reason, it cannot get a correct corresponding ACK, then it should retransmit the DATA packet. Let N_{retry} represent the Nth retransmission of a certain DATA packet, starting from zero for the first attempt, then CW is calculated as follows:

$$\text{CW} = \min((2^{N_{\text{retry}}} \times (\text{CWmin} + 1)) - 1, \text{CWmax}). \tag{2.3}$$

When the random integer number for waiting is chosen, the STA should use CS mechanism and wait for an idle DIFS or EIFS to be able to decrease the backoff counter. After that, the STA should decrement its backoff counter by one, each time it is able to see a complete idle SlotTime. The backoff procedure would be suspended as soon as a busy medium is detected by CS mechanism. Then the STA should again wait for an idle DIFS or EIFS and then try to decrement its backoff counter. When the backoff counter reaches zero, the STA will initiate its transmission cycle. An example of this procedure is illustrated in Figure 2.12.

Error Recovery in DCF

Error in transmission cycle can happen in any of the involved packets. It can be due to collision in the transmission initiation or due to the channel effects or any other possible reasons. When an error occurs in a transmission cycle, regardless of the packet which contains the error, it is responsibility of the STA that has initiated the transmission cycle to recover that by trying to retransmit the DATA packet.

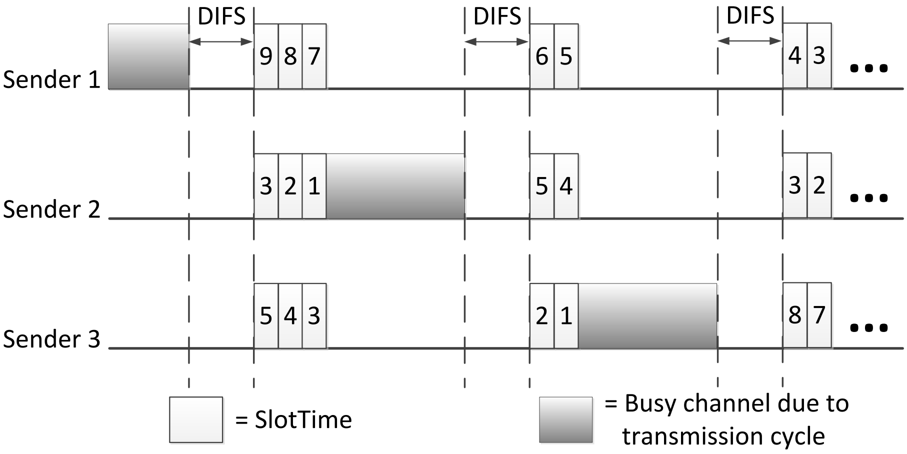

Figure 2.12. *Backoff procedure example in DCF*

There are two different retry counters defined in each STA, namely STA Short Retry Count (SSRC) and STA Long Retry Count (SLRC). When the RTS/CTS scheme is used and there is an error in RTS transmission, SSRC will be incremented by one and it will be reseted to zero as soon as a correct CTS is received. A STA decides that there is an error in RTS when the corresponding CTS is not received correctly or no packet reception is started within an interval called CTSTimeout. When a DATA packet is sent and the corresponding ACK is not received correctly or no packet reception is started within an interval called ACKTimeout, SLRC will be incremented by one.

There are certain limits defined for SSRC and SLRC. The limit for SSRC is called ShortRetryLimit and LongRetryLimit is the upper bound for SLRC. The packet will be dropped when either of these retry counters reaches its limit. Retransmission procedure should continue until the transmission cycle is successful, or the packet is dropped. In Both cases, SSRC and SLRC should be reseted to zero.

2.5 Physical Layer

The IEEE 802.11 standard specifies different PHY layers for exchanging packets between different MACs and various media. It defines four different transmission techniques, namely Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), Orthogonal Frequency Division Multiplexing (OFDM) and Infra Red (IR) [31].

Regardless of transmission techniques, PHY is divided into two sublayers: Physical Layer Convergence Procedure (PLCP) and Physical Medium Dependent (PMD). PLCP which is placed between MAC and PMD, maps MAC frames into a frame format suitable for transmission by the PMD. PMD is the unit responsible for actual transmission and reception of the PHY entities through the wireless medium including modulation and demodulation and having interface with air medium. [32]

IEEE 802.11ah which operates on sub-1 GHz is based on OFDM technology and has its unique PLCP and PMD layers. In this section, some basic topics related to IEEE 802.11ah is discussed.

2.5.1 Channelization

Physical layer of the IEEE 802.11 is based on 10-times down-clocked version of PHY of IEEE 802.11ac. To achieve higher data rates, in addition to 20 MHz and 40 MHz channel bandwidths defined in IEEE 802.11n, IEEE 802.11ac provides 80 MHz, 160 MHz and non-contiguous 160 MHz channel bandwidths. Therefore, 2 MHz, 4 MHz, 8 MHz, and 16 MHz channels are defined in IEEE 802.11ah. In addition to the previous channels, IEEE 802.11ah introduces a new 1 MHz channel to be able to achieve higher coverage defined in this amendment. [33]

IEEE 802.11ah has defined the channelization based on the available wireless spectra in various countries, for example, 863-868 MHz (Europe), 916.5-927.5 MHz (Japan), 755-787 MHz (China), 917.5-923.5 MHz (South Korea), 866-869 MHz, 920-925 MHz (Singapore) and 902-928 MHz (U.S.), because of different available sub-1 GHz ISM bands in different countries.

2.5.2 Channel and Path Loss Models

There are different channel models and path losses defined for IEEE 802.11ah. Based on being outdoor or indoor, they are listed as follows [35]:

Outdoor

The outdoor channel models are based on 3GPP/3GPP2 spatial channel model (SCM) [36] which are used for both SISO and MIMO links. Path loss models for the outdoor scenarios are listed as follows [37]:

- *Macro deployment*: For the cases where antenna hight is 15m above rooftop, the path loss in dB is given by the formula $PL = 8 + 37.6 \times \log_{10}(d)$.
- *Pico/Hotzone deployment*: If the antenna hight is assumed at rooftop, then the path loss would be $PL = 23.3 + 36.7 \times \log_{10}(d)$.
- *Device to device*: This refers to the cases where antenna height is assumed to be 1.5m. The path loss formula in these cases is $PL = -6.17 + 58.6 \times \log_{10}(d)$.

The above mentioned path loss formulas are tuned for carrier frequency equal to 900 MHz where d is the distance in meters. For the first two path loss models, in other frequencies, a correction factor of $21 \times \log_{10}(f/900\text{MHz})$ and 10 dB penetration loss should be added when the AP is outdoor and STAs are indoor.

Indoor

For the indoor scenarios, the indoor channel model is based on the IEEE 802.11n channel models [38] with relevant changes developed for TGac [39]. The path loss model defined for indoor scenarios is calculated as follows:

$$PL = PL_{FreeSpace} = 20 \times \log_{10} \frac{4\pi d \times 900\text{MHz}}{C} \qquad ford \leq d_{BP} \qquad (2.4)$$

$$PL = PL_{FreeSpace} + 35 \times \log_{10} \frac{d}{d_{BP}} \qquad ford > d_{BP} \qquad (2.5)$$

where d is the distance in meters and C is the speed of light.

The above formulas are valid for single floor scenarios. Multi floor scenarios and other details regarding this path loss model can be found in [35].

2.5.3 Modulation and Coding Scheme (MCS)

IEEE 802.11ah supports different transmission modes ranging from the most robust one to the one with the highest data rate. These transmission modes are dependent on the used modulation and coding. Therefore, they are also called Modulation and Coding Schemes (MCS).

OFDM subcarriers in IEEE 802.11ah are modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM), 64-QAM and 256-QAM. Binary convolutional and LDPC codings are two types of Forward error correction (FEC) coding which are employed with coding rates (R) of 1/2, 2/3, 3/4 and 5/6.

Set of MCS and its corresponding data rates is dependent on bandwidth of the channel, number of spatial streams N_{ss} in MIMO and the used Guard Interval (GI). Throughout this thesis, BW is assumed to be 2 MHz, N_{ss} is 1 since MIMO is not used and GI is set to 8us. Table 2.1 shows the set of MCSs provided in IEEE 802.11ah with the specified parameters [3].

A brief description of the mentioned parameters and some common ones which are not specified in Table 2.1 can be seen in the following:

- N_{BPSCS} is the number of coded bits per subcarrier per spatial stream.
- N_{CBPS} is the number of coded bits per symbol.
- N_{DBPS} is the number of data bits per symbol.

Table 2.1. *IEEE 802.11ah MCSs for 2MHz, Nss = 1, GI = 8us*

Index	Modulation	R	N_{BPSCS}	N_{CBPS}	N_{DBPS}	Data rate (Kbps)
0	BPSK	1/2	1	52	26	650
1	QPSK	1/2	2	104	52	1300
2	QPSK	3/4	2	104	78	1950
3	16-QAM	1/2	4	208	104	2600
4	16-QAM	3/4	4	208	156	3900
5	64-QAM	2/3	6	312	208	5200
6	64-QAM	3/4	6	312	234	5850
7	64-QAM	5/6	6	312	260	6500
8	256-QAM	3/4	8	416	312	7800

- N_{SD} is the number of data subcarriers per OFDM symbol and is always equal to 52.

- N_{SP} is the number of pilot subcarrier per OFDM symbol and is always equal to 4.

3. SYSTEM-LEVEL SIMULATION MODEL

Network simulators are being widely used for different purposes like evaluating the performance of new protocols, testing changes and extensions to the existing ones, allowing network administrators to detect and correct potential problems before deploying a complex (and possibly expensive) scenario and lots of other examples. By using network simulators, the behavior of a real system can be mimicked while lots of money and time can be saved compared to setting up an entire testbed containing multiple networking devices.

However, network simulators are not perfect. They can not perfectly model all the details of the networks. If well modeled, they will be close enough to give a meaningful insight into the network under test, and how changes will affect its operation. The accuracy of a network simulation in following a real system's behavior depends on lots of parameters including processing power, time limitations, details included in simulator and etcetera. One of the main parameters is the tool used for simulating the network. There are over a dozen network simulators like ns-2 [40], ns-3 [41], OMNeT++ [42], JiST [43] and OPNET [44]. As suggested in [45], OMNeT++ which is employed to perform the simulations in this thesis is one of the best options currently available.

First part of this chapter tries to introduce the OMNeT++. The common simulation model's settings used throughout this thesis is presented in the last part.

3.1 OMNeT++

OMNeT++ is an object-oriented modular discrete event network simulation framework [46]. In discrete event system simulators, the state variable changes only at a discrete set of points in time [47]. In contrast to aforementioned simulators, OMNeT++ is not a network simulator by definition, but a general purpose simulation framework which has generic architecture to be used in various problem domains:

- modeling of communication networks
- protocol modeling
- modeling of queuing networks
- modeling of distributed hardware systems

- validating of hardware architectures
- evaluating performance aspects of complex software systems
- ...

One of the main features of the OMNeT++ is its component-based architecture. Models of OMNeT++ are assembled from reusable components called modules which can be combined in various ways. Simple modules are the ones that can not be divided any further. A compound module consists of simple modules and other compound modules. Depth of the compound modules hierarchy is unlimited in OMNeT++. Figure 3.1 illustrate this hierarchy.

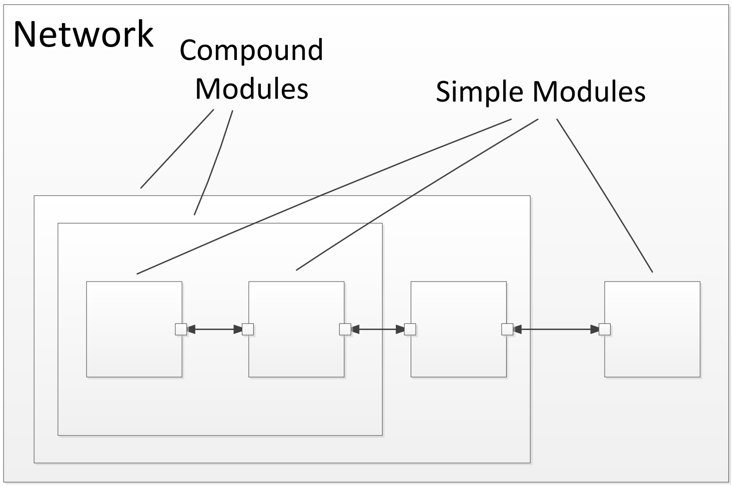

Figure 3.1. *Modules in OMNeT++*

OMNeT++ rests upon C++ for the implementation of simple modules. However, the composition of these simple modules into compound modules and thus the setup of network simulation takes place in NED, the network description language of the OMNeT++. NED is transparently rendered into C++ code when the simulation is compiled as a whole. Moreover, NED supports the specification of variable parameters in the network description. For example the number of nodes in a network can be marked to be dynamic and later on configured at runtime. In this case, the modules representing the nodes are dynamically instantiated by the simulator during execution. This feature is a direct consequence of the simulator's strict object-oriented design. [45].

Modules communicate by exchanging messages. Messages can contain arbitrarily complex data structures. Simple modules can send messages either directly to their destination or along a predefined path, through gates and connections. In a network simulation, messages can represent frames or packets or can be used to deliver information from one layer to the other one. Messages can arrive from another module or even from the same module to implement timers.

Gates are the input and output interfaces of modules. Messages are sent out through output gates and arrive at input gates.

Each connection (also called link) is created within a single level of the module hierarchy, meaning that within a compound module, a connection can connect the corresponding gates of two submodules, or a gate of one submodule and a gate of the compound module. [46]

OMNET++ provides two user interfaces, namely TKENV and CMDENV. TKENV which is OMNET++'s graphical user interface (GUI) provides three methods:

- *Automatic animations*: is capable of animating the flow of messages on network charts.
- *Module output windows*: are able to open separate windows for the output of individual modules or module groups.
- *Object inspectors*: is a GUI window associated with a simulation object. It can be used to display the state or contents of an object in the most appropriate way as well as manually modifying the object.

These methods in addition to some other features in OMNeT++ provide powerful capabilities which makes writing extra code by the simulation programmer for tracing and debugging unnecessary. CMDENV is a pure command-line interface which is useful for batched simulation runs. [48] [49]

There are other components in OMNeT++ listed below which make it one of the most powerful yet easy-to-work-with simulating tools:

- Simulation kernel library
- Compiler for the NED topology description language (nedc)
- Graphical network editor for NED files (GNED)
- Graphical output vector plotting tool (Plove)
- Graphical output scalars visualization tool (Scalars)
- Model documentation tool (opp_neddoc)
- Utilities (random number seed generation tool, makefile creation tool, ...)
- Documentation, sample simulation and etcetera.

As mentioned before, OMNeT++ is a general purpose simulation framework not a network simulator. There are lots of frameworks built upon OMNeT++ for various purposes including communication networks. The developed IEEE 802.11ah system-level simulator used in this thesis is based on INET framework [50], which is an open-source communication networks simulation package. Providing several application and link layer models, TCP protocol implementations, support for mobile and wireless simulations and other communications related capabilities make INET a powerful tool for simulating communication networks.

3.2 Simulation Model's Settings

The developed IEEE 802.11ah system-level simulator provides possibility to change all the simulation settings whenever needed. In contrast to some settings which need to be changed from one run to another, like the number of nodes, there are some settings which are fixed during all the simulations. This section presents the common parameters used in all the simulations throughout this thesis and they are fixed unless otherwise specified.

3.2.1 IEEE 802.11ah Constants

These fixed simulation settings are mostly the constant parameters defined in IEEE 802.11ah amendment. They are the current values specified for IEEE 802.11ah and they might change in the future since IEEE 802.11ah is still under development. Table 3.1 summarizes these fixed parameters and their corresponding values.

Table 3.1. *System parameters*

T_{sym}	40 us
MAC header	14×8 bits
PHY header	$6\times T_{\text{sym}}$
ACK	PHY header
RTS	20×8 bits + PHY header
CTS	PHY header
Basic data rate	650 Kbps (MCS 0)
SlotTime	52 us
SIFS	160 us
DIFS	SIFS + 2×SlotTime
m_{short}	7
m_{long}	4
CWmin	15
CWmax	1023

In Table 3.1, m_{short} and m_{long} are respectively ShortRetryLimit and LongRetryLimit and T_{sym} is the duration of an OFDM symbol which is constant and does not depend on the used MCS.

It should be noted that MAC refers to the length of MAC header in bytes. PHY header should be sent with the most robust MCS (MCS 0), which is referred to as the basic data rate. Therefore, it always requires a certain amount of OFDM symbols to be transmitted. Since T_{sym} is constant, the time it takes to transmit the PHY header is constant. PHY shows the time it takes to send the PHY header, not the length of that in bytes.

3.2.2 Environment

Since the purpose of this study is not to evaluate the ad-hoc scenario, which is also implemented in the simulator, and infrastructure BSSs are the target of this study, there is always at least one AP in the network serving variable number of sensors. Therefore, based on the number of APs available in the network, simulations can be divided into the following two groups:

One Cell

In case of having only one AP in the network, all the STAs are associated to that particular AP. It requires all the STAs to be in the basic service area served by the AP, meaning that the STAs are positioned with a uniformly random distribution in a circle defined by the AP in the center and radius equal to maximum distance in which power of the signal transmitted by the AP is still higher than the sensitivity. Transmission from STAs to the AP are guaranteed to be heard by the AP by using equal transmission powers in STAs and AP.

The transmission power of the STAs is assumed to be 1 mW. Taking into account the transmission power and path loss model, radius of the coverage area can be calculated with respect to minimum sensitivity level.

Since the maximum coverage is the radius of the circle, it is possible that two STAs in two different sides of the AP cannot hear each other's transmissions. Therefore, they will be hidden node for one another.

Multi Cell

If the number of APs are higher than one, then the STAs are associated to their nearest AP. Each STA choose its nearest AP based on the SNR of the received beacons. Similar to the case with one AP, STAs are positioned with a uniformly random distribution. However, the simulation environment is not a circle and its shape varies in these simulation scenarios.

3.2.3 Channel Effects

The path loss model employed in this thesis is the macro deployment path loss model described in 2.5.2. The thermal noise is added as the background noise which is calculated based on the following equation:

$$P_{watt} = kTB. \tag{3.1}$$

In (3.1), k is Boltzmann's constant in joules per kelvin which is equal to 1.38×10^{-23}, T is the temperature in kelvins and it is assumed to be 300 and B which is the bandwidth equals to 2 MHz. Therefore, thermal noise would be -111 dBm. It should be noted that 7 dB is added to this value as the receiver noise figure.

3.2.4 Beacon

Beacon frame is one of the management frames in IEEE 802.11 networks. Beacon frames are transmitted by the Access Point (AP) periodically in an infrastructure BSS. Beacon contains all the information about the network.

Although DCF is the only coordination function employed in this thesis and there is no need to have beacons sent by the AP in such scenarios, in order to make the simulations closer to the real cases and also to implement some extra features, beacons are considered during simulations.

Beacon interval is assumed to be 100ms and beacons are sent using basic data rate. The duration of a beacon frame is 1280us.

3.2.5 Traffic

Uplink data is the only source of traffic considered. It means that AP does not send DATA packet to the STAs and STAs should always initiate the transmission cycle.

Since there is no downlink data available in the network and the only receiver for uplink data is the AP, STAs can be sure that they are not needed in any activity in the network as long as they do not have anything to send. Therefore, in order to save power, STAs will go to sleep mode if they do not have any DATA packet in their transmission queue.

There are mainly two traffics considered: saturation and non-saturation. Saturation scenarios are the ones in which STAs always have a packet to transmit and their transmission queue is never empty. In non-saturation cases, each STA generates DATA packets periodically with an interval equal to a beacon interval. In order not to have collisions periodically, the start of packet generation is distributed in a uniformly random manner in an interval with duration of beacon interval starting at the start of the simulation time.

3.2.6 DATA Packet's Size and Sensitivity

One of the use cases of the IEEE 802.11ah is the sensors and meters which is exploited in the Internet of Things (IoT).

IoT will introduce a novel dimension to the world of information and communication technology where connectivity is available anytime, anywhere, and for anything [51]. Consequently, this will implicitly mean a huge number of devices and stations that need to communicate with the IoT network. The Wireless World Research Forum predicts that by 2017, there will be 7 trillion wireless devices serving 7 billion people [52]. Most of these wireless devices are going to operate in IoT. Therefore, one of the most important use cases for IEEE 802.11ah are IoT networks.

For this reason, the chosen DATA packet's size (L_{payload}) is the same as the one specified in IoT use cases, equal to 256 Bytes [23]. For this use case, the packet error ratio (PER) should be less than 10%, which results in the minimum sensitivity levels shown in Table 3.2 [3].

Table 3.2. *Minimum sensitivity level for various MCSs when* $L_{\text{payload}} = 256$ *Bytes*

MCS index	Data rate (Mbps)	Minimum Sensitivity (dBm)
0	0.65	-92
1	1.30	-89
2	1.95	-87
3	2.60	-84
4	3.9	-80
5	5.2	-76
6	5.85	-75
7	6.5	-74
8	7.8	-69

3.2.7 Energy Consumption Parameters

For evaluating the performance from energy consumption point of view, which is mostly calculated in mJ/bit to show the energy consumed to send one correct bit of payload, each state of the transceiver should have a particular power consumption.

Table 3.3 summarizes the energy consumption in different modes of a STA with respect to the transmission power which is equal to 1 mW. Transmission mode is only used for sending RTS and DATA, receiving mode refers to receiving beacon, CTS and ACK, sleep mode refers to the times when STA does not have anything to send and all the other timings are considered to be idle. It should be noted that values corresponding to receiving and sensing modes are assumed to be the same since the baseband processing energy consumption which is the additional energy in the receiving mode is negligible compared to the whole receiving energy consumption.

Table 3.3. *Energy consumption values in different modes*

Mode	Energy consumption (mW)
Transmission	255
Receive and channel sensing	135
Sleep	1.5

4. PERFORMANCE EVALUATION

In order to evaluate the quality of IEEE 802.11ah prior to its deployment, its performance should be predicted by IEEE 802.11ah network simulator. The performance can be evaluated in different scenarios with respect to various parameters. For example, a simulation can evaluate the fairness of a network when there is no error in the sent packets or throughput can be predicted when a certain DATA packet size is used or etcetera.

Another alternative to evaluate the performance of a system is to model that analytically which is faster in providing a reliable network's performance. However, due to the complexity of these models, there are always some significant assumptions to simplify them which make the analytical models not complete.

The problem with network simulator is that they cannot be trusted if they are not tested with some alternative reliable sources. For this reason, network simulators are usually tested with analytical models with some basic assumptions to check if they are reliable, then the assumptions are corrected and network simulators will be the only source to model complicated networks.

In this chapter, the network simulator is tested with two different analytical models. In the last part, the basic performance of a IEEE 802.11ah network is evaluated using the IEEE 802.11ah OMNeT++ model.

4.1 Maximum Throughput of IEEE 802.11ah

The theoretical maximum throughput (TMT) that can be achieved in an IEEE 802.11 network depends on the DATA packet size and the constants specified in each amendment [53].

In this section, TMT is calculated for the IEEE 802.11ah. In the analysis, the behavior of a single station which always has a packet available for transmission is studied for both cases where RTS/CTS procedure is used and not used (basic access mechanism). For this study, the following assumptions are made:

- Beacons are not considered.
- There is no error in transmission of frames (BER = 0).
- There are no losses due to collisions.

- Propagation delay is not considered.

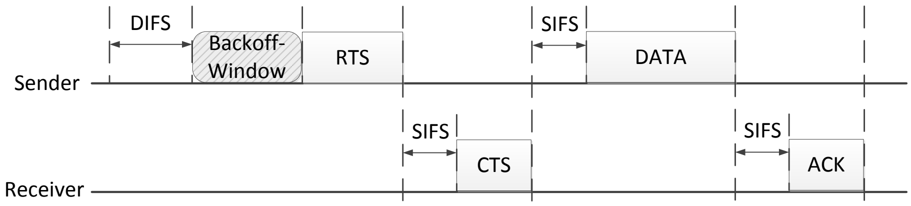

Figure 4.1. *One complete transmission cycle in RTS/CTS access scheme*

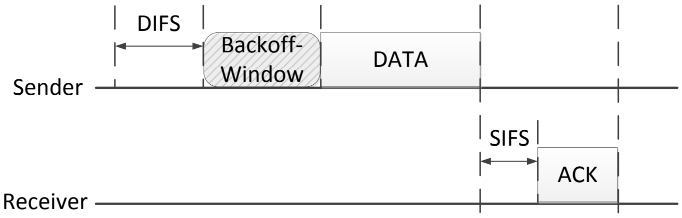

Figure 4.2. *One complete transmission cycle in basic access scheme*

Based on the previous assumptions, once a transmission cycle is started, it is assured that it would be successful. Therefore, in order to calculate TMT in bits per second, the size of the DATA packet in bits should be divided by the time it takes for having a complete transmission cycle. Based on Figure 4.1 and Figure 4.2, TMT for RTS/CTS and basic access schemes can be written as (4.1) and (4.2) respectively.

$$TMT^{\text{rts}} = \frac{8 \times L_{\text{payload}}}{\text{DIFS} + T_{\text{BO}} + \text{RTS} + \text{CTS} + \text{DATA} + \text{ACK} + 3 \times \text{SIFS}} \tag{4.1}$$

$$TMT^{\text{basic}} = \frac{8 \times L_{\text{payload}}}{\text{DIFS} + T_{\text{BO}} + \text{DATA} + \text{ACK} + \text{SIFS}} \tag{4.2}$$

RTS, CTS, DATA and ACK specified in (4.1) and (4.2) are the duration of those packets and T_{BO} is the average time taken for backoffs before initiating the transmission cycle.

Since there is no error in the transmission of packets, the contention window will not increase exponentially. Therefore, T_{BO} is constant and can be calculated as follows

$$T_{\text{BO}} = \frac{\text{CWmin}}{2} \times \text{SlotTime}. \tag{4.3}$$

In addition to PHY header; RTS, CTS and ACK which are control frames should be also sent with the basic data rate. Therefore, duration of the control frames can be calculated using (4.4).

$$T_{\text{control}} = \text{ceil}\left(\frac{8 \times L_{\text{control}}}{L_{\text{sym}}^{\text{basic\_datarate}}}\right) \times T_{\text{sym}} + \text{PHY} \tag{4.4}$$

Use of ceiling in the equation is due to using OFDM as the transmission technique which requires integer number of symbols to be transmitted for each packet.

The difference between duration of the DATA and control frames is that the DATA packets can be sent using any MCS available. Therefore, data rate should also be taken into account in the calculation of the duration of the DATA packets. Duration of DATA packets is expressed in (4.5) in which R shows the data rate used to send the DATA packet and $L_{\text{sym}}^{\text{basic\_datarate}}$ represents the number of data bits in one OFDM symbol (N_{DBPS}) when basic data rate is used which is equal to 26 bits as can be seen in Table 2.1.

$$T_{\text{data}} = \text{ceil}\left(\frac{8 \times (L_{\text{payload}} + \text{MAC})}{\frac{R}{\text{basic\_datarate}} \times L_{\text{sym}}^{\text{basic\_datarate}}}\right) \times T_{\text{sym}} + \text{PHY} \tag{4.5}$$

Figure 4.3 shows the TMT, calculated for three different MCSs of IEEE 802.11ah, with lines representing the analytical formulas and symbols showing the simulation results.

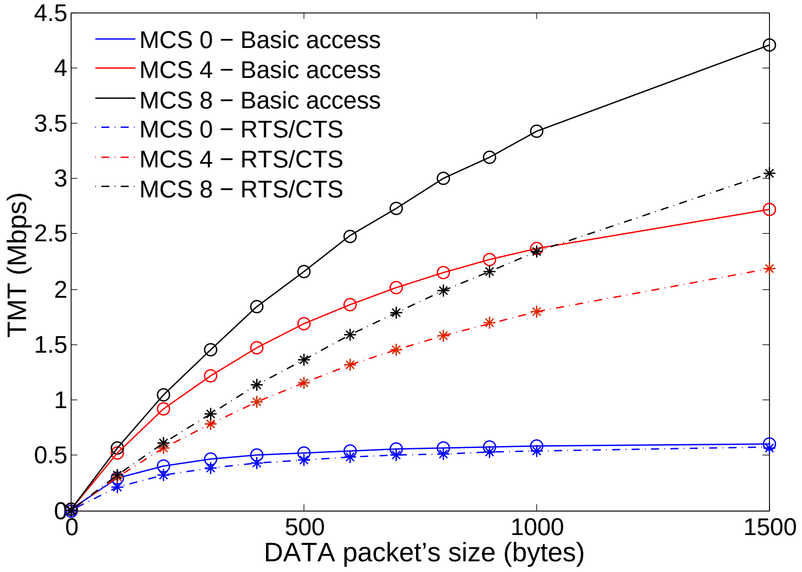

Figure 4.3. *Theoretical maximum throughput of IEEE 802.11ah*

Since the analytical model is proved to be precise [53], perfect matching of analytical and simulation results proves the accuracy of the simulator. As it was expected, since there is neither collisions nor errors in the transmissions, basic access scheme has the better performance in all the MCSs, compared to RTS/CTS scheme, due to not being forced to send excessive packets in each transmission cycle.

4.2 Throughput and Energy Efficiency Analysis

In this section, saturation throughput and energy efficiency of IEEE 802.11ah are analyzed by a a new analytical model discussed in [54]. The difference between this study and the previous one is that the DATA packet size is fixed to the default value (256 Bytes) and errors due to collision and channel effects are considered in this analysis. It is assumed that probability of having collision (p_c) and packet error probability for DATA packets (p_e) are known.

Let us first consider a system using RTS/CTS mechanism. In this case, S^{rts} which represents the throughput in bits per second can be calculated by (4.6).

$$\begin{aligned} S^{\text{rts}} = & \frac{p_s^{\text{rts}} \times 8 \times L_{\text{payload}}}{\sum_{i=0}^{m_{\text{short}}-1} \sum_{j=0}^{m_{\text{long}}-1} \left(\binom{i+j}{i} p_c^i p_e^j (1-p_c)^{j+1} (1-p_e) T_{i,j}(R) \right)} \\ & \times \frac{1}{\sum_{j=0}^{m_{\text{long}}-1} \left(\binom{j+m_{\text{short}-1}}{m_{\text{short}-1}} p_c^{m_{\text{short}}} p_e^j (1-p_c)^j T_{m_{\text{short}},j}(R) \right)} \\ & \times \frac{1}{\sum_{i=0}^{m_{\text{short}}-1} \left(\binom{i+m_{\text{long}-1}}{m_{\text{long}-1}} p_c^i p_e^{m_{\text{long}}} (1-p_c)^{m_{\text{long}}} T_{i,m_{\text{long}}}(R) \right)} \end{aligned} \tag{4.6}$$

$T_{i,j}(R)$ used in (4.6) shows the average time it takes for a successful transmission in case of having i collision and j error in sending the DATA packet. It is calculated as follows:

$$\begin{aligned} T_{i,j}(R) = & \, i \times T_c^{\text{rts}}(R) + j \times T_e^{\text{rts}}(R) + T_s^{\text{rts}} + \text{SlotTime} \\ & \times \sum_{k=0}^{i+j} \frac{\min(2^k(\text{CWmin}+1), \text{CWmax}+1)}{2}. \end{aligned} \tag{4.7}$$

$T_{m_{\text{short}},j}(R)$ and $T_{i,m_{\text{long}}}(R)$ refer to the average time taken from the channel to drop a packet due to exceeding respectively m_{short} and m_{long}. $T_j^{m_{\text{short}}}(R)$ is calculated using (4.8) and $T_i^{m_{\text{long}}}(R)$ is expanded in (4.9).

$$\begin{aligned} T_{m_{\text{short}},j}(R) = & \, m_{\text{short}} \times T_c^{\text{rts}}(R) + j \times T_e^{\text{rts}}(R) + \text{SlotTime} \\ & \times \sum_{k=0}^{j+m_{\text{short}-1}} \frac{\min(2^k(\text{CWmin}+1), \text{CWmax}+1)}{2} \end{aligned} \tag{4.8}$$

$$\begin{aligned} T_{i,m_{\text{long}}}(R) &= i \times T_c^{\text{rts}}(R) + m_{\text{long}} \times T_e^{\text{rts}}(R) + \text{SlotTime} \\ &\times \sum_{k=0}^{i+m_{\text{long}-1}} \frac{\min(2^k(\text{CWmin}+1), \text{CWmax}+1)}{2}. \end{aligned} \tag{4.9}$$

In (4.6), p_s^{rts} shows the probability of having the packet transmitted successfully and is expressed in (4.10).

$$p_s^{\text{rts}} = \sum_{i=0}^{m_{\text{short}}-1} \sum_{j=0}^{m_{\text{long}}-1} (\binom{i+j}{i} p_c^i p_e^j (1-p_c)^{j+1}(1-p_e)) \tag{4.10}$$

T_c^{rts} is the time it takes for having a collision, T_e^{rts} is the time it takes when there is an error in sending the DATA and T_s^{rts} is the time it takes to successfully send a DATA packet and they can be seen respectively in (4.11), (4.12) and (4.13).

$$T_c^{\text{rts}} = \text{DIFS} + \text{RTS} + \text{Timeout} \tag{4.11}$$

$$T_e^{\text{rts}} = \text{DIFS} + \text{RTS} + \text{CTS} + \text{DATA} + 2 \times \text{SIFS} + \text{Timeout} \tag{4.12}$$

$$T_s^{\text{rts}} = \text{DIFS} + \text{RTS} + \text{CTS} + \text{DATA} + \text{ACK} + 3 \times \text{SIFS} \tag{4.13}$$

Since the length of the CTS and ACK are equal, Timeout in (4.11) and (4.12) represents both CTSTimeout and ACKTimeout. The duration of Timeout can be seen in the following equation.

$$\text{Timeout} = \text{SIFS} + \text{SlotTime} + \text{PHY} \tag{4.14}$$

In case of having basic access as the access mechanism, the effect of collision and having error in DATA packet are the same. They both waste T_f^{basic} of channel time described as

$$T_f^{\text{basic}} = \text{DIFS} + \text{DATA} + \text{Timeout}. \tag{4.15}$$

For this reason, probabilities of collision and error in DATA packets are not going to be discussed separately and all the failures are taken into account in p_f which can be expressed as

$$p_f = p_c + (1 - p_c) \times p_e. \tag{4.16}$$

S^{basic} which is throughput in bits per second when basic access is used can be shown as the following

$$S^{\text{basic}} = \frac{p_s^{\text{basic}} \times 8 \times L_{\text{payload}}}{\sum_{i=0}^{m_{\text{long}}-1}(p_f^i(1-p_f)T_i(R)) \times p_f^{m_{\text{long}}} \times T^{m_{\text{long}}}(R)}. \tag{4.17}$$

In (4.17), definitions of $T_i(R)$, p_s^{basic}, T_s^{basic} and $T_{m_{\text{long}}}(R)$ are respectively the same as definitions of $T_{i,j}(R)$ in (4.7), p_s^{rts} in (4.10), T_s^{rts} in (4.13) and $T_{i,m_{\text{long}}}(R)$ in (4.9). The only differences are that they are used for basic access mechanism and there is no m_{short} and retransmission of RTS. $T_i(R)$, p_s^{basic}, T_s^{basic} and $Tm_{\text{long}}(R)$ can be calculated using respectively (4.18), (4.19), (4.20) and (4.21).

$$\begin{aligned} T_i(R) = i \times T_f^{\text{basic}}(R) + T_s^{\text{basic}} + \text{SlotTime} \\ \times \sum_{k=0}^{i} \frac{\min(2^k(\text{CWmin}+1), \text{CWmax}+1)}{2} \end{aligned} \tag{4.18}$$

$$p_s^{\text{basic}} = \sum_{i=0}^{m_{\text{long}}-1} p_f^i(1-p_f) \tag{4.19}$$

$$T_s^{\text{basic}} = \text{DIFS} + \text{DATA} + \text{ACK} + \text{SIFS} \tag{4.20}$$

$$\begin{aligned} T_{m_{\text{long}}}(R) = m_{\text{long}} \times T_f^{\text{basic}}(R) + \text{SlotTime} \\ \times \sum_{k=0}^{m_{\text{long}-1}} \frac{\min(2^k(\text{CWmin}+1), \text{CWmax}+1)}{2}. \end{aligned} \tag{4.21}$$

To calculate energy efficiency in mJ/bit which shows the energy consumed to send one correct bit of payload, (4.6) and (4.17) should be inversed and all the timings in the new numerator should be multiplied by the energy consumption of their respective mode. Transmission mode is only used for sending RTS and DATA, receiving mode refers to receiving CTS and ACK and all the other timings are considered to be idle since we are evaluating saturation mode and all the STAs always have some packets to send and they do not go to sleep mode.

In the simulation, MCS 0 is used for sending DATA packets and p_e is always 0.1. As it can be seen in Figure 4.4 and Figure 4.5, which are showing respectively throughput and energy efficiency in IEEE 802.11ah network, the analytical model is extremely accurate: analytical results (lines) practically coincide with the simulation results (symbols), in both basic access and RTS/CTS cases.

It can be concluded from Figure 4.4 and 4.5 that RTS/CTS access is necessary when L_{payload} is relatively large, since the collision time taken from the channel would be very long in those cases. For IoT use cases in which L_{payload} is equal to 256 bytes, results in Figure 4.4 and 4.5 justify that there is no advantage in using RTS/CTS access mechanism and sending RTS and CTS would only waste the channel resources.

Based on the two previous studies in this chapter, it is concluded that it is more efficient not to use RTS/CTS mechanism for IoT networks with relatively small

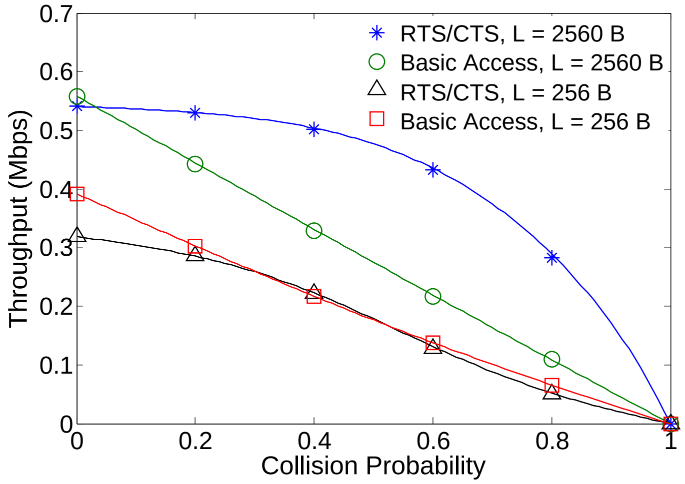

Figure 4.4. *Analytical model's saturation throughput*

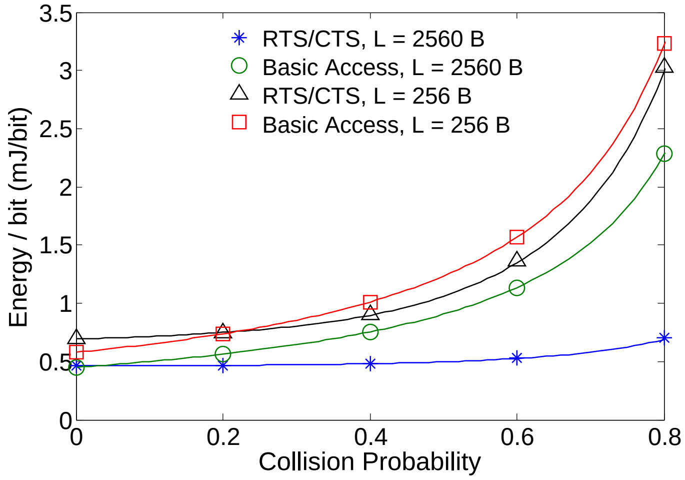

Figure 4.5. *Analytical model's energy efficiency*

packet sizes (256 Bytes). Therefore, in the remaining of this thesis, the only access mechanism used is basic access scheme.

In this analysis and its supporting simulations, it is assumed that each node should go through all of its generated backoff before accessing the channel. It means that STAs cannot decrease their backoff values if there is another STA with smaller backoff in the network. This assumption is to simplify the calculation of the backoff value before sending a packet and being able to use the average in [0, CW]. This assumption does not hold in other studies in the rest of this thesis.

4.3 Performance Evaluation of DCF

Since IEEE 802.11ah is a new standard, there is a lot of interest to see how a typical IEEE 802.11ah would perform without any of the previous assumptions. In this section, performance of IEEE 802.11ah for saturation and non-saturation scenarios is evaluated based on the following metrics:

- *Throughput*: refers to the average rate of successfully sent data over a communication channel. It is measured in bits per second (bps).
- *Energy efficiency*: is defined as the amount of consumed energy in the network to send successful data. It is calculated in mJ/packet which shows the average energy consumed in mJ to send one successful DATA packet.
- *Delay*: specifies how long it takes for a packet to travel across the network from the sender to the receiver. In this thesis, delay is defined for each DATA packet and it is the time interval starting from the generation of the DATA packet, until the successful reception of the corresponding ACK. The delay would not be considered if the DATA packet gets dropped.
- *Fairness*: determines whether STAs are able to successfully send fair number of DATA packets. It is defined as follows [55]:

  $$Fairness = \frac{(\sum_{i=1}^{n} T_i)^2}{n \times \sum_{i=1}^{n} T_i^2} \tag{4.22}$$

  where T_i represents the throughput of ith station and n is the number of STAs. The result ranges from $\frac{1}{n}$ (worst case) to 1 (best case), and it is maximum when all users receive the same allocation.

To gain broader information about IEEE 802.11ah, performance is evaluated using 3 different MCSs: MCS 0, MCS 4 and MCS 8. As explained in Section 3.2.2, since the transmission power and the path loss are fixed, the coverage is depending on the minimum sensitivity level. Therefore, the network using MCS 0 will have the highest coverage and the lowest coverage corresponds to MCS 8.

4.3.1 Saturation

How a certain network operates under saturation conditions, has always been an important factor in analyzing the general performance of that particular network. The information gained from saturation analysis varies with the number of users in the system and it reflects in a sense the capacity of the system and provides significant insights in understanding the limiting behavior of a network.

The saturation performance of an IEEE 802.11ah network using basic access scheme is evaluated based on the afore-mentioned metrics. Figure 4.6 shows the throughput, Figure 4.7 illustrates the energy efficiency, Figure 4.8 shows the average delay of successfully sent packets and the results regarding fairness can be seen in Figure 4.9.

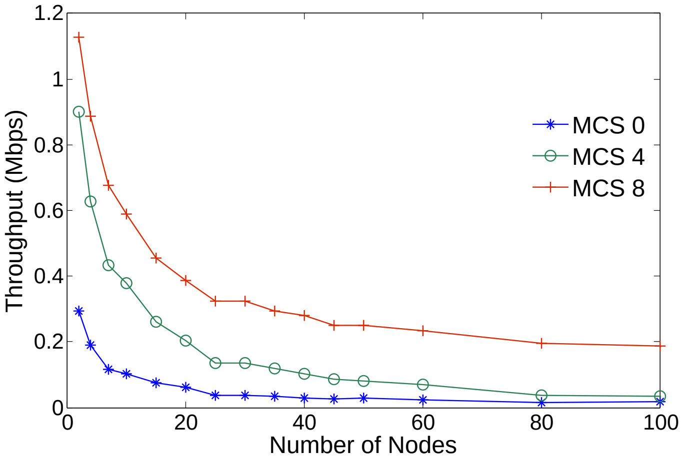

Figure 4.6. *Throughput for different MCSs in saturation scenario*

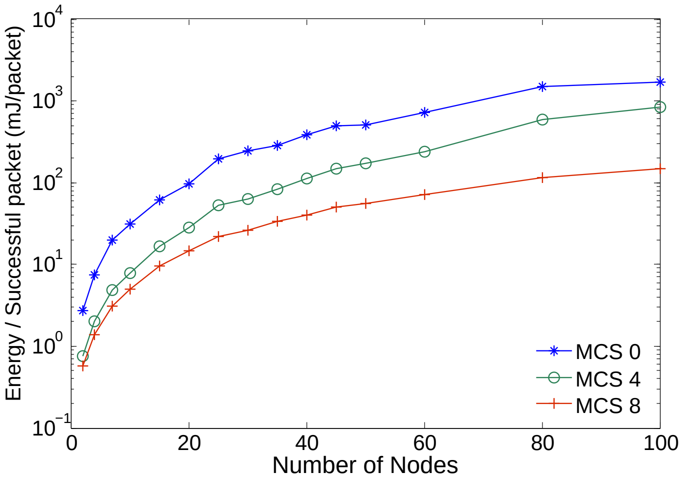

Figure 4.7. *Energy efficiency for different MCSs in saturation scenario*

The rippling which can be seen on the curves are due to the number of repetitions of the simulation and can be smoothened by having higher number of repetitions. As it was expected, the performance decreases due to more collisions as the number of STAs increases. The performance is also directly related to the MCS with which the DATA packets are transmitted.

Using higher MCSs results in having higher data rates which makes the duration of the transmission of DATA packets shorter. Since the STAs always have packets to be transmitted, there will be more transmissions in a certain time which results in having higher throughput and less average delay.

When higher MCSs are used, the same amount of payload can be delivered in less time and therefore less energy consumption. This is why the network is more energy efficient when higher MCSs are employed.

If there are no collisions, the network would be completely fair (Fairness would be one), due to having random backoff times in the STAs. However, when two STAs

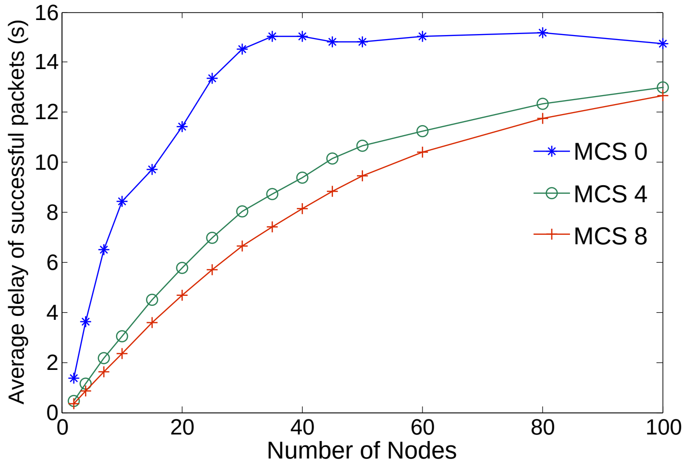

Figure 4.8. *Average delay for different MCSs in saturation scenario*

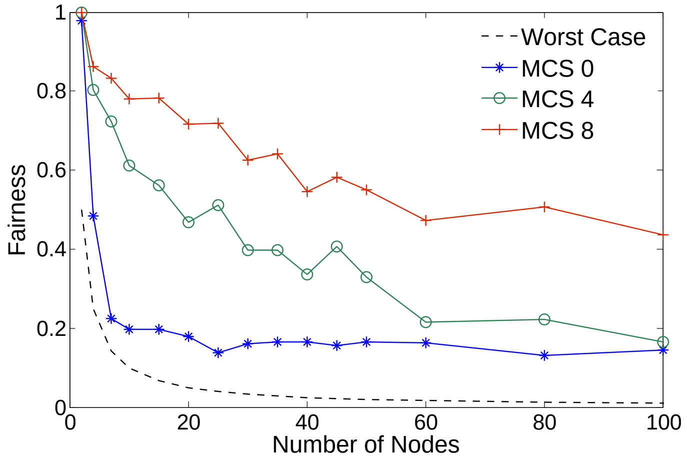

Figure 4.9. *Fairness for different MCSs in saturation scenario*

are transmitting at the same time, AP is able to detect and decode the DATA packet transmitted from the nearer STA, if the difference between the powers of the two packets is high. This is the reason of having lower fairness when there are more collisions in the network (due to having more STAs in the network). Having higher fairness in higher MCSs can be explained by smaller coverage areas of the higher MCSs, which results in the smaller differences in the power of the received DATA packets in case of collisions.

4.3.2 Non-Saturation

Although studying the saturation scenario provides valuable information regarding the performance of a network, analyzing the non-saturated case is vital since the traffic in real networks are mostly not saturated.

Except the traffic, all the settings and metrics in this study are the ones employed in the saturation case. The results regarding the throughput, energy efficiency, delay and fairness can be seen in Figures 4.10, 4.11, 4.12 and 4.13 respectively.

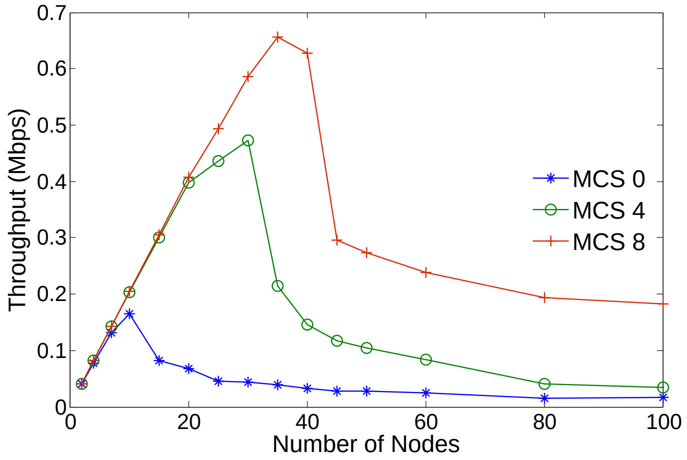

Figure 4.10. *Throughput for different MCSs in non-saturation scenario*

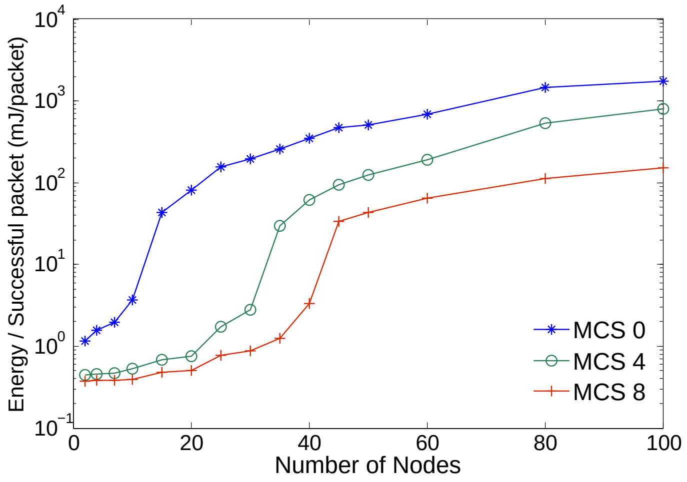

Figure 4.11. *Energy efficiency for different MCSs in non-saturation scenario*

As it can be seen in Figure 4.10, regardless of the used MCS, there is a point in all the cases in which the non-saturated network is behaving like a saturated one. As the MCS index gets larger, this point corresponds to the higher number of STAs. This can be explained by the fact that because of higher data rates, higher number of transmission cycles can fit in a certain time when the higher MCSs are used.

Before that certain point, all the generated packets in all the STAs can be delivered successfully to the AP which results in having the same throughput and maximum fairness in all the MCSs. However, the performance is better from energy consumption and average delay points of view when the MCS index is larger and that is because of higher data rate which results in less transmission times as discussed in saturation scenario.

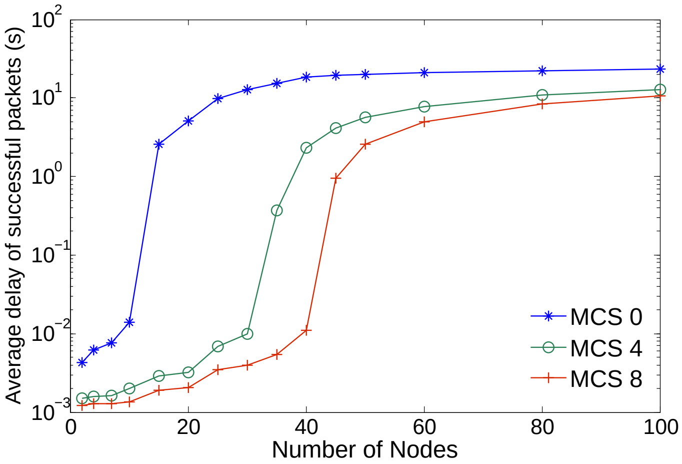

__Figure 4.12.__ Average delay for different MCSs in non-saturation scenario

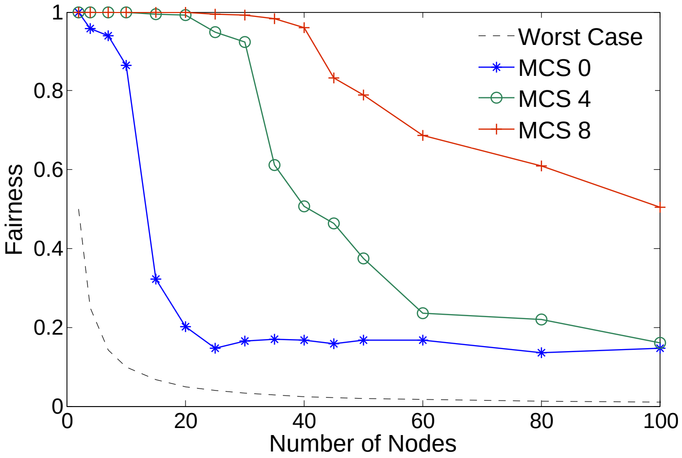

__Figure 4.13.__ Fairness for different MCSs in non-saturation scenario

It should be noted that since it is assumed that the TX power is the same in all the cases, the cost of having higher performance in higher MCSs is the lower coverage. In case the coverage area is fixed, the higher energy consumption would be the expense of the better performance of higher MCSs.

5. CASE STUDIES

There are some additional features introduced mainly in IEEE 802.11ah amendment and unlimited scenarios in which a network can be evaluated. In order to get an understanding about how an IEEE 802.11ah network performs, in addition to evaluating the performance of the default model and scenarios, one needs to study different cases and also optional features of this amendment.

This chapter summarizes some of the most important cases that are vital to be studied, namely OBSS effects, link adaptation algorithms, RAW and optimizing system parameters.

5.1 Overlapping Basic Service Sets (OBSS)

The OBSS problem refers to the case in which two or more BSSs, which are unrelated to each other and are operating at the same channel, are close enough to hear each other physically. In these cases, transmissions by some STAs in one BSS will affect the STAs in the other BSS. [56]

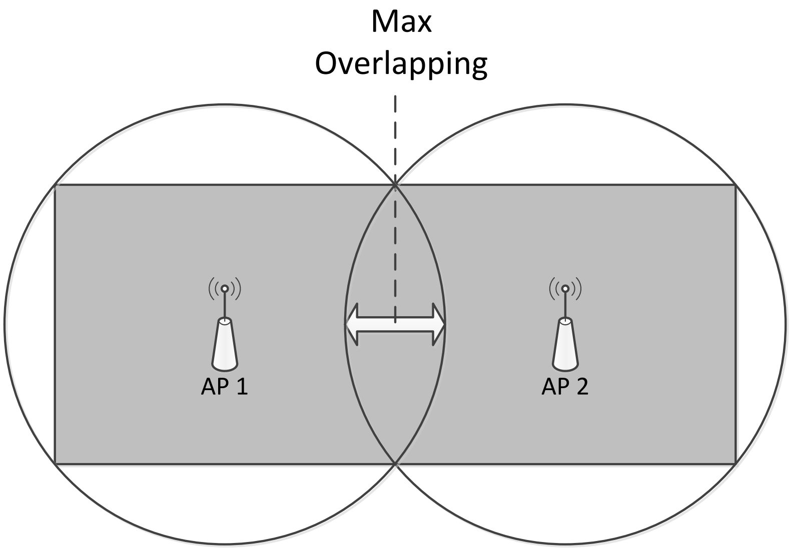

Figure 5.1. *OBSS problem setting*

The OBSS problem may degrade the overall network system performance severely mainly due to the interference caused by the BSSs to each other and expansion of the hidden node problems [57]. It may also cause the exposed node problem which is discussed in [58]. Due to its severeness, there are many literatures which have covered the effect of OBSS on the performance of IEEE amendments, such as [59] for IEEE 802.11b and [60] for IEEE 802.11a.

In this section, effect of OBSS problem on IEEE 802.11ah is evaluated using one of the scenarios introduced in [61], in which there are two BSSs and two APs as illustrated in Figure 5.1.

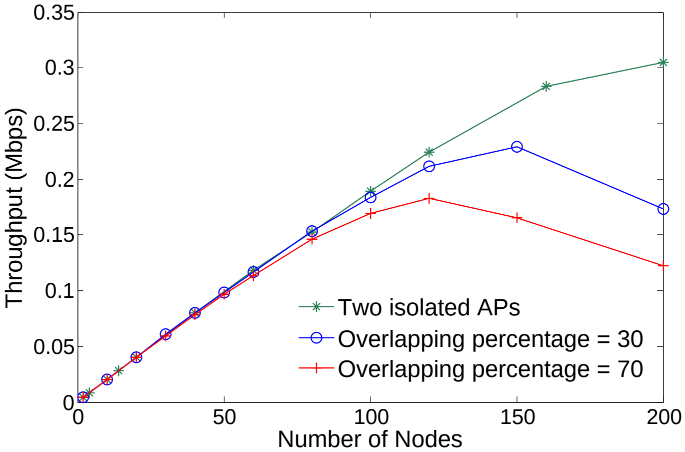

Figure 5.2. *Throughput in OBSS scenarios*

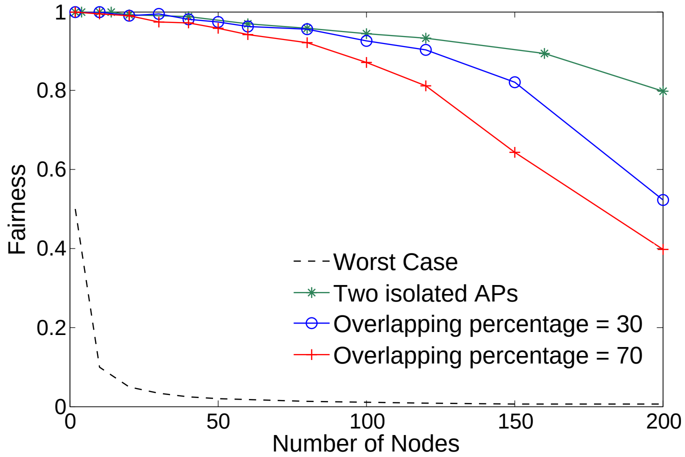

Figure 5.3. *Fairness in OBSS scenarios*

To study the OBSS effect, the cases in which there are OBSS problems with different max overlapping area (shown in Figure 5.1) are compared to the two isolated BSS case, all using MCS 0 with with lower traffic (a packet is generated in each second). Due to limitations in the simulation model, STAs are randomly positioned in a shadowed rectangular shown in Figure 5.1. To simulate the isolated scenario, one BSS is simulated with STAs randomly positioned in a square within that and two BSSs case is approximated by multiplying the number of STAs and throughput of one BSS by 2. Results regarding throughput, fairness, energy efficiency and delay can be seen in Figures 5.2, 5.3, 5.4 and 5.5 respectively. "Overlapping percentage"

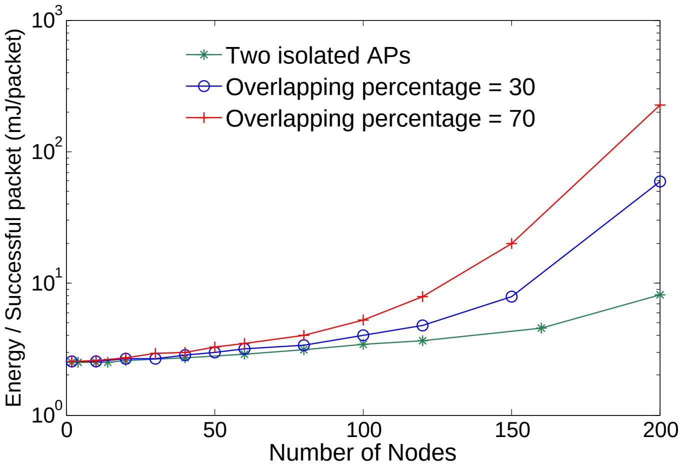

Figure 5.4. *Energy efficiency in OBSS scenarios*

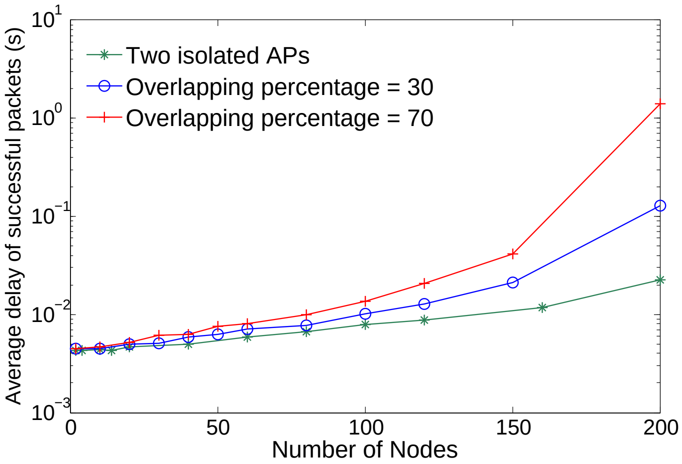

Figure 5.5. *Average delay in OBSS scenarios*

parameter in the results shows the amount of overlapping area, with "0" being the case that two BSSs are tangent to each other and "100" as the case in which two BSSs are exactly on top of one another.

As it can be seen in the figures, the performance is obviously degraded in all the metrics and this degradation has direct relation with the "Overlapping percentage". These results highlight the importance of considering inter-AP geographical and channel separation when deploying BSSs, to effectively increase the performance of the network.

There are lots of mechanisms to cope with OBSS problems such as sectorization [3], power control [62] and etcetera.

5.2 Link Adaptation

IEEE 802.11ah supports different MCSs and hence different data rates, ranging from 0.65 Mbps to 8.7 Mbps. To get the best performance of the network, as it is shown in the previous sections, it is better to use higher MCSs. However, higher MCS means denser modulation encoding which results in higher BER (bit error rate). Higher BER results in larger number of retransmissions which will waste the channel resources. Therefore, the tradeoff is between data rate and BER which was seen as the loss of coverage in the previous sections.

In the case that the coverage is important and cannot be reduced or when the channel conditions are changing due to frame collision from simultaneous transmissions, signal fading due to distance, interference from other sources and etcetera, it is dispensable to use algorithms which adapt the data rates based on the channel conditions to exploit the scarce wireless resources optimally. Link adaptation is the process of dynamically switching data rates to match the channel conditions, with the goal of selecting the rate that will give the optimum throughput for the given channel conditions [63].

To get an estimate about current channel conditions, link adaptation algorithms generally use information based either on signal-to-noise ratio (SNR) or frame loss ratio. For the latter, channel conditions are assessed based on the number of successive successful transmissions or the observation of the loss rate [64].

In this section, performance evaluations of two different link adaptation algorithms, one based on measuring SNR and one based on statistical information of transmissions, are presented.

5.2.1 Beacon Based

Receiver Based Auto Rate (RBAR) [63] algorithm uses SNR information taken from RTS/CTS to select the optimum data rate used in sending the DATA packets. In this algorithm destination STA uses SNR information of RTS and determines the optimum data rate that can be used in the current channel to send DATA packet. The destination STA embeds this information in CTS and sends it back to source STA. By this method, all STA which are not hearing the DATA packet but can hear CTS are also able to know the time that it takes for the DATA packet to be sent with new data rate. The source STA uses that information to make the final decision of data rate.

This algorithm has two drawbacks. First, it relies on using RTS/CTS procedure which in some cases wastes our channel resources. Second, it needs some modification in IEEE 802.11 standard.

In the modified version which is named beacon based, these drawbacks are overcome by using the fact that IEEE 802.11ah use cases mostly work in infrastructure mode. In infrastructure mode when there is only uplink data, the destination STA is always the AP which sends beacons periodically. In beacon based link adaptation each STA gets SNR information from the beacon and uses that information to select

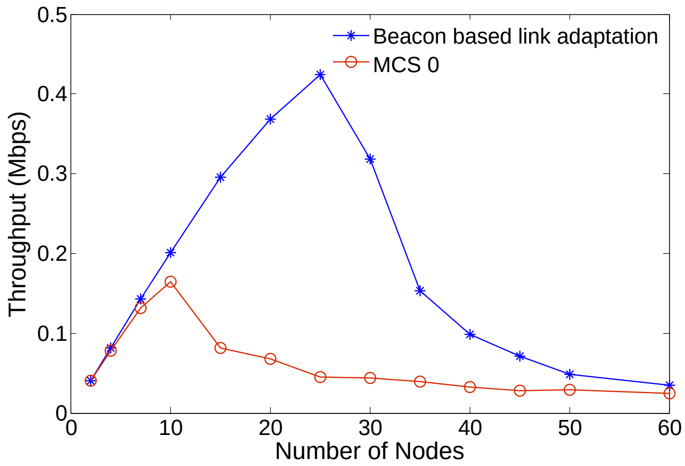

Figure 5.6. *Throughput of beacon based link adaptation*

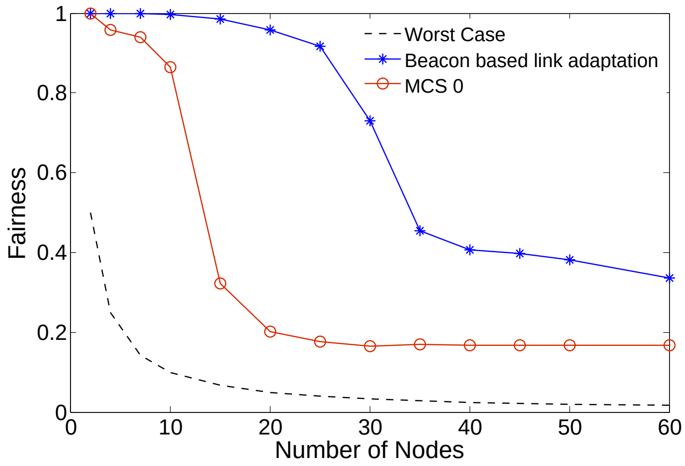

Figure 5.7. *Fairness of beacon based link adaptation*

the best possible data rate until receiving another beacon.

Obviously, this case is most useful when link conditions are not changing rapidly in order to be able to track the changes only by beacon information. To evaluate the performance of beacon based link adaption, the settings are assumed to be exactly the same as Section 4.3.2 when MCS 0 is used.

Comparison between performance of beacon based link adaptation and MCS 0 is summarized in Figures 5.6, 5.7, 5.8 and 5.9 which are showing throughput, fairness, energy efficiency and delay respectively.

Since the STAs are static and the effect of hidden nodes and their interference is not dramatic, the optimum data rate chosen by SNR value of the beacon does not change over time. In this scenario as it can be seen in the figures, beacon based link adaptation outperforms normal MCS 0 in all the metrics. It is concluded that using bacon based link adaptation is vital for the cases in which channel conditions are not changing rapidly.

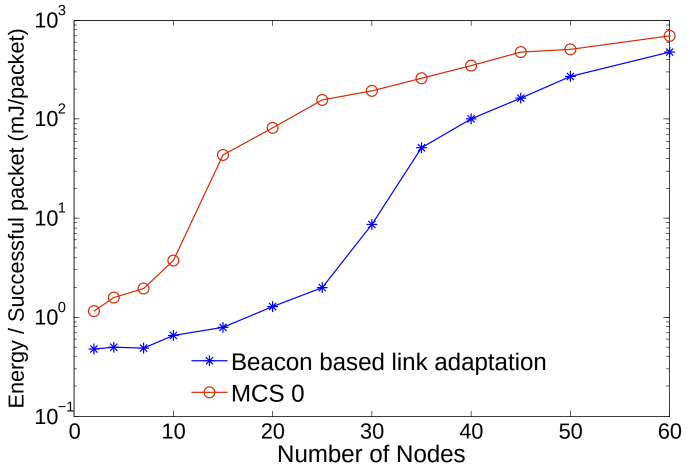

Figure 5.8. *Energy efficiency of beacon based link adaptation*

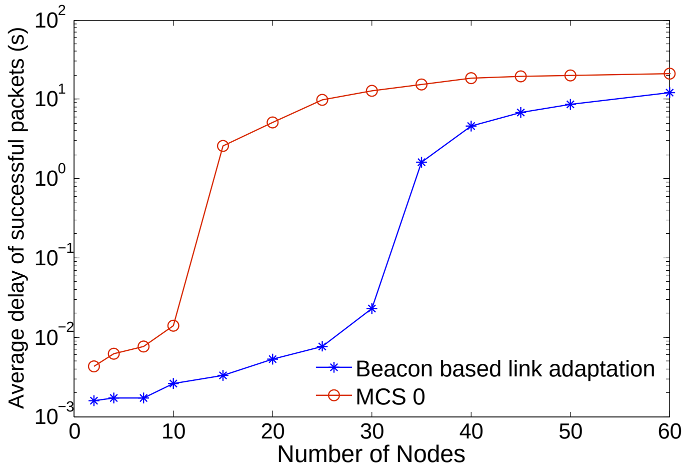

Figure 5.9. *Average delay of beacon based link adaptation*

5.2.2 Auto Rate Fallback (ARF)

ARF [65] algorithm uses frame success and loss rates. The ARF algorithm used in our model is as follows [66]:

- Each STA starts transmitting its packets with the lowest possible data rate.
- Each STA has transmission success counter j and failure counter k. Upon a transmission success (failure), the STA increases j (k) by one and resets k (j) to zero.
- Upon S consecutive transmission successes ($j = S$), the STA transmits a data frame at the next higher rate for probing. If the probing is successful, the data rate of the STA remains as increased, otherwise, returns to the previous one and the counters would be reseted to zero.
- Upon F consecutive transmission failures ($k = F$), the STA decreases the rate

with reseting the counters.

To evaluate if the link adaptation mechanisms are able to increase the performance in the scenarios in which there is considerable amount of interference, the simulation environment includes 9 BSSs which cover a square in which all the STAs are randomly positioned. Length of the square's sides are 500 m and the transmission powers are increased to have the full coverage in all parts of the square. Figure 5.10 illustrates this simulation environment.

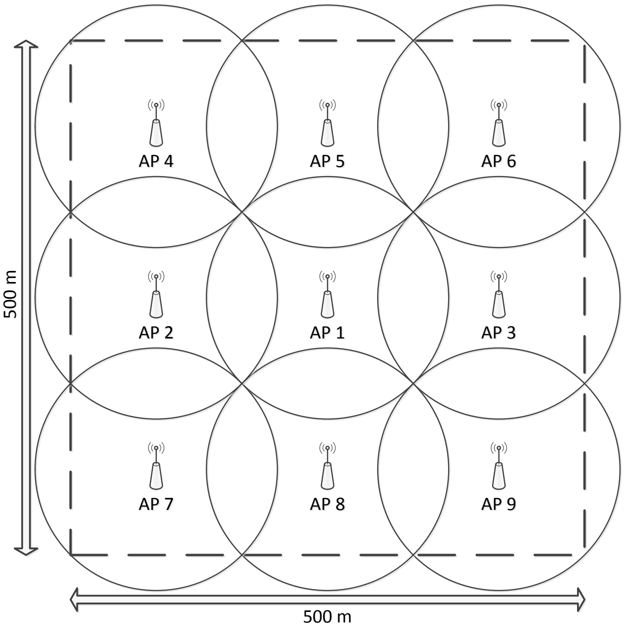

Figure 5.10. *Simulation environment to evaluate the performance of ARF link adaptation*

As it can be seen in Figure 5.10, there are lots of overlapping areas which introduce lots of interference and are expected to decrease the performance of the system severely as it is concluded in Section 5.1. It is interesting to see if the ARF is able

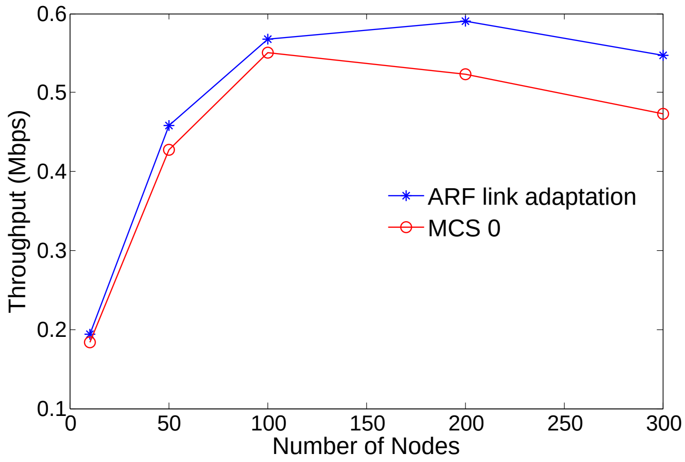

Figure 5.11. *Comparing throughput of ARF and MCS 0*

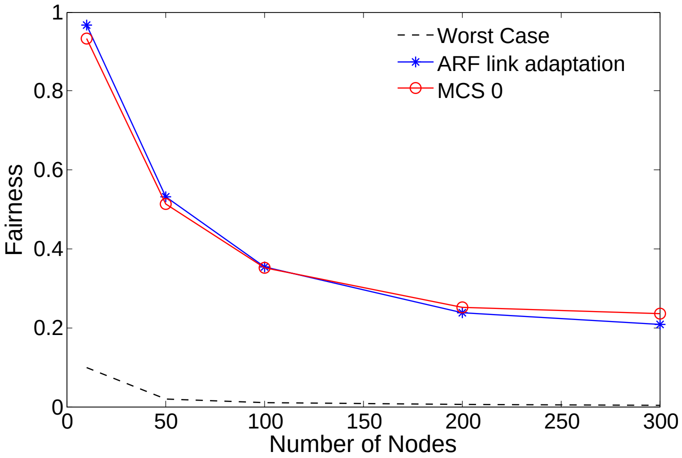

Figure 5.12. *Comparing fairness of ARF and MCS 0*

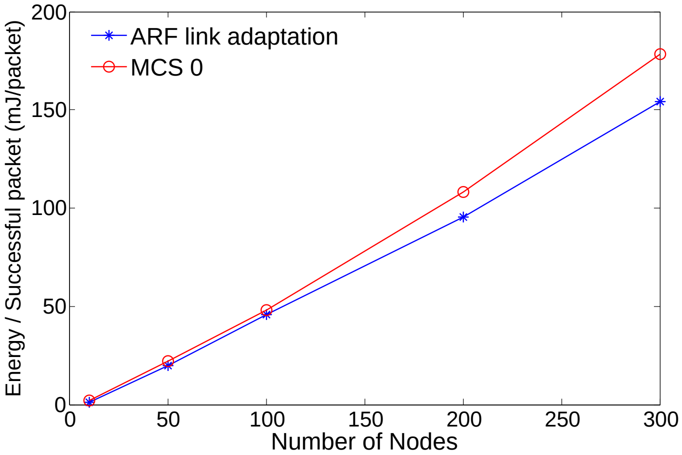

Figure 5.13. *Comparing energy efficiency of ARF and MCS 0*

to improve the performance of the network or it is better to use MCS 0 as the most robust MCS when the level of interference is high. It should be noted that S which is the number of consecutive transmission successes needed to increase the MCS is chosen to be 10 and F is equal to 2 and represents the number of consecutive transmission failures to decrease the MCS [65].

As it can be seen in Figure 5.12, there is no advantage in using ARF from fairness point of view and it can be explained by the fact that regardless of using ARF, those STAs which have poor link conditions are not able to send any successful packets which decreases the fairness. However, results in Figures 5.11, 5.13 and 5.14 prove that even in the scenarios in which the interference degrades the channel dramatically, ARF scheme is able to improve the system performance by allowing the very few STAs which are experiencing a good link condition to use higher data rates and let the channel be free for other ones.

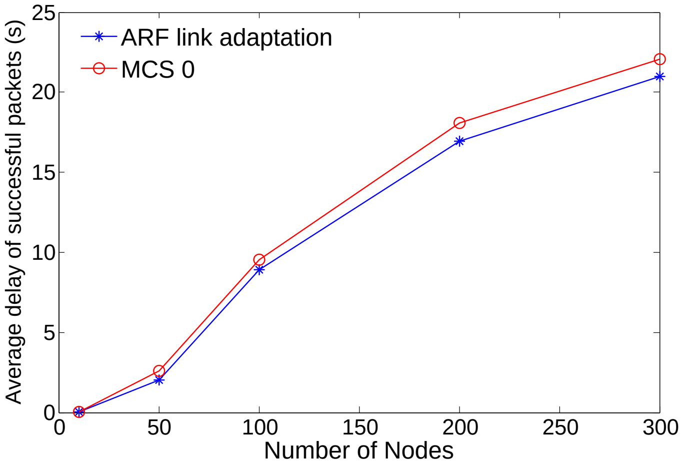

Figure 5.14. *Comparing average delay of ARF and MCS 0*

5.3 Restricted Access Window (RAW)

The collision problem in IEEE 802.11 standard makes it hard to achieve the requirements regarding the number of STAs which should be supported in the network and also degrades the performance harshly. To overcome this problem, IEEE 802.11ah has introduced the restricted channel access (RAW) control mechanism. It manages access to the wireless medium to avoid simultaneous transmissions from a large number of STAs and enables fair channel access among them [3]. For example, right after the beacon reception, there could be hundreds or even thousands of STAs trying to send their uplink data. To reduce the number of collisions and improve the efficiency of the medium utilization, RAW mechanism restricts uplink channel access to a small number of STAs at each given time instance and spreads their uplink access attempts over a much longer period of time.

In this method, AP allocates a medium access period in the beacon interval, called RAW, which is divided into one or more time slots. The AP may assign to a group of STAs a time slot inside the RAW at which the STAs are permitted to contend for medium access. A STA that receives RAW information in a beacon transmitted by the AP determines whether it is allowed to use RAW interval, it also determines the start time of the RAW and the duration of the RAW. If a STA has uplink data and is allowed to access the wireless medium in the RAW, it will contend for medium access at the start of the assigned time slot. A STA in its assigned time slot can start contending as soon as it gets any uplink data from upper layers. STAs stop attempting to access the medium as soon as their assigned time slot is finished. It should be noted that there may be some STAs which are not allowed to use the RAW.

In the RAW information encapsulated in the beacon, there is a parameter called Cross Slot Boundary. In the case that Cross Slot Boundary is allowed, uplink transmission may extend beyond the end of the allocated time slot. If it is not allowed, each STA tries to access the medium if the remaining time in the allocated slot boundary is enough to complete the transmission and any acknowledgment. Otherwise, it should not initiate transmission of a frame even though the remaining slot duration is nonzero.

Based on the information about the duration of the RAW (T_{RAW}) and the duration of one time slot in the RAW (T_{slot}) which can be found in the beacon, each STA calculates the number of time slots in the RAW (N_{RAW}). The time slots in the RAW are indexed from 0 to (N_{RAW} - 1). A STA determines the index of the time slot, i_{slot}, in which it is allowed to start accessing the medium based on the following mapping function

$$i_{\text{slot}} = (x + N_{\text{offset}}) \bmod N_{\text{RAW}}. \tag{5.1}$$

In (5.1) mod X indicates the modulo X operation. x is the index of the STA itself. N_{offset} represents the offset value in the mapping function, which improves the fairness among the STAs in the RAW, and it also encapsulated as T_{RAW} information in the beacon. By changing N_{offset} in beacons, AP prevents having constant delay in some specific STA's uplink data. A RAW example in which the whole beacon interval is not assigned to RAW can be seen in Figure 5.15. In Figure 5.15, N_{RAW} is 4, index of the STA is chosen to be 3 and N_{offset} equals to 2.

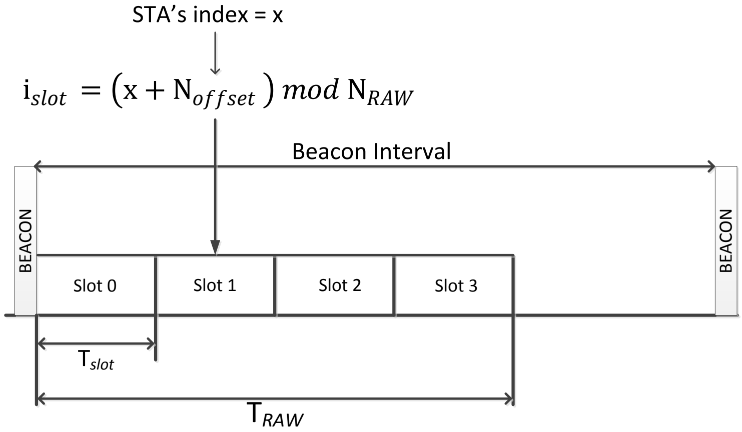

Figure 5.15. *Slot assignment procedure in RAW*

In the case that RAW is activated, each STA maintains two backoff function states. First backoff function state is used outside the RAW and the second one is used inside that. These two backoff functions are independent and their value does not affect the other one. When a STA is allowed to contend in the RAW, it suspends its first backoff at the start of RAW and stores the first backoff function state. At the end of RAW, the previously stored backoff function state is restored and the first backoff function resumes. If the previously stored backoff function state is empty, the STA invokes a new backoff value. In the first RAW interval, the STA invokes a new second backoff function using the RAW backoff parameters. STAs can count down their second backoffs only in their assigned slots within the RAW. At the end of the RAW interval, STAs store their second backoff function and it will be restored and resumed at the next RAW interval.

In the first part, RAW performance using MCS 0 is evaluated with various N_{RAW} values, and the best possible N_{RAW} is chosen for further evaluations. The second part presents the performance evaluation of the different MCSs with the chosen N_{RAW}.

5.3.1 Different values for N_{RAW}

One of the main parameters of RAW mechanism is N_{RAW} which represents the number of time slots in the RAW period. Choosing N_{RAW} to be small does not express any benefits or possible shortcomings of having RAW. On the other hand, when N_{RAW} is high, the duration of a time slot (T_{RAW}) would become shorter until the case that it is not enough to send one successful packet.

In order to find an optimum N_{RAW}, throughput and energy consumption of networks are compared for different values of N_{RAW} keeping all the parameters the same as default. The results of throughput and energy consumption comparison are shown respectively in Figure 5.16 and Figure 5.17.

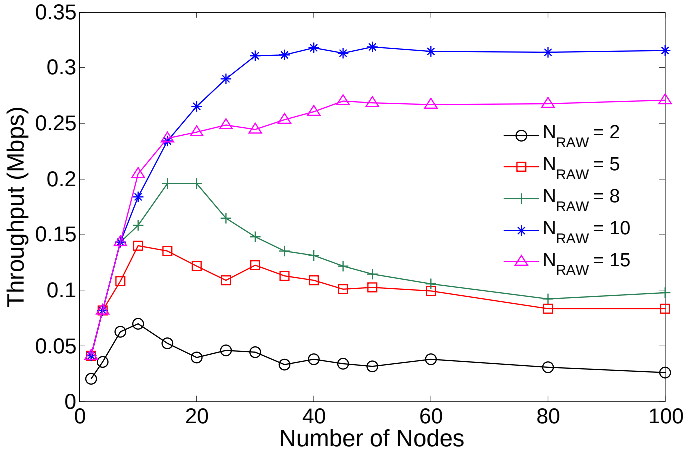

Figure 5.16. *Throughput with different values for* N_{RAW}.

Based on Figure 5.16 and Figure 5.17, it can be concluded that N_{RAW} equal to 10 is the best option for these sets of parameters. It has considerably higher throughput, while the difference in energy efficiency is negligible. The best way is to choose N_{RAW} adaptively based on the network configuration and used parameters.

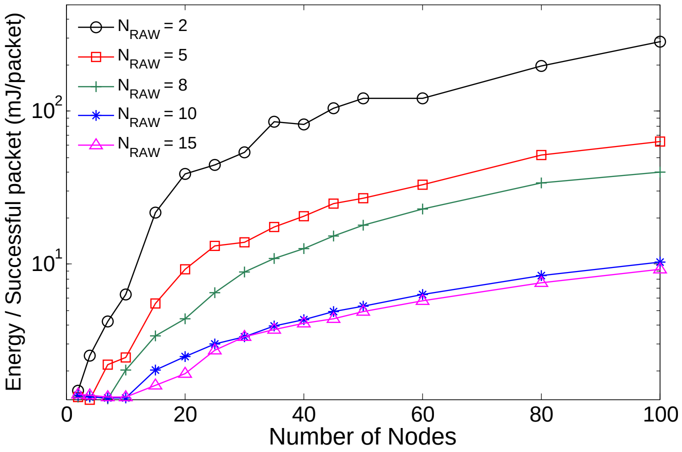

Figure 5.17. *Energy consumption with different values for* N_{RAW}.

5.3.2 Different MCSs

In this section, performance of RAW mechanism when different MCSs are used is evaluated. Performance evaluation is based on comparing throughput, fairness, energy efficiency, and delay.

All the assumptions and parameters in simulating RAW with different values for N_{RAW} holds for the simulations in this section. Based on the previous results N_{RAW} is chosen to be 10 for the remaining simulations.

Figures 5.18, 5.19, 5.20 and 5.21 are showing throughput, fairness, energy efficiency and delay respectively. To compare the RAW mechanism and normal DCF without RAW, dashed lines represent the normal DCF results from Section 4.3.2 and solid lines are the results of RAW scenarios.

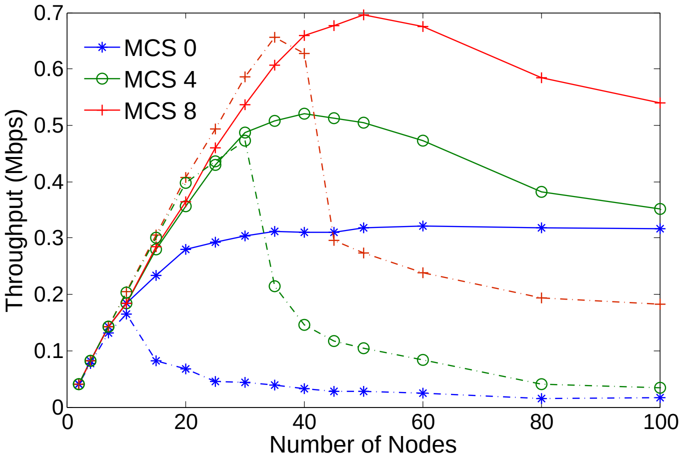

Figure 5.18. *RAW throughput for different MCSs*

It can be concluded from all the results that when the number of STAs are low and there are limited number of packets to be sent, normal DCF without RAW mechanism performs a bit better. Especially, results from delay shows that in the

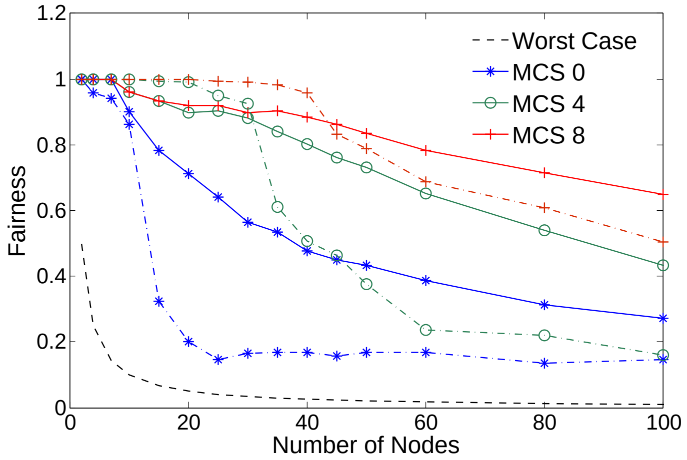

Figure 5.19. *RAW fairness for different MCSs*

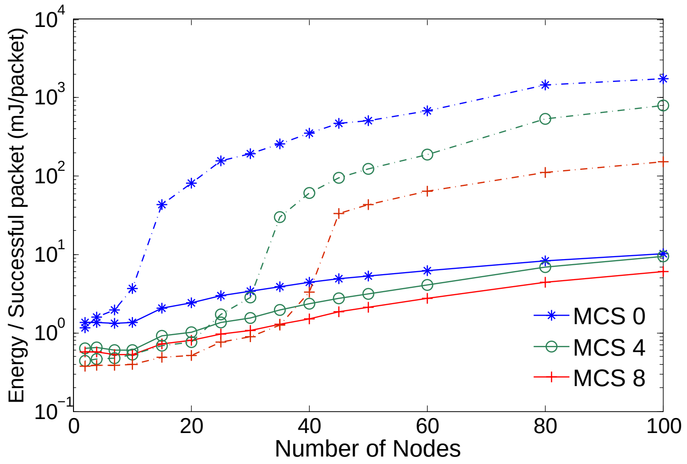

Figure 5.20. *RAW energy consumption for different MCSs*

case that system is not heavily loaded, it is better to use normal DCF and let each STA sends its DATA packets as soon as they are generated. RAW mechanism only forces them to go to sleep mode and not even try to access the channel for a while which causes delay in sending the packets.

However, when the network gets over-loaded RAW mechanism improves the throughput and energy efficiency ,which are two of the most important metrics, substantially. Fairness is also increased in these cases since the STAs with poor link quality have to compete with lower number of STAs and it will improve their chances to send packets successfully. Comparing delays shows that when system is over-loaded, the difference between the RAW and normal DCF is negligible and this can be explained by the fact that delay in the comparisons refers to the duration from when the DATA packet is generated in the STA until the time that STA receives the ACK from AP. Delay will not be counted in the simulations, if the packet is dropped due to exceeding the number of allowed retransmissions.

Based on the presented results, the RAW mechanism has superiority in most of

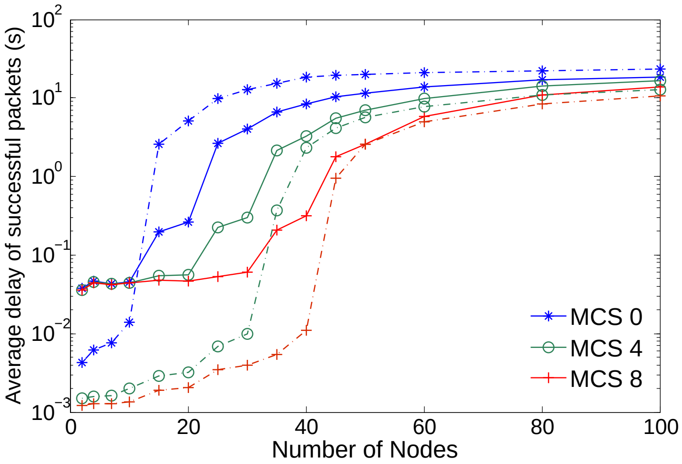

Figure 5.21. *Delay in successfully sending a packet for different MCSs using RAW*

the cases with high number of collisions. It is concluded that the RAW mechanism should be used in the majority of the practical use cases of IEEE 802.11ah since there are lots of STAs and the collision probability is high.

6. CONCLUSIONS

In this thesis, a system-level simulator was developed to analyze and optimize the performance of a new Wi-Fi standard called IEEE 802.11ah. This standard is introduced mainly for large device population based applications with tight power consumption constraints like in IoT networks. IEEE 802.11ah which operates in sub-1 GHz band is expected to assure 1 km coverage with at least 100 Kbps data rate.

The developed simulator was tested by two different analytical models: an existing model which calculates the maximum achievable throughput assuming no collisions and no error in the transmission of the packet and a simple analytical model considering the saturation throughput and energy efficiency of the DCF scheme. The second analytical model, which is introduced in this thesis, assumes that the collision probability and probability of having error in DATA packets are known. Comparison of these two analytical models and simulation results showed that the simulation model is extremely accurate. Based on the obtained results, it is concluded that for IoT DATA packets with relatively small data size (256 bytes), it is better to use basic access mechanism.

Results from the OBSS problem study in which two BSSs, working at the same channel and close enough to physically hear each other, showed the direct relation between degradation in the performance and the amount of overlapping area. Due to severeness of this degradation, many methods have been developed in the literature to deal with OBSS problem, including management of power and frequencies, network-wise resource and path allocations and etcetera.

The basic performance evaluation proved that there would be improvements in all the examined metrics, if higher MCSs are used to send the DATA packets. Since using higher MCSs for all the STAs is not possible without losing coverage, two link adaptation methods were studied to be used in IEEE 802.11ah. Beacon based link adaptation showed substantial improvement in the networks where the channel is not changing at fast pace, while ARF proved that link adaptation methods can also be useful in the networks with rapidly changing link conditions.

This thesis also investigated the performance of Restricted Access Window (RAW), which is an optional mechanism in IEEE 802.11ah standard to cope with high number of collisions. In the standard, there is no specific N_{RAW} required to be used. As it was shown, the best way is to choose N_{RAW} adaptively based on the network configuration and the used parameters. The RAW mechanism has proven its superiority in most of the cases with relatively high number of collisions. Advantages of the RAW mechanism in throughput, fairness and energy consumption were presented in congested networks, while it is concluded that the RAW mechanism does not improve the average delay. However, it is concluded that it is better to use normal DCF if the system is lightly loaded.

There are lots of other features currently introduced in IEEE 802.11ah and are not covered in this thesis. There also might be some additional proposals in the feature, since IEEE 802.11ah is still not finalized. Evaluating these features by simulation is vital in the development stage and is left for future work.

Selected parts of this thesis have been presented at fourth Nordic SNOW 2013 workshop [67]. Additionally, a workshop paper has been accepted and is to be published in IEEE WiMob 2013 Workshop on Internet of Things (IoT) Communications and Technologies [68]. Furthermore, a conference paper has been submitted from selected parts to IEEE Wireless Communications and Networking Conference and it is under review at this moment [54].

REFERENCES

[1] Zheng, J., Simplot-Ryl, D., Bisdikian, C., Mouftah, H.T., "The internet of things [Guest Editorial]," Communications Magazine, IEEE , vol.49, no.11, pp.30-31, November 2011.

[2] Uusitalo, M.A., "Global Vision for the Future Wireless World from the WWRF," Vehicular Technology Magazine, IEEE , vol.1, no.2, pp.4-8, 2006.

[3] 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 6: Sub-1 GHz License Exempt Operation," IEEE P802.11ah/D0.1, New York, May 2013, 311 p.

[4] Hazmi, A., Rinne, J., Valkama, M., "Feasibility study of IEEE 802.11ah radio technology for IoT and M2M use cases," Globecom Workshops (GC Wkshps), 2012 IEEE, Anaheim, CA, pp.1687,1692, 3-7 Dec. 2012.

[5] IEEE-SA [WWW]. [accessed on 29.8.2013]. Available at: `http://standards.ieee.org/about/ieeesa.html`.

[6] IEEE Standard for Information Technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007), New York, March 2012, 2695 p.

[7] Supplement to IEEE Standard for Information Technology–Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks–Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer in the 5 GHz Band," IEEE Std 802.11a-1999, New York, 1999, 82 p.

[8] IEEE Standard for Information technology– Local and metropolitan area networks–Specific requirements. Part 11: Wireless LAN Medium Access Control (MAC)and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput," IEEE Std 802.11n-2009 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, and IEEE Std 802.11w-2009), New York, Oct. 29 2009, 502 p.

[9] Van Nee, R., "Breaking the Gigabit-per-second barrier with 802.11AC," Wireless Communications, IEEE , vol.18, no.2, pp.4, April 2011

[10] Halasz, D., "Sub-1 GHz license-exempt PAR and 5C," July 2010, IEEE 802.11-10/0001r13.

[11] Gast, M. S., "802.11 Wireless Networks: The Definitive Guide," Second Edition, Sebastopol, CA 2005, O'Reilly Media, Inc., 672 p.

[12] de Vegt, R., "Potential Compromise for 802.11 Use Case Document," March 2011, IEEE 802.11-11/0457r0.

[13] U.S. Department of Energy, "The Smart Grid: An Introduction," [accessed on 09.07.2013]. Available at: `http://www.oe.energy.gov/DocumentsandMedia/DOE_SG_Book_Single_Pages(1).pdf`.

[14] Liu, Y., "Wireless sensor network applications in smart grid: recent trends and challenges," International Journal of Distributed Sensor Networks, vol. 2012, Article ID 492819, pp.1,8, July 2012.

[15] Aust, S., "Proposed IEEE 802.11ah Use Cases," January 2011, IEEE 802.11-11/0017r5.

[16] Song, W., "IEEE 802.11ah Use Case - Outdoor Environmental / Agricultural Monitoring," February 2011, IEEE 802.11-11/0253r0.

[17] Iwaoka, M., "IEEE 802.11ah Use Case - Industrial Process Automation," February 2011, IEEE 802.11-11/0260r1.

[18] Park, M., "Additional Indoor Use Cases for 802.11ah," February 2011, IEEE 802.11-11/0241r0.

[19] Mateska, A., Pavloski, M., Gavrilovska, L., "RFID and sensors enabled In-home elderly care," MIPRO, 2011 Proceedings of the 34th International Convention, Opatija, pp.285-290, 23-27 May 2011.

[20] Shimada, S., "Supplemental Use Cases in Industrial Apps," January 2011, IEEE 802.11-11/0014r2.

[21] Porat, R., "Additional Outdoor Use Case for 802.11ah," February 2011, IEEE 802.11-11/0243r0.

[22] Kim, S., "IEEE 802.11ah Use Case - Outdoor Wi-Fi for cellular traffic offloading," February 2011, IEEE 802.11-11/0244r1.

[23] Cheong, M., "TGah Functional Requirements and Evaluation Methodology," January 2012, IEEE 802.11-11/0905r5.

[24] Perahia, E., Stacey R., "Next Generation Wireless LANs". Cambridge University Press, 2013. Cambridge Books Online. Web. 13 August 2013, 452 p.

[25] 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," IEEE P802.11-REVmc/D1.2, New York, April 2013, 3138 p.

[26] Jangkeun, J., Hyuntai, K., Taeyoung, L., Jitae, S., "An analysis of hidden node problem in IEEE 802.11 multihop networks," Networked Computing and Advanced Information Management (NCM), 2010 Sixth International Conference on, pp.282-285, 16-18 Aug. 2010

[27] Shinder, D.L., "Computer networking essentials". Indianapolis 2002, Cisco Press. 743 p.

[28] Haitao, W., Shiduan, C., Yong, P., Keping, L., Jian, M., "IEEE 802.11 distributed coordination function (DCF): analysis and enhancement," Communications, 2002. ICC 2002. IEEE International Conference on , vol.1, pp.605-609, 2002.

[29] Sikdar, B., "Delay analysis of IEEE 802.11 PCF MAC based wireless networks," Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE , vol.1, 28 Nov.-2 Dec. 2005.

[30] Coleman, D.D., Westcott, D.A., "CWNA: Certified Wireless Network Administrator Official Study Guide: Exam PW0-105". Third edition. Indianapolis 2012, Wiley. 768 p.

[31] Valadas, R.T., Tavares, A.R., Duarte, A.M.deO., Moreira, A.C., Lomba, C.T., "The infrared physical layer of the IEEE 802.11 standard for wireless local area networks," Communications Magazine, IEEE , vol.36, no.12, pp.107-112, Dec 1998.

[32] Roshan, P., Leary, J., "802.11 Wireless LAN Fundamentals". Indianapolis 2003, Cisco Press. 312 p.

[33] Sun, W., Choi, M., Choi, S., "IEEE 802.11ah: A Long Range 802.11 WLAN at Sub-1 GHz," Journal of ICT Standardization Vol. 1, pp.83-107, May 2013.

[34] Park, M., "Specification Framework for TGah," May 2013, IEEE 802.11-11/1137r15.

[35] Porat, R., Yong, S., Doppler, K., "TGah Channel Model" , IEEE 802.11-11/0968r3, November 2011.

[36] 3GPP TR 25.996 - Technical Specification Group Radio Access Network; Spatial channel model for Multiple Input Multiple Output (MIMO) simulations, Section 5.

[37] 3GPP TR 36.814 - Further advancements for E-UTRA physical layer aspects, Annex A.2- system simulation scenario.

[38] Erceg, V. and et. al., TGn Channel Models, IEEE P802.11 Wireless LANs Std. IEEE 802.11-03/940r4, May 2004.

[39] Breit, G., TGac Channel Model Addendum - IEEE 802.11-09/308r12.

[40] The network simulator ns-2 [WWW]. [accessed on 29.8.2013]. Available at: `http://www.isi.edu/nsnam/ns/`

[41] The network simulator ns-3 [WWW]. [accessed on 29.8.2013]. Available at: `http://www.nsnam.org/`

[42] OMNeT++ [WWW]. [accessed on 29.8.2013]. Available at: `http://www.omnetpp.org/`.

[43] JiST [WWW]. [accessed on 29.8.2013]. Available at: `http://jist.ece.cornell.edu/`

[44] OPNET Technologies Inc. OPNET modeler. [WWW]. [accessed on 29.8.2013]. Available at: `http://www.riverbed.com/products-solutions/products/network-planning-simulation/Network-Simulation.html`.

[45] Weingartner, E., vom Lehn, H., Wehrle, K., "A Performance Comparison of Recent Network Simulators," Communications, 2009. ICC '09. IEEE International Conference on , Dresden, pp.1-5, 14-18 June 2009.

[46] OMNeT++ User Manual [WWW]. [accessed on 29.8.2013]. Available at: `http://www.omnetpp.org/doc/omnetpp/manual/usman.html`

[47] Banks, J., Carson, J., Nelson, B.L., Nicol, D., "Discrete-Event System Simulation". 4th Edition, New Jersey 2004, Prentice Hall. 624 p.

[48] Xian, X., Shi, W., Huang, H., "Comparison of OMNET++ and other simulator for WSN simulation," Industrial Electronics and Applications, 2008. ICIEA 2008. 3rd IEEE Conference on , pp.1439-1443, 3-5 June 2008.

[49] Varga, A., "Using the OMNeT++ discrete event simulation system in education," Education, IEEE Transactions on , vol.42, no.4, pp.11, Nov 1999.

[50] INET Framework [WWW]. [accessed on 29.8.2013]. Available at: `http://inet.omnetpp.org/`

[51] International Telecommunications Union, ITU Internet Reports 2005: The Internet of Things. Executive Summary, Geneva: ITU, 2005.

[52] Uusitalo, M.A., "Global Vision for the Future Wireless World from the WWRF," Vehicular Technology Magazine, IEEE , vol.1, no.2, pp.4-8, 2006.

[53] Jangeun, J., Peddabachagari, P., Sichitiu, M., "Theoretical maximum throughput of IEEE 802.11 and its applications," Network Computing and Applications, 2003. NCA 2003. Second IEEE International Symposium on , pp.249-256, April 2003.

[54] Raeesi, O., Pirskanen, J., Hazmi, A., Valkama, M., "Performance Evaluation of IEEE 802.11ah and its Restricted Access Window Mechanism," Wireless Communications and Networking Conference (WCNC 14), 2014 IEEE, submitted.

[55] Jain, R., Chiu, D., Hawe, W., "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems", Technical Report DEC-TR-301, Digital Equipment Corporation, September 1984.

[56] Yue, F., Daqing, G., McDonald, A.B., Jinyun Z., "A two-level carrier sensing mechanism for overlapping BSS problem in WLAN," Local and Metropolitan Area Networks, 2005. LANMAN 2005. The 14th IEEE Workshop on , Crete, pp.6, 18 Sept. 2005.

[57] Tandai, T., Toshimitsu, K., Sakamoto, T., "Interferential Packet Detection Scheme for a Solution to Overlapping BSS Issues in IEEE 802.11 WLANs," Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on , Helsinki, pp.1-5, 11-14 Sept. 2006.

[58] Deepanshu, S. , Chandran-Wadia, L., Iyer, S., "Mitigating the exposed node problem in IEEE 802.11 ad hoc networks," Computer Communications and Networks, 2003. ICCCN 2003. Proceedings. The 12th International Conference on , Mumbai, 20-22 Oct. 2003.

[59] Heck, K., "Wireless LAN performance in overlapping cells," Proc. in IEEE VTC 2003 fall, vol. 5, pp.2895-2900, Oct. 2003.

[60] Dunat, J.C., Elicegui, L., Bonnet, C., "Impact of inter-cell interference in a IEEE 802.11a network with overlapping cells," Proc. In IEEE PIMRC 2004, vol.2, pp.825-829, Sept. 2004.

[61] Ashley, A., "OBSS Requirements," July 2008, IEEE 802.11-08/0944r5.

[62] Ho, I.W.-H., Liew, S-C., "Impact of Power Control on Performance of IEEE 802.11 Wireless Networks," Mobile Computing, IEEE Transactions on , vol.6, no.11, pp.1245,1258, Nov. 2007.

[63] Holland, G., Vaidya, N., Bahl, P., "A rate-adaptive MAC protocol for multi-Hop wireless networks". In Proceedings of the 7th annual international conference on Mobile computing and networking (MobiCom '01). ACM, New York, NY, USA, pp.236-251, 2001.

[64] Biaz, S., Wu, S., "Rate adaptation algorithms for IEEE 802.11 networks: A survey and comparison," Computers and Communications, 2008. ISCC 2008. IEEE Symposium on , Marrakech, pp.130-136, 6-9 July 2008.

[65] Kamerman, A., Monteban, L., "WaveLAN-II : A High-performance wireless LAN for the unlicensed band". Bell Lab Technical Journal, pages 118-133, Summer 1997.

[66] Yun, J.-H., "Throughput analysis of IEEE 802.11 WLANs with Automatic Rate Fallback in a lossy channel," Wireless Communications, IEEE Transactions on , vol.8, no.2, pp.689-693, Feb. 2009.

[67] Raeesi, O., Hazmi, A., Pirskanen, J., Valkama, M., "Link Adaptation Performance Evaluation in IEEE 802.11ah,? Unpublished paper presented at fourth Nordic SNOW 2013 workshop, Ylläs, Finland, April 2013.

[68] Badihi Olyaei, B., Pirskanen, J., Raeesi, O., Hazmi, A., Valkama, M., "Performance comparison between Slotted IEEE 802.15.4 and IEEE 802.11ah in IoT based applications," 1st International Workshop on Internet of Things Communications and Technologies (IoT2013), Lyon, France, pp.343,348, Oct. 2013.