TAMPERE UNIVERSITY OF TECHNOLOGY

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Evaluation of IEEE 802.11ah Technology for Wireless Sensor Network Applications

Master of Science Thesis

Examiner: Prof. Mikko Valkama
Examiner and topic approved by
The Faculty Council of the Faculty of
Computing and Electrical Engineering
on March 4, 2015.

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master’s Degree Programme in Information Technology
ARAIZA LEON, JULIO CESAR: Evaluation of IEEE 802.11ah Technology for Wireless Sensor Network Applications
Master of Science Thesis, 69 pages
February 2015
Major: Communications Engineering
Examiner: Prof. Mikko Valkama
Keywords: IEEE 802.11ah, Wireless Sensor Networks, Analytical Model, Restricted Access Window

We are entering into a new computing technological era where communications are established not just user to user, or user to machine, but also machine to machine (M2M), machine to infrastructure, machine to environment. This then brings out the idea of acquiring data from the environment, process that data and use it to obtain a benefit, and the way to make this happen is by deploying a network of sensors which will provide an application with the desired sensed data. A sensor network is for practical reasons, nowadays considered as a Wireless Sensor Network (WSN).

As we move from static web to social networking and furthermore to ubiquitous computing, the amount of wireless devices out there is increasing exponentially. This has triggered a series of challenges for communications technologies as many new requirements need to be addressed. Low-cost, low-power and long-range coverage are the key requirements when designing a WSN. Since the communications subsystem in a WSN is the one dragging most resources, the WSN market is demanding new communication technologies to improve the performance of their current applications, but also to empower innovation by creating new application possibilities. Consequently, a new technology proposal has emerged as a solution to the previously mentioned requirements; the IEEE 802.11ah. This is an amendment to the well-known legacy IEEE 802.11 technologies and promises coverage for up to 1km with at least 100kbps, and support a large amount of stations.

This Master’s Thesis offers an insight to this new technology by evaluating its performance through an analytical model which is first developed and then evaluated in MatLab 2014b. A series of performance metrics have been considered in this work with the intention of evaluating its feasibility for WSNs. Different use cases are presented to give an idea of how this new communications standard would perform in real-life scenarios.

Based on the obtained results, it is concluded that the standard would perform well when implemented in WSN. But what differentiates the IEEE 802.11ah from its close competitors is the fact that substantial infrastructure using IEEE802.11ah and its amendments already exists, for which the transition to its use seems to be an easy bet.

The IEEE 802.11ah is still under development and is expected to be ready for 2016.

PREFACE

The research throughout this Master's Thesis work was conducted during the academic year 2014-2015 at the Department of Electronics and Communications Engineering, Tampere University of Technology.

First of all, I would like to express my gratitude to CONACYT Mexico (Consejo Nacional de Ciencia y Tecnologia), for the economic support provided throughout this International Master's Degree program.

Also, I would like to thank Prof. Mikko Valkama and Dr. Marko Hännikäinen for their time and dedication provided to the completion of this research. I am also thankful to M.Sc. Orod Raeesi for his help, sharing his experience and knowledge on the subject.

I would like to extend my appreciation to all my friends in Tampere which made me feel at home by taking me into their hearts, making this experience the most exciting so far to this date.

Furthermore, a special mention to my good friends Pekka Laaksonen and Esa Mattila for their support throughout my studies and life in Finland, I definitely felt like I was part of your family, thank you guys for everything.

Although I come from a different culture, principles and values are universal, and they are what I experienced during my time in this beautiful country. I will always be grateful for giving me this career opportunity, for giving me the chance to become a better human being, and the opportunity to pass on to others all the gained knowledge through the path of my life.

Last but not the least; I would like to express my deepest feelings to my family, my parents Rosario and Jose, and my brother Edgar for never letting me down, for believing in me, and for your unconditional love which kept me warm and close to you every single moment, without any doubts you are the source of my inspiration.

Tampere, February 2015

Julio Cesar Araiza Leon

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TERMS AND DEFINITIONS OR LIST OF SYMBOLS AND ABREVIATIONS

3GPP	3^{rd} Generation Partnership Project
ACK	Acknowledgement
AID	Association Identifier
AP	Access Point
BPSK	Binary Phase Shift Keying
BS	Base Station
BSS	Basic Service Set
CFE	Comision Federal de Electricidad
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
D7A	DASH7 Alliance
D7AQP	DASH7 Query Protocol
DC	Direct Current
DCF	Distributed Coordination Function
DIFS	Distributed Coordination Function Inter-Frame Space
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum
DTIM	Delivery Traffic Indication Map
ECG	Electrocardiogram
EEG	Electroencephalography
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMG	Electromyography
ERP	Effective Radiated Power
ESS	Extended Service Set
FFD	Full Function device
FFT	Fast Fourier Transform
GI	Guard Interval
GIS	Geographic Information Systems
GTS	Guaranteed Time Slot
HSPA	High Speed Packet Access
I/O	Input/output

IBBS	Independent Basic Service Set
IE	Information Element
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
ISI	Inter Symbol Interference
ISM	Industrial, Scientific and Medical Bands
LAN	Local Area Network
LTE	Long-Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control Layer
MCS	Modulation and Coding Scheme
MCU	Multipoint Control Unit
MIMO	Multiple Input Multiple Output
MSDU	Medium Access Control Service Data Units
NAV	Network Allocation Vector
NC	Network Coordinator
NDBPSCS	Number of Data Bits Per Sub-Carrier Per Symbol
NDP	Null Data Packet
NDPS	Number of Data Bits Per Symbol
NSCDT	Number of Sub-Carriers for Data Transmission
NSS	Number of Spatial Streams
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnection
OTA	Over The Air
PC	Personal Computer
PFC	Point Coordination Function
PHY	Physical Layer
PSM	Power Saving Mode
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R	Rate
RA	Resource Allocation
RAM	Random Access Memory

RAW	Restricted Access Window
RFD	Reduced Function Device
RFID	Radio Frequency Identification
RPS	Restricted Access Window Parameter Set
RTS/CTS	Request to Send, Clear to Send
SBF	Short Beacon Frame
SDU	Service Data Units
SIFS	Short Inter-Frame Space
SRAM	Static Random-Access Memory
STA	Station
SUN	Smart Utility Network
TDMA	Time Division Multiple Access
TGAH	IEEE 802.11ah Task Group
TIM	Traffic Indication Map
TMT	Theoretical Maximum Throughput
TWT	Target Wake Time
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WWRF	World Wireless Research Forum

1. INTRODUCTION

One of the most important concerns for human beings has always been the way people communicate with each other, setting the starting point for development and progress. During the last decades the world has witnessed a numerous of technological advances which have changed the way we think and act, especially in recent times with the arrival of the Internet, a revolution in the entire world has begun by just not changing the way we communicate with each other, but most importantly it has given us a new approach on how we carry on with our daily life activities, it has become part of our lives, and it has become us.

We are entering into a new computing technological era where communications are established not just user to user or user to machine, but also machine to machine (M2M), machine to infrastructure, machine to environment, and this is what brings out the idea of acquiring data from the environment, process that data and use it to obtain a benefit, the way to make this happen is by deploying a network of sensors which will provide an application with the desired sensed data.

A sensor network is composed of many devices called nodes; these ones are spatially distributed in order to perform a task pointed by an application. The main component of a node is a sensor which is used to monitor physical conditions of the real world on real time, such as temperature, pressure, sound, vibration, intensity, humidity, movement, materials and many others at different locations of an established area, then comes a microcontroller, a transceiver and an energy source. A sensor network essentially performs three basic functions: sensing, computing and communicating by using hardware, software and algorithms, respectively, all this regardless of the goal of the task in the application [1].

A sensor network is for practical reasons, nowadays considered as a Wireless Sensor Network (WSN), however in some cases they might be wired or hybrid types. The sensing device has to be inexpensive and small so it can be manufactured and deployed in large quantities, and since its nature is to be wireless the communication engineering and the energy efficiency play very important roles when designing a WSN for a desired application.

The potential of this technology has been studied intensively during the last decades as we are going towards a world where everything is connected to the Internet, devices which help us in our daily life activities such as traffic lighters, cameras, security systems, healthcare devices, home electronics, etcetera, all this to provide data to applications in order to make real time decisions which would improve our quality of life by taking the right action at the right time,.

As we move from static web to social networking and further to ubiquitous computing, the amount of wireless devices out there are increasing exponentially, World Wireless Research Forum (WWRF) has predicted that 7 trillion wireless devices for 7 billion people will be deployed by 2020 [2]. These devices will serve multiple tasks in a wide variety of disciplines which will challenge the world of communication and information technologies, demanding connectivity protocols and information systems tailored suited for specific applications, and here is where the review of technologies start, submerging ourselves in the quest for the right one which complies with our desired requirements.

1.1 Problem statement

An exponential growth in the use of wireless devices have triggered a series of challenges for communication technologies, a wide range of different necessities need to be addressed as every application needs to meet specific requirements [2]. Low-cost, low-power and long-range coverage are key requirements when designing a WSN. Since the communications subsystem in a WSN is the one dragging more resources, the WSN market is demanding new communication technologies to improve the performance of their current applications, but also to empower innovation by creating new application possibilities.

1.2 Thesis objective and scope

When designing a WSN several requirements have to be considered so that an application can be implemented. The main requirements of a WSN are the following:

- Low power (battery powered).
- Scalability of the network (high node density).
- Small size and robust design.
- Demanding applications.

This Master’s Thesis evaluates the IEEE 802.11ah amendment to the well-known IEEE 802.11 wireless communication standard, evaluates its performance in relation to the properties listed above, and makes a conclusion about its feasibility for WSN applications. This new amendment will operate on the sub-1 GHz bands and is still under development by the IEEE, and it is expected to be fully developed by 2016.

1.3 Thesis outline

A general outlook to the WSN technology is given in Chapter 2, where its most important characteristics and capabilities are listed, following its architecture details covering hardware, software and the protocol stack which conforms them.

In Chapter 3 the overview of the IEEE 802.11ah is well addressed, containing information such as the protocol stack in which special focus is set for this Master Thesis, the network topology and architecture, routing protocols and algorithms, channelization, MAC and Physical (PHY) layers, this with the objective of giving away its operational idea.

There are many other protocols currently playing an important role in the implementation of WSN, some of them very popular and robust, and as is very important to know what else is out there to serve as a reference point to add or remove features, especially because IEEE 802.11ah is still under development and the first devices will be launched in 2015, Chapter 4 briefly addresses related technologies such as Zigbee, DASH7, IEEE 802.15.4g and other somehow related such as 3GPP (3rd Generation Partnership Project) LTE (Long-Term Evolution), Low power IEEE 802.11b and WIMAX.

From the information gathered in previous chapters, Chapter 5 defines an analytical model is defined in order to perform several metrics of performance to the standard; metrics such as maximum theoretical throughput, saturation throughput, average end-to-end delay and energy efficiencies. Also two use cases are defined to have an idea of how well the IEEE 802.11ah performs in real-life scenarios.

Chapter 6 marks the conclusion of this Master Thesis work, addressing the IEEE 802.11ah feasibility for WSN applications.

2. WIRELESS SENSOR NETWORKS

Generally, a sensor node refers to any device that is capable to sense its environment. WSN as a technology is a collection of sensor devices that cooperate with each other [24]. The basic function of a WSN is to perform networked sensing of real-world phenomena such as humidity, temperature, light, vibrations, etc., by using a large number of inexpensive devices. The capabilities of wireless communication, small size and low power consumption enable WSN devices to be deployed in different types of environment including terrestrial, underground and underwater, with the possibility to operate under battery power for years makes them potentially disposable. Therefore, a WSN is not only a sensing component, but also on-board processing, communication and storage capabilities, with this enhancements a sensor node is often not just responsible for data collection, but also for network analysis, correlation, and fusion of its own sensor dada and the others data as well. Due to its ultra-low power operation this capabilities are limited. WSN address a wide range of application such as: security and surveillance, healthcare, monitoring and control, home automation, environmental and military.

2.1 Characteristics and capabilities of WSN

Compared to the traditional computer networks, WSN have unique characteristics listed below:

- High network size and density.
- Communication paradigm.
- Application specific.
- Network lifetime.
- Low cost.
- Dynamic nature
- Capable of random deployment.

Not every WSN shares all the characteristics listed above, but many of them share most of them [24].

The capabilities of sensor nodes in a WSN can vary widely and not just monitor a single phenomenon but several instead, there are complex devices combining several sensing techniques (temperature, pressure, humidity, etc.), but also they are capable of using different communications technologies (infrared, radio frequency, etc.) and processing units for more demanding applications.

Wireless sensor nodes don't communicate only with each other but also with a Base Station (BS) using their radios, allowing them to disseminate their acquired data to remote processing, visualization, analysis and storage systems [25]. Figure 2.1 shows two sensor fields in different geographic areas connected to remote systems through a BS using the internet.

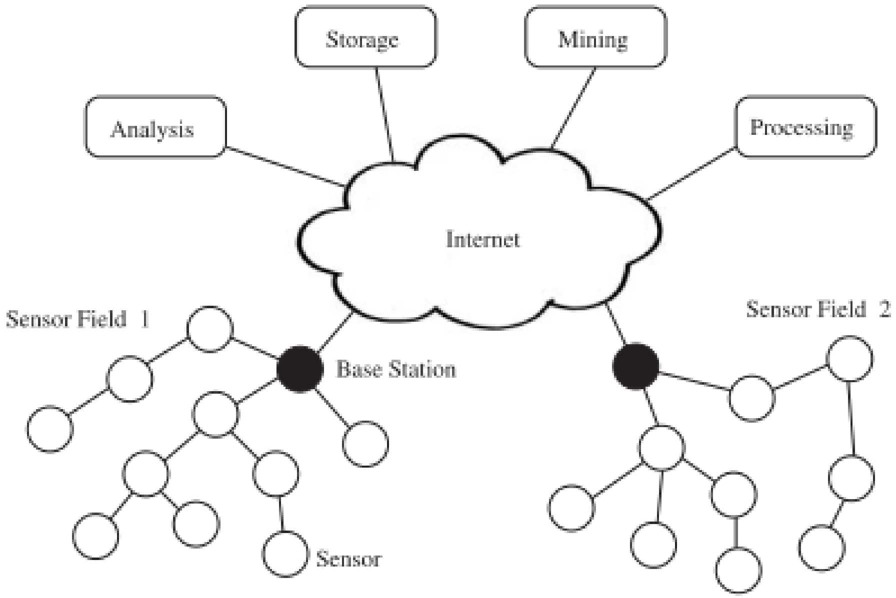

Figure 2.1 *WSN connected to remote systems through BS using the internet [25].*

2.2 Architecture

On the basis of targeting an application a new architecture can be developed. In the case of WSN it is important to perform a qualitative analysis of the possible applications in order to gather identification of more accurate design goals. Basically WSN architectures are divided three sectors; hardware, software and the protocol stack. In comparison with traditional WLANs (Wireless Local Area Network) where hardware affects very significantly on the achieved performance and the energy consumption of network terminals, in WSN the energy efficiency is implemented mostly by the MAC (Media Access Control) layer of the protocol stack, which at best can reduce the activity of a hardware below 1% in low data-rate monitoring applications [28]. For this reason an analysis of the technological trends has to be performed when designing a WSN architecture in order to maximize its performance.

2.2.1 Hardware architecture

The design and implementation of a wireless sensor node is a critical step; the quality, size and frequency of the sensed data that can be extracted from the network depend in great part to the physical resources available to the node. A WSN node consists of the following hardware subsystems:

- Communication subsystem; enables wireless connectivity.
- Sensing subsystem; the interface between the virtual and the physical world.
- Processing subsystem; the central element of the node, the choice of a processor determines the tradeoff between flexibility and efficiency.
- Power subsystem; provides Direct Current (DC) power to all the other subsystems in order to operate.

A general hardware architecture for a WSN node platform is presented in figure 2.2.

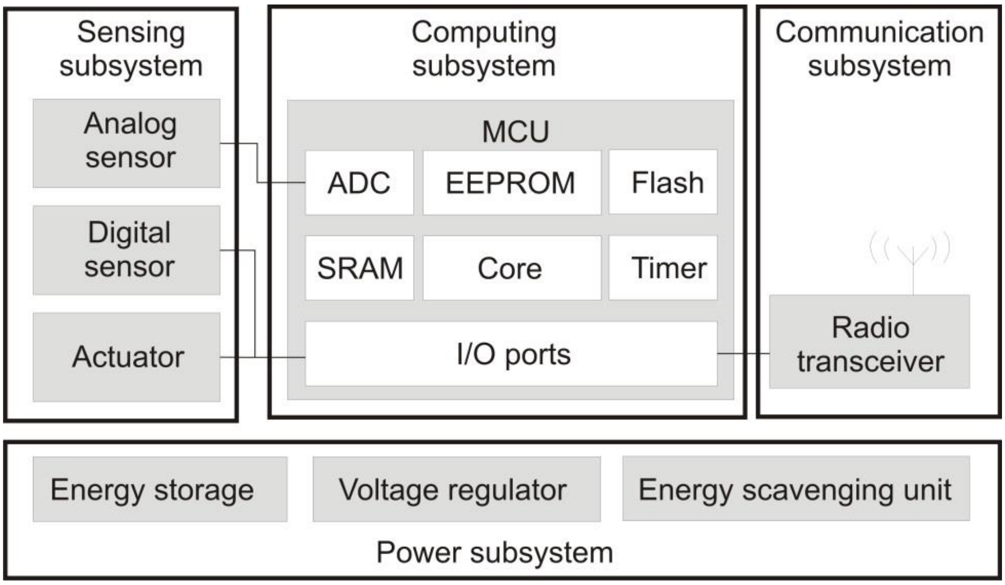

Figure 2.2 *General hardware architecture of a WSN Node [24].*

2.2.2 Protocol stack

A simplified protocol stack for WSNs follows the Open System Interconnection (OSI) model and is summarized in Figure 2.3. The physical layer (PHY) addresses the needs of simple but robust modulation, transmission and receiving techniques. Since the environment is noisy and sensor nodes can be mobile, the medium access control (MAC) protocol in the data-link layer must be power-aware and able to minimize collision with neighbors. The network layer takes care of the data supplied by the transport layer and then delivered to their destination via routing techniques. The transport layer helps to maintain the flow of data if the sensor network application requires it. Depending on the sensing tasks, different types of application software can be built and used on the application layer.

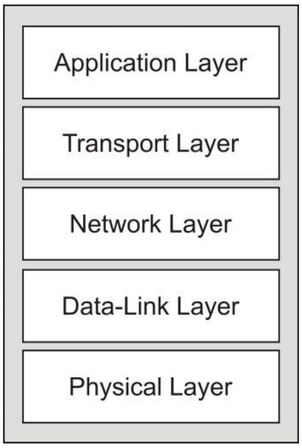

Figure 2.3 *Protocol stack for WSN.*

2.2.3 Software architecture

A critical step towards achieving the goal of having a functional WSN node is to design a software architecture that bridges the gap between raw hardware capabilities and a complete system. It must be efficient in terms of memory, processing and power, but also able to execute multiple applications using each of the hardware subsystems. Figure 2.3 shows the software architecture of a WSN.

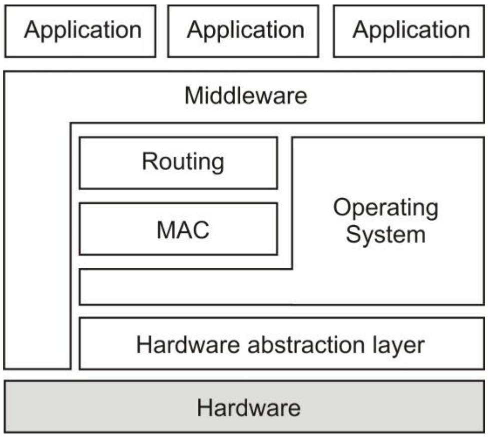

Figure 2.3 *Software architecture of a WSN node [24].*

3. IEEE 802.11AH OVERVIEW

The IEEE 802.11ah is a standard currently under development by the IEEE SA (IEEE Standard Association). The standard has the intention of providing ultra-low power WLAN connectivity to fixed, portable and moving STAs.

3.1 Background; IEEE 802.11

The wireless local area network (WLAN) is today a ubiquitous device taken for granted as a default infrastructure for networked devices for users and manufacturers alike. Ultimately adopted in 1997 [27], the IEEE 802.11 communication standard has as purpose to provide wireless connectivity for fixed, portable, and moving stations within a local area. This standard also offers to regulatory bodies, means of standardizing access to one or more frequency bands for the purpose of local area communication [4]. The IEEE 802.11 standard defines an over-the-air (OTA) interface between a wireless station (STA) and a base (BS) station or access point (AP), or between two or more wireless clients. One of the requirements of the IEEE 802.11 standard is to handle mobile as well as portable STAs. A portable STA is one that is moved from location to location, but that is only used while at a fixed location. Mobile STAs actually access the LAN while in motion [26].

3.1.1 Network architecture

The IEEE 802.11 architecture consists of several components that interact to provide a WLAN that supports STA mobility to upper layers:

- **The basic service set (BSS)** is the basic building block of an IEEE 802.11 LAN, a set of stations controlled by a single configuration function that determines when a station can transmit or receive; Figure 3.1 shows a graphic representation of a BSS.
- **The independent basic service set (IBSS)** enables two or more STAs to communicate directly and is usually established without preplanning, for as long as the LAN is needed, this type of operation is often referred as an ad-hoc network; Figure 3.2 shows an IBSS.
- **Distribution system (DS)** is a system to interconnect a set of BSS.
- **Extended service set (ESS)** is a set of one or more BSSS interconnected by a DS; Figure 3.3 shows two BSS connected through a DS.

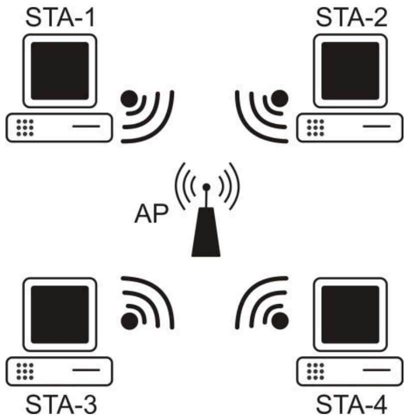

Figure 3.1 *Basic Service Set (BSS).*

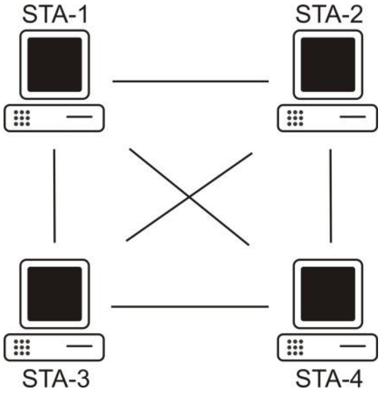

Figure 3.2 *Independent Basic Service Set (IBBS).*

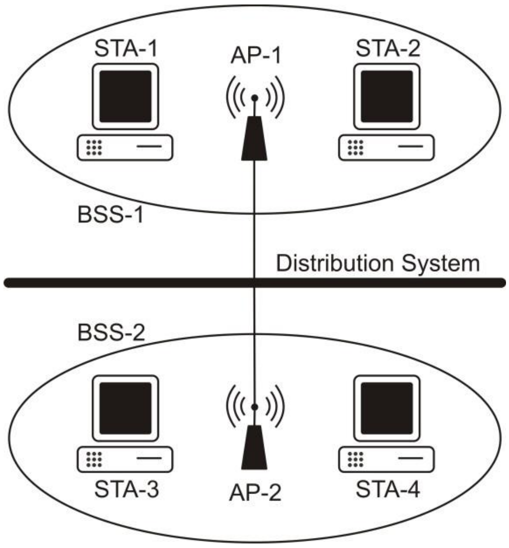

Figure 3.3 *Distribution System (DS).*

3.1.2 Amendments of the IEEE 802.11

New capabilities were added to the standard as amendments, and these amendments define different operational characteristics such as: maximum speed and radio frequency band of operation, how data is encoded for transmission, and the characteristics of the transmitter and receiver. These are some of the most popular amendments of the IEEE 802.11:

- **IEEE 802.11a**; 54 Mbps @ 5 GHz [6].
- **IEEE 802.11b**; 11 Mbps @ 2.4 GHz [7].
- **IEEE 802.11g**; 54 Mbps @ 2.4 GHz [5].
- **IEEE 802.11n**; up to 600 Mbps @ 2.4 or 5 GHz [8].
- **IEEE 802.11ac**; at least 500 Mbps @ 5 GHz [9].
- **IEEE 802.11ah**; at least 100 Kbps @ sub-1 GHz [10].

The IEEE 802.11 and its amendments were designed to operate on several bands of the wireless spectrum for use without a government license. To operate in these bands though, devices were required to use “spread spectrum” technology, meaning that this technology spreads radio signal out over a wide range of frequencies, making the signal less susceptible to interference and difficult to intercept [6].

3.2 Motivation for development of 802.11ah

The increasing market of WSN brought the need of developing a new standard in order to comply with very specific tasks for which the current amendments to the IEEE 802.11 standard haven’t been designed for; in fact the IEEE 802.11 standard was designed to be used by personal computers and not by WSN devices, this is what brings out the need for new amendments to fulfill new requirements.

This new emerging standard in the M2M communications area, first introduced in 2010 has been developed with very specific intentions: to deliver long range transmission above 1Km, with data rates above 100 Kbps and very low power consumption, but also to support a large number of nodes in the network while maintaining its operability with a very low power consumption policy.

With the development of the IEEE 802.11ah, the WLANs now will offer a very cost-effective solution to WSN applications such as smart metering, plan automation, surveillance and also enabling operation in environment demanding scenarios such as natural or nuclear disasters just to mention a few.

Apart from the goals mentioned above, is very important to note that the IEEE 802.11ah Task Group (TGah) wants to achieve them when minimizing the changes respect to the widely adopted IEEE 802.11 standard, moreover the proposed PHY and MAC layers are based on the IEEE802.11ac amendment, trying to achieve an efficiency gain by reducing some control/management frames and the MAC header length.

The advantages offered by the standardization of sub-1GHz WLANs are several; very simple to use in outdoor environments in addition to excellent propagations characteristics at low frequencies in different levels of installation scenarios on Industrial, Scientific and Medical (ISM) bands. High sensitivity and link margin increase the reliability of the IEEE 802.11ah standard [12].

3.3 Use cases

Three main use cases have been adopted by the IEEE 802.11ah task group (TGah):

- Sensors and meters.
- Backhaul sensor/meter data.
- Extended range Wi-Fi.

In this subchapter we analyze the potential use of the IEEE 802.11ah amendment for several scenarios.

3.3.1 Sensor networks

When large amount of nodes have been deployed to cover large areas, the battery performance is a key factor in order to select a standard to develop a device. Sensor networks are one of the three adopted use cases by the TGah. Due to the increased penetration through walls and other scatters at lower frequencies, a higher number of nodes can be deployed in a one hop fashion. The versatility that IEEE 802.11ah offers can benefit many industrial applications.

3.3.1.1 Smart grid metering

When having many smart meters in urban areas one concern is to obtain data across many scatters, and to improve reliability having a less centralized network to collect data is a key factor. Electricity, gas and water companies have presence everywhere in the modern world, high transmission speeds are not an important factor due to the fact that the amount of data which needs to be transmitted is very low and the time frame between one transmission and another is considerable big. Besides the feature mentioned before, covering rural areas could be a major advantage when using this standards due to its long range capabilities. The proposed infrastructure can be seen in Figure 3.4.

Comision Federal de Electricidad (CFE) provides electricity for 127 million people in Mexico, and since 2011 has been deploying smart grids in order to improve productivity in its operational processes, companies like this have been a major influence to the development of the IEEE 802.11ah standard [13].

3.3.1.2 Demanding environments

During the recent years environmental research has been a priority for many countries of the world, undergoing a major technological revolution as interfaces develop between environmental science, engineering and information technology. These advancements are focused on understanding the impact that modern society has to our planet, in order to come up with the necessary strategies; strategies that could lead us to minimize the environmental degradation and global warming that have been causing a major negative impact on the people's quality of life.

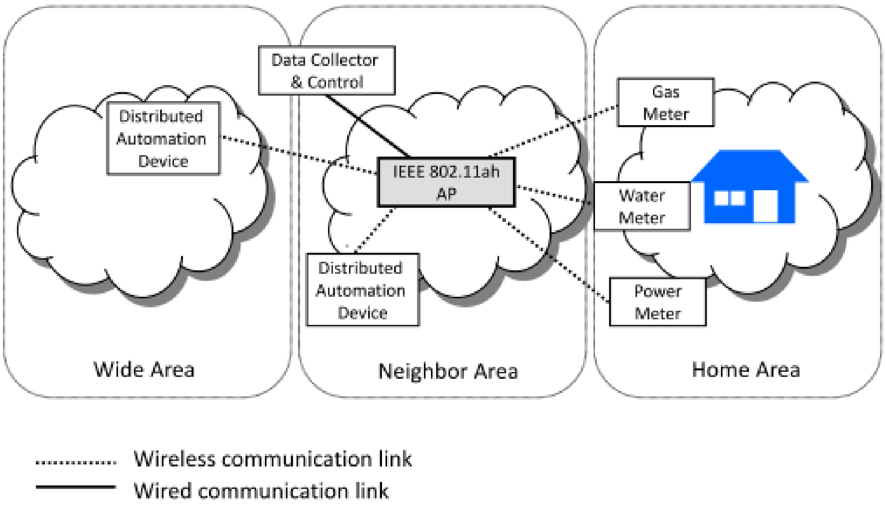

Figure 3.4 *Proposed infrastructures for Smart Grid applications using IEEE 802.11ah*

Sensors and sensor networks have an important impact in meeting environmental challenges as they contribute to more efficient use of resources and thus a reduction of greenhouse gas emissions and other sources of pollution [17].

Taking a different approach the author has adopted a use case for the IEEE 802.11ah in terms of deploying a WSN for sensing the consequences of natural and man-made disasters. As pointed in [18] the devices must run Geographic Information Systems (GIS) to receive and transmit information about the disaster, hence, it is necessary to create mechanisms for WSN to process such queries efficiently, especially in relation to energy consumption, but also to able to provide long range connectivity to cover large areas. There are already ideas of products like the one shown on Figure 3.5[19] which have been inspired by the nuclear disaster in Fukushima after the unfortunate earthquake and tsunami struck Japan on 2011, are using ZigBee (a similar technologie to the IEEE 802.11ah), this devices have been proposed to address nuclear disasters scenarios, see Figure 3.6 for a graphical interpretation of the proposed framework.

3.3.2 Backhaul networks for sensors

Backhaul networks for sensors are the second use case adopted by the TGah. This kind of networks usually operate in a many-to-one network scheme, the traffic load is highly asymmetrical; nodes closer to the sink node have heavier relay load as illustrated in Figure 3.7. Thus, the traffic load and the corresponding power consumption are location-dependent and the lifetime of the network can be limited by nodes with heavy traffic load as they require higher power consumption [14].

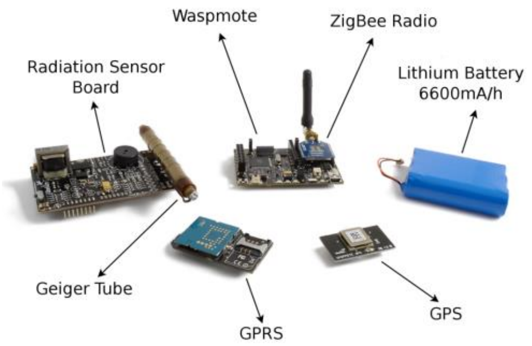

Figure 3.5 *Proposed Waspmote for nuclear disasters.*

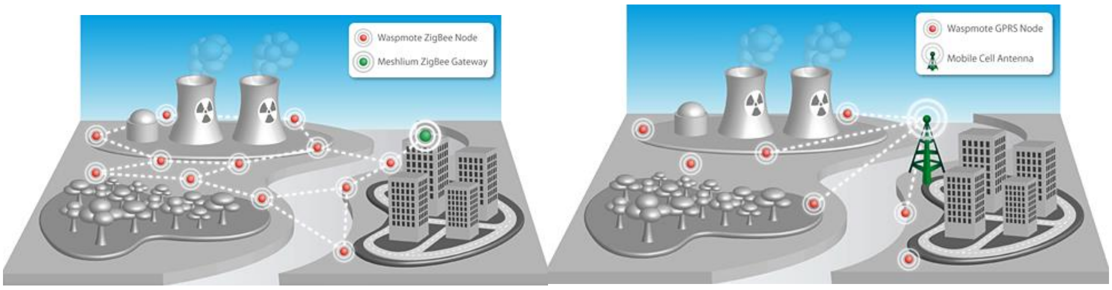

Figure 3.6 *Nuclear disaster WSN representations.*

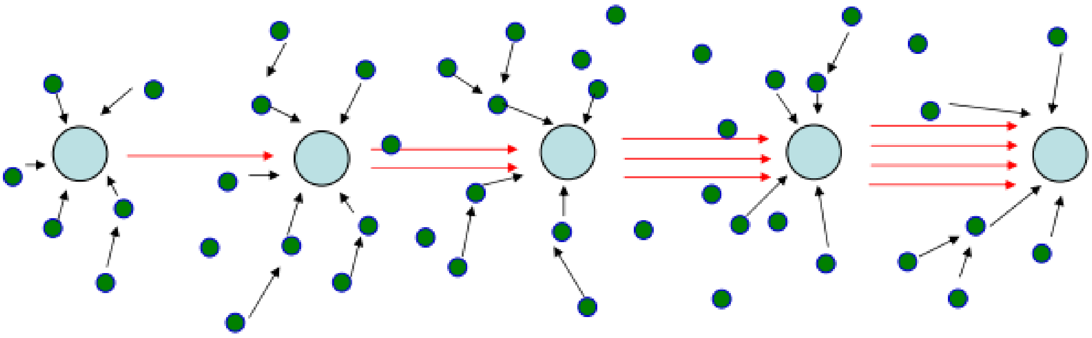

Figure 3.7 *A hierarchical linear network of sensors.*

One of the main advantages of the IEEE 802.11ah is the long range coverage that it offers, and this characteristic allows networks design to link sub-1 GHz AP's together, for example as wireless mesh networks; Figure 3.8 shows the adopted use case by the TGah for backhaul sensor networks [12].

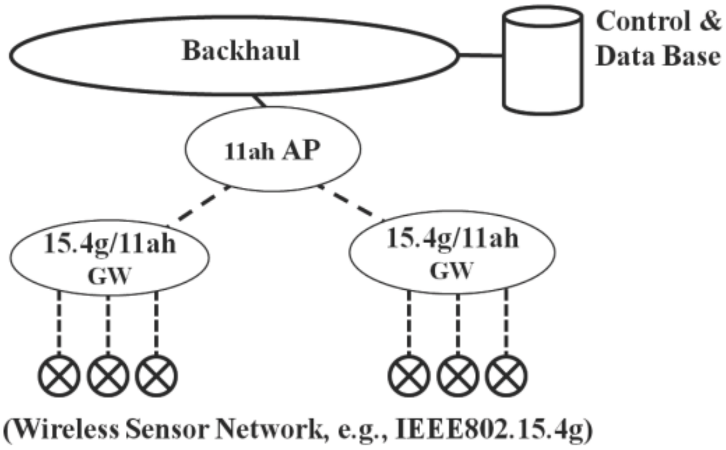

Figure 3.8 *Adopted TGah use case: sensor backhaul network.*

3.3.3 Extended Wi-Fi range for cellular traffic off-loading

In the recent years, mobile carriers have been experiencing a massive growth in their traffic loads thanks to the mainstream use of internet connected wireless devices such as smart phones and tablets. This massive consumption levels have created new requirements for building a lot more wireless network capacity to cope with the user's needs. Users are expecting to have access to high-speed internet connection anywhere and anytime. In the US alone nearly two thirds of mobile phone owners use their phone to go online, and one in five mobile phone owners do most of their online browsing on their mobile phone, and Figure 3.9 just shows how this trend is continuing to grow [15].

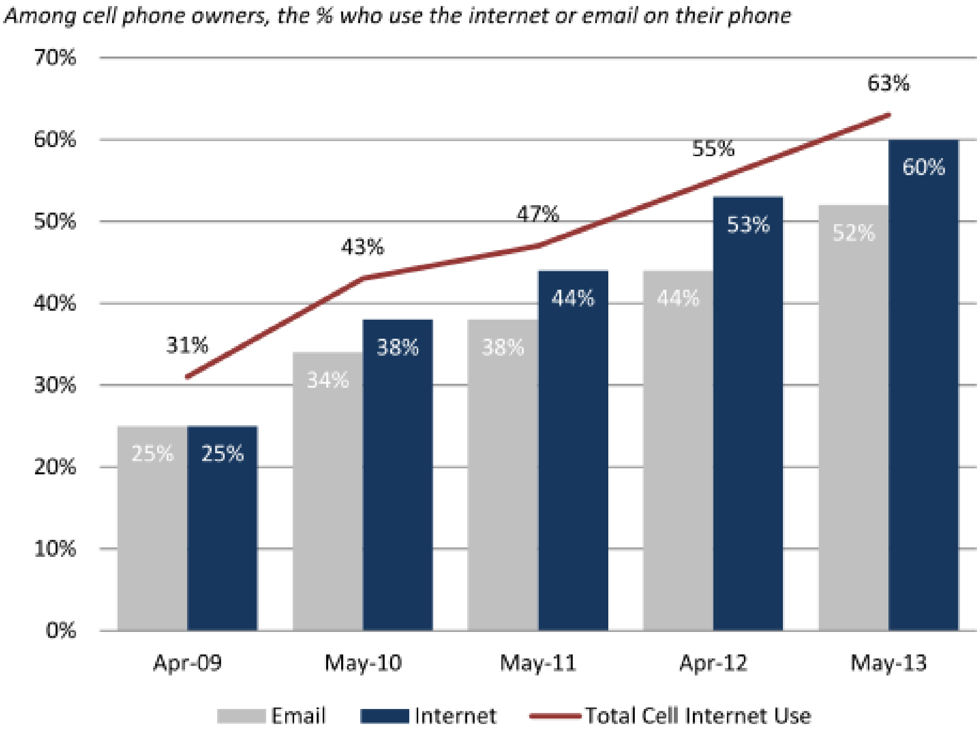

Figure 3.9 *Internet's mobile phone usage in the USA.*

Operators are rolling out of increased bandwidth via High Speed Packet Access (HSPA), Long Term Evolution (LTE) and other upgrades. But simply increasing the speed may not always be economical effective, and there may not be enough bandwidth even with 4G [16].

Because of this growing market the TGah has adopted this use case considering the technical requirements for a Wi-Fi based cellular traffic off-loading in this standard. Although other amendments of the IEEE 802.11 such as the IEEE 802.11n have been pointed to be a better solution to improve the off-loading because of its higher bandwidth characteristics, the long range coverage and low power consumption of the IEEE 802.11ah are key features to fulfill battery operated mobile devices requirements, and this is the main reason for this amendment to be chosen by the TGah.

3.4 PHY design

The PHY design of the IEEE 802.11ah has been based on previous amendments of the IEEE 802.11 standard, based on the PHY design of the IEEE 802.11ac which operates a 20 MHz, 40 MHz, 80 MHz and 160 MHz channel bandwidths [9], we can determine that the IEEE 802.11ah’s PHY is a ten times down-clocked version of it as it will operate in the 2 MHz, 4 MHz, 8 MHz and 16 MHz channel bandwidths, and an additional 1 MHz channel which has been intended to improve coverage. Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) multicarrier wireless system composed of a total of 64 tones will be used, which has been borrowed from the IEEE 802.11a to operate on the sub-1 GHz ISM bands.

This sub-chapter is the author’s interpretation of the Specification Framework for the development of IEEE 802.11ah available in [20].

3.4.1 Channelization

As mentioned before, the IEEE 802.11ah supports 1 MHz, 2 MHz, 4 MHz, 8 MHz and 16 MHz PHY transmissions, and a Wireless Station (STA) supports reception of 1 MHz and 2 MHz PHY transmissions. The available sub-1 GHz ISM bands are defined by the wireless spectrum established in different countries.

For South Korea the ISM bands defined for its operation start 917.5 MHz ending at 923.5 MHz, a total of 6 MHz band is available as represented in Figure 3.10. The 0.5 MHz offset is to avoid interference with wireless legacy systems at lower frequencies.

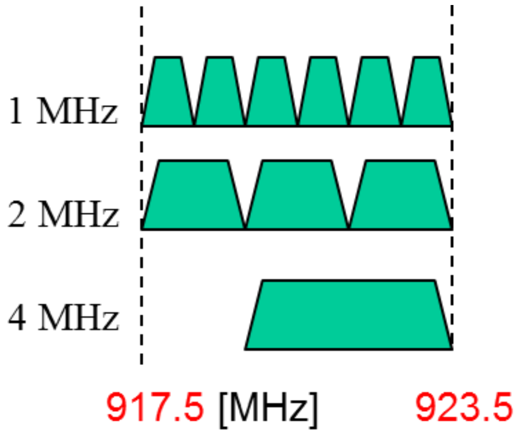

Figure 3.10 *Adopted IEEE 802.11ah channelization model for South Korea.*

For Europe a total of 5 MHz band has been assigned, from 863 MHz to 868 MHz, assuming 600 KHz as a guard band as represented in Figure 3.11.

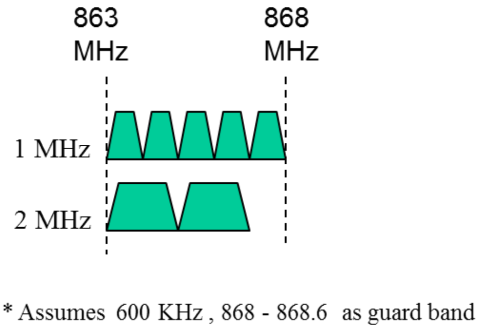

Figure 3.11 *Adopted IEEE 802.11ah channelization model for Europe.*

In figure 3.12 the adopted channelization model for Japan is represented, starting from 916.5 MHz and ending at 927.5 MHz giving a total of 11 MHz band, with a 0.5 MHz offset to specify center frequencies instead of start/stop bands as the country regulations demand [21].

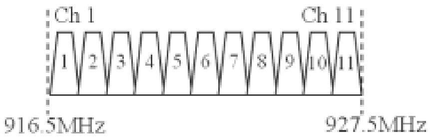

Figure 3.12 *Adopted IEEE 802.11ah channelization model for Japan.*

In figure 3.13 the channelization model adopted for China is shown, starting at 755 MHz and ending at 787 MHz, limiting the Effective Radiated Power (ERP) to 5 mW from 755 MHz to 779 MHz, and to 10 mW from 779 MHz to 787 MHz, giving the standard a total of 32 MHz band available.

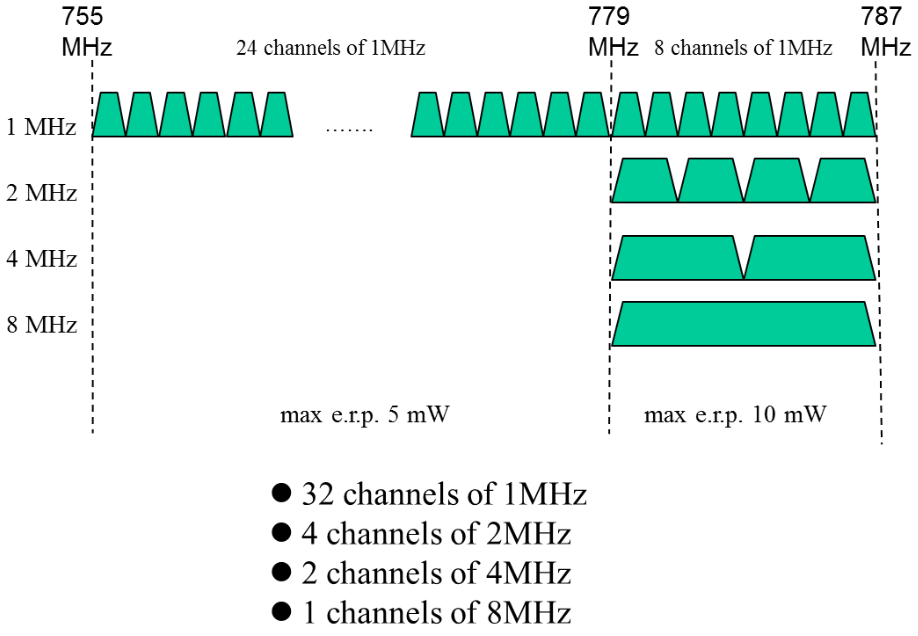

Figure 3.13 *Adopted IEEE 802.11ah channelization model for China.*

In figure 3.14 the channelization model adopted by Singapore is shown, allowing the standard to operate from 866 MHz to 869 MHz and from 920 MHz to 925 MHz bands, giving the standard a total of 8 MHz band.

The United Stated of America is the country with the most bands available, a total of 26 MHz band has been adopted starting at 902 MHz and ending at 928 MHz, making it the only country able to operate with a bandwidth of 16 MHz as shown in Figure 3.15.

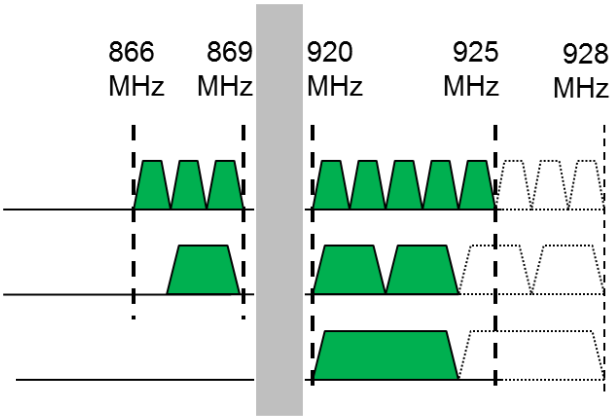

Figure 3.14 *Adopted IEEE 802.11ah channelization model for Singapore.*

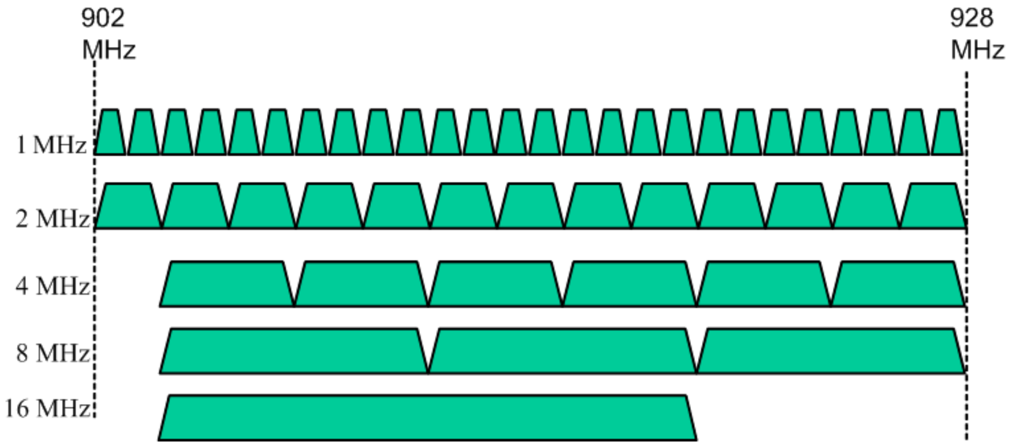

Figure 3.15 *Adopted IEEE 802.11 channelization model for The United States of America.*

From the figures shown above we can observe how the standard in order to achieve a higher bandwidth maintains the same channel bonding used in IEEE 802.11n and IEEE 802.11ac [22], making The United States of America the country with the biggest available bandwidth (16 MHz) due to the availability of the ISM bands.

3.4.2 Transmission modes

According to the Specifications Framework of the standard [20], the PHY design has been addressed in two categories; the first one comprehending 1 MHz channel bandwidth transmissions mode, and the second comprehending >=2 MHz channel bandwidth transmission mode.

For the first case it uses the same tone plans as the corresponding Fast Fourier Transform (FFT) sizes of IEEE 802.11ac, a PHY using an OFDM waveform with a total of 64 tones spaced by 31.25 KHz, and for the second case the tone spacing is also 31.25 KHz but the OFDM waveform is formed by 32 tones.

These transmission modes have been designed to operate at different Modulation and Coding Schemes (MCS), in order to achieve two main performance scenarios, long-range connectivity and high data rate capabilities. The modulations supported by the standard are BPSK and QSPK and QAM.

For 2 MHz channel with a single spatial stream, a 64 FFT is used to generate an OFDM symbol and among the 64 subcarriers only 52 are used to transmit data. OFDM symbol duration is 32 µs plus a Guard Interval (GI) of 8 µs in order to prevent Inter Symbol Interference (ISI); data rate formula can be written as (3.1):

$$Data\ Rate = \frac{R*N_{SS}*N_{SCDT}*N_{DBPSCS}}{OFDM_{SD}} = \frac{N_{DBPS}}{OFDM_{SD}} \qquad (3.1)$$

Where:

- N_{SS} = Number of spatial streams.
- N_{SCDT} = Number of sub-carriers for data transmission.
- N_{DBPSCS}= Number of data bits per sub-carrier per symbol.
- N_{DPS} = Number of bits per symbol.
- $OFDM_{SD}$ = OFDM symbol duration.
- R = Rate.

Values are taken from the timing-related constants defined by the draft of the IEEE 802.11ah amendment as shown in Table 3.1 [4].

Parameter	**CBW1**	**CBW2**	**CBW4**	**CBW8**	**CBW16**	**Description**
N_{SD}	24	52	108	234	468	Number of data subcarriers per OFDM symbol
N_{SP}	2	4	6	8	16	Number of pilot subcarrier per OFDM symbol
N_{ST}	26	56	114	242	484	Total number of useful subcarriers per OFDM symbol
N_{SR}	13	28	58	122	250	Highest data subcarrier index per OFDM symbol
Δ_F	31.25 kHz					Subcarrier frequency

			spacing
T_{DFT}	$32\ \mu s = 1/\Delta_F$		IDFT/DFT period
T_{GI}	$8\ \mu s = T_{DFT}/4$		Guard interval duration
T_{DGI}	$16\ \mu s$		Double guard interval
T_{SGI}	$4\ \mu s = T_{DFT}/8$		Short guard interval duration
T_{SYML}	$40\ \mu s = T_{DFT} + T_{GI} = 1.25 \times T_{DFT}$		Duration of OFDM symbol with normal guard interval
T_{SYMS}	$36\ \mu s = T_{DFT} + T_{GIS} = 1.125 \times T_{DFT}$		Duration of OFDM symbol with short guard interval
T_{SYM}	T_{SYML} or T_{SYMS} depending on the GI used		OFDM symbol duration
T_{STF}	$160\ \mu s = 4 \times T_{SYML}$	$80\ \mu s = 2 \times T_{SYML}$	STF field duration
T_{DSTF}	n.a.	$40\ \mu s = T_{SYML}$	≥2 MHz long preamble D-STF field

			duration
T_{LTF1}	160 µs = $4 \times T_{DFT} + 2 \times T_{GI} + T_{GI2}$	80 µs = $2 \times T_{DFT} + T_{GI2}$	First LTF field duration
T_{LTFs}	40 µs = T_{SYML}		Second and subsequent LTF field duration
T_{DLTF}	n.a.	40 µs = T_{SYML}	≥2 MHz long preamble D-LTF field duration
T_{SIG}	240 µs = $6 \times T_{SYML}$	80 µs = $2 \times T_{SYML}$	SIG field duration
T_{SIGA}	n.a.	80 µs = $2 \times T_{SYML}$	≥2 MHz long preamble SIGA field duration
T_{SIGB}	n.a.	40 µs = T_{SYML}	≥2 MHz long preamble SIGB field duration

Table 3.1 *IEEE 802.11ah timing-related constants.*

Table 3.2 shows the MCSs with their corresponding data rates for 2 MHz transmission mode, the descriptions of the parameters are the following:

MCS_{Index}	Modulation	R	N_{SS}	N_{SCDT}	N_{DBPSCS}	N_{DBPS}	$OFDM_{SD}$	Mbps
0	BPSK	1/2	1	52	1	26	40 µs	0.65
1	QPSK	1/2	1	52	2	52	40 µs	1.3
2	QPSK	3/4	1	52	2	78	40 µs	1.95
3	16-QAM	1/2	1	52	4	104	40 µs	2.6
4	16-QAM	3/4	1	52	4	156	40 µs	3.9
5	64-QAM	2/3	1	52	6	208	40 µs	5.2
6	64-QAM	3/4	1	52	6	234	40 µs	5.85
7	64-QAM	5/6	1	52	6	260	40 µs	6.5
8	256-QAM	3/4	1	52	8	312	40 µs	7.8

Table 3.2 *IEEE 802.11ah Modulation and Coding Schemes.*

Also very important parameters defined by the draft of the amendment are the PHY characteristics shown in table 3.3 [4].

3.5 MAC design

Like in all shared-medium networks, medium access control (MAC) is an important technique that enables the successful operation of the network; it is responsible for regulating access to the shared medium in the PHY layer. To design a good MAC protocol for WSNs, the follow attributes have to be considered. The first one is the energy efficiency as sensor nodes are likely to be battery powered, therefore prolonging network lifetime for these nodes is a critical issue. To be able to reach adequate energy efficiency, a MAC protocol should be able to minimize [28]:

Characteristics	Value
aSlotTime	52 us
aCCATime	40 us
aAirPropagationTime	6 us
aSIFSTime	160 us
aPHY-RX-START-Delay	1MHz preamble: 600us 2MHz/4MHz/8MHz/16MHz: 280us

Table 3.3 *IEEE 802.11ah PHY characteristics.*

- **Idle listening:** Occurs when a node is actively receiving a channel but there is no meaningful activity, resulting in a waste of energy.

- **Collisions:** When two nodes transmit at the same time at the same frequency channel, their transmissions collide. The received data is most probably corrupted and useless, therefore retransmission is needed resulting in waste of energy.
- **Overhearing:** A unicast transmission on a shared wireless broadcast medium may cause other nodes than the intended destination to receive a data packet, which is most probably useless to them and consumes unnecessarily energy.
- **Protocol overhead:** The headers of data packets and the control packet exchange may cause significant reception and transmission cost for nodes consuming unnecessarily energy.
- **Power modes transitions:** The transitions from sleep mode to active mode and vice versa dissipate a lot of energy.

The second is network scalability and adaptability to changes in network size, node density and topology. A good MAC protocol should address such network changes. The IEEE 802.11ah's MAC design is an enhanced version of the MAC presented in the IEEE 802.11 standard, taking into account the challenges stated above, this enhancements are presented in this sub chapter.

3.5.1 MAC frame types

The legacy IEEE 802.11 MAC frame format comprises a set of fields that occur in a fixed order in all frames, Figure 3.16 depicts the general MAC frame format. The first three fields (Frame Control, Duration/ID, and address) and the last field (FCS) in Figure 3.16 constitute the minimal frame format and are present in all frames, including types and subtypes. The rest of the fields are present in only certain frame types and subtypes [26].

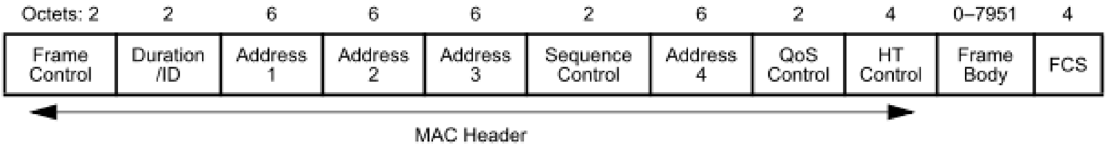

Figure 3.16 *MAC frame format [26].*

In the IEEE 802.11ah there are a few changes in the elements of the Frame Control field related to the combination of type and subtype combinations. One of the important changes has been done in the PS-Poll frame format; Figure 3.17 depicts the legacy IEEE 802.11 format and the adopted by the TGah.

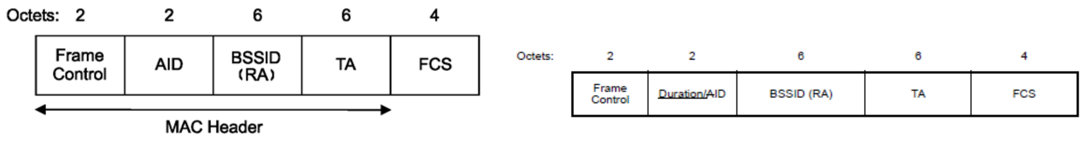

Figure 3.17 *IEEE 802.11 and 802.11ah PS-Poll frame formats.*

The Duration/ID field contains Duration if the PS-Poll is sent as the initial frame of a Speed Frame exchange by a STA, otherwise the Duration/ID field contains Association Identifier (AID). Also a completely new frame is introduced by the 802.11ah is the Null Data Packet (NDP). The NDP MAC frame formats are defined to decrease MAC protocol overhead in IEEE 802.11 BSS. Table 3.4 list the possible values for this type of frame.

Value	Meaning	Type
0	NDP CTS	Control frame
1	NDP PS-Poll	Control frame
2	NDP ACK	Control frame
3	NDP Modified ACK	Control frame
4	NDP Block ACK	Control frame
5	NDP Beamforming Report Poll	Control frame
6	NDP Paging	Control frame
7	NDP Probe Request	Management frame

Table 3.4 *NDP MAC frames.*

For more information about the MAC Frame types, please go to the Proposed TGah Draft Amendment for the IEEE 802.11ah [4].

3.5.2 Support of large number of STAs

In the IEEE 802.11 system, the MAC layer defines that the AP assigns an AID to each STA during the association state, and its maximum number of stations is mapped to 2007 in legacy 802.11 networks [26], this due to the limited length of the partial virtual bitmap of the Traffic Indication Map (TIM) Information Element (IE) where each bit indicates the corresponding STA’s AID. In order to comply with the requirements for proper WSN MAC design, the TGah has designed a novel and hierarchical distribution of the AID structure, Figure 3.18 shows the AID structure designed by the TGah.

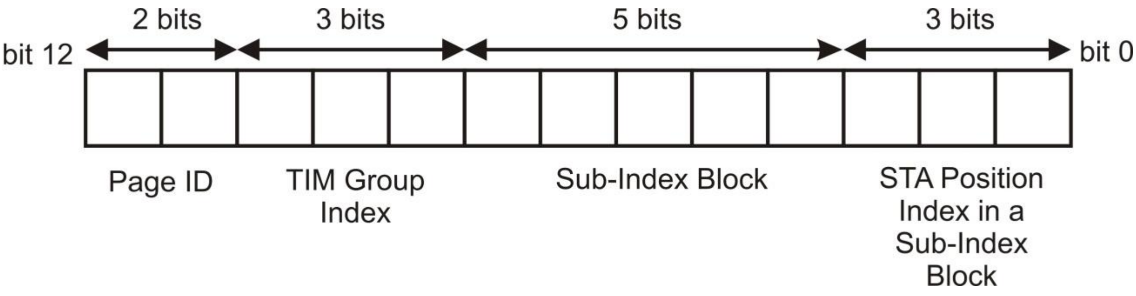

Figure 3.18 *AID structure for IEEE 802.11ah MAC.*

The new hierarchical AID structure consists of 13 bits, and accordingly, the number of stations that it can express is up to $2^{13} – 1$, which gives support for a total of 8191 STAs. It is composed of four hierarchical levels, four pages, each page containing eight TIM groups, and each group containing thirty two sub blocks as illustrated on Figure 3.19. The hierarchical structure makes grouping of STAs much easier. It is an effective way to categorize STAs respect to their type of application, battery consumption, resource allocation and efficient channel access.

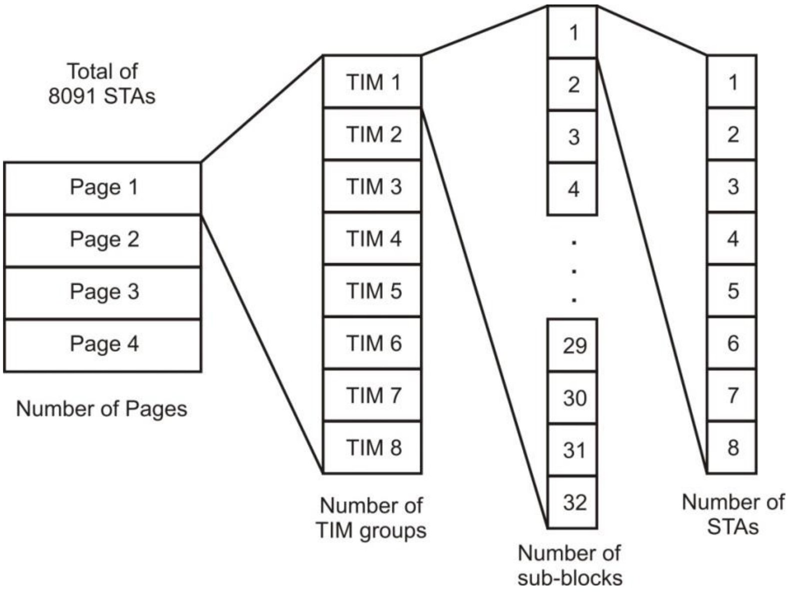

Figure 3.19 *Hierarchical distributions of STAs in IEEE 802.11ah networks.*

3.5.3 Power saving mode

As specified in the IEEE 802.11 standard, a wireless network interface can choose to stay in one of the two states at any time, awake or sleep. In the awake state the radio is powered up and the wireless interface can perform data communications, or just stay in idle. In the sleep state, on the contrast, the radio is turned off and the wireless interface can’t detect or sense the behavior of the network. This state is specified in the IEEE 802.11 standard as Power Saving Mode (PSM), in this mode, the AP buffers incoming frames destined for mobile stations in PSM until the station wakes up and requests the delivery of the buffered traffic, after finishing the reception the station goes back to PSM. For this matter in the IEEE 802.11ah standard there are two classes of signaling beacon frames:

- **Delivery Traffic Indication Map (DTIM):** Informs which groups of STAs have pending data at the AP.
- **Traffic Indication Map (TIM):** Informs a group of STAs about which of them have pending data at the AP.

Both DTIM and TIM beacon structures are based in one Short Beacon Frame (SBF) plus Information Elements (IE) for different purposes (Figure 3.20):

- **SBF:** Advertises the AP presence and synchronizes the STAs.
- **TIM IE:** When the AP splits the whole partial bitmap corresponding to one or more TIM Groups, it introduces which stations from its corresponding TIM Group has pending data to receive.
- **DTIM IE:** STAs can deduce their assignment in TIM groups and their wake up intervals.
- **RAW IE (Restricted Access Window IE):** Responsible of signaling information like the time periods in which selected STAs contend for accessing the channel. Its IE includes time from the beacon to the RAW, duration of the RAW and mechanisms to generate sub-slots within the RAW contention period.

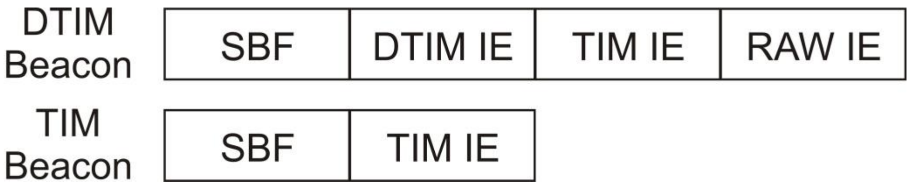

Figure 3.20 *DTIM and TIM structures.*

For the IEEE 802.11ah the TGah has defined three different types of STAs [20]:

- **TIM STAs:** Listen to DTIM and TIM beacons to send or receive data. Similar to the concept of PSM in legacy IEEE 802.11.
- **Non-TIM STAs:** Only listen to DTIM beacons to send or receive data. Buffering is not included in TIM IE assuming there is no need for them to wake up periodically for the beacon reception. This enables STAs to stay in PSM over longer periods of time without worrying about beacon reception, suggesting being an Ultra-Low Power Mode.
- **Unscheduled STAs:** These STAs do not need to listen beacons and can send or receive data at any time.

The IEEE 802.11 PSM is based on the inclusion of an IE field in each TIM beacon; it carries the information of existing packets in the downlink buffer for each STA in PSM mode. Accordingly, every STA in PSM needs to wake up periodically to receive a beacon in order to realize if there are buffered packets aimed to it. If there is data the STA then transmit a control frame called Power Saving (PS)-Poll Frame to the AP to request the delivery of the buffered packets. Any STA can enter to PSM mode if it observes in the TIM beacon that there is no data aimed to it.

As the IEEE 802.11 wasn't designed for WSN devices which generally are battery operated, its PSM has major drawbacks such as:

- Every STA in PSM would need to listen to every TIM beacon, shortening their time in PSM.
- In a densely populated network the beacon frame may be too long, as the TIM IE would need to map the all the STAs in the network, resulting very expensive in terms of energy consumption.
- If the buffered traffic is too heavy that it couldn't fit within a beacon interval, STAs would keep active in order to receive the rest of the packets.

In order to cope with these drawbacks of the IEEE 802.11 for WSN, the TGah has adopted a new scheme for the PSM called TIM and Page Segmentation.

3.5.3.1 TIM and page segmentation

As the IEEE 802.11 standard wasn't specifically designed for WSN, challenges in terms of energy efficiency have driven the TGah to develop a new PSM scheme for the new amendment. This new scheme has as primary target to save energy of SATAs when in PSM, the mechanism works as follows. First the AP fragments the TIM IE into equal sized TIM segments consisting of Page segment with a subset of STAs AIDs (the AP splits the whole partial virtual bitmap corresponding to one page into multiple page segments), now each beacon is responsible of carrying the buffering status of only a certain page segment, allowing the STAs to wake up at the transmission time of the beacon that carries the buffering information of the segment it belongs to. Now, TIM segments carry a new IE called Segment Count IE and it carries the segmentation information, Figure 3.21 illustrates the operation of TIM and page Segmentation. STAs with TIM Segmentation capability set to true shall follow the following rules [4]:

- TIM segments may be assigned within a DTIM beacon interval and segment count element indicates the sequence of page segments among scheduled TIM segments.
- The Segment Count IE is only transmitted in DTIM beacons frames and not in TIM beacons (Non-TIM STAs).

- Each TIM segment shall use a fixed length page segment within one DTIM beacon interval. However, the length of page segment may vary over multiple DTIM beacon intervals.
- Each ordered page segment is assigned sequentially to TIM segments where the first segment may be assigned to the DTIM segment, second page segment in first TIM segment and so on.

The Segment Count IE indicates assignment of STAs in Page segments corresponding to their assigned TIM segments. In order to wake up at the appropriate TIM segment, the STAs may compute the Page segment assignment to the TIM segments using the length of the Page Bitmap field and the value in the Page Segment Count fields of Segment Count IE.

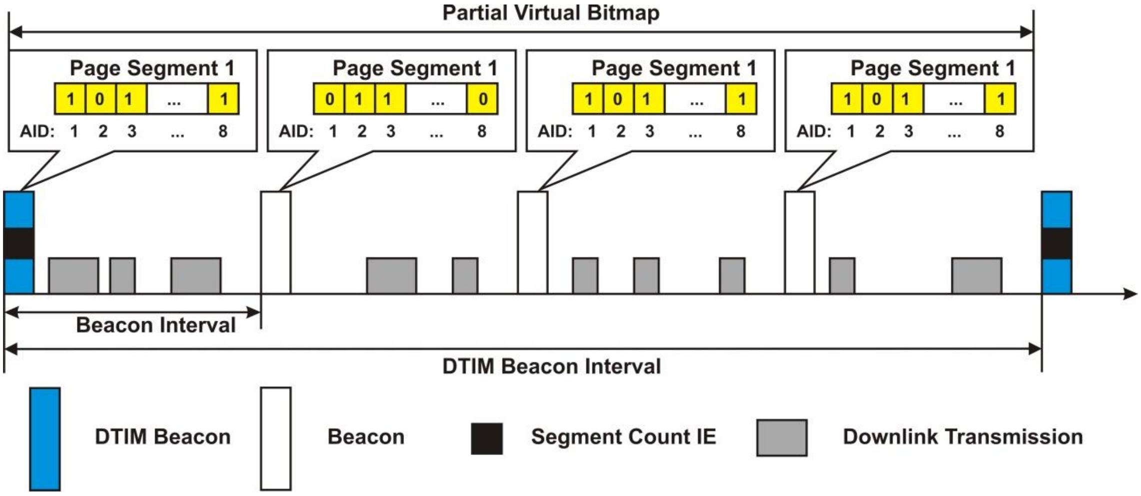

Figure 3.21 *Illustration of TIM and Page Segmentation with Segment Count IE [10].*

3.5.4 Channel access

In the IEEE 802.11 communications standard legacy MAC, the basic and mandatory channel access mechanism is the Distributed Coordination Function (DCF), which is based on Carrier Sense Multiple Access with Collision Avoidance (CSM/CA). DCF describes two techniques to employ for packet transmission, the default scheme called Basic Access mechanism, which is a two-way handshake. In addition to this mechanism an optional four-way handshake named Request-To-Send/Clear-To-Send (RTS/CTS) mechanism has been standardized.

3.5.4.1 Distributed coordination function (DCF)

In DCF a STA with a new packet to transmit monitors the channel activity, if the channel is idle for a period of time called DCF Inter-frame Space (DIFS) plus an additional back-off time. Only when the channel remains idle during all this time a STA can initiate the transmission. The back-off time is an integer multiple of a basic time slot drawn randomly between 0 and the Contention Window (CW), being this the collision avoidance feature of the standard. After this point the back-off value is decreased by one for every idle time slot. When the Channel becomes busy the back-off is frozen until the channel is idle for DIFS period of time. After that the STA starts decreasing the back-off value by one for each subsequent time slot. When the back-off value reaches zero the STA can transmit data in the next time slot. Since CSMA doesn't rely on the capability of stations to detect a collision by hearing their own transmission, a positive acknowledgement (ACK) is transmitted by the destination station to inform of the successful reception of the packet. If the transmitting STA doesn't receive the ACK within a specified ACK-Timeout, or it detects the transmission of a different packet on the channel, it reschedules the packet transmission according to the given back-off rules [29]. This two-way handshake is called Basic Access mechanism and is graphically explained in Figure 3.22.

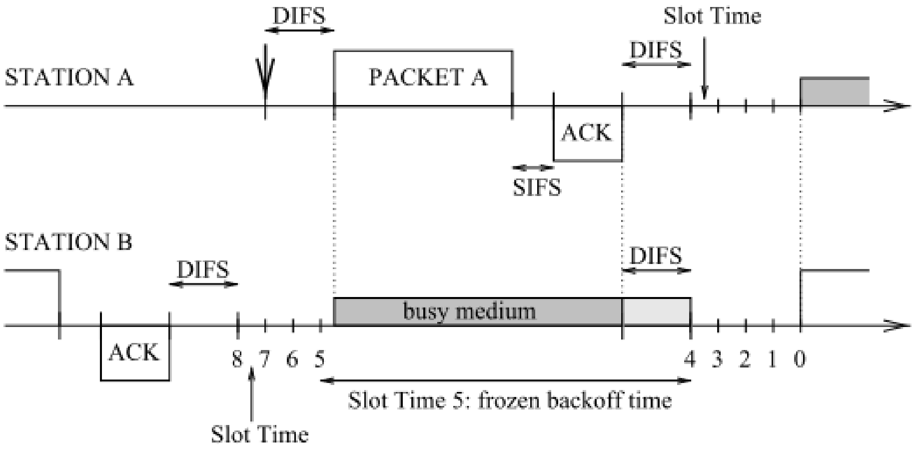

Figure 3.22 *Basic Access mechanism in DCF [29].*

The optional channel mechanism used by the DCF is RTS/CTS, and is used to reduce the impact of hidden nodes where two STAs not hearing each other want to send packets to the STAs in their ranges (Figure 3.23).

A STA intending to transmit must first transmit a RTS packet, upon receiving a RTS packet, the receiving STA transmit a CTS packet back to the sender, and then the sender can start sending a data packet. Finally the receiver informs the sender of successful reception by sending back an ACK packet. Except for the RTS, each STA has to sense the channel idle for Short Inter Frame Space (SIFS) period of time before sending any packet. Since SIFS is shorter than DIFS only the RTS packet will be vulnerable to collision if all STAs are in the same area [30]. The RTS/CTS frames carry information about the length of the packet to be transmitted, and this information can be read by any listening STA, which is then able to update a Network Allocation Vector (NAV) containing the information of the period of time in which the channel will remain busy [29]. Figure 3.24 illustrates the RTS/CTS mechanism.

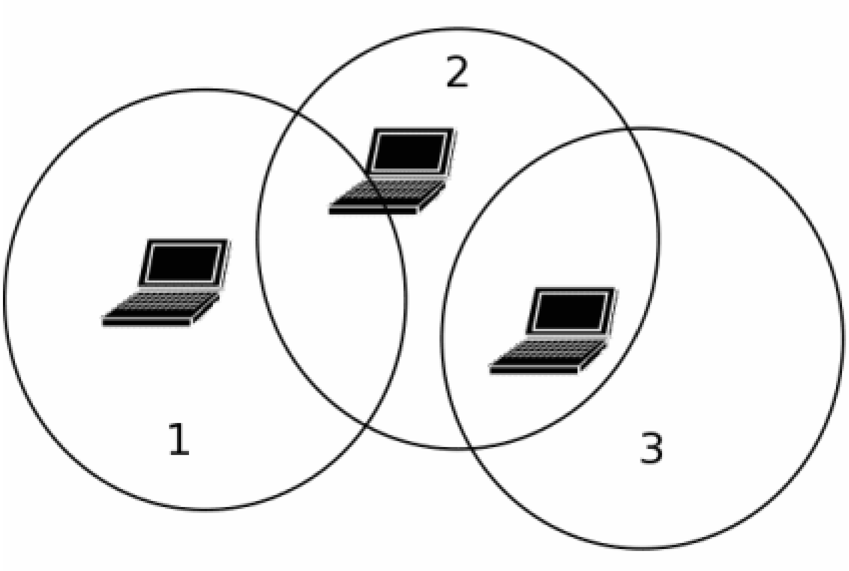

Figure 3.23 *Hidden node problem scheme.*

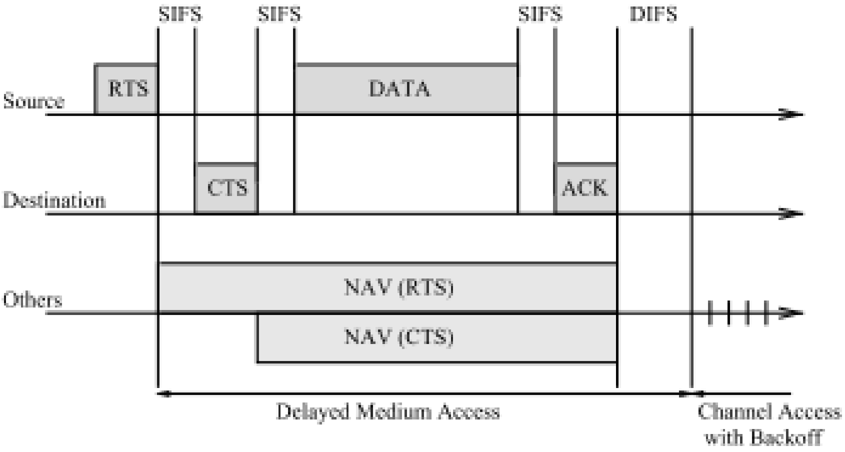

Figure 3.24 *RTS/CTS access mechanism [29].*

3.5.4.2 IEEE 802.11ah channel access mechanisms

Because the legacy channel access mechanisms in the legacy IEEE 802.11 MAC layer are not designed for WSN STAs the TGah has developed new channel access mechanisms.

When the AP associates a new STA, it is included in a TIM Group and in its corresponding Multicast distribution group along with the other TIM Group STAs, Figure 3.25 shows how time between two consecutive TIMs is split into one Download segment, one Uplink segment and one Multicast segment placed immediately after each DTIM beacon.

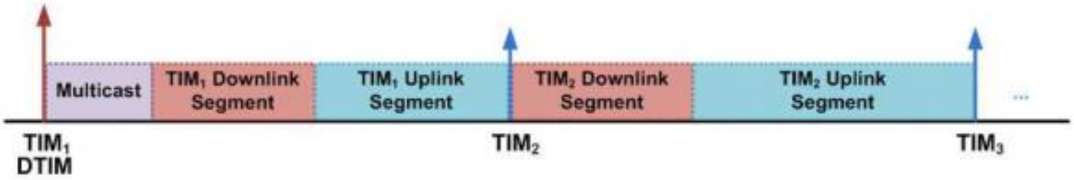

***Figure 3.25** Distribution of channel access into Downlink and Uplink segments.*

3.5.4.2.1 Target wake time

For non-TIM STAs the AP allows the STAs to request buffered downlink traffic from it or to transmit uplink traffic upon waking up at any time. This approach is very trivial and can lead to problems related to network performance, for example when a large number of STAs wake up at the same time there could be much uncontrollable traffic and the contention among the stations could result in excessive channel access delays or even collisions. For this reason, the TGah has developed a mechanism where the AP let the STAs wake up at a predefined time so that the channel access could be temporally spread out. For this mechanism to work out the TGah has defined a new function called Target Wake Time (TWT). This function permits an AP to define a specific time or set of times for individual STAs to access the medium [4]. The AP brings the TWT value(s) to each STA with a new IE element called TWT IE which is illustrated in Figure 3.26 and the Request Type field format is in Figure 3.27, this elements are exchanged by the association request and association response frames and are used to determine when and how often a station wakes up for downlink and/or uplink transmissions.

	Element ID	Length	Control	Request Type	Target Wake Time	TWT Group Assignment	Nominal Minimum Wake Duration	Wake Interval Mantissa	TWT Channel	NDP Paging
Octets:	1	1	1	2	8	3	2	2	1	4

***Figure 3.26** TWT element format.*

	B0	B1 B3	B4	B5	B6	B7 B9	B10 B15
	TWT Request	TWT Command Reply	Direction	Implicit	Flow Type	TWT Flow Identifier	Wake Interval Exponent
Bits:	1	3	1	1	1	3	6

***Figure 3.27** Request Type field format.*

The TWT Request subfield is set to 1 to indicate that the TWT element is being sent from a TWT requesting STA to a TWT responding STA. The TWT Request subfield is set to 0 to indicate that the TWT element is from a TWT responding STA to a TWT requesting STA.

When there are buffered packets for a non-TIM STA, the AP can send to the STA a NDP frame at its target wake up time, which contains the information of buffering status. If the STA detects buffered packets at the AP after successfully receiving the NDP paging frame, it then is able to request the delivery of the data by transmitting a PS-Poll frame. If the NDP paging frame is not transmitted by the AP at the target wake up time, the STA then can transmit uplink frames if the channel is idle.

3.5.4.2.2 Restricted access window

For TIM STAs the TGah has adopted the existing contention-based channel access mechanisms, but it has developed a new type of contention-free channel access mechanism due to the high probability of experiencing hidden node problems because of the large number of supported STAs. For example, the TIM element can cover few hundreds to few thousands STAs with their TIM bits set to one. This can trigger too many simultaneous PS-Poll/trigger frame transmissions from the STAs right after the Beacon reception. Restricting uplink channel access to a small number of STAs and spreading their uplink access attempts over a much longer period of time significantly improves the efficiency of the utilization of the medium by reducing collisions[4]. As a result, the TGah came up with a concept called RAW. A STA receives a new element called RAW Parameter Set (RPS) in a beacon transmitted by the AP with which it is associated and determines whether it belongs to the group indicated in the RAW Group field, the start time of the RAW and its duration. If the STA belongs to the group then it is allowed to contend for medium access at the start of the assigned time slot. Also, an AP may allocate more than one RAW for different groups of STAs within a beacon interval with different RPS. Moreover, an AP assigns STAs a time slot in the RAW at which they are able to access the medium. Figure 3.28 illustrates the RAW structure and timing diagram.

The AP indicates the RAW allocation and slot assignment within the RAW by including the RPS and TIM elements in a beacon frame. In order to enable an AP to adaptively manage the RAW allocation a new management frame named Resource Allocation (RA) frame has been proposed by the TGah, it contains the scheduling information of each individual STA, through which the STA can learn the time slot during which it is allowed to access the medium. The goal is to allocate time slots only to the STAs which are certainly ready to transmit or receive packets rather than to all of the TIM station.

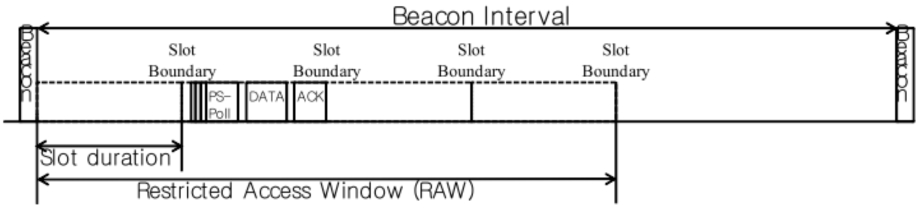

Figure 3.28 *Restricted Access Window (RAW) [4].*

4. RELATED TECHNOLOGIES TO THE IEEE 802.11AH

As research in sensor networks has grown, so has the range of applications proposed to make use of this rich source of data. This diversity of applications translates to differing requirements for the design of a WSN, being this the reason for the industry to focus on delivering tailored solutions with the goal of achieving better performance.

There are already several technologies out there being used for the design and deployment of WSNs, the common aim of these developments are extending the network life and improve range capabilities while offering decent data rates. This chapter briefly describes related technologies to the IEEE 802.11ah for WSN applications.

4.1 IEEE 802.15.4/ZigBee

Low-rate, low-power and low-cost communication reliable devices for monitoring and controlling are the key points that lead to the specification of the IEEE 802.15.4/ZigBee standard. This communications standard first released in 2004 by joined forces of the IEEE 802.15 Wireless Personal Area Network (WPAN) Task Group 4 (TG4) and the ZigBee Alliance, is the direct competitor for the IEEE 802.11ah, in fact companies like Green Peak have questioned the development of this new standard, stating that it would be a waste of time and effort as ZigBee is already rolling out today in large volumes to different sectors of the industry [23].

The PHY layer of ZigBee operates at 868 MHz for European applications, 902-928 MHz for North American applications and 2.4 GHz for worldwide applications offering coverage from 10 m up to 75 m and data rates up to 250 Kb/s. Modulation scheme is BPSK for Sub-GHz bands and offset-QPSK for the 2.4-2.483 GHz bands [31].

The MAC layer of ZigBee offers basic services such as beacon generation, supporting Personal Area Network (PAN) association and disassociation, supporting optional device security, managing channel access via CSMA/CA, maintaining Guaranteed Time Slot (GTS) communication, providing message validation and message ACKs [33]. The network topologies supported by the standard are star, mesh and cluster tree, as depicted in Figure 4.1 [32]. The most relevant features of ZigBee are:

- Support for multiple network topologies such as point-to-point, point-to-multipoint and mesh networks.
- Low duty cycle – provides long battery life.

- Low latency.
- Direct Sequence Spread Spectrum (DSSS).
- Up to 65,000 nodes per network.
- 128-bit AES encryption for secure data connections.
- Collision avoidance, retries and acknowledgements.

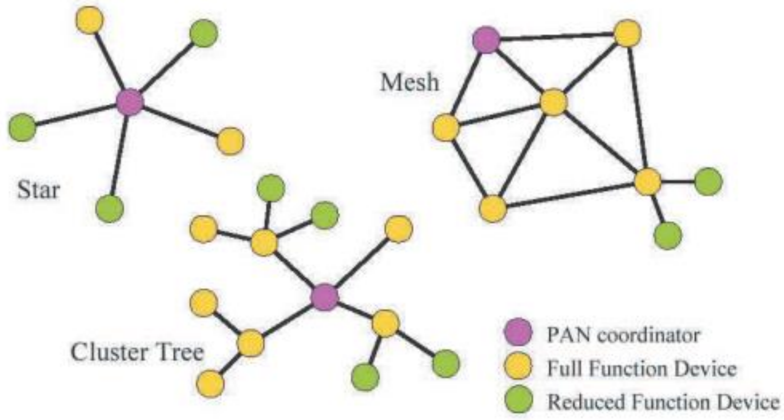

Figure 4.1 *Topology models for ZigBee*

4.2 DASH7

Developed for Machine-to-Machine (M2M) communications, DASH7 is a standard introduced in 2009 by the DASH7 Alliance (D7A) based on the ISO/IEC 1800-7 standard for active Radio Frequency Identification (RFID). It operates in the 433 MHz unlicensed ISM band and was originally created for military use but now it is being re-purposed for many commercial applications to take over well-known standards like ZigBee.

In contrast to typical WSN standards such as ZigBee (built on top of IEEE 802.15.4), the DASH7 specification defines a full functional RFID tag. This means it does include high level functionality optimized for RFID applications. However, it can also be extended for non-RFID applications [35]. In contradiction to legacy RFID systems, D7A supports tag-to-tag communication [34].

As for the MAC layer DASH7 supports two communication models: pull and push. As in most RFID systems, dialogs between tags and interrogators are query response based (the pull model), as shown in Figure 4.2(a). This request response mechanism is described by the D7A Query Protocol (D7AQP). Data transfer initiated from the tags to the gateway on the other hand is based on the push model. This is shown in Figure 4.2(b). This approach can, for instance, be implemented as an automated message or beacon which is sent on specific time intervals. In D7A, this system is called Beacon Transmit Series [36]. DASH7 has been designed to operate using the “BLAST” concept: Bursty, Light-data, ASynchronous, Transitive. Despite being another acronym of questionable genuineness, BLAST does actually correlate to the DASH7 operational philosophy on a one-to-one basis [37].

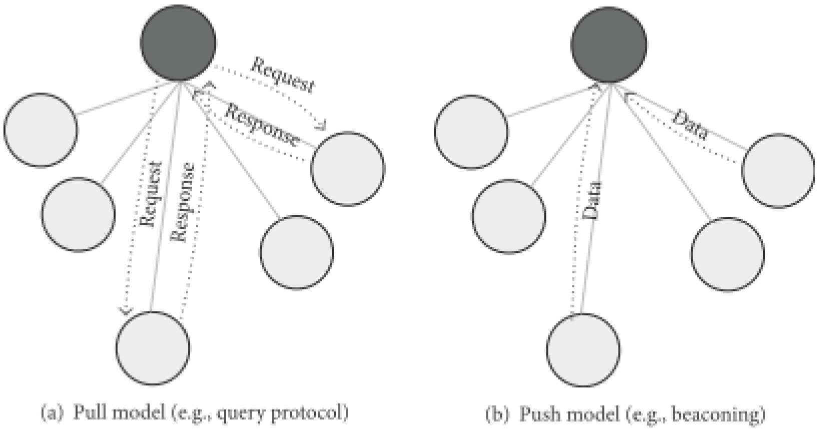

Figure 4.2 *DASH7's communication models.*

4.3 IEEE 802.15.4g WPAN

The IEEE 802.15.4g is a communication standard first introduced in 2009 [3], was established specially as a PHY amendment to the IEEE 802.15.4 standard. The IEEE 802.15.4g Task Group (TG4g) aims to support a low-complexity, low-cost, low-power wireless communication for Smart Utility Network (SUN) applications such as smart grid systems. In early stage of standardization, IEEE 802.15.4 amendment was considered. However, the communication range, robustness, and coexistence characteristics required for SUN application have not been met with existing 802 standards including IEEE 802.15.4. Therefore, new PHY for SUN application was requested in IEEE 802.15.4g. Three alternative PHYs are provided for SUN devices [39]:

1. MR-FSK; selected to provide good transmit power efficiency due to the constant envelope of the transmit signal.
2. MR-O-QPSK (DSSS); shares the characteristics of the current IEEE 802.15.4-2006 O-QPSK, making multi-mode systems more cost effective and easier to design.
3. MR-OFDM; designed to provide higher data rates in channels that have significant delay spread.

There are 27 channels distributed across three frequency bands. The channel numbers range from 0 to 26. There is only one channel for Europe's 868 MHz frequency band, 10 channels for North America's 915 MHz frequency band and 16 channels available across the worldwide 2.4 GHz frequency band [31]. The IEEE 802.15.4g network is comprised of one centralized node named coordinator, sometimes to be called Network Coordinator (NC). This coordinator initiates the communications in the network and is also responsible for network management. A network must have at least one network device and one network coordinator. The network devices are either Full Function Device (FFD) or Reduced Function Device (RFD) in IEEE 802.15.4g. FFD includes fully carried out MAC services and it can act as network coordinator or network device in the network. Unlikely FFD, RFD is includes partially carried out MAC services and only participates as a network device in the network. Devices employ CSMA/CD as a medium access technique to avoid collisions. Time Division Multiple Access (TDMA) can be used sometimes for guaranteed transmission, too.

5. PERFORMANCE EVALUATIONS

In this work, the MAC layer of the IEEE 802.11ah standard is modeled analytically in MatLab R2014a. The aim is to justify the development of the technology; by applying a series of performance metrics on different real-life scenarios, it is possible to evaluate the network performance.

5.1 Model environment

The purpose of this study is to evaluate the infrastructure BSSs, meaning that there is always at least one AP in the network serving a variable number of STAs. Star topology will be evaluated in this model; STAs send and receive packets directly to the AP without intermediate nodes, meaning that packets will arrive to the AP or STA in one single hop. Single hop transmissions are superior to multi-hop transmissions in terms of reliability as they impose less delay which can be crucial for sensitive applications. No hidden nodes are considered, and the channel is considered to be ideal. The considered Payload for the analysis is equal to 1024 bytes.

5.1.1 Model parameters

The model parameters used in this study are classified in three categories: constant parameters which remain unchanged during the entire analysis, variable parameters which vary from one run to another (e.g. number of nodes, payload, etc.) and energy consumption parameters. The constant parameters are listed in Table 5.1.

Parameter	**Value**
T_sym	40 µs
PHY Header	192 bits
MAC Header	224 bits
Slot_Time	52 µs
SIFS	160 µs
DIFS	SIFS + 2 x Slot_Time
ACK	112 + PHY Header
CTS	112 + PHY Header
RTS	20 x 8 bits + PHY Header
CW_{max}	1023
CW_{min}	15
Retry Data	4
Retry RTS	7

Basic Data Rate	650 Kbps
Data Rate	Variable depending on MCS#
L_Sym	Variable depending on MCS#
T_PHY	6 x T_Sym

Table 5.1 *Fixed model parameters.*

Energy consumption as mentioned in the previous chapters is a very important metric for network performance evaluations. It is mostly calculated in J/packet to show the energy consumed to send or receive one correct bit of payload. Table 5.2 summarizes the energy consumption for each operating mode of a STA. Transmission mode is used to send RTS and DATA packets, receiving mode is used to send ACK packets, and sleep mode refers to a STA when has nothing to send or receive at all and is considered to be idle.

Mode	**Energy Consumption (mW)**
Transmitting	250
Receiving	135
Idle	1.5

Table 5.2 *Energy consumption values in different operational modes.*

5.2 Definition of performance metrics

Network performance metrics are needed to verify and ensure that the QoS parameters of a technology or service are being met. The main goal of employing performance metrics is to maximize the satisfaction of it users by efficiently employing the available resources, to conveniently support applications with diverse nature and specific QoS requirements. The following performance metrics will be evaluated in this section:

- Maximum theoretical throughput.
- Saturation throughput.
- Average delay.
- Energy efficiency.

5.2.1 Maximum theoretical throughput

We define the upper limit of the throughput that can be achieved in an IEEE 802.11 network as its theoretical maximum throughput (TMT). Since the 802.11 standard convers the MAC and PHY layers in terms of the OSI reference model, we are interested in the actual throughput provided by the MAC layer. Therefore, the TMT of 802.11 can also be defined as the maximum amount of MAC layer service data units

(SDUs) that can be transmitted in a time unit [44].In this section we will calculate the TMT for the 802.11ah assuming the following:

- Bit error rate (BER) is zero.
- There are no losses due to collisions.
- Point coordination function (PFC) is not used.
- No packet loss occurs due to buffer overflow at the receiving node.
- Sending node always has sufficient packets to send.
- The MAC layer does not use fragmentation.
- Management frames such as beacon and association frames are not considered.

In order to calculate the TMT, we first convert all the overheads at each sub layer into a common unit; time. To obtain the TMT, we will divide the MAC SDU (MSDU) by the time it takes to transmit it:

$$TMT = \frac{MSDU\ size}{Delay\ per\ MSDU} \tag{5.1}$$

Control frames such as RTS, CTS and ACK are always transmitted at 1Mbps for backward compatibility. Figures 5.1 and 5.2 illustrates how data packets are transmitted in Basic and RTS/CTS access mechanisms respectively. The same pattern will be repeated with a specific cycle when back-to-back traffic is offered at the transmitting node. As illustrated the timing diagram is different for Basic and RTS/CTS access. The exact duration of each block varies for different spread spectrum technologies and basic data rates.

The contention window size (CW) does not increase exponentially since there are no collisions. Thus, CW is always equal to the minimum contention window size (CW_{min}), which varies with different spread spectrum technologies. The back off time is selected randomly following a uniform distribution of (0, CW_{min}) giving the expected value of $CW_{min}/2$. Equation (5.1) shows how the back off delay can be calculated as a constant.

$$T_{BO} = \frac{CW_{min}}{2} \times\ SlotTime \tag{5.2}$$

The total delay per MSDU is calculated as a summation of all the delay components in a complete transmission cycle on the access scheme. Based on Figure 5.1 the delay for RTS/CTS and CSMA/CA can be written as (5.3) and (5.4) respectively.

$$\begin{aligned} Delay\ per\ MSDU_{RTS/CTS} = (&DIFS + T_{BO} + RTS + CTS + DATA + ACK \\ &+ (3 \times SIFS)) \end{aligned} \tag{5.3}$$

$$Delay\ per\ MSDU_{Basic} = (DIFS + T_{BO} + DATA + SIFS + ACK) \tag{5.4}$$

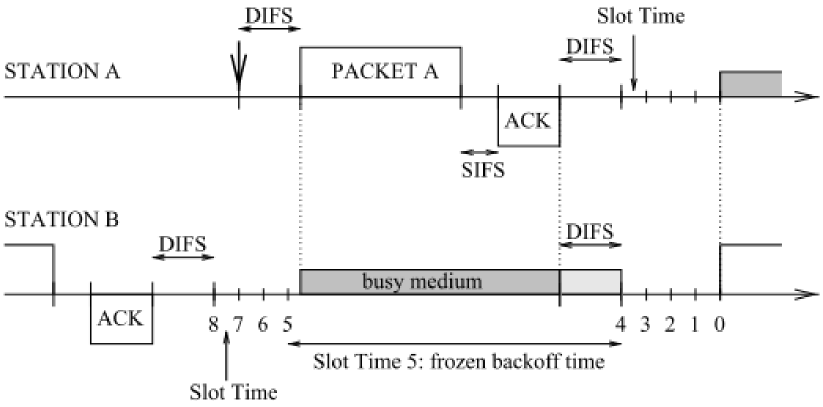

Figure 5.1 *Basic access mechanism in DCF [29].*

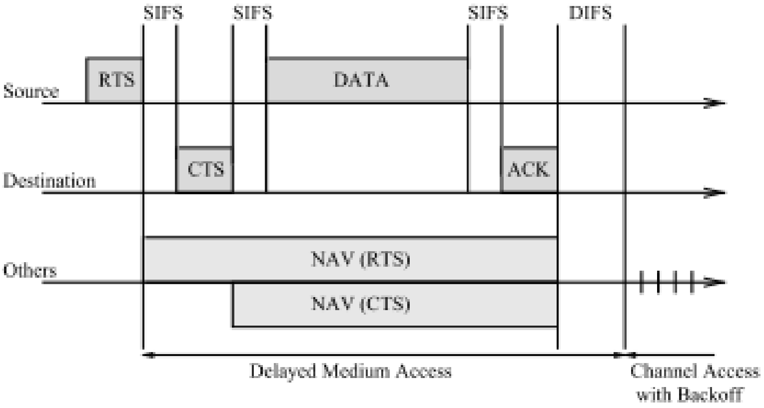

Figure 5.2 *RTS/CTS access mechanism in DCF [29].*

We can get the TMT simply by dividing the number of bits in MSDU (8x) by the total delay for RTS/CTS (5.3) and Basic DCF (5.4) respectively.

$$TMT_{RTS} = \frac{L_{payload}}{DIFS+T_{BO}+RTS+CTS+DATA+ACK+(3\times SIFS)} \tag{5.5}$$

$$TMT_{Basic} = \frac{L_{payload}}{DIFS+T_{BO}+DATA+SIFS+ACK} \tag{5.6}$$

The IEEE 802.11ah states that the control frames RTS, CTS and ACK should be sent with the most robust MCS available considered being the basic data rate. The DATA packets can be transmitted using any MCS available, therefore, data rate should be considered when calculating the duration of the DATA packets. For more information on MCS and data rates, please review Table 3.2. The duration of the control frames can be easily calculated using the approach seen in [53]:

$$T_{control\_frames} = ceil\left(\frac{L_{control\_frames}}{L_{basic\_datarate\_sym}}\right) \times T_{sym} + PHY \tag{5.7}$$

and the duration of the DATA frames by:

$$T_{DATA} = ceil\left(\frac{(L_{payload}+MAC)}{\frac{R}{basic\_datarate}\times L^{basic\_datarate\_sym}}\right)\times T_{sym} + PHY \tag{5.8}$$

Where R refers to the data rate used to send the DATA packet according to the MCS available and $L^{basic\_datarate\_sym}$ represents the number of data bits in OFDM symbol (N_{DBPS}) as can be seen in Table 3.1.

Figures 5.3 and 5.4 illustrate the calculated TMT for the Basic Acces and RTS/CTS mechanisms respectively for five different MCS of the IEEE 802.11ah. From the figures we can clearly observe the advantage of the Basic Access over the RTS/CTS mechanism in ideal conditions (neither collisions nor error), this is due to the fact that the RTS/CTS mechanism has to send a lot more control frames than the Basic Access mechanisms, therefore the better performance.

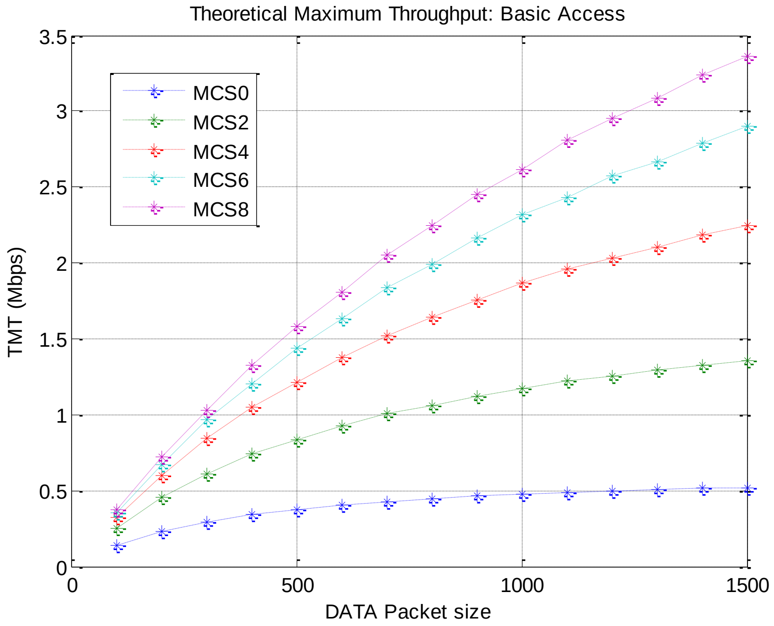

***Figure 5.3** Theoretical maximum throughput of IEEE 802.11ah using basic access mechanism.*

5.2.2 Analysis under saturation conditions

In this section the Saturation conditions for the IEEE 802.11ah network system is evaluated. The saturation throughput can be defined as the limit reached by the system throughput as the offered load increases, and represents the maximum load that the system can carry in stable conditions. Average end to end delay and energy efficiency are also studied. These are few of the fundamental metrics used in the performance analysis of the IEEE 802.11 MAC protocol. The information gathered from the saturation analysis gives an incredible insight on the behavior of the network depending on the number of its users at a determined point.

The following model is based on Bianchi's approach [48], using Markov's chain model to study the behavior of a single STA to obtain the stationary probability τ that the STA transmits a packet in a generic (randomly chosen) slot time. This probability doesn't depend on the access mechanism employed (RTS/CTS or Basic). Then, by studying the events that can occur within a generic slot time, we express the throughput of both access mechanisms as a function of the computed value τ.

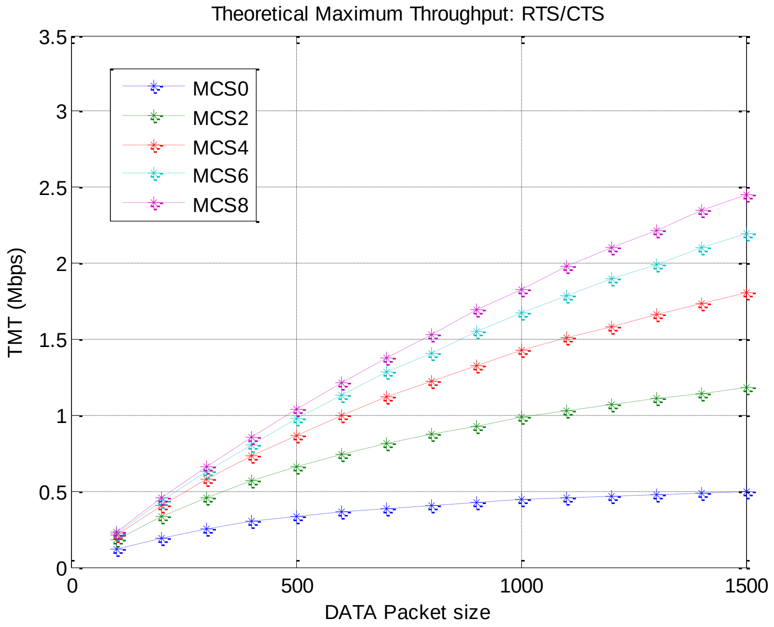

Figure 5.4 *Theoretical maximum throughput of IEEE 802.11ah using RTS/CTS access mechanism.*

5.2.2.1 Markov chain model

The Markov chain model used by Bianchi [48] does not consider the frame retry limits, thus it may overestimate the throughput of the IEEE 802. For this reason we base our approach on the Markov Chain proposed by Haitao Wu [50].

The contending STAs are supposed to be a fixed number, *n*. Let *b(t)* be the stochastic process representing the back-off window size for a given station at slot time *t*. Note that the slot time is referred to as the constant value of σ and the variable time interval between two consecutive back off time counter decrements. As in Bianchi's approach [48], the key approximation in this model is that the probability *p* that a transmitted packet collides is independent on the state *s(t)* of the STA. Thus, the bi-dimensional process *{s(t), b(t)}* is a discrete-time Markov chain as depicted in Figure 5.5.

The parameters of the IEEE 802.11ah are, CW_{min} equal to 15 and CW_{max} equal to 1023 as shown in Table 5.1, therefore we have

$$\begin{cases} W_i = 2^i W & i \leq m' \\ W_i - 2^{m'} W & i \geq m' \end{cases} \tag{5.9}$$

Where W = (CW_{min}+1), and $2^{m'}$W = (CW_{max}+1), so for IEEE 802.11ah we have m'=6. Unlike Bianchi [48], here m represents maximum back off stage. As specified by the IEEE 802.11 standard this value could be larger than m', while the CW will be hold after that, which is shown at Equation (5.9). In fact, here m also means the maximum retransmission count, which is different for data frame and RTS, i.e. 5 and 7 respectively. Bianchi's approach [48] doesn't distinguish the two cases; the difference is that our Markov chain model is different, as it does consider the effects of frame retransmission limit.

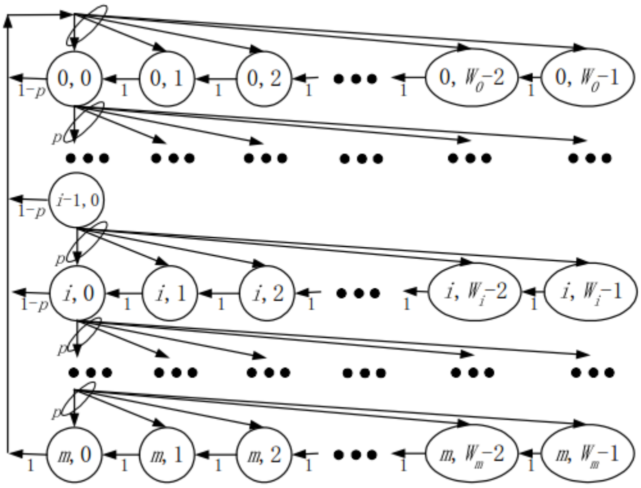

Figure 5.5 *Markov chain model with retransmission count.*

In this Markov chain, the only non-null one-step transition probabilities are:

$$\begin{cases} P\{i,k|i,k+1\} = 1 & k \in [0, W_i - 2] i \in [0, m] \\ P\{0,k|i,0\} = (1-p)/W_0 & k \in [0, W_0 - 1] i \in [0, m-1] \\ P\{i,k|i-1,0\} = p/W_1 & k \in [0, W_i - 1] i \in [1, m] \\ P\{0.k|m,0\} = 1/W_0 & k \in [0, W_0 - 2] \end{cases} \qquad (5.10)$$

These transition probabilities account, respectively for:

1. The decrements of the back off timer.
2. After a successful transmission, the back off timer of the new packet starts from the back off stage.
3. An unsuccessful transmission makes the back off stages increase.
4. At the maximum back off stage, the CW will be reset if the transmission is unsuccessful or restart the back off stage for new packet if the transmission is successful.

Let $b_{i,k}$ be the stationary distribution of the Markov chain. First note that:

$$b_{i-1,0} * p = b_{i,0} \qquad 0 < i \le m \tag{5.11}$$

$$b_{i-1,0} = p^i b_{0,0} \qquad 0 \le i \le m \tag{5.12}$$

Since the chain is regular, so for each $k \in (0, W_{i-1})$ we have:

$$b_{i,k} = \frac{W_i - k}{W_i}\begin{cases}(1-p)\sum_{j=0}^{m-1} b_{j,0} + b_{m,0} & i=0\\ p b_{i-1,0} & 0<i\le m\end{cases} \tag{5.13}$$

With (5.12) and transitions in the chain, equation (5.13) can be simplified as:

$$b_{i,k} = \frac{W_i k}{W_i} b_{i,0} \qquad 0 \le i \le m \tag{5.14}$$

Therefore, by using the normalization condition for stationary distribution, we have:

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} = \sum_{i=0}^{m} b_{i,0} \frac{W_i + 1}{2} \tag{5.15}$$

Using equations (5.9), (5.14) and (5.15), we have:

$$b_{0,0} = \begin{cases}\dfrac{2(1-2p)(1-p)}{W(1-(2p)^{m+1})(1-p)+(1-2p)(1-p^{m+1})}\ for\ m \le m' \\ \dfrac{2(1-2p)(1-p)}{W\left(1-(2p)^{m'+1}\right)(1-p)+(1-2p)(1-p^{m+1})+W2^{m'}p^{m'+1}(1-2p)\left(1-p^{m-m'}\right)}\ for\ m > m'\end{cases} \tag{5.16}$$

Now the probability τ that a STA transmits in a randomly chosen slot time can be expressed as:

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1-p^{m+1}}{1-p} b_{0,0} \tag{5.17}$$

In the stationary state, a STA transmits a packet with probability τ , so we have:

$$p = 1 - (1-\tau)^{n-1} \tag{5.18}$$

Therefore, equations (5.16), (5.17) and (5.18) represent a nonlinear system in the two unknowns τ and p, which can be solved by numerical results. Note that we must have $p \in (0,1)$ and $\tau \in (0,1)$.

5.2.2.2 Throughput analysis

Let P_{tr} be the probability that there is at least one transmission in the considered slot time, and let P_s be the probability that a transmission is successful, given the probability P_{tr} we have:

$$P_{tr} = (1 - \tau)^n \tag{5.19}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{5.20}$$

Now we are able to express the normalized system throughput S as the ratio,

$$S = \frac{L_{Payload}}{Length\ of\ a\ slot\ time} = \frac{P_S P_{tr} L_{Payload}}{(1-P_{tr})\sigma + P_S P_{tr} T_S + (1-P_S) P_{tr} T_C} \tag{5.21}$$

In equation (5.21), T_S and T_c are the average time the channel is sensed busy because of a successful transmission or a collision respectively. The *Payload* is the average packet length and σ is the duration of an empty time slot.

For the Basic access mechanism we define:

$$\begin{cases} T_s{}^{bas} = DIFS + T_{DATA} + T_{ACK} + T_{PHY} \\ T_c{}^{bas} = DIFS + T_{DATA} + Timeout + T_{PHY} \end{cases} \tag{5.22}$$

and for the RTS/CTS access mechanism:

$$\begin{cases} T_s{}^{RTS} = DIFS + T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + (3 * SIFS) + Timeout + T\_PHY \\ T_c{}^{RTS} = DIFS + T_{DATA} + Timeout + T_{PHY} \end{cases} \tag{5.23}$$

From equations (5.22) and (5.23) we can calculate the duration of a control frame ($T_{RTS}, T_{CTS}\ and\ T_{ACK}$) and the duration of the Data frame (T_{DATA}) from equations (5.7) and (5.8) respectively.

$$T_{control\_frames} = ceil\left(\frac{L_{control\_frames}}{L^{basic\_datarate\_sym}}\right) \times T_{sym} + PHY \tag{5.7}$$

$$T_{DATA} = ceil\left(\frac{(L_{payload} + MAC)}{\frac{R}{basic\_datarate} \times L^{basic\_datarate\_sym}}\right) \times T_{sym} + PHY \tag{5.8}$$

First we see the results of the Basic access mechanism, which is shown in Figure 5.6, and then the results for the RTS/CTS access mechanism in Figure 5.7.

From these results we are able to see that the RTS/CTS access mechanism is useful to compensate the performance degradation due to collision, whose probability increases with the number of STAs. Note that we can get these results because in this analysis we are using a Payload length of 1024 bytes, which is large enough to compensate the overheads introduced by the RTS/CTS access mechanism. Clearly we can determine that the RTS/CTS access mechanism offers an advantage when we have over 100 STAs in our network.

5.2.2.3 Energy efficiency analysis

Energy calculations are an important performance metric when designing a WSN. In a laptop PC platform the radio consumes only 9% of the total available energy [49], seems not to be a very important factor. Considering that the radio in a WSN node consumes most of its available energy, energy efficiency becomes a lot more significant.

To calculate the energy consumed to transmit a DATA packet in Joules, equation (5.21) should be inversed and all the timings in the new numerator (equations (5.22) and (5.23)) need to be multiplied by the energy consumption of its respective operation mode; see Table (5.2). As a result we have equation (5.24).

$$e = \frac{(1-P_{tr})\sigma + P_S P_{tr} T_S + (1-P_S) P_{tr} T_C}{P_S P_{tr} L_{Payload}} \tag{5.24}$$

Transmission mode is used for RTS and DATA frames, receiving mode is used for CTS and ACK frames, and all the other timings are considered to be idle as we are evaluating a saturation environment and all the STAs always have something to transmit. Considering the operational modes Transmit, Receive and Idle as P_t, P_r and P_i respectively.

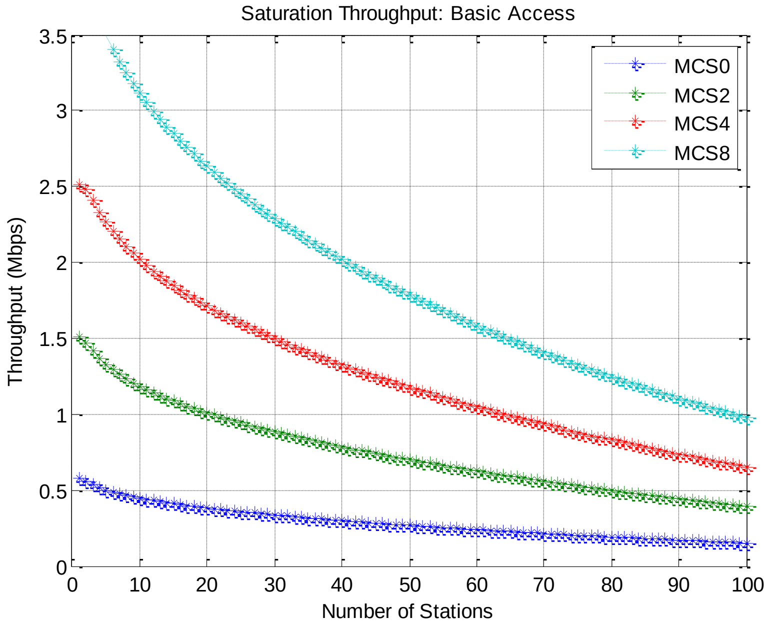

Figure 5.6 *Saturation throughput of the IEEE 802.11ah using basic access mechanism*

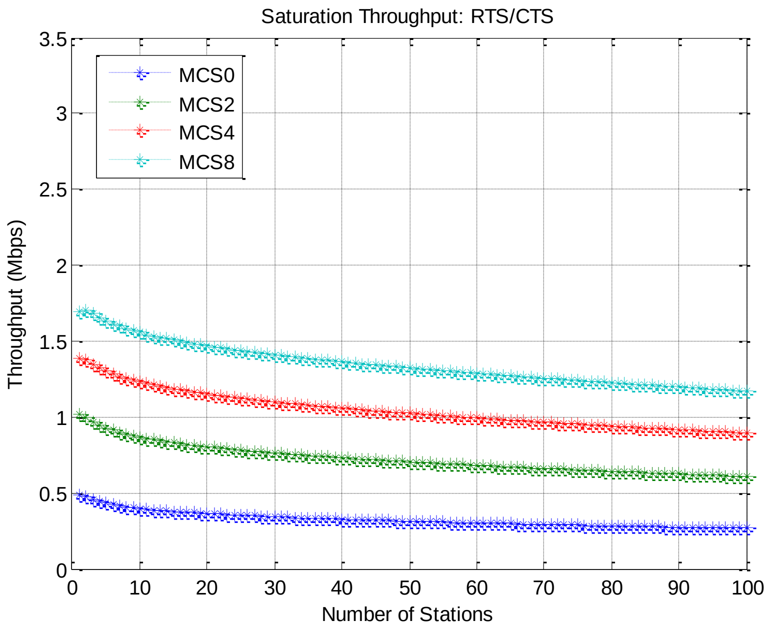

Figure 5.7 *Saturation throughput of the IEEE 802.11ah using RTS/CTS access mechanism.*

$$\begin{cases} T_s^{\,bas} = DIFS * P_i + T_{DATA} * P_t + T_{ACK} * P_r + T_{PHY} * P_i \\ T_c^{\,bas} = DIFS * P_i + T_{DATA} * P_t + Timeout * P_i + T_{PHY} * P_i \end{cases}$$
$$\begin{cases} T_s^{\,RTS} = DIFS * P_i + T_{RTS} * P_t + T_{CTS} * P_r + T_{DATA} * P_t \\ \qquad\qquad + T_{ACK} * P_r + (3 * SIFS) * P_i + Timeout * P_i + T_{PHY} * P_i \\ T_c^{\,RTS} = DIFS * P_i + T_{DATA} * P_t + Timeout * P_i + T_{PHY} * P_i \end{cases} \qquad (5.25)$$

Energy analysis for Basic and RTS/CTS access mechanisms are shown in Figures 5.8 and 5.9 respectively. Note that for saturated conditions, listening to the channel is considered as receiving, and as all the STAs have always something to transmit; $P_i = P_r$ for saturated conditions.

5.2.2.4 Average delay

Since no hidden nodes are considered and collisions take place because two or more contending STAs choose the same back off slot to transmit. The time needed for a frame transmission is considered to start when a frame becomes head of the STAs queue and is finalized when a positive acknowledgement is received.

Assuming that the frame drop probability is very low and can be neglected, the average frame delay $E[D]$ is given by:

$$E[D] = E[X] * E[length\ of\ a\ slot\ time] \qquad (5.26)$$

Moreover, $E[X]$ is equal to:

$$E[X] = \sum_{i=0}^{m-1}\left(p^i * \frac{W_i+1}{2}\right) + \frac{p^m}{1-p} * \frac{W_m+1}{2} \tag{5.28}$$

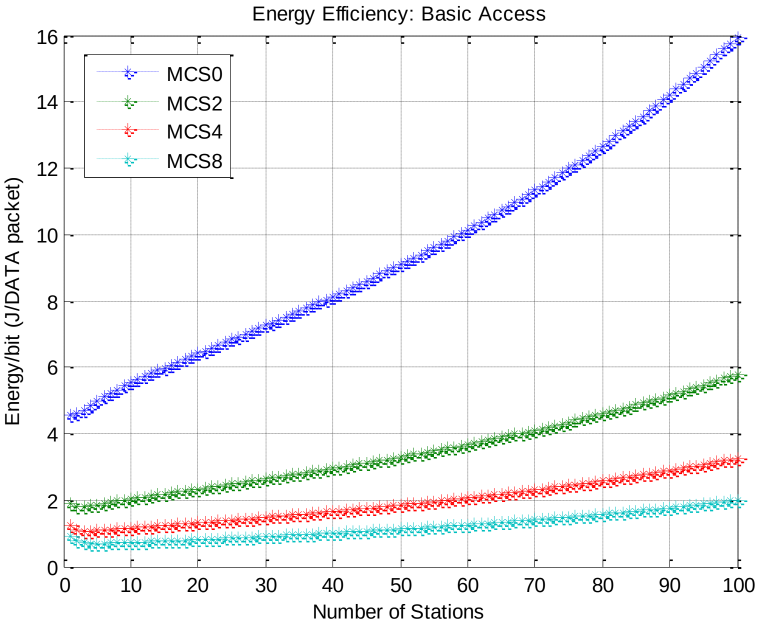

Figure 5.8 *Energy efficiency using basic access mechanism for different MCS in saturation conditions.*

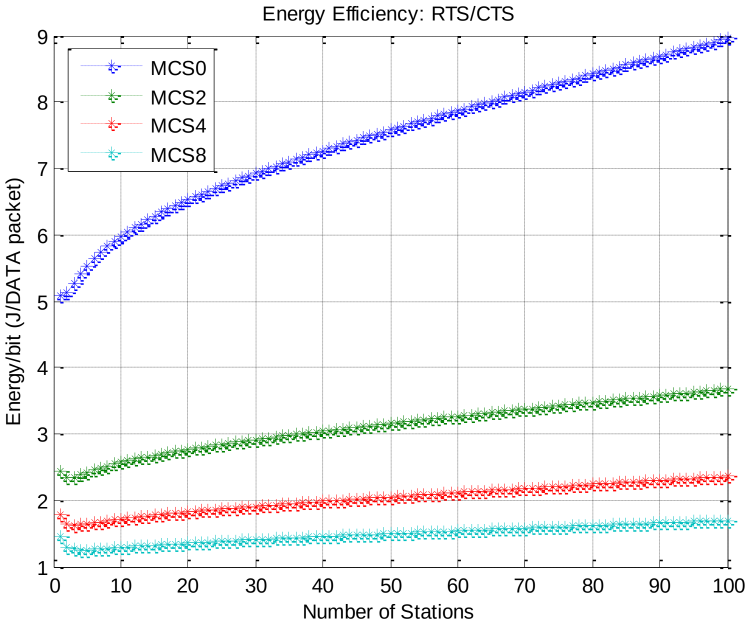

Figure 5.9 *Energy efficiency using RTS/CTS access mechanism for different MCS in saturation conditions.*

After some algebra equation (5.28) reduces to:

$$E[X] = \frac{(1-2p)(W+1)+pW(1-(2p)^m)}{2(1-2p)(1-p)} \tag{5.29}$$

Now, substituting equations (5.27) and (5.29) in (5.26), the average frame delay is calculated. Figures 5.10 and 5.11 depict the average frame delay for Basic and RTS/CTS access mechanisms respectively [51].

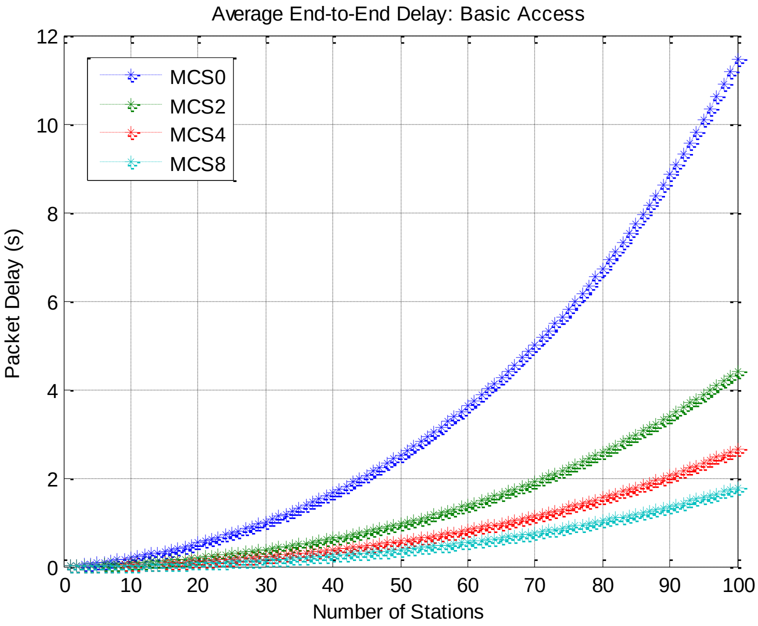

Figure 5.10 *Average frame delay for basic access mechanism in saturation conditions.*

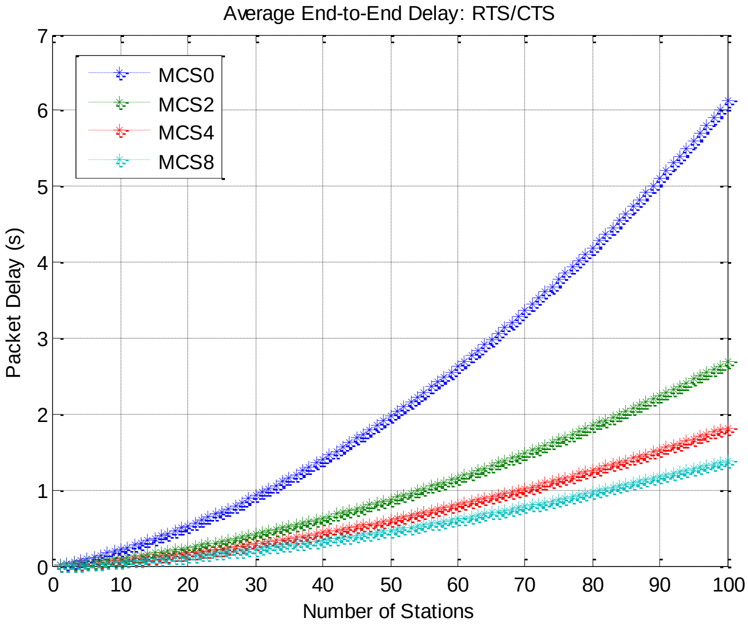

Figure 5.11 *Average frame delay for RTS/CTS access mechanism in saturation conditions.*

5.2.3 Analysis under non-saturated conditions

Since the behavior of most of the networks in real life is non-saturated, in this section a new model including traffic load with a Poisson distribution is applied to the IEEE 802.11ah. Throughput, average end to end delay and energy efficiency are the metrics applied to this non-saturated environment.

5.2.3.1 Markov chain model

Following the model in [54], we assume that each station can buffer one packet and there is a constant probability q of at least one packet arriving per state. Thus in this new model we introduce states $(0,k)_e$ for $k \in [0, W-1]$, representing a node which has transmitted a packet, but has none waiting. Note that $i=0$ in all suck states, because if $i>0$ then a collision has occurred, so we must have a packet awaiting transmission.

We now derive relationships between: p, the probability of collision; P, the Markov chain's transitions matrix; b, the stationary distribution; and τ, the transmission probability per station. These relationships can be solved for p and τ, and the network throughput predicted. It is important to note that the Markov chain's evolution is not real-time, and so the estimation of throughput requires an estimate of the average state duration.

Using $(1-\tau)^{n-1}$ as the probability that the medium is idle. As noted by Bianchi [48], $1-p=(1-\tau)^{n-1}$, thus out transition probabilities only depend on p and q.

Solving for the stationary distribution, b, yields:

$$\frac{1}{b_{(0,0)}} = (1-q) + \frac{q^2W(W+1)}{2(1-(1-q)^W)} + \frac{q(W+1)}{2(1-q)}\left(\frac{q^2W}{1-(1-q)^W} + p(1-q) - q(1-p)^2\right) + \frac{pq^2}{2(1-q)(1-p)}\left(\frac{W}{1-(1-q)^W} - (1-p)^2\right) \cdot \left(2W\frac{1-p-p(2p)^{m-1}}{1-2p} - (1-p)\right) \tag{5.30}$$

and

$$\tau = \sum_{i=0}^{m} b_{(i,0)} + b_{(0,0)}q(1-p)$$
$$\tau = b_{(0,0)}\frac{q^2}{1-q}\left(\frac{W}{(1-p)(1-(1-q)^W)} - (1-p)\right) \tag{5.31}$$

For given values of q, W, n and m, we may solve (5.31) against (5.18) to determine p and τ. In the limit $q \to 1$, our model goes to a saturated condition.

5.2.3.2 Throughput, average delay and energy efficiency

Following the same approach as in sections 5.2.2.2 to 5.2.2.4, we calculate the throughput, average end to end delay and energy efficiency for the IEEE 802.11 under non-saturated conditions. To match the model with experiment we must relate q to offered packet load. Modeling a saturated system, i.e. there is always a packet awaiting service, is achieved by setting $q=1$. If packets arrive in a Poisson manner with exponentially distributed inter-packet arrival times with rate λ, then $1-q$ is the probability that no packet arrives in a typical slot of length T. That is $1-q=\exp(-\lambda T)$ and therefore $q=1-\exp(-\lambda T)$; where T is the denominator in equation (5.21). In this analysis $\lambda=0.5$ is assumed. Figures 5.12 and 5.13 show results for Basic and RTS/CTS access mechanisms respectively with a traffic load of a packet every 2 seconds.

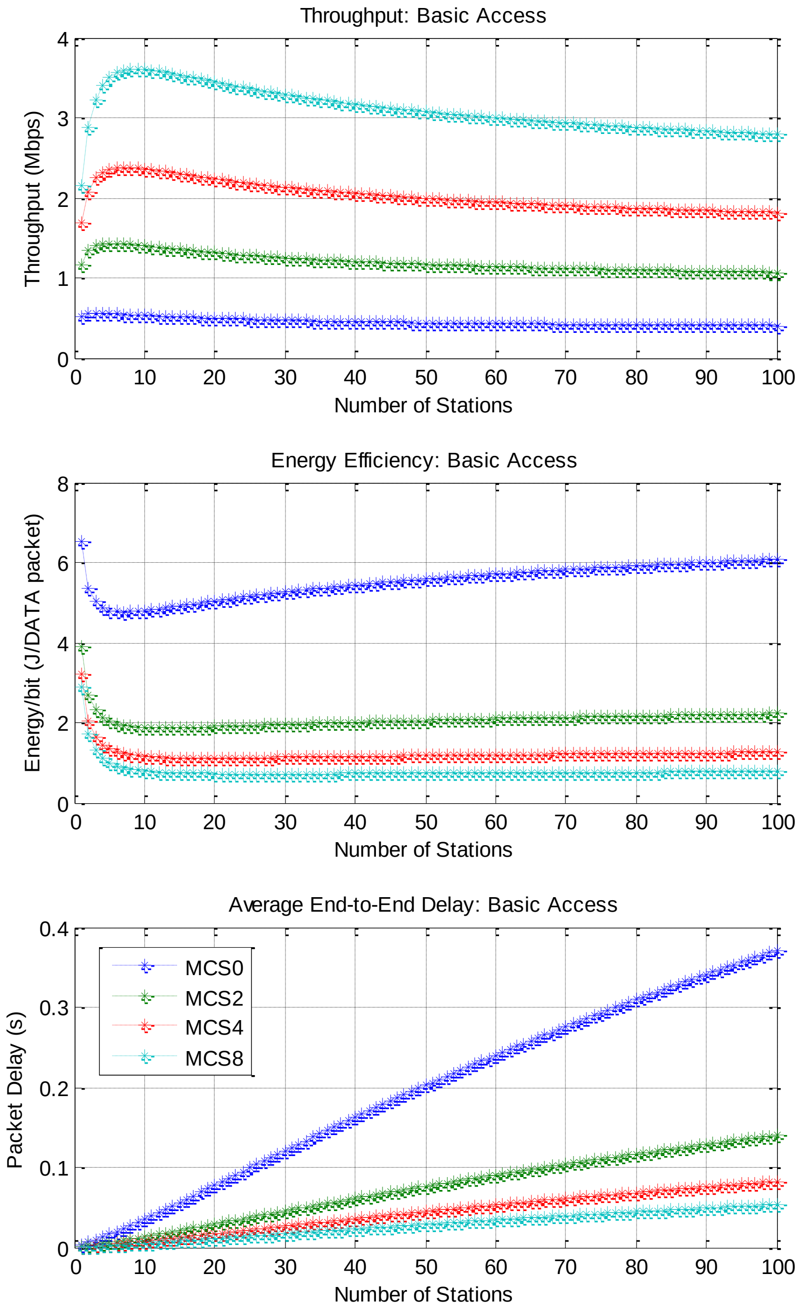

Figure 5.12 *Results under non-saturated conditions using the Basic access mechanism.*

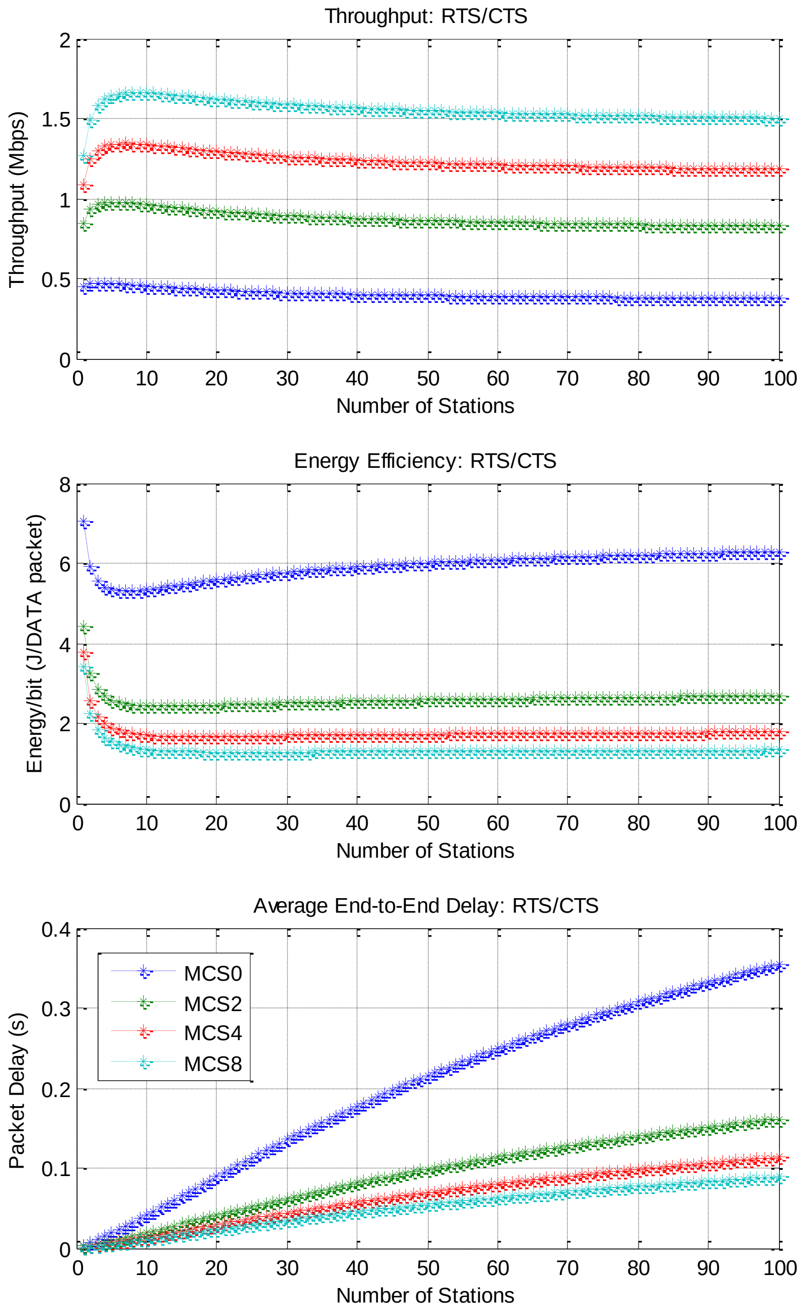

__Figure 5.13__ Results under non-saturated conditions using the RTS/CTS access mechanism.

5.3 Use cases

In this section the performance of the IEEE 802.11ah is measured analytically towards real-life use cases; smart grid systems and healthcare devices. The standard will be evaluated by applying the same metrics of performance as in the previous subchapters taking into account the following assumptions:

- The network deployed will be using a star topology.
- Ideal communications environment is considered.
- Disaggregation for the sampling rates is not considered.
- RTS/CTS and Basic access mechanisms are used depending on payload size.
- Non-saturated conditions.

From here, what is on pursuit is to determine if the standard is able to perform as described in Chapter 3, and as promised by the TGah. Average end-to-end delay will let us know in the case of the healthcare devices if the standard is suited for such critical conditions. But, in the case of the smart grids we will focus more into the scalability. Energy consumption is also analyzed to determine the energy cost of the amendment.

5.3.1 Scenario A: smart grid metering

Smart grids are modern electric power grid infrastructures, which provide smooth integration of alternative and renewable energy sources though modern communication and sensing technologies [40]. The potential benefits of smart grids are numerous and they can be outlined as follows [41]:

- Increased energy consumption information available to consumers.
- Improved physical and operational security and resilience against attacks or disasters.
- Increased energy efficiency.
- Improved reliability and safety.
- The integration of a higher percentage of renewable energy sources.
- Easy integration of plug-in vehicles.
- A reduction in peak energy demand.
- Environmental benefits.

Recent advances in embedded systems and wireless sensor networking have made possible to implement low-cost monitoring and diagnostic systems for smart grids. These systems receive information from WSN nodes, which monitor critical smart grid equipment and are used to monitor and respond to the changing conditions in a proactive manner. Hence, WSN have been recognized as a promising and complementary technology for various smart grid applications. However, harsh and complex propagation environments and a wide variety of scatters, very common in electric power distribution networks, cause wireless communication challenges in terms of reliability and delay, and require special attention during installation in smart grid applications. Also, guaranteeing a specific quality of service (QoS) is a challenging issue in WSN.

5.3.1.1 Parameters and assumptions

To make this use case practical, this study focus on the management of the electric consumption of a complex of apartment buildings located in Insinöörinkatu 56, Tampere, 3370 Finland. The building complex consists of 7 towers with 40 apartments in each of them on an area of approximately 98696.5 m^2 as depicted in Figure 5.14, assuming that every household is equipped with one smart meter we are talking of a scenario of about 240 STAs.

According to The Dutch Smart Meter requirement document [45], which defines the size and function of the information sent by the smart meters, and based on this information the user generated data is considered as: data from self-generation, failure statistics and additional energy metering (e.g. 3-phase installation, gas metering) as shown on Table 5.3. Although the meters can sample at a rate even higher than 1MHz, many of existing deployments have chosen to accumulate to 15 min or even longer intervals to ensure reliable data transmission [52]. For this analysis a payload size of 433 Bytes has been selected with a packet arrival of $\lambda = 6$; meaning that the STAs have 6 packets to transmit per second. Because of the small payload size, from the results obtained in section 5.2.3.2 the Basic access mechanism has been selected.

Figure 5.14 *Apartment Complex for smart metering.*

Data Use in Metering	Size in bytes
Consumption only	193
Consumption/production	245
Consumption/production, instantaneous power (3-phase) and current	530
Consumption-production, instantaneous power (3-phase), current, failures and gas metering.	1,100
Data Use in Smart Devices	**Size in bytes**
Electric vehicle consumption only	193
Electric vehicle consumption/feed-in, instantaneous power (3-phase) and current	245
Electric vehicle consumption/feed-in, instantaneous	1,100

power (3-phase), current, failure and gas metering	
Battery	200
Intelligent appliances	200
Payload size for analysis	**433 Bytes**
Packets per second	$\boldsymbol{\lambda = 6}$

Table 5.3 *Data size for various parameters/devices/services in bytes per sample.*

5.3.1.2 Results

From Figure 5.15 we can observe how the throughput is completely acceptable for the proposed use case.

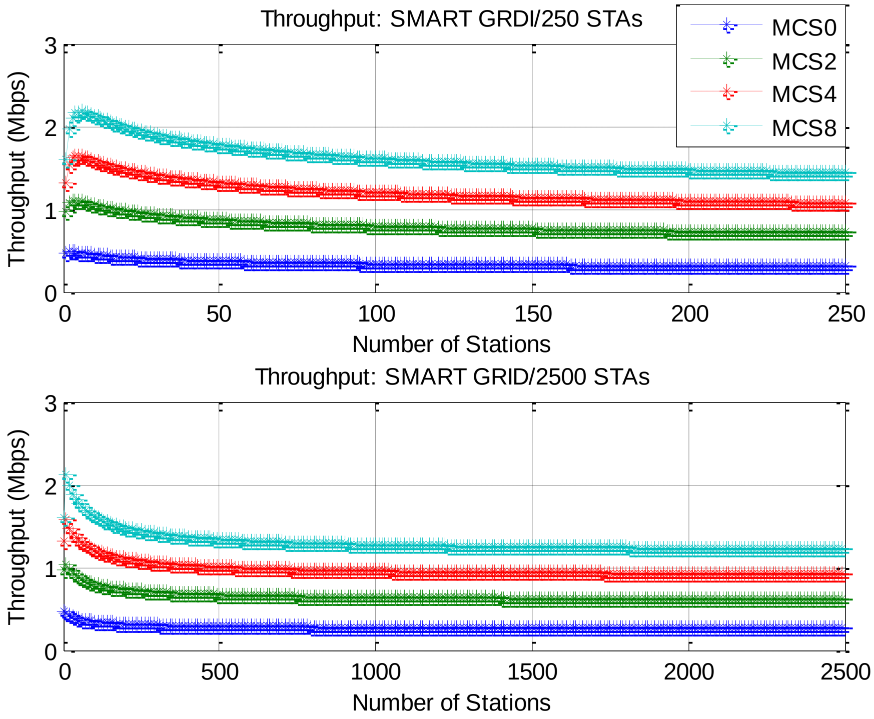

Figure 5.15 *Throughput for use case: smart grid; non-saturated conditions.*

In terms of average end-to-end delay, as depicted in Figure 5.16 we can observe the standard meeting the requirements of the use case, having at its lowest MCS a little below 0.4 seconds to transmit every DATA packet. The energy efficiency behavior shown in Figure 5.17 is also very acceptable with only a little above 8 Joules per DATA packet.

5.3.2 Scenario B: hospital monitoring systems

In a hospital health care monitoring system it is necessary to constantly monitor the patient’s physiological parameters. Body sensor network systems can help people by providing healthcare services such as medical monitoring, memory enhancement, medical data access, and communications with the healthcare provider. Although present system allows continuous monitoring of patient vital signs, these systems require the sensors to be placed beside monitors or PCs, and limit the patient to his bed. But now, there is no relation between the sensors and the bedside equipment due to the wireless devices and wireless networks [43].

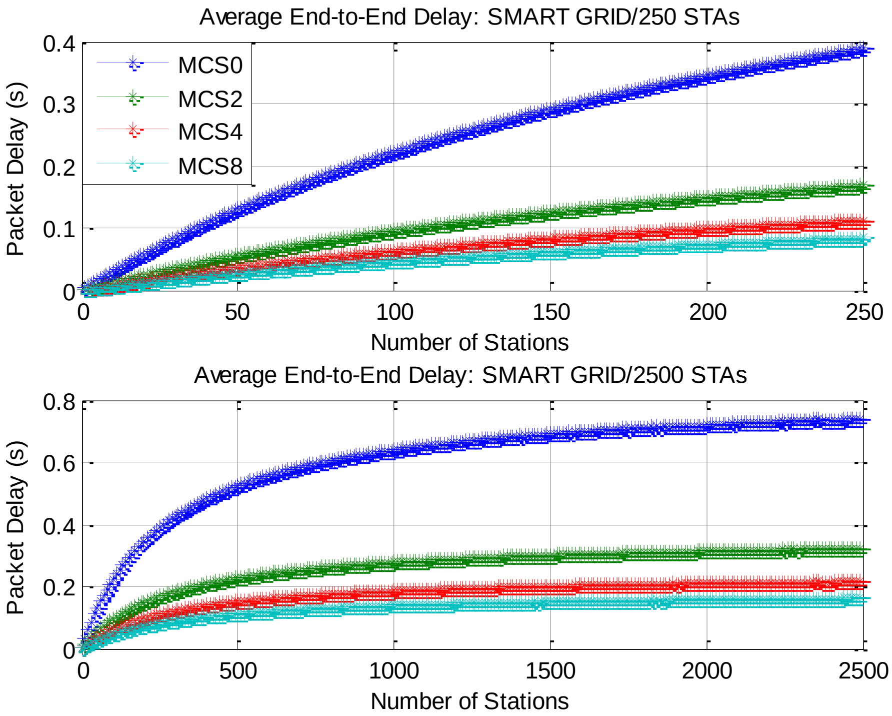

Figure 5.16 *Average end-to-end delay under non-saturated conditions for use case: smart grid.*

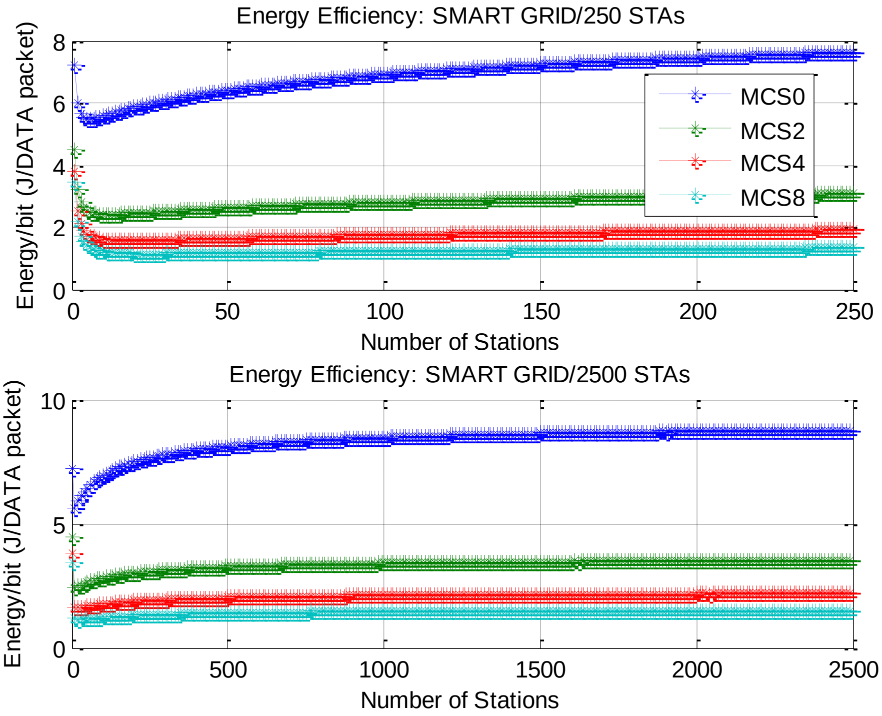

Figure 5.17 *Energy efficiency under non-saturated conditions for use case: smart grid.*

Few companies have started or had success to build the equipment which fulfills the healthcare requirements, and there is still a lot of work on this area that needs to be done. WSNs in healthcare require addressing a multitude of technical challenges. These challenges reach above and beyond the resource limitations that all WSNs face in terms of limited network capacity, processing and memory constraints, as well as scarce energy reserves. Specifically, unlike applications in other domains, healthcare applications impose tight requirements on system reliability, QoS, and particularly privacy and security.

5.3.2.1 Parameters and assumptions

Clinically, biomedical signals are primarily acquired for monitoring (detecting or estimating) specific pathological/physiological states for purposes or diagnosis and evaluating therapy [46]. For each specific examinee the anticipated range of signal parameters is different. For example, heart rate may vary between 25 and 300 beats/min for nominal people; likewise, breathing rate could be between 5 and 50 breaths/min. EEG (electroencephalography), ECG (electrocardiogram) and EMG (electromyography) are considerably more complex signals with spectra spanning up to 50 kHz; Table 5.4 data resumes the pertinent data for healthcare monitoring devices [47].

For the evaluation of the 802.11ah on healthcare applications the values of Table 5.4 will be addressed as referencing points in order to validate the amendment.

Device	**Number of users = sensors**	**Sample rate (Hz)**	**Resolution (b/sample)**	**Information rate (b/s)**	**Payload Size (b)**	λ	**Access Mecha-nism**
ECG	5-9	1250	12	15,000	5000	3	Basic
Heart sound	2-4	10,000	12	120,000	20,000	6	RTS/ CTS
Heart rate	2	25	24	600	600	1	Basic
EEG	20	350	12	4,200	1,400	3	Basic
EMG	2+	50,000	12	600,000	100,000	6	RTS/ CTS

Table 5.4 *Biomedical measurements [47].*

Note that λ as described in section 5.2.3.2 is measured in $packets/s$. Also the access mechanism has been chosen according to the obtained results in section 5.2.3.2 where tests have been done with a payload size of 1024 Bytes.

5.3.2.2 Results

Based on the number of sensors (STAs) field in Table 5.4, we have evaluated the different devices using its maximum sensor number for 10 devices. For healthcare devices, the most critical metric of performance could be the average end-to-end delay, followed by the throughput and the energy efficiency at last; for medical reasons is very important to have real-time data available at all times and here the first two metrics play along making the ideal to be 1 second, but the energy efficiency may not be of critical importance as the batteries can easily be recharged or replaced. Figure 5.18 shows the results for the ECG.

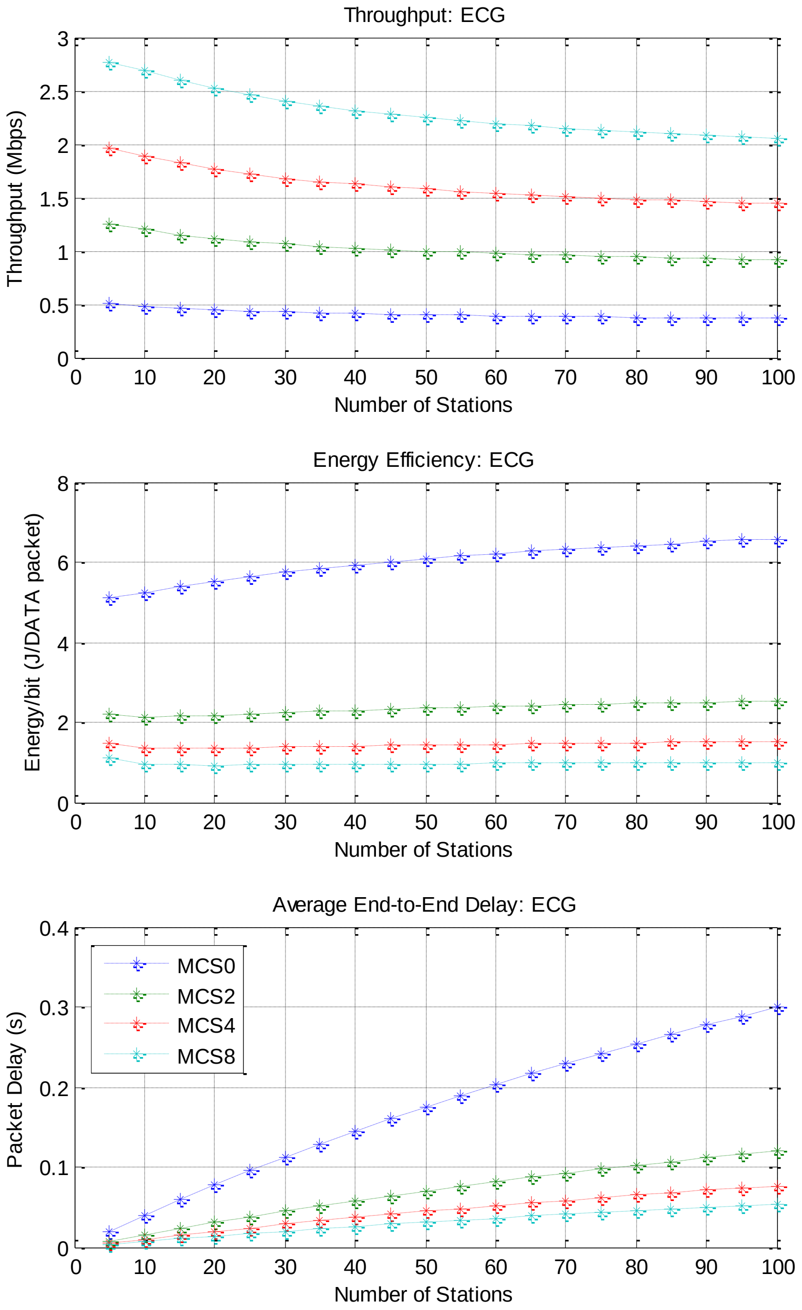

Figure 5.18 *Performance results for ECG devices under non-saturated conditions.*

Figure 5.19 shows the results for the heart sound device. Note that RTS/CTS access mechanism has been used due to the large payload.

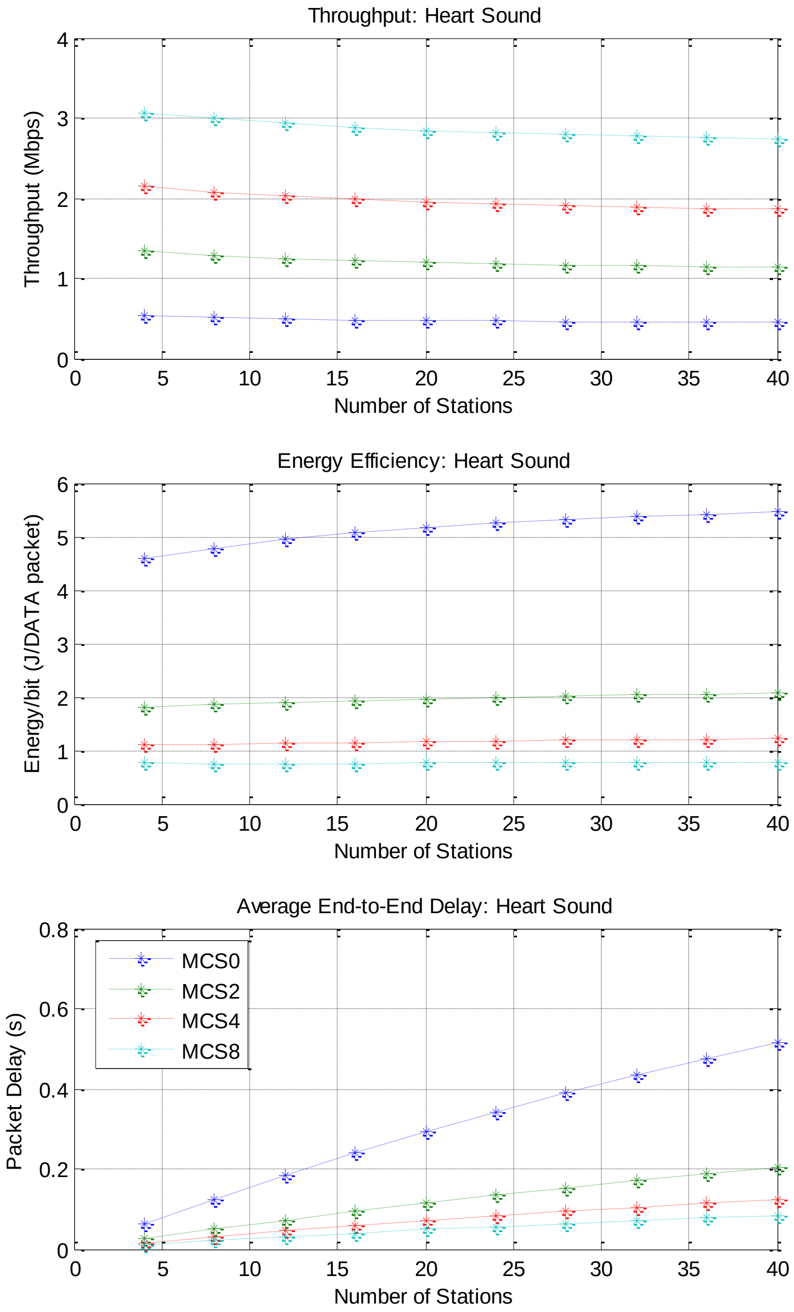

Figure 5.19 *Performance results for heart sound devices under non-saturated conditions.*

Figure 5.20 shows the results for the heart rate device. Note that basic access mechanism has been used due to the small payload size.

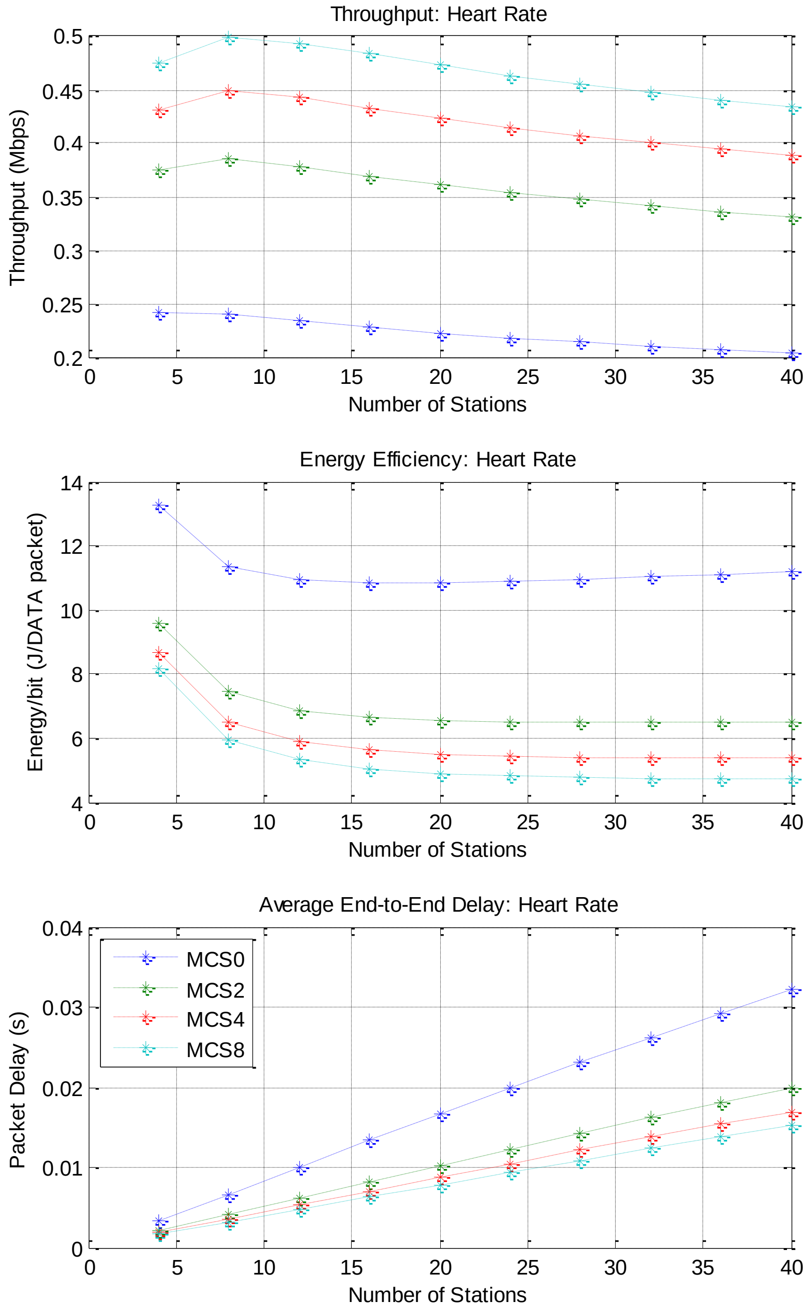

Figure 5.20 *Performance results for heart rate devices under non-saturated conditions.*

Figure 5.21 shows the results for the EEG device. Note that basic access mechanism has been used due to the small payload size.

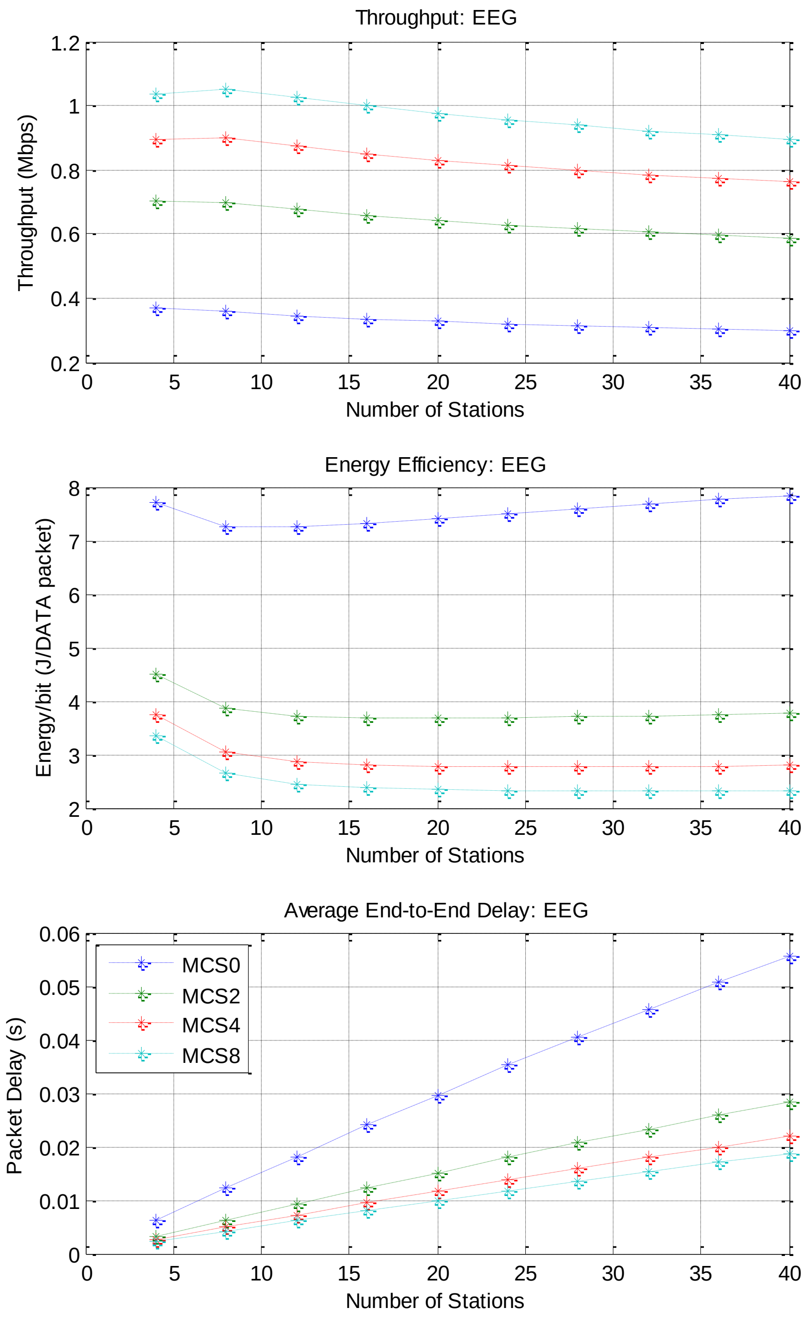

Figure 5.21 *Performance results for EEG devices under non-saturated conditions.*

Figure 5.22 shows the results for the EMG device. Note that RTS/CTS mechanism has been used due to the large payload size.

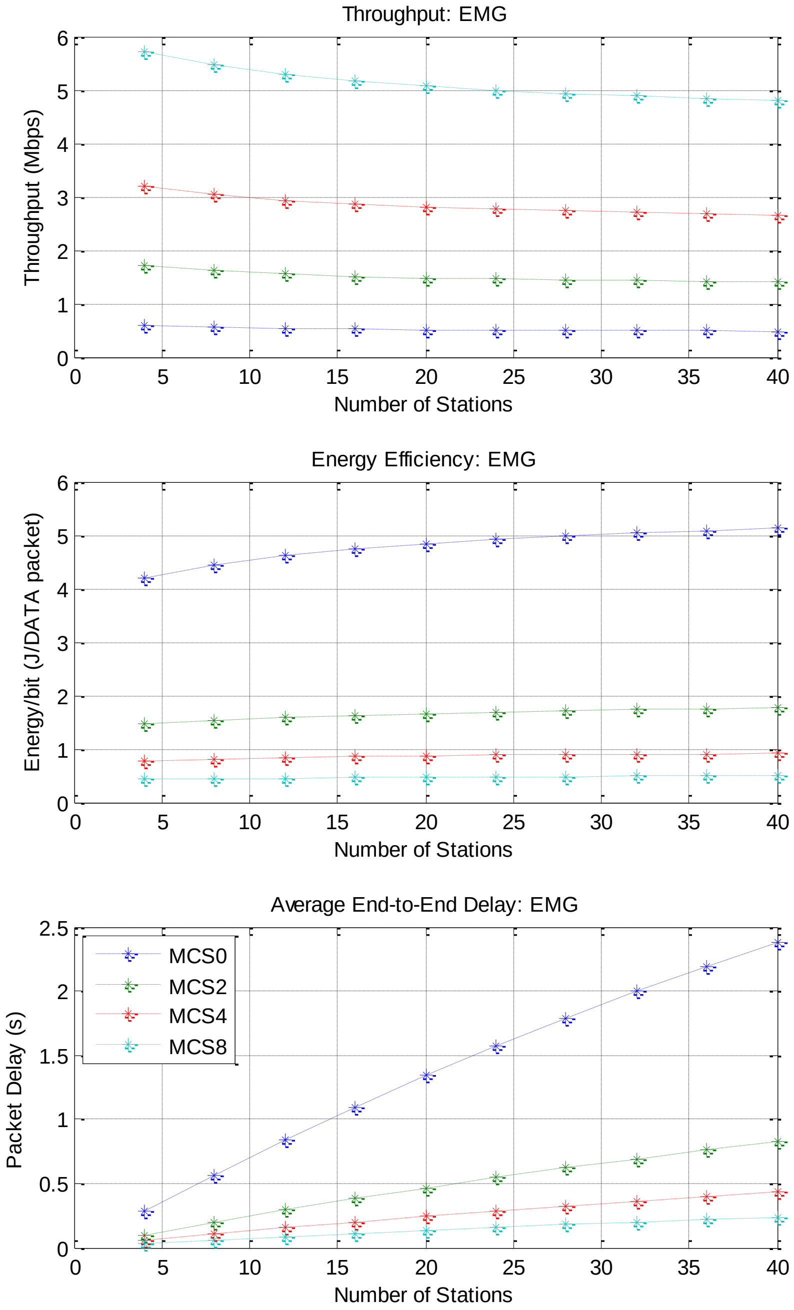

Figure 5.22 *Performance results for EMG devices under saturation conditions.*

As we can observe in the obtained results, the IEEE 802.11ah performs well with every healthcare device tested on the model, proving its feasibility.

6. CONCLUSIONS

In this Master Thesis work, the characteristics of the new IEEE 802.11ah standard are evaluated from a Wireless Sensor Networks perspective. Offering ultra-low power consumption, a long-range coverage, support for a large number of stations (STAs) with data rates of at least 100 Kbps, this new standard promises to be a great choice for future deployments of WSN.

In this thesis work, an analytical model was developed and thereon evaluated in MatLab2014b in order to apply a series of performance metrics related to the standard deployment. The first part of the model calculates the maximum available throughput assuming ideal conditions (no hidden nodes, ideal channel conditions, no collisions or errors in the transmission) for a single STA.

The second part of the analytical model, takes into account a modified Markov Chain model, based on Giuseppe Bianchi’s [48] approach but taking into account retransmission counts to calculate saturation throughput, energy efficiency and average end-to-end delay of the Distributed Coordination Function (DCF) scheme. This new Markov Chain was presented by Nokia China R&D in 2002 by Haitao Wu [50].

The third part also analyzes the performance of the DCF scheme under non-saturated conditions. Taking into account a different Markov Chain model proposed by Ken Duffy in [54], we are able to include a traffic load variable related to each STA in our new Markov Chain model, assuming that the packets arrive at the STA buffer in a Poisson manner. The resulting inter-arrival times are exponentially distributed.

From this analysis it is determined that for small payloads (i.e. IoT applications) the basic access mechanism is superior to the RTS/CTS, due to the overhead that the latter one carries. On the other hand, when the payload size and the number of STAs is relatively large the RTS/CTS access mechanism is the best choice.

Several modulation and coding schemes (MCS) were analyzed in the model, where in saturation conditions the most robust MCS0 offering a data rate of 650Kbps was the most expensive in terms of energy consumption and the slowest due to its limited data rate, in contrast to the MCS8 which offers data rates of up to 7.8Mbps.

The IEEE 802.11ah Task Group (TGah) is under way to standardize wireless local area networks that will use carrier frequencies in the 900MHz industry, scientific and medical (ISM) bands by 2016. This will offer an alternative to the IEEE 802.15 short-range sensor systems and will enable cost-efficient machine to machine (M2M) and internet of things (IoT) wireless access networks. By being an amendment of the legacy IEEE 802.11, the most widely used WLAN communication standard, the IEEE 802.11ah offers the advantage of not requiring a set of additional architectural elements to operate on most of the existing infrastructures, a characteristic that commercial-wise will empower the technology to further development, and eventually, a full deployment with many applications in the WSN world and IoT era.

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