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Contributions to IEEE 802.11-based long range communications

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This thesis is dedicated to the memory of my beloved father

Víctor B. Baños Acosta (1954-2010).

Abstract

The most essential part of the Internet of Things (IoT) infrastructure is the wireless communication system that acts as a bridge for the delivery of data and control messages between the connected things and the Internet. Since the conception of the IoT, a large number of promising applications and technologies have been developed, which will change different aspects in our daily life.

However, the existing wireless technologies lack the ability to support a huge amount of data exchange from many battery-driven devices, spread over a wide area. In order to support the IoT paradigm, IEEE 802.11ah is an Internet of Things enabling technology, where the efficient management of thousands of devices is a key function. This is one of the most promising and appealing standards, which aims to bridge the gap between traditional mobile networks and the demands of the IoT.

To this aim, IEEE 802.11ah provides the Restricted Access Window (RAW) mechanism, which reduces contention by enabling transmissions for small groups of stations. Optimal grouping of RAW stations requires an evaluation of many possible configurations.

In this thesis, we first discuss the main PHY and MAC layer amendments proposed for IEEE 802.11ah. Furthermore, we investigate the operability of IEEE 802.11ah as a backhaul link to connect devices over possibly long distances. Additionally, we compare the aforementioned standard with previous notable IEEE 802.11 amendments (i.e. IEEE 802.11n and IEEE 802.11ac) in terms of throughput (with and without frame aggregation) by utilizing the most robust modulation schemes. The results show an improved performance of IEEE 802.11ah (in terms of power received at long range while experiencing different packet error rates) as compared to previous IEEE 802.11 standards.

Additionally, we expose the capabilities of future IEEE 802.11ah in supporting different IoT applications. In addition, we provide a brief overview of the technology contenders that are competing to cover the IoT communications framework. Numerical results are presented showing how the future IEEE 802.11ah specification offers the features required by IoT communications, thus putting forward IEEE 802.11ah as a technology to cater the needs of the Internet of Things paradigm.

Finally, we propose an analytical model (named e-model) that provides an evaluation of the RAW configuration performance, allowing a fast adaptation of RAW grouping policies, in accordance to varying channel conditions. We base the e-model in known saturation models, which we adapted to include the IEEE 802.11ah's PHY and MAC layer modifications and to support different bit rate and packet sizes. As a proof of concept, we use the proposed model to compare the performance of different grouping strategies,

showing that the e-model is a useful analysis tool in RAW-enabled scenarios. We validate the model with existing IEEE 802.11ah implementation for ns-3.

“One, remember to look up at the stars and not down at your feet. Two, never give up work. Work gives you meaning and purpose and life is empty without it. Three, if you are lucky enough to find love, remember it is there and don't throw it away”

Stephen Hawking

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Gracias totales.

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3GPP	3rd Generation Partnership Project.
A-MPDU	Aggregate MPDU.
A-MSDU	Aggregate MSDU.
AC	Access Category.
ACK	Acknowledgement.
AI	Artificial Intelligence.
AID	Association Identifier.
AP	Access Point.
BA	Block ACK.
BCC	Binary Convolutional Code.
BDT	Bi-directional TxOP.
BER	Bit Error Rate.
BLE	Bluetooth Low Energy.
BP	Blood Pressure.
BSS	Basic Service Set.
CAPEX	Capital Expenditure.
CBW	Channel Bandwidth.
cIoT	consumer IoT.
CRC	Cyclic Redundancy Check.
CSMA	Carrier Sense Multiple Access.
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance.

CTS	Clear to Send.
DCF	Distributed Coordination Function.
DIFS	DCF Inter-frame Space.
DTIM	Delivery TIM.
ECG	Electrocardiography.
EDCA	Enhanced Distributed Coordination Access.
EDCF	Enhanced DCF.
EEG	Electroencephalography.
GI	Guard Interval.
GSM	Global System for Mobile Communications.
HCCA	HCF Controlled Channel Access.
HCF	Hybrid Coordination Function.
HT	High Throughput.
HVAC	Heating, Ventilating and Air-Conditioning.
ICT	Information and Communication Technologies.
IE	Information Element.
IEEE	Institute of Electrical and Electronics Engineers.
IETF	Internet Engineering Task Force.
iIoT	industrial IoT.
IoE	Internet of Everything.
IoH	Internet for Humans.
IoT	Internet of Things.
ISM	Industrial, Scientific and Medical.
LoS	Line-of-Sight.
LP-WUR	Low-Power Wake-Up Receiver.
LPWAN	Low Power Wide Area Network.
LRLP	Long-Range Low-Power.
LTE	Long-Term Evolution.

M2H	Machine to Human.
M2M	Machine to Machine.
MAC	Medium Access Control.
MCS	Modulation and Coding Schemes.
MIMO	Multiple Input Multiple Output.
MPDU	MAC Protocol Data Units.
MSDU	MAC Service Data Units.
MTC	Machine Type Communications.
MU	Multi User.
MU-MIMO	Multiple User MIMO.
NAV	Networks Allocation Vector.
NB-IoT	Narrowband Internet of Things.
NDP	Null Data Packets.
NIC	Network Interface Card.
NLoS	Non-Line-of-Sight.
OFDM	Orthogonal Frequency Division Multiplexing.
OPEX	Operation Expenditure.
PCF	Point Coordination Function.
PDU	Protocol Data Unit.
PER	Packet Error Rate.
PHY	Physical Layer.
PS-Poll	Power Save-Polling.
PSDU	PLCP Service Data Unit.
QoS	Quality of Service.
RAW	Restricted Access Window.
RD	Reverse Direction.
RPS	RAW Parameter Set.
RTS	Request To Send.

S1G	below 1 GHz.
SG	Study Group.
SIFS	Short Interframe Space.
SIG	Signal.
SPF	Speed Frame Exchange.
SS	Spatial Stream.
SST	Sub-Channel Selective Transmission.
STAs	Stations.
TCP	Transmission Control.
TG	Task Group.
TIG	Topic Interest Group.
TIM	Traffic Indication Map.
TWS	TV White Spaces.
TWT	Target Wake up Time.
TxOP	Transmit Opportunity.
UANs	Urban Automation Networks.
UDP	User Datagram Protocol.
VANETs	Vehicular Ad-hoc Networks.
WG	Working Group.
Wi-Fi HaLow	IEEE 802.11ah standard.
WLAN	Wireless Local Area Networks.
WSN	Wireless Sensor Networks.
WuR	Wake-up Radio.

1. Introduction

Technology is a fundamental part of our daily life, and it appears to us in an intangible way. In the case of wireless communications, wireless networks are used 24 hours per day and 7 days per week around us without even being noticed. Information and communication technologies (ICT) have been evolving in a fast way. As a part of this evolution, in the last 3 decades the Internet grew-up from a simple network formed by hundreds of users until today's mega-network that is capable to connect hundreds of millions of users among them.

Human curiosity evolves each day and takes us each time to new and hardest boundaries, as is the idea that the Internet was not made just to interconnect people. The Internet concept has been improved with the addition of the idea that it must connect things (sensors, machines, smart devices, cars, cities) with people at the same time, thus envisioning and making a new scenario that needs to develop new network communication standards or technologies to fulfill the new requirements.

Besides, these new technologies must be capable to develop and satisfy the user's new needs, such as covering the mobility of the users across the cities, better data transfer rates, longer coverage ranges, and low latency response time systems. As a response to the Internet network enhancement required by the new scenarios, the ubiquity concept comes to the scene and can be explained as a pervasive networking feature that consists of having network connectivity everywhere the users move around.

Ubiquitous networking data and ubiquitous computing perform the latest edge experiences, such as virtual reality gaming, work at a distance, business applications, infrastructure, remote surgery, and artificial intelligence applications that people and companies envision, among others. As well, cloud and edge intelligent applications are also included as part of this enhancement's services offered to people to improve how they operate and compete to offer real-time response solutions in a rapidly changing world, evolving and reshaping people's needs all the time.

Apart from this, both new scenarios and users' requirements create the need to develop new standards, which must be able to interconnect people and smart objects (smart things) such as computers, e-health devices, sensors for environmental metrics, home automation, autonomous and semiautonomous vehicles, among others.

Giving meaning to the Internet of Things (IoT), which its single motto is "to have network connectivity between users at any time any place". The telemetry concept is needed to be settled as a stream of data that IoT devices generate, and open the novel scenarios for telemetry values in different use-cases where acceleration, humidity, location, pressure, temperature, and velocity are involved. Additionally, the so-called "Industry 4.0" is a new edge in the industrial process using IoT technologies and use-cases that are beneficiated by IoT in its production lines, retail shelves, retail checkouts, driving equipment, etc.

Undoubtedly, the Institute of Electrical and Electronics Engineers (IEEE) 802.11 wireless networks technology or so-called "Wi-Fi", that is world spread and widely used nowadays, is a technology that is one of the prominent enablers that could be used to tackle the new challenges and requirements for the smart applications.

As a result of the millions of wireless communication technologies users around the world, and the massive number of devices connected to the IoT, it is estimated that around 50 billion devices are connected in 2020 [1]. Furthermore, the success of wireless networks generated the need for the creation of the Wi-Fi Alliance [2], which is an organization that certifies products indicating that they have met industry standards for security, interoperability, and applications for specific protocols.

The IEEE 802.11 standard is evolving by developing the next generation of wireless IEEE 802.11 networks. Evidently, Wireless Local Area Networks (WLAN) popularity locates it as one of the most reliable and world-spread technology with presence practically everywhere.

Moreover, IEEE 802.11 identified the need to develop a new standard focused on IoT requirements, which is capable of supporting thousands of stations (STAs) within the same network, allowing large coverage range distances and providing energy savings mechanisms.

As the so-called Wi-Fi HaLow [3] by the Wi-Fi Alliance certification, this new technology was tailor-made covering these IoT features, and the IEEE 802.11ah standard [4] was released at the end of 2016. Further information about IEEE 802.1ah is presented in the next chapters.

This thesis explores IEEE 802.11ah, as the principal standard for long-range wireless communications and as a part of the next generation of wireless standards for IoT communications. Chapter 2 presents thoroughly the 802.11ah amendment. Thereafter, in Chapter 3, a performance evaluation of Wi-Fi HaLow is provided. Subsequently, IEEE 802.11ah is compared against other notable IoT competitors to enable IoT applications in Chapter 4. In Chapter 5, the network simulation tool used in this dissertation is presented and validated. The Restricted Access Window (RAW) feature is studied in Chapter 6, where we propose our “e-model” based on different strategies to get the best RAW configuration. In addition, to conclude, the final discussion is presented in Chapter 7.

1.1 IEEE 802.11 next generation wireless networks for IoT communications

Considering that wireless network communication standards evolve accordingly to the user's needs and, due to constant research and development, we have witnessed in the last years how wireless networks have been fulfilling the Internet for Humans (IoH) requirements. In order to support the addition of the IoT to the IoH, it will require the improvement in distinct mechanisms and enhancing features that will be needed to face the particular use-cases generated by these new scenarios.

Following the IoH and IoT characteristics, and joining the concept of the Internet of Everything (IoE) (cf. Figure 1), a next-generation of wireless networks by the IEEE 802.11 has been developed. The main standard focused on IoT application requirements is IEEE 802.11ah (Subsection 1.1.1). On the other hand, the forthcoming IEEE 802.11ba amendment includes IoT as a field of application (Subsection 1.1.2). Also, notice that the Physical layer (PHY) and Medium Access Control Layer (MAC) characteristics are the ones that give a distinction between the different IEEE 802.11 specification standards.

1.1.1 IEEE 802.11ah

IEEE 802.11 a/g, n, or ac amendments were not focused on developing any IoT specification. Furthermore, the new standard IEEE 802.11ah was released in 2016, highlighting the IEEE 802.11 approaches to the IoT. This standard is intended to provide a low-cost mode of operation, with greater coverage area, and thousands of associated stations per cell (further discussion about the IEEE 802.11ah main features are presented in Chapter 2). To assess how this new IEEE 802.11ah standard adds value to the IEEE 802.11 families in terms of range and throughput for new use cases, we compare its performance against current IEEE 802.11 amendments in Chapter 3.

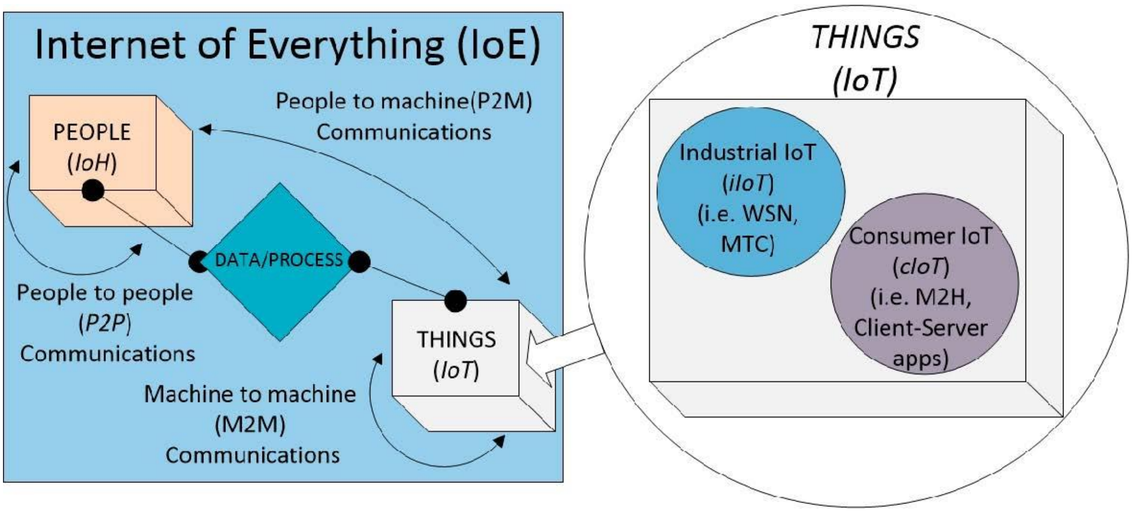


Figure 1. Internet of Everything concept.

1.1.2 IEEE 802.11ba

Most recently, the IEEE 802.11 Working Group (WG) has triggered other future specifications to include the IoT use case. As of July 2015, the creation of a new Topic Interest Group (TIG) on Long-Range Low-Power (LRLP) operation for IoT was initiated [5], which aimed to bring some of the new IEEE 802.11ah features to the 2.4 GHz band while keeping compatibility with mainstream IEEE 802.11 devices on that band.

In May 2016 the TIG agreed to focus on the low power consumption issue (leaving aside the long-range feature), creating a Study Group (SG), the LP-WUR (Low-Power Wake-Up Receiver) SG. Therefore, the LRLP TIG has been dissolved. Despite that, from December 2016 and after significant interest in this subject made by researchers and Scientifics, IEEE 802.11ba WG is working on drafts documents of the amendment, defining characteristics in PHY and MAC layers to have a successful functionality of a Wake-up Radio (WuR) system [6].

The principal characteristics of IoT devices include low-power and low-latency responses. In order to support the low-power characteristic, the IEEE 802.11ba Task Group (TG) included a paramount feature as is the WuR feature in this future standard [6].

Thus, in order to enhance power saving, the WuR typically works as an additional radio interface, where the power consumption is uncommonly down, and this allows the AP to transmit control data to the STAs, meanwhile, the primary radio is in doze state. To sum up, the less time that the devices wake up to receive information, the more energy saving. Notice that the TG aims to release this standard in 2020.

1.2 IEEE 802.11 mainstream wireless networks

The mainstream IEEE 802.11 wireless networks have a paramount place in our daily lives. Aiming to improve features such as spectrum efficiency, and area throughput, and taking into consideration the constantly increasing number of users for indoor and outdoor deployments in reduced areas across the cities, as well as, considering the presence of thousands of stations that perform as an interfering source between each other. As a consequence of the aforementioned goals, IEEE 802.11 identifies heterogeneous network challenges in dense scenarios and tackles them with both the IEEE 802.11ac and IEEE 802.11ax standards.

1.2.1 IEEE 802.11ac

IEEE 802.11ac specification (Wi-Fi 5 by the Wi-Fi Alliance) provides high rates until 6.93 Gbps, uses Multiple Input Multiple Output (MIMO) enhanced with up to 8 streams, includes 160 MHz and (80 + 80 MHz) signal bandwidth, 256 QAM modulation and introduces Multiple User MIMO (MU-MIMO) [7]. MU-MIMO is a technique that allows an AP to interchange data with multiple STAs simultaneously aiming with this to decrease the time each STA has to wait for transmission, thus, improving the throughput (cf. Section 2.6.7).

1.2.2 IEEE 802.11ax

Forthcoming IEEE 802.11ax specification (Wi-Fi 6 by the Wi-Fi Alliance [8]) is focused on facing increased device density and high throughput requirements, challenges that are currently present in Wi-Fi environments. Considering as target scenarios of the aforementioned standard, environments such as home (dense apartment buildings), enterprise, and office buildings, IEEE 802.11ax standard is focused on providing high throughputs on ultra-dense scenarios [9].

Wi-Fi 6 main characteristics are: the use of the MU-MIMO (downlink and uplink), the increased bandwidths from 20 to 160 MHz channel utilization capability, the Fast Fourier Transform (FFT) size 256 to 2048 to increase robustness, a 78.125 kHz subcarrier spacing to increase the range over coverage of Orthogonal Frequency Division Multiplexing (OFDM) systems, the use of one to eight spatial streams (SS), the inclusion of the 1024 Quadrature Amplitude Modulation for improving throughput, and the use of the Target Wake up Time (TWT) feature, which enhances the power savings [10].

1.3 IEEE 802.11 long-range wireless networks

A key feature in IoT wireless communications is the coverage range. In contrast to IEEE 802.11 legacy characteristics, where the coverage range could not be more than some hundreds of meters, the new technologies, such as IEEE 802.11ah, aim to increase this coverage substantially. Moreover, the development of the IEEE 802.11af standard covers this characteristic by improving the distance range feature to reach thousands of meters.

One of the main characteristics of the IEEE 802.11af standard is the operation in TV White Spaces (TWS, 470-790 MHz in Europe), which was released in 2014. Using this transmission frequency condition allows the coverage range of an AP to increase.

Additionally, it is worth mentioning that the PHY of this standard is similar to Wi-Fi 5. Besides that, an additional guard band was added to avoid adjacent channels interferences due to TV transmissions [11]. Note that the IEEE 802.11af operates in licensed frequency bands.

1.4 Main wireless technologies for IoT

Low-power devices have a crucial role in the IoT applications, which include Machine to Machine (M2M) or Machine to Human (M2H) communications. Likewise, IEEE 802.11 specifications prone IoT, similarly other new technologies appear in the IoT arena that include particular features that are attractive for different scenarios and applications, like Low Power Wide Area Network (LPWAN) technologies as LoRaWAN, Sigfox and Narrowband Internet of Things (NB-IoT).

In addition, technologies as ZigBee, Bluetooth Low Energy (BLE) and 3rd Generation Partnership Project (3GPP) Machine Type Communications (MTC) form part of the available technologies that are able to fulfill the IoT applications requirements.

1.4.1 LoRaWAN

The standard LoRaWAN is made for long-range, low-power and low-data-rate applications [12]. It operates in an unlicensed frequency band of 867 to 928 MHz, offering data rates up to 25 kbps. With regard to the coverage range, this technology reaches approximately up to 20 km, supporting more than 10,000 devices [13]. Notice that the aforementioned LoRaWAN is a proprietary technology.

1.4.2 Sigfox

Sigfox shares the LPWAN network technology characteristics, and one of the main features of Sigfox technology is that it includes data rates in the range of the 1 kbps or lower, with a coverage range up to 40 km and the support of more than 1,000,00 devices [14].

Same as LoRaWAN, Sigfox is also a proprietary technology. Sigfox together with the LoRaWAN have higher complexity interconnection and limited available bandwidth in contrast with the IEEE 802.11ah, which can offer the highest bandwidths and a better interconnection.

1.4.3 NB-IoT

The 3GPP introduced the NB-IoT, which allows operators to use a minimal portion of the available spectrum (Long-Term Evolution, LTE, or Global System for Mobile Communications, GSM, networks). NB-IoT presents long coverage ranges and an increased number of supported devices [15]. It works in a licensed frequency band (700-900 MHz) and it has coverage range of up to 15 km and transmission data rates up to 50 kbps. This technology also supports more than 100,000 devices.

Notice that IEEE 802.11ah transmits under unlicensed frequency bands that can be considered as an advantage against the NB-IoT. Additionally, the costs of deployment and operation will be higher than the ones for IEEE 802.11ah.

1.4.4 ZigBee/IEEE 802.14.4e

The most appealing feature of ZigBee/IEEE 802.14.4e standard is the low implementation cost, being this technology used in most of the Wireless Sensor Networks (WSN). It allows a large number of supported devices (up to 65000 devices) and offered data rates from 20 up to 250Kbps [16], reaching coverage range up to 100 meters and working in the 2.4 GHz frequency band. Notice that in comparison to IEEE 802.11ah, lower data rates are supported by the ZigBee/802.15.4e technology.

1.4.5 Bluetooth low energy

BLE consists of an amendment of the legacy Bluetooth with enhanced characteristics to be part of the IoT communications environment and been focused on energy consumption and short-range low-rate communication [17]. The success of this technology is based on the fact that it operates in the 2.4 GHz frequency band, reaching data rates up to 1 Mbps.

Additionally, it covers areas of maximum of 50 meters and it is capable to support an unlimited number of devices (depending of the configured address space). Observe that BLE reaches lower speeds than the IEEE 802.11ah data rates.

1.4.6 3GPP MTC

The GSM spectrum has been reorganized allowing sub 1 GHz frequencies, these are the frequencies used by 3GPP MTC and they are included in releases 12 and 13.

3GPP MTC includes the largest coverage range feature and the highest number of supported devices (more than 100,000 devices) [18]. The 3GPP MTC specification works in a licensed spectrum at frequency bands below 5 GHz, with a data rate transmission up to 1 Mbps, reaching the ranges of 100km coverage.

In the same way as with the NB-IoT technology, IEEE 802.11ah transmits under unlicensed frequency bands and the costs of deployment and operation of 3GPP MTC can be higher than the ones for IEEE 802.11ah.

1.5 Motivation

IoT environment encompasses network communications and different kinds of applications that are in the vogue of the world’s improvements.

Nowadays the challenges to supply the required coverage range are better reception and transmission quality for user experience both indoor and outdoor spaces, supporting point to multipoint applications, long life periods battery usage, and supporting hundreds of devices transmitting data at the same time.

Simultaneously to this evolution of the people’s needs, IEEE 802.11 WG develops an outstanding standard to compete for the IoT communications usage; this feature is based on the requirements of the IoT environment as tailor-made in new technology such as IEEE 802.11ah.

The research developed within this thesis is about studying standard IEEE 802.11ah, since the draft specification until its release and beyond, including MAC and PHY new features and paradigms. Furthermore, contributions to the state of the art on Wi-Fi HaLow are made, in order to support the standard as one of the finest and remarkable technologies in actual IoT networks communication scenario.

1.6 Thesis main objectives

Throughout the development of this thesis, evaluations have been done based on analytical models developed, together with the use of a network simulator that includes modifications to support the IEEE 802.11ah. Taking into account the challenges of the new IoT scenarios and being IEEE 802.11 standards one of the most remarkable technologies used for indoor applications, in this subchapter, main dissertation objectives are discussed and answered, according to the evolution and the research results obtained in this thesis.

The IEEE 802.11 WG developed a standard focused solely on IoT scenarios, as it is IEEE 802.11ah. Throughout the development of this thesis, a thorough study of the IEEE 802.11ah has been performed starting since the early draft versions (at the beginning of this study) until the release of the IEEE 802.11ah standard. In addition, analytical models have been developed, and the use of a network simulator tool has been done. In this subchapter, the main thesis objectives are presented.

1.6.1 IEEE 802.11ah characterization of the PHY and MAC layer against other standards

According to this objective, a comparison of the new IEEE 802.11ah standard amendment against the IEEE 802.11 legacy is performed, including the main new features and the ones that are backward compatible.

Comparisons are made particularly in the throughput and coverage range, including the frame aggregation mechanisms, and taking into account the short IEEE 802.11ah MAC headers. Furthermore, we evaluate network performance under distinct propagation conditions and error rates. Please refer to Chapter 3.

1.6.2 IoT applications characterization and evaluation against IEEE 802.11ah capabilities

Aiming to demonstrate this objective, we evaluate and show if the Wi-Fi HaLow is one of the best options among the other main technologies competing in the IoT arena.

In order to characterize this evaluation, and as a part of the present dissertation, the generated traffic metrics and requirements for multiple different M2M applications, such as health smart systems, smart transportation, smart vehicles, smart grids, smart security systems, smart homes, among others, are presented.

As a part of the performing evaluation, a test was performed of each particular kind of application and the requirements needed by them, against the capabilities of the IEEE 802.11ah standard specifications. Please refer to Chapter 4.

1.6.3 Identification of MAC layer problem in IEEE 802.11ah

In IoT scenarios, where dense networks are inheritably part of it, the association of multiple STAs at the same time can cause collisions, loss of data, and retransmissions of data frames.

Hence, IEEE 802.11ah MAC layer includes new features focusing on tackle this problem, as the contention access method mechanism denominated RAW. This mechanism has as a feature the ability to reduce the number of hidden and exposed nodes, and the problems due to thousands of STAs associated to the same Access Point (AP). In order to satisfy this identified problem, the next objective (Subsection 1.6.4) has a notable impact trying to help solving this as a part of the research development of this thesis.

1.6.4 IEEE 802.11ah restricted access window: analytical tool and evaluation of grouping strategies

After the MAC problem identification pointed out in the previous Subsection 1.6.3, a thorough study of the RAW mechanism has been made as a part of the development of the present dissertation. We proposed, developed, and evaluated a new RAW model based on RAW grouping strategies called "e-model". Additionally, the creation of the "e-model" made necessary the development of a benchmark that was done by using both analytical models and simulation software to achieve this objective. Please refer to Chapter 6.

1.7 Research methodology

For a proper procedure according to this thesis and the research made, the methodology process was as follows. First, we start formulating the research questions. After each successful research question obtained, we continue with a thorough state-of-the-art study, aiming to identify and design the approach to follow, and finishing with the development of an analytical model and a set of experiments. Based on the response of the experiments performed, we end this procedure with the publication of the results obtained.

1.8 Thesis contributions

This thesis explores thoughtfully and deeply on long-range communications based on IEEE 802.11 and the IEEE 802.11ah standard. Regarding contributions produced in the development of this thesis, in this subsection, the two journal papers published and one conference paper under review are going to be mentioned.

Additionally, the multiple state of the art contributions done in each publication are going to be mentioned.

- *V. Baños, M. S. Afaqui, E. Lopez, and E. Garcia, "Throughput and Range Characterization of IEEE 802.11ah," IEEE Lat. Am. Trans., vol. 15, no. 9, pp. 1621–1628, 2017* [19].

Journal Impact Factor: 0.502, quartile: Q4, published in 2017 Area: Computer Science, Information Systems

The principal contributions of this journal paper are in the first place, a brief but updated overview of the IEEE 802.11ah standard. Second, we perform a novel performance comparison of IEEE 802.11ah standard with previous amendments (i.e., IEEE 802.11a/n/ac) in terms of range and throughput (with and without frame aggregation). Finally, we highlight the significance of IEEE 802.11ah as one of the most effective technologies to provide good throughput at larger distances and thus give substance to IEEE 802.11ah backhaul use case.

- *V. Baños-Gonzalez, M. S. Afaqui, E. Lopez-Aguilera, and E. Garcia-Villegas, "IEEE 802.11ah: A technology to face the IoT challenge," Sensors (Switzerland), vol. 16, no. 11, p. 1960, Nov. 2016* [20].

Journal Impact Factor: 2.677, quartile: Q1, published in 2016 Area: Instruments & Instrumentation

The potential coverage at reasonably high rates exhibited by IEEE 802.11ah makes it an attractive alternative in fulfilling the needs of future IoT communications. In this journal article, we provide a comparison between different technologies contending to cover the IoT communications framework, and thus indicate IEEE 802.11 technology as one of the strongest contenders. We evaluate the main characteristics and benefits provided in terms of throughput and transmission range by the most notable IEEE 802.11 specifications compared to IEEE 802.11ah amendment. The analysis of the results presents IEEE 802.11ah with more than 8 times improvement in coverage range against any other IEEE 802.11-based amendment and shows that it can provide throughput close to 100kbps in the worst-case scenario, which is enough to cover most IoT applications. We give a thorough analysis of the requirements of many typical IoT applications (classified as permanent connectivity, event-based applications, audio, video, data, and biometrics), assessing the number of supported devices per AP, with up to 1 km of coverage. In the cases where the required coverage distance is larger than 1km, IEEE 802.11ah can be used to build a multi-hop distribution system. We also provide an analysis of the implementation and infrastructure costs that make IEEE 802.11ah a very appealing technology in front of other IEEE 802.11 specifications and competing wireless technologies. Overall, the expected performance of IEEE 802.11ah asks for a remarkable place in the IoT.

- *V. Baños-Gonzalez, E. Lopez-Aguilera, and E. Garcia-Villegas, "E-model : An analytical tool for fast adaptation of IEEE 802 . 11ah RAW grouping strategies."*

Has been accepted for presentation and publication at the IEEE GLOBECOM 2020 conference.

The main contributions of this paper are following. First, we adapt a multi-rate analytical model for IEEE 802.11 wireless networks published in the literature to the MAC and PHY layers of the IEEE 802.11ah. Secondly, we demonstrate the application of the proposed model, comparing the performance of different grouping policies, and showing that, despite the assumptions of the analytical model, it is always able to identify the best strategy among those compared. Unlike other models, our proposed metric considers different RAW combinations based on configurations including different MCSs, payloads, and group sizes. Simulation results highlight the proposed model as a useful analysis tool in RAW-enabled scenarios. Additionally, to the best of our knowledge we are the first to evaluate the accuracy of ns-3 IEEE 802.11ah models by comparing it with analytical model results.

- The thesis contributed to the amended of the Task Group 802.11ah indoor channel propagation loss model.

During the development of this dissertation we found a mistake in the channel model of the TGah, which was addressed in the document: corrections to TGah channel model, particularly in the pathloss model section [21].

1.9 Thesis organization

This dissertation is composed of seven chapters. Chapter 2 illustrates the IEEE 802.11ah amendment that aims to conquer the IoT network communications.

Following the IEEE 802.11ah amendment overview, Chapter 3 highlights a performance evaluation with regard to throughput and coverage range.

The thesis explores and provides in Chapter 4 a thorough research development, aiming to evaluate IEEE 802.11ah as a technology to face the IoT challenge.

Chapter 5 is devoted to show the simulation environment developed and performed for this thesis.

In order to face the MAC layer Restricted Access Window, Chapter 6 shows a RAW model based on RAW grouping strategies called "e-model", capable to utilize multi-rate IEEE 802.11 data rates and distinct configurations across the time in transmission.

The final Chapter 7 presents the concluding remarks and possible ways to extending this work in the near future.

2. IEEE 802.11ah (Wi-Fi HaLow) amendment

Nowadays, billions of IoT devices are already deployed, IoT network communications have to support transmissions of the already connected devices and prepare for the upcoming 75 billion devices that are expected to be connected by 2025 [22] scenarios. These massive implementations of the IoT paradigm will bring changes to many aspects of our lives. The debate on which technology should lead this revolution has not been settled yet. Over the years, there were multiple contenders, while Wi-Fi seemed to be observing from the bench.

Taking into account the new world scenario for IoT communications, IEEE 802.11 WG released the IEEE 802.11ah standard or HaLow, as branded by the Wi-Fi Alliance. IEEE 802.11ah has been developed for supporting IoT applications and the challenges needed for those IoT networks, such as: large number of autonomous devices sending traffic simultaneously, low power consumption and long sleep periods; and large coverage range. Therefore, IEEE 802.11ah is the first approximation of IEEE 802.11 WG that can enable IoT specific features within thousands of stations operating at Sub 1 GHz Industrial, Scientific and Medical (ISM) frequency band. [23], [24],[25].

In the present chapter, the fundamentals for the IEEE 802.11ah IoT communications standard are going to be presented. In order to tackle the requirements of the IoT scenarios, enhancement on the PHY and MAC layer are explained in detail. Furthermore, a comparison of the main characteristics of IEEE 802.11ah and prior IEEE 802.11 amendments is made. Part of this chapter has been published in [19].

2.1 Overview of the IEEE 802.11ah amendment

IEEE 802.11ah standard aims to organize communications between various devices used in IoT applications such as smart grids, smart meters, smart houses, healthcare systems, and smart industry. In order to expose the key mechanisms of the upcoming IEEE 802.11ah amendment, the authors in [1] provide a comprehensive overview.

Similarly, in [26] authors detail the distinct features of IEEE 802.11ah. In [27], the authors highlight the importance of IEEE 802.11ah standard as one of the key enabling technology for low cost, energy efficient and massive deployment for IoT devices in future.

Furthermore, the authors evaluate maximum achieved throughput in three different Modulation and Coding Schemes (MCS) of IEEE 802.11ah using significant assumptions. Also, in [26], the authors show performance results for measurement data of IEEE 802.11ah in terms of rate and range. They compare IEEE 802.11ah with 802.11b and 802.11n for three indoor cases without taking into account outdoor scenario that is the most usable case for IEEE 802.11ah.

The work in [24] provides a comprehensive overview of IEEE 802.11ah. Furthermore, the authors summarize standardization procedures as well as the technical challenges expected in the adaptation of IEEE 802.11ah standard. In [28] , the authors define different innovative use cases for IEEE 802.11ah standard.

Among the proposed use cases, the authors highlight an interesting case where IEEE 802.11ah standard will be able to provide appropriate feature as a backhaul link to accommodate traffic exchange over long distances (i.e. leaf sensors and stream of camera images or surveillance videos).

2.2 Use cases

Some of the main challenges created by the IoT environment are the distinct scenarios that can be characterized in multiple ways according to the requirements of a single application. The amendment has been designed based on the smart sensors and meters case, the backhaul aggregation case that is illustrated in Figure 2, and the extended range hotspot and cellular offloading [28].

2.2.1 Smart sensor and meters

In this use case, the AP covers a high number of sensor devices. There are thousands of stations contending for the channel, operating at long transmission ranges, along with stationary mobility. The AP to station ratio is expected in the range of 1/6000. The most common scenarios are large indoor spaces and outdoor in urban, suburban, and rural environments. In these scenarios, devices typically send traffic of the order of 100 kbps of bit rate, consisting of short frames.

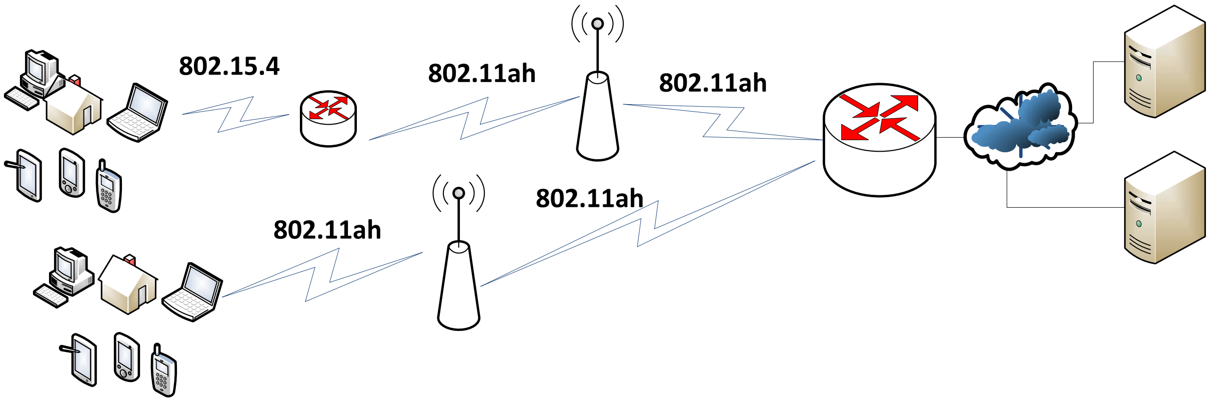


Figure 2. Backhaul Sensor Network

2.2.2 Backhaul aggregation and extended range hotspot

IEEE 802.15.4-based sensor devices show extended battery life; however, the transmission range and available data rates are very low (some kbps). Thus, a scenario in which IEEE 802.15.4 routers gather data from leaf devices (i.e. sensors) and forward information to servers using IEEE 802.11ah links results very attractive (cf. Figure 2). This use case is addressed to outdoor industrial and rural environments with lower than 1 Mbps of bit rate per station, along with stationary or low mobility devices. The AP to station ratio is of 10/500.

2.2.3 Extended range hotspot and cellular offloading

Both high throughput and long transmission range make below 1GHz (S1G) attractive for extending hotspot range and for traffic offloading in mobile networks, which is a significant issue for operators and vendors due to mobile traffic explosion.

IEEE 802.11ah will provide real additional value, especially in countries with wide available S1G spectrum (e.g. USA). This use case is addressed to outdoor use in urban and suburban environments with less than 20 Mbps of bit rate, along with pedestrian mobility.

IEEE 802.11ah shall consider traffic models for 802.11ah-specific applications such as web browsing with 256 kbps per link and a MAC service data units (MSDU) size of 1000 Bytes on Transmission Control Protocol (TCP), video/audio streaming with 100 kbps to 4 Mbps per link and an MSDU size of 512 Bytes on User Datagram Protocol (UDP), and audio streaming with 64 kbps to 256 kbps per link and an MSDU size of 418 Bytes (UDP). The AP to station ratio is 1/50.

2.3 Background: Legacy IEEE 802.11

One of the fundamental MAC operations in legacy IEEE 802.11 technologies is the use of a protocol defined as Distributed Coordination Function (DCF), which operates by using the carrier sense paradigm, with a backoff mechanism aiming to ensure the less probability of simultaneous transmissions attempts performed by multiple stations. Besides, the DCF mechanisms support transmissions in the presence of interferences operating over shared unlicensed bands.

Another remarkable protocol is the medium access mechanism “listen before talk type”, as is the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA); this aforementioned mechanism is used in 802.11 WLANs to handle collisions. Hence, CSMA/CA transmitter senses the media, waiting for an idle slot to start a new transmission by using the already defined algorithms, so, if the medium is detected busy (a busy state specifies ongoing transmission form other devices) the demanding device that wants access to the channel has to defer its transmission.

Therefore, the CSMA/CA was designed to reduce collision probability in the cases when multiple STAs shared the same channel, particularly at the most probable time that could happen collisions, this collision time happens when the medium becomes idle following a transmission. Both the CSMA/CA mechanism and a random backoff feature are used to minimize potential medium contention conflicts.

The CSMA/CA based on DCF protocol is a mechanism that is employed independently in each IEEE 802.11 station in a distributed method, typically in IEEE 802.11 WLANs is used the two-way handshake, where an acknowledgment (ACK) frame is transmitted by the receiver and the confirmation reception after a Short Interframe Space (SIFS). At this point, if an ACK is not received, this transmission is considered a collision by the transmitter.

Notice that MAC protocols with CSMA/CA are prone to have the hidden and exposed nodes problems. Hence, by using this technique, the collision probability is increased at the same rate as the number of stations. In consequence, in the case of communicating thousands of stations using this type of operation could be considered inadequate for the IoT scenarios. Thus, the IEEE 802.11ah must improve the efficiency to accomplish transmission on IoT environments.

In regard to the PHY layer, the OFDM is a remarkable transmission technique, it is a multiplexing technique where the available bandwidth is divided into multiple orthogonal frequency subcarriers. Therefore, OFDM uses a large number of carriers, transporting low bit rate data each one, for the above, and this technique resists the selective fading, interferences, and multipath effects, at the same time that provides spectral efficiency. Besides, MIMO is a technique that allows multiple transmitters and receivers to transfer more data to all of them at the same time, thus, improving the throughput.

The legacy IEEE 802.11 standard was originally developed for indoor home and office scenarios with recognized worldwide success. Nowadays, IEEE 802.11 can be considered as a ubiquitous technology, found in a wide range of consumer electronic devices, and used in heterogeneous scenarios. However, up until now, IEEE 802.11 has not shown a significant presence in the IoT market, without any specification focused on IoT and its singularities. Taking into account the near-future scenario for IoT communications, IEEE 802.11 WG aims to bridge the gap by introducing the new amendment IEEE 802.11ah.

2.4 Physical layer

This standard intends to modify the current IEEE 802.11 standard (at PHY and MAC) in order to extend it to operate S1G for ubiquitous access in a less interfered frequency band and to support a large number of associated stations within the network. Due to the deficiencies encountered in the scarce availability of sub 1 GHz bands, the physical layer modifications are intended to improve the spectral efficiency.

The physical layer of IEEE 802.11ah inherits its main characteristics from IEEE 802.11ac, but is adapted to operate at S1G frequency band. It is designed to operate by utilizing OFDM along with MIMO including MU-MIMO over the downlink. Additionally, it supports various MCSs (i.e. from MCS0 to MCS10).

IEEE 802.11ah introduces the novel MCS10, that is, an MCS with the particular characteristic to be more robust, it was developed to facilitate long-range transmission. Conversely, this MCS gives the lowest data rates of the standard, even though these data rates are enough for most of IoT applications. Further details are presented in subchapter 2.4.2

However, given limited capabilities and limited data transfer requirements for certain applications, high-order modulations, or even multiple streams are not likely to be widely supported or required for first Wi-Fi certifications. Besides the capabilities to work up to 16 MHz, it is expected that early commercial devices support up to 4 MHz in IEEE 802.11ah.

Table 1 highlights the key PHY layer characteristics of 802.11ah. In the following section, we expose the main physical layer amendments proposed for IEEE 802.11ah that substantiates its operation for IoT devices.

Table 1. PHY layer parameters for IEEE 802.11ah.

Parameter	Value	Parameter	Value
Carrier Frequency (GHz)	Below 1	**Bandwidth (MHz)**	1, 2, 4, 8, 16
Number of data/total subcarriers per OFDM symbol	24/32 (1 MHz) 52/64 (2 MHz) 108/124 (4 MHz) 234/256 (8 MHz) 468/512 (16 MHz)	**Preamble type**	Short (1 MHz). Long (2, 4, 8, 16 MHz)
Number of space time streams (SS)	1 – 4	**Subcarrier spacing (KHz)**	31.25

2.4.1 *Available spectrum*

Due to limited availability of license-exempt spectrum in 1 GHz and owing to the intention of enabling Wi-Fi devices to gain access of channel for short-term transmissions, the basic channel width utilized in IEEE 802.11ah is 1 MHz. However, channel bonding can be applied to bond two or more adjacent available spectrum in order to create up to 16 MHz-wide channels (cf. Tables 1 and 2), and so to provide higher data throughputs.

2.4.2 *Transmission modes*

IEEE 802.11ah supports mandatory and global interoperability of 1 MHz and 2 MHz in order to allow different IoT use cases to operate (as mentioned in subchapter 2.2). Furthermore, the PHY layer can be categorize by its transmission mode of 1 MHz and 2 MHz (and above) of channel bandwidth, respectively. Table 3 highlights the available 1, 2, 4, 8, 16 MHz channels count allocated for IEEE 802.11ah within different countries.

Table 2. Comparison of IEEE 802.11 standards.

	802.11 a/g	**802.11n**	**802.11ac**	**802.11ah**
Antenna Configuration	1×1 SISO	4×4 MIMO	8×8 MIMO	4×4 MIMO
Highest Order Modulation	BPSK to 64-QAM	BPSK to 64-QAM	BPSK to 256-QAM	BPSK to 256-QAM
Channel Bandwidth	5, 10 MHz (11a), 20 MHz (11a/g)	20 and 40 MHz mode	20, 40, 80 and 160 MHz	1, 2, 4, 8, and 16 MHz
FFT Size	64	64 (20MHz) and 128 (40MHz)	64, 128, 256 and 512	32, 64, 128, 256 and 512
Year Approved	1999/2003	2009	2014	2016
Min and Max Bit rate	6 and 54 Mbps	6.5 and 600 Mbps	6.5 and 6933.3 Mbps	0.15 and 86 Mbps
Maximum number of supported stations	2007	2007	2007	About 8000

1MHz channel bandwidth

The main objective for this mode is to extend the range of operation and thus to facilitate IoT devices (placed at greater distances) that require low data rates. This aforementioned requirement is fulfilled by IEEE 802.11ah standard by using a new MCS index (called MCS10), only available in 1 MHz transmission mode. This scheme is effectively MCS0 with an addition of 2x repetition (where OFDM symbols repetition is performed with subcarrier permutation).

2MHz (and above) channel bandwidth

Apart from 1 MHz, IEEE 802.11ah standard also supports 2, 4, 8, and 16 MHz where the PHY layer is effectively 10 times a down-clocked version of IEEE 802.11ac, i.e. OFDM symbol in IEEE802.11ah standard is 10 times longer than IEEE 802.11ac.

Hence, by increasing the symbol duration, both the required data rate and the bandwidth are reduced. On the other hand, the transmission becomes more robust against the negative effects of multipath propagation.

Table 3. 1, 2, 4, 8 and 16 MHz bands allocated by different countries for IEEE 802.11ah.

Regulatory Domain	Europe	United States	Japan	China	Korea	Singapore	Australia & New Zealand
Number of 1 MHz channels	5	26	11	24	6	8	13
2 MHz channels	2	13	N/A	4	3	3	6
4 MHz channels	N/A	6	N/A	2	1	1	3
8 MHz channels	N/A	3	N/A	1	N/A	N/A	1
16 MHz channels	N/A	1	N/A	N/A	N/A	N/A	N/A

2.5 MAC layer

The MAC layer of IEEE 802.11ah includes improvements address specifically the requirements of long-range communication and IoT use cases. Furthermore, the MAC layer is optimized to encompass a low power mode of operation and methods to support a larger number of devices over a single cell. In the following section, we describe in detail the MAC layer enhancements proposed by the IEEE 802.11ah.

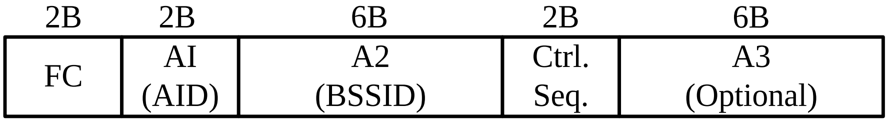
2.5.1 Compact frame format to increase throughput.

IEEE 802.11ah stations in most of the use cases are expected to operate at low data rates and intend to exchange small data frames. Specifically, for IoT devices, the overhead associated with frame headers (e.g. MAC header) may be considerable when compared to the size of the payload. In order to counter overheads and to improve the efficiency and thus, increase the overall throughput, reduce the energy per frame and reduce the resource utilization, the MAC design of IEEE 802.11ah introduces compact frame formats.

a. Short MAC header format

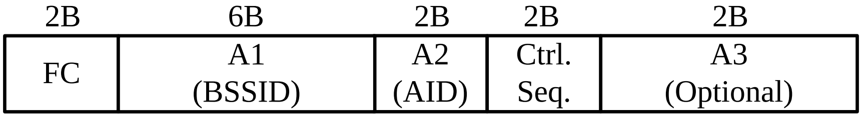
The significant change in the new header design is the inclusion of only two mandatory address fields as compared to four address fields present in the legacy MAC header. The QoS and HT fields are shifted into the SIG field in PHY header and the Duration/ID field is removed (because the virtual carrier sensing is not used while utilizing short MAC header). Thus, the short MAC header is able to reduce the overhead from 30 Bytes to 18 Bytes (cf. Figure 3).

This enhancement can be highlighted for instance, on a 100 Bytes data frame, according to the transmission with the IEEE 802.11 legacy mode, the overhead in the transmission is close to 25%, whereas with the header reduction implemented in IEEE 802.11ah that overhead is reduced to 15%.



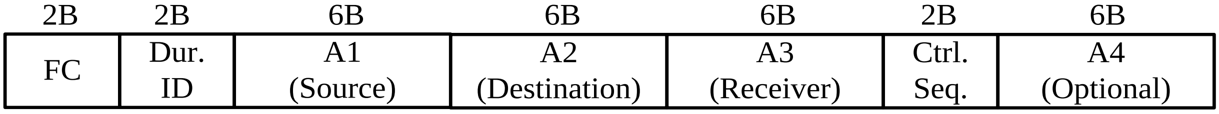
2B	2B	6B	2B	6B
FC	AI (AID)	A2 (BSSID)	Ctrl. Seq.	A3 (Optional)

IEEE 802.11ah downlink MAC header format.



2B	6B	2B	2B	2B
FC	A1 (BSSID)	A2 (AID)	Ctrl. Seq.	A3 (Optional)

IEEE 802.11ah uplink MAC header format.



2B	2B	6B	6B	6B	2B	6B
FC	Dur. ID	A1 (Source)	A2 (Destination)	A3 (Receiver)	Ctrl. Seq.	A4 (Optional)

IEEE 802.11 legacy MAC header.

Figure 3. MAC header comparison IEEE 802.11 legacy vs IEEE 802.11ah

b. Short MAC control frames

To reduce the overhead induced by control frames, the IEEE 802.11ah utilizes Null Data Packets (NDP), which contain PHY header without any data. Different control frames (e.g. Clear to Send (CTS), ACK, Power Save-Polling (PS-Poll) frame, etc.) are substituted by NDP frames to reduce protocol overhead.

2.5.2 Restricting the effects of fading.

In order to tackle time and frequency selective fading over narrowband channels, the IEEE 802.11ah implements a new feature called Sub-Channel Selective Transmission (SST). This scheme allows stations to switch rapidly among a specific set of sub-channels during transmission, where the channel is selected based on measurements indicating short-term fading conditions and/or the level of interference from other stations.

2.5.3 Large number of stations with hierarchical grouping.

IEEE 802.11 defines that, during the association phase, an AP assigns an Association Identifier (AID) to each STA. For the legacy version, the AID determines the maximum number of stations (2007), which is mapped according to the limited length of the partial virtual map of the Traffic Indication Map (TIM) Information Element (IE). Inside the IE, each bit indicates the correlated STA's AID.

For increasing the number of supported stations, IEEE 802.11ah utilizes a novel hierarchical AID structure.

2b	3b	5b	3b
Page ID	Block Index	Sub-block Index	Station index in sub-block

Figure 4. Structure of AID in IEEE 802.11ah MAC.

The AID assigned by the AP during association consists of 13 bits and thus the number of stations that it can associate is up to 8,191. AID structure consists of four hierarchical levels as page, block, sub-block, and station's index in sub-block (cf. Figure 4). IEEE 802.11ah utilizes the aforementioned structure to group stations based on similar characteristics (e.g. traffic pattern, location, battery level among others).

2.5.4 Channel access.

Apart from supporting the existing Enhanced Distributed Coordination Access (EDCA), the IEEE 802.11ah defines a new contention-free channel access period called RAW. This access method is designed to reduce collisions by improving channel efficiency. The AP coordinates the uplink channel access of the stations by defining RAW time intervals, in which specific classes of devices are given exclusive access of the shared medium by dividing stations into different groups and restricting channel access only to a group at a particular time period, the RAW feature will be more deeply exposed in subchapter 6.1

Figure 5. Speed Frame Exchange method

Efficiency is also enhanced in IEEE 802.11ah by means of speed frame exchange (SPF) method, which enables an AP and non-AP station to exchange a sequence of uplink and downlink frames during a reserved Transmit Opportunity (TxOP). Aiming to reduce contention, in this mechanism the client station contents of the shared medium, waking up afterward sleep. The client sends data to AP, then the AP reply with a short interframe gap, which enables a station to go sleep mode at the moment. For that reason, SPF saves time used in two-way acknowledgments and longer inter-frame spaces in the station side. This operation enhances the battery life of stations.

Figure 5 depicts the Speed Frame Exchange method, in which, PS-Poll is a legacy PS mechanism that allows the STA to inform the AP that is going to doze-mode until the next beacon. In addition, the probe delay is a part of the handoff mechanism, which includes the probe, authentication, and re-association delay times.

2.5.5 BSS color

For proper operation in ultra-dense WLAN networks, such as IoT scenarios, the standard includes a scheme to increase throughput by assigning a specific color to each Basic Service Set (BSS) designated in the physical layer LSIG field. Consequently, reduces the collisions or interference caused by neighboring BSS and increments the transmission opportunities in the network.

Hence, the BSS color is used to distinguish transmissions from distinct networks. If the transmissions belong to the same color, it is considered an intra-BSS frame transmission. Oppositely, if the detected frame belongs to another color/network, the transmission is considered as an inter-BSS frame from an overlapping BSS. This technique could improve throughput on IoT scenarios (cf. Figure 6).

Notice that the IEEE 802.11ah amendment introduced this mechanism that also performs a notable improvement in the IEEE 802.11ax standard [29].

Figure 6. BSS Color

2.5.6 Power saving mode.

In order to support numerous IoT devices, the TGah has placed paramount importance on developing and enhancing power saving mechanisms. As mentioned before, adding mechanisms like speed frame exchange method and MAC layer enhancements and other new features (headers reduction mechanism, control frame reductions, reduced contention between STAs by using RAW, etc.) provide, as a consequence, an improved power-saving in the IEEE 802.11ah.

In addition, instead of using same Max idle period (time during which a non-AP station can refrain from transmitting to the AP before being disassociated due to inactivity) for all nodes (i.e. 18.64 hrs.), IEEE 802.11ah aims to utilize different periods for different devices (i.e. from 18.64 hrs. to 186 hrs.). Furthermore, IEEE 802.11ah enables a station to inform the AP about the duration of the time it intends to remain in sleep mode. During the sleep mode, the station will not listen to beacons, and then it will be able to reduce its power consumption.

Aside from STAs, which regularly wake-up by the TIM information, the IEEE 802.11 created a non-TIM category for STAs. These aforementioned non-TIM STAs are characterized by the longer doze periods and without beacons, the non-TIM STA negotiate a transmission time allocated in a periodic RAW.

Moreover, to ensure minimum energy consumption, IEEE 802.11ah defined the unscheduled stations, which are STAs that do not need to listen to any beacons as the non-TIM STAs do (including inside any RAW). They can send a poll frame to the AP, asking for instantaneous access to the channel, where the response frame gives to them an interval during which unscheduled STAs are allowed to access the channel. Typically, unscheduled STAs are the ones that are sporadically joining the network.

Furthermore, the TWT mechanism allows an AP to set up a specific time (or set of times) for each STA to access the medium. Notice that the TWT that an AP assigns can be aperiodic or periodic. However, distinct STAs can also share the same TWT, and in such cases, the Networks Allocation Vector (NAV) procedure is the one in charge to avoid collisions, by doing this, the TWT is able to reduce signaling overhead. As a result of the use of this mechanism, we can have a considerable improvement in energy saving.

2.6 Mechanism reused from legacy IEEE 802.11

This section introduces features that are reused from the IEEE 802.11 legacy by the IEEE 802.11ah specification, mechanisms that include the principal PHY and MAC features that can be shared between them. On the other hand, features that are unique for IEEE 802.11ah have been discussed in subchapter 2.4 and 2.5.

2.6.1 Backwards compatibility

Unfortunately, IEEE 802.11ah is not going to be backward compatible with other legacy standards due to the frequency band that operates, focusing on the IoT applications. Besides, from the IEEE 802.11a standard up to IEEE 802.11ac standards, the IEEE 802.11 standards were backward compatible with previous amendments.

2.6.2 Traffic indication map

The standard 802.11ah includes communication between the AP and a group of STAs to share information about which is going to be the next to access the medium. TIM and Delivery TIM (DTIM) indicate the presence of multicast frames, this method requires waking up and listening to beacons for the STAs that are part of a particular TIM (cf. Figure 7).

On the other hand, the beacon frame is the one in charge to communicate power savings to doze stations and inform each one of them about the presence of traffic that belongs to them on the AP side. At this point, the beacon frame is sent in a bitmap form and each bit represents the AID of stations. [30]. The current technique is available for the entire main IEEE 802.11 standard (IEEE 802.11-2007, IEEE 802.11n, IEEE 802.11ac, and the IEEE 802.11ah).

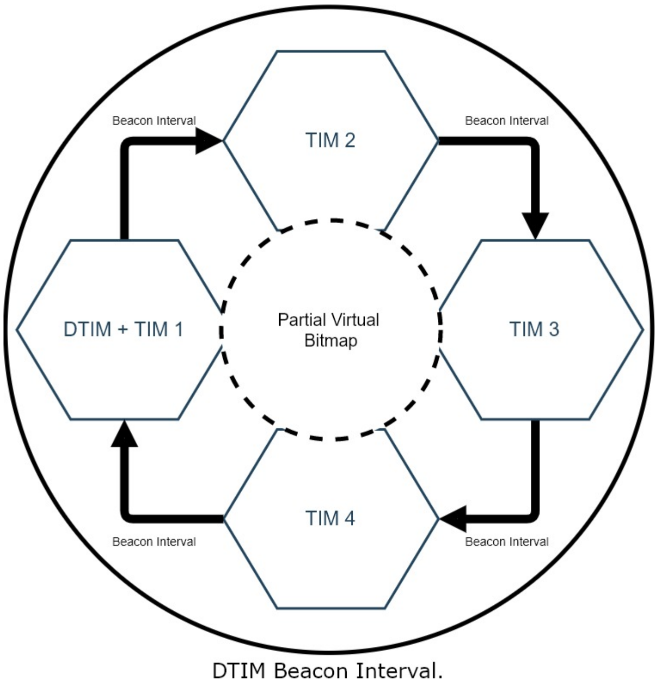


Figure 7. TIM mechanism

2.6.3 Hybrid Coordination Function

Hybrid Coordination Function (HCF) is a mechanism that enhanced the contention based on DCF and includes QoS awareness. It combines the aspects of both the contention-based DCF and controlled channel access-based Point Coordination Function (PCF), which is a QoS aware MAC protocol that includes an appropriate service differentiation mechanism. HCF defines two methods of channel access: enhanced DCF (EDCF) and HCF Controlled Channel Access (HCCA).

2.6.3.1 HCCA

This technique is included in IEEE 802.11-2007, IEEE 802.11n, and IEEE 802.11ah. To determine which station is able to start a data transmission, HCCA uses a polling scheme, similar to PCF. In addition, this technique uses the previous polling mechanism on QoS-enabled stations to assign TxOP [31].

2.6.3.2 EDCA

An extension of the DCF mechanism, EDCA tries to classify the traffic by distinct categories, each category with different priority, aiming to implement a service differentiation. In addition to this feature a traffic class can statistically reduce its transmission delay using the Access Category (AC) noticing that has higher priority in a shared channel contention, aiming to make itself a high priority traffic class [32]. Similarly, IEEE 802.11 standard (IEEE 802.11-2007, IEEE 802.11n, IEEE 802.11ac, and the IEEE 802.11ah) includes this technique as a part of each standard.

2.6.4 TxOP

A period of time during which a station is allowed to transmit multiple frames (not requiring a channel access for all the frames) while accessing the channel, notice that this technique is already defined in the IEEE 802.11-2007 standard.

RD protocol

The Reverse Direction (RD) protocol is included as a part of the IEEE 802.11n, IEEE 802.11ac and in the IEEE 802.11ah standards. RD is an improved version of TxOP and consists of a reverse mechanism that enables the allocation of the TxOP unused time to share by the holder of the TxOP with its receiver, thus improving the channel utilization and reverse traffic flows.

BDT

As expected, the new IEEE 802.11ah standard introduces a new technique in TxOP, where a non-AP station can improve the energy savings, by introducing the bi-directional TxOP (BDT). The fundamentals of BDT are a combination of reception and transmission frames in a single TxOP, where the required frame exchange is reduced, and enabling improvements in the battery lifetime. Additionally, this technique helps in the use of contention-based channel access efficiency.

It seems that RD and BDT are similar techniques, but the mode of operation of BDT allows operating during the exchange procedure without needing to acknowledge explicitly the received frame by means of ACK frames. Furthermore, BDT enhances energy savings due to the use of the doze- mode enablement at the moment the communication with the AP [33].

2.6.5 Frame aggregation

IEEE 802.11n, IEEE 802.11ac, and IEEE 802.11ah standards include the frame aggregation mechanism, combining multiple data frames into one larger transmission that carries the aforementioned small frames within one single channel access.

Despite the benefits of the network efficiency and better throughputs, we have improvement by reducing the overhead caused by preambles or frames headers and reducing the backoff period in success transmissions. This mechanism could also increase the waiting times for other transmissions to access the channel since they have to wait their turn to access the medium.

Frame aggregation in IEEE 802.11n employs two different modes of operation. The MSDU at the top of the MAC called A-MSDU and the second in the bottom of the MAC, called MAC Protocol Data Units A-MPDU.

A-MSDU maximum length is 7395 Bytes. Recall that the transmission overhead is reduced by the frame aggregation. Nevertheless, noisy environments can affect the efficiency of the A-MSDU, where an entire A-MSDU can be rejected by only one corrupted MSDU. Note that the A-MSDU is completed when the oldest frame reaches a pre-assigned maximum delay or when reaches the maximum A-MSDU threshold size.

A-MPDU maximum length is 65535 Bytes, and additionally, a unique STA must be the recipient of all the MPDUs belonging to an A-MPDU. Please note that the maximum number of frames of MPDUs in one A-MPDU is 64 frames. In addition, the A-MPDU gives its own MAC header and Cyclic Redundancy Check (CRC) to each MPDU that is part of it. Compared to A-MSDU, this adds overhead to the transmission, although it provides a more reliable transmission.

Concerning IEEE 802.11ac and IEEE 802.11ah, frame aggregation methods are used, furthermore, the frame aggregation technique has a maximum size of an A-MPDU that is increased for IEEE 802.11ac up to 1,048.575 Bytes [34].

In addition, the Multi-User (MU) aggregation technique is a mechanism that supports the aggregation of MPDUs addressed to different receivers into a single Protocol Data Unit (PDU). In order to aggregate and achieve optimal spectrum efficiency, the AP selects stations with similar conditions [35] and it’s only for transmission from an AP to multiple STAs (i.e. only in downlink direction).

2.6.6 Block ACK

A mechanism that enables transmission of a single ACK frame as a response to a series of frames received by the station, enabling an enhanced airtime efficiency as compared to traditional ACK, where acknowledgment frames are sent for every successfully received unicast frame.

In the case of the IEEE 802.11n, this technique is enhanced by supporting multiple MPDUs in an A-MPDU. In the case that one or more MPDUs have been received incorrectly, the Block ACK will not include an acknowledgment for them and, therefore, the sender will just retransmit those missing MPDUs instead of the whole A-MPDU.

Additionally, for the case of IEEE 802.11ah, the receiver includes the preferred MCS and the bandwidth information in the Block ACK. Whilst, IEEE 802.11 adds a fragment Block ACK procedure, where the fragments obtained in a fragmented MSDU can be followed by the regular Block ACK procedure or can be acknowledged by the immediate ACK, as a result, the receiver responds with NDP Block ACK frames[36].

2.6.7 Multi User MIMO (MU-MIMO)

MU-MIMO is technique introduced by the IEEE 802.11ac standard. This technique consists of one single transmission to multiple stations overlapped in the same time-frequency resources and aiming to exploit the propagation of channel by the spatial diversity. MU-MIMO feature is designed to operate over the downlink in Wi-Fi HaLow.

In order for the receiver to be able to establish if the data payload is single or multi-user. Notice, that the Group-ID field is the one in charge to notify a MU-MIMO transmission. Thus, this is accomplished when a receiving node identifies whether it is targeted in the next MU-MIMO transmission.

Moreover, MU users can be part of the same Group-ID, where the stations that belong to that Group-ID, are scheduled for a joint transmission by the MU-MIMO beamforming mechanism [37]. This technique allows an AP to interchange data with multiple STAs simultaneously (data inputs and outputs) aiming with this to decrease the time each STA has to wait for transmission, thus, improving the throughput.

3. Performance evaluation of IEEE 802.11ah amendment

After exposing the main characteristics of the IEEE 802.11ah in Chapter 2, such as the use-cases based on Wi-Fi HaLow and the PHY and MAC layers' enhancements of the IEEE 802.11ah standard. As a part of the research developed on this thesis, in the present chapter, we introduce a comparison between IEEE 802.11ah and 802.11(a, n, ac) amendments in terms of throughput and transmission range.

As well, we will expose the channel model used in this evaluation, in addition to the path loss models. This scenario consists of a radio link between a transmitter and a receiver, i.e. there is no contention with other stations, and the retransmissions are only due to bit errors caused by noise. Finally, we present the results obtained in this evaluation.

In [28], the authors define different innovative use cases for the IEEE 802.11ah standard. Among the proposed use cases, the authors highlight an interesting case where the IEEE 802.11ah standard would be able to provide appropriate features as a backhaul link to accommodate traffic exchange over long distances (i.e. leaf sensors and streams of camera images or surveillance videos). We focus our performance evaluation presented in this chapter in this backhaul link scenario. In [25] the authors evaluate maximum achieved throughput in three different MCS of IEEE 802.11ah using significant assumptions.

Also in [26], the authors show performance results for measurement data of IEEE 802.11ah in terms of rate and range. They compare IEEE 802.11ah with 802.11b and 802.11n for three indoor cases, however, without taking into account outdoor scenarios, which are the most usable cases for IEEE 802.11ah (in our current work, we include comparison between both indoor and outdoor use cases). Notice that part of this work has been published in [19].

3.1 Channel and pathloss models

We consider the pathloss models chosen by TGah [38] as follows:

Macro deployment: outdoor scenario with antenna height of 15 m above rooftop:

$$PL = 8 + 37.6log10(d) \tag{1}$$

where d corresponds to the distance in meters between transmitter and receiver, and radio frequency carrier is 900 MHz. For other frequencies, a correction factor of $21\log_{10}$ (*f/900 MHz*) should be applied.

Pico/hot zone deployment: outdoor scenario with antenna placed at rooftop:

$$PL = 23.3 + 36.7\log(d) \tag{2}$$

where the same conditions regarding distance and frequency as in Eq. (1) are applied.

TGah indoor path loss model: it is modelled by directly scaling down the frequency operations of the TGn path loss model. It consists of the free space loss model (slope of 2) up to a breakpoint distance (d_{BP}), and employs a slope of 3.5 after the breakpoint. We consider the large indoor open space scenario with non-line-of-sight (NLoS) conditions (Model C with d_{BP} of 5 m), and with line-of-sight (LoS) conditions (Model D with d_{BP} of 10 m). Both indoor channel models would correspond to a factory/warehouse type of environment.

$$L(d) = \begin{cases} L_{FS}(d) = 20log_{10}\left(\frac{4\pi f_c}{c}\right) \text{ d } \le d_{BP} & (3) \\ L_{FS}(d_{BP}) + 35log_{10}\left(\frac{d}{d_{BP}}\right) \text{ d} > d_{BP} & (4) \end{cases}$$

where d corresponds to the distance in meters between transmitter and receiver, fc is the center carrier frequency in MHz and c the speed of light in m/s. Note that TGah indoor channel propagation loss model was amended according to [21].

3.2 Throughput and coverage range analysis in error prone scenarios

In this subchapter we analyze and evaluate the throughput and the coverage range of the IEEE 802.11ah against the IEEE 802.11a, IEEE 802.11n and IEEE 802.11ac including the Packet Error Rate characteristic. It is worth to mention that we will compare them by using the most robust MCS.

3.2.1 Throughput analytical model

Initially, we consider ideal transmission conditions, aiming to obtain the throughput in saturation reached by the different technologies tested. Hence, we follow the throughput expression *S* in Mbps used in [39]:

$$S = \frac{L_{data} \times 8}{T_{message}} \tag{5}$$

where L_{data} corresponds to the payload size and $T_{message}$ is computed as:

$$T_{message} = DIFS + T_{DATA} + SIFS + T_{ACK} + 2\delta \tag{6}$$

DIFS and *SIFS* are given in Table 4, δ is the propagation delay, T_{ACK} corresponds to the duration of an ACK frame and T_{DATA} represents the transmission time of a data frame, which depends mainly on the size of the payload and the PHY rate. T_{DATA} and T_{ACK} computation also depend on the IEEE 802.11 amendment used in the transmission. T_{DATA} is computed according to equation (7). Frame sizes are given in bytes and frame durations in µs.

$$T_{DATA} = T_{Preamble\&Header} + \left(T_{Sym} * N_{sym}\right) \tag{7}$$

where T_{Sym} is the duration of a symbol and N_{sym} is the number of symbols of the PLCP Service Data Unit (PSDU). N_{sym} for the most robust MCS of the different standards (i.e. IEEE 802.11ah at 0.15 Mbps, 6.5 Mbps for IEEE 802.11ac and IEEE 802.11n and IEEE 802.11a at 6 Mbps) is given in equations (8) to (10).

$N_{\frac{\frac{symAC}{N2.4}}{N5}}$ calculations are the same as in equation (19) with constant value of 22 instead of 14, corresponding to the number of bits in the service field plus the multiplication of the number of tail bits per binary convolutional code (BCC) encoder and the number of BCC encoders. Also, the denominator is changed from 6 to 26, which corresponds to the number of bits per symbol of the most reliable modulation,

$$N_{symAH} = \left\lceil \frac{14 + (L_{Header} + L_{data}) * 8}{6} \right\rceil \tag{8}$$

$$N_{\frac{symAC}{\frac{N2.4}{N5}}} = \left\lceil \frac{22 + (L_{header} + L_{data}) * 8}{26} \right\rceil \tag{9}$$

$$N_{symA} = \left\lceil \frac{22 + (L_{Header} + L_{data}) * 8}{24} \right\rceil \tag{10}$$

Table 4. MAC/PHY Parameters.

Specification	**SIFS (µs)**	**DIFS (µs)**	**$T_{Preamble \& Header}$ (µs)**	**MAC&LLC Header Size (Bytes)**	**Signal Extension (µs)**	**T_{Sym} (µs)**	**T_{Slot} (µs)**	**CW_{min}**	**CW_{max}**
802.11ah CBW 1 MHz	160	264	560	26 (Short) 36 (Long)	n/a	40 (long GI) 36 (short GI)	52	15	1023
802.11ah Short Preamble CBW 2, 4, 8 and 16 MHz	160	264	240	26 (Short) 36 (Long)	n/a	40 (long GI) 36 (short GI)	52	15	1023
802.11ah Long Preamble CBW 2, 4, 8 and 16 MHz	160	264	320	26 (Short) 36 (Long)	n/a	40 (long GI) 36 (short GI)	52	15	1023
802.11ac	16	34	40	36	n/a	4	9	15	1023
802.11n 2.4 GHz	10	28	36	36	6	4	9	15	1023
802.11n 5 GHz	16	34	36	36	0	4	9	15	1023

T_{ACK} calculation employs previously exposed T_{DATA} equations with 14 Bytes instead of L_{header} + L_{data}. Moreover, in case NDP is utilized as an acknowledgement, there is no data field and the number of symbols (N_{sym}) is equal to 0.

Note that all previous expressions are presented without taking into account reception errors. Subsequently, we consider an error-prone scenario and compute throughput expression (in Mbps) as follows:

$$S = \frac{(1 - PER)L_{data} \times 8}{T_{message}} \tag{11}$$

where *PER* corresponds to Packet Error Rate and its value depends on the MCS used and the number of transmitted bits. On the other hand, the presence of errors causes retransmissions and therefore, the effect of IEEE 802.11 exponentially increasing backoff mechanism should now be considered in the expression of $T_{message}$:

$$T_{message} = DIFS + T_{BACKOFF} + T_{DATA} + SIFS + T_{ACK} + 2\delta \tag{12}$$

$T_{BACKOFF}$ consists in the total time spent in backoff state due to data frame retransmissions and is computed as follows [39]:

$$T_{BACKOFF} = \sum_{i=1}^{\infty} PDR(i) T_{backoff}(i) \tag{13}$$

where *i* is the number of retransmissions, *PDR(i)* is the probability of a successful reception after *i* retransmissions, and $T_{backoff}(i)$ is the average backoff time after *i* consecutive retransmissions of the same frame. Note that, the first time a frame is transmitted, no backoff is employed.

A successful transmission requires that neither the data frame nor the ACK are received with errors. Given that, the ACK frame is shorter and that it is sent using the most reliable modulation, we consider *PER* corresponding to ACK frames negligible. Then *PDR(i)* is given by:

$$PDR(i) = (1 - PER) * PER^{i} \tag{14}$$

$T_{backoff}(i)$ follows next expression[39]:

$$T_{backoff}(i) = \begin{cases} \frac{2^{i-1}(CW_{min} + 1) - 1}{2} T_{Slot} & , 1 \leq i < m \quad (15) \\ \frac{CW_{max}}{2} T_{Slot} & , i \geq m \quad (16) \end{cases}$$

where m is the maximum number of backoff stages and corresponds to 6 (i.e. $CW_{max} = 2^6 CW_{min}$). CW_{min}, CW_{max} and T_{Slot} are all standard-dependent parameters (cf. Table 4). For each retransmission, the range of values that can be given to $T_{backoff}(i)$ is doubled until CW_{max} is reached.

For throughput computation including Aggregate MAC Protocol Data Units (A-MPDUs), we consider following expressions:

$$S = \frac{(1 - PER)L_{data} \times 8 \times K}{T_{message}} \tag{17}$$

$$T_{message} = DIFS + T_{BACKOFF} + T_{DATA} + SIFS + T_{BA} + 2\delta \tag{18}$$

where T_{BA} corresponds to the duration of an Block ACK frame and T_{DATA} represents the transmission time of A-MPDU frame, which depends mainly on the size of the payload and on the PHY rate. T_{DATA} and T_{BA} computation also depends on the IEEE 802.11 amendment used in the transmission. Observe that K corresponds to the number of aggregated data frames.

Note that now the number of symbols N_{sym} is as follows.

$$N_{symAH} \quad = \left\lceil \frac{8*K*(L_{Header}+L_{data})+14+(K-1)*(L_{deli}*8)}{6} \right\rceil \tag{19}$$

$$N_{\frac{symAC}{\frac{N2.4}{N5}}} = \left\lceil \frac{8*K*(L_{Header}+L_{data})+22+(K-1)*(L_{deli}*8)}{26} \right\rceil \tag{20}$$

L_{deli} is the size of the delimiter between aggregated frames (4 Bytes). T_{BA} calculation employs previously exposed T_{DATA} equations but a frame of 32 Bytes is considered instead of $L_{Header} + L_{data}$.

3.2.2 Evaluation and results

After describing in detail, the analytical model, we highlight in the subchapter the results obtained on the evaluation. We consider the different pathloss models given in Section 3.1 for the range comparison, and follow the expressions given in Section 3.2 to compare the expected throughput for different IEEE 802.11 technologies.

For each of the technologies studied (IEEE 802.11ah/ac/n/a), we use the PHY configuration providing the longest range; that is, we select the most reliable MCS with the narrowest possible bandwidth (lowest sensitivity required), and we set the maximum transmitted power allowed for each band (cf. Table 5).

Table 5. PHY configuration for most robust links[1].

Specification	802.11ah	802.11ac	802.11n	802.11a
Frequency (GHz)	0.9	5.15, 5.45	2.4	5.15, 5.45
Ptx (mW)	1000	200, 1000	100	200, 1000
Sensitivity (dBm)	-98	-82	-82	-88
Bandwidth (MHz)	1	20	20	5
Modulation	BPSK	BPSK	BPSK	BPSK
Coding rate	1/2 with 2x rep.	1/2	1/2	1/2
Bit rate (Mb/s)	0.15	6.5	6.5	1.5
Long guard interval (ns)	8000	800	800	800

The results are given in Table 6. IEEE 802.11ah benefits from a lower frequency band, incurring in less propagation losses, a narrower bandwidth, improving power spectral density, and a more robust coding scheme. For these reasons, IEEE 802.11ah has the widest coverage. In all cases, IEEE 802.11ah coverage range shows, at least, a fivefold increase with respect to IEEE 802.11a (second-best range), and more than ten times the range provided by IEEE 802.11n in the 2.4 GHz band (worst case scenario).

None of the indoor scenarios considered in the IEEE 802.11ah use case set (e.g. factory, warehouse, open office, etc.) will require such a long-range; in those cases, the increased range offered by IEEE 802.11ah may not compensate for the sacrifice in throughput, as explained next. Note that in Eq. (3) and (4), it is not considered the effect of walls. Also, note that we do not consider the gain of the spatial diversity techniques enabled by MIMO technology. Those techniques could increase the range of IEEE 802.11n/ac/ah between 10 and 30 m, depending on the scenario and the antenna configuration.

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[1] Note that the IEEE 802.11 standard provides support for the half-clocked and quarter-clocked operation (i.e. 10 and 5 MHz) only in Clause 18 (11a).

Table 6. Maximum coverage range.

Specification	802.11ah	802.11ac	802.11n	802.11a
Frequency (GHz)	0.9	5.15, 5.45	2.4	5.15, 5.45
Maximum Distance (meters)				
Macro Deployment	1561	151,221	191	211,311
Pico-Hot zone	721	65,93	81	91,141
Indoor C	1138	94,142	118	140,211
Indoor D	1531	125,191	158	185,283

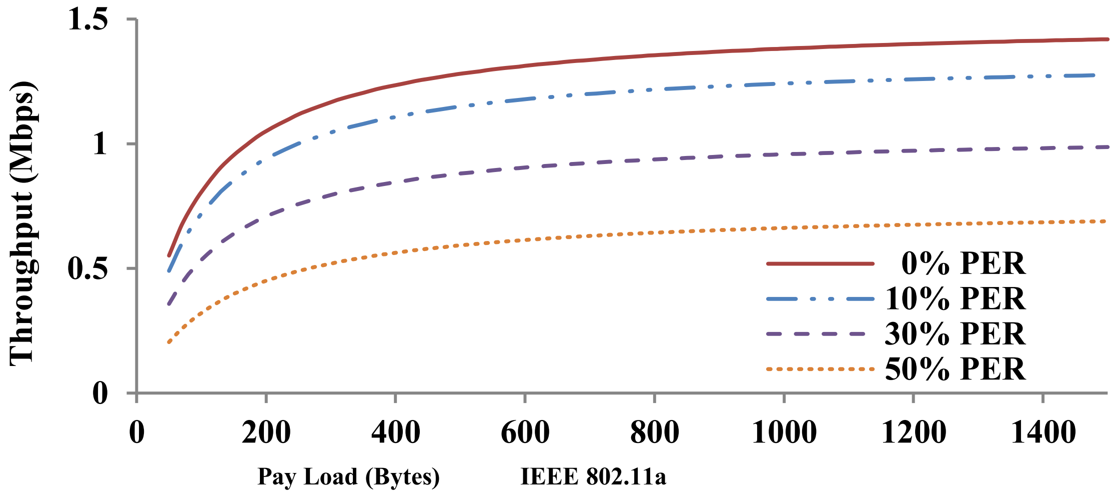

Figure 8. Throughput vs Payload size for IEEE 802.11a.

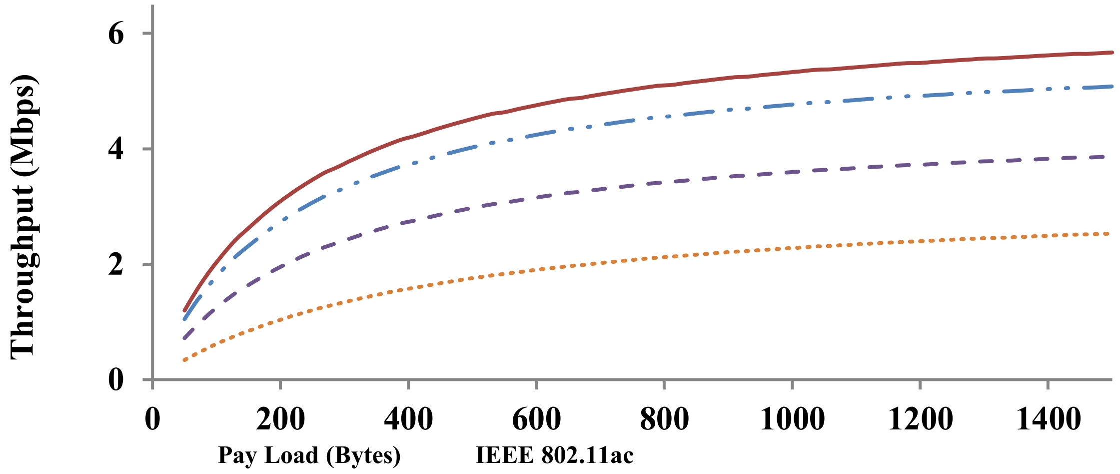

Figure 9. Throughput vs Payload size for IEEE 802.11ac.

Next, in Figures 8 to 10, we show the throughput that could be achieved between a single transmitter and receiver pair at the limits of their coverage. Note, that Figures 9 to 12 follow the same lines colors, and nomenclature as shown in Figure 8. We show throughput values for different payload sizes (between 12 and 1500 Bytes) and different PER. Sensitivity values are given in Table 5 guarantee PER < 10%, but a link can be usable at higher error ratios; hence, we provide throughput values for PER between 0 and 50%.

Logically, increasing the payload reduces the overhead, enabling higher effective throughput. Note that the use of aggregation would increase IEEE 802.11n/ac/ah (cf. Figures 10 and 11) efficiency even further, closer to the limit imposed by the PHY rate (cf. Table 5). However, the impact of aggregation is limited since, using the slowest modulations; we cannot take advantage of a high level of aggregation without exceeding the maximum duration allowed for a frame at the physical layer. Also, note that, since the scenarios of interest are outdoors or open indoor spaces, we considered the long guard interval in all cases.

Figure 8 shows the evolution of IEEE 802.11a operating at PHY of 1.5 Mbps. It provides a maximum throughput of 1.43 Mbps (no errors and payload of 1500 Bytes), which is more than halved (0.70 Mbps) when PER increases to 50%. With payload of 50 Bytes, the maximum throughput is reduced to 0.60 Mbps with no errors, and 0.22 Mbps with PER of 50%.

Given that the differences between the throughput obtained by IEEE 802.11n and 11ac are minimal at the 6.5 Mbps rate, we only show results for IEEE 802.11ac in Figure 9. Besides, for both IEEE 802.11ac and 11n, the maximum throughput with 1500 Bytes payload is around 5.6 Mbps, which is reduced to 2.5 Mbps when the PER is 50%. In the other extreme, i.e. with a payload size of 12 Bytes, the throughput obtained with PER = 50% is less than one-fourth of the throughput with no errors (from 0.33 to 0.08 Mbps).

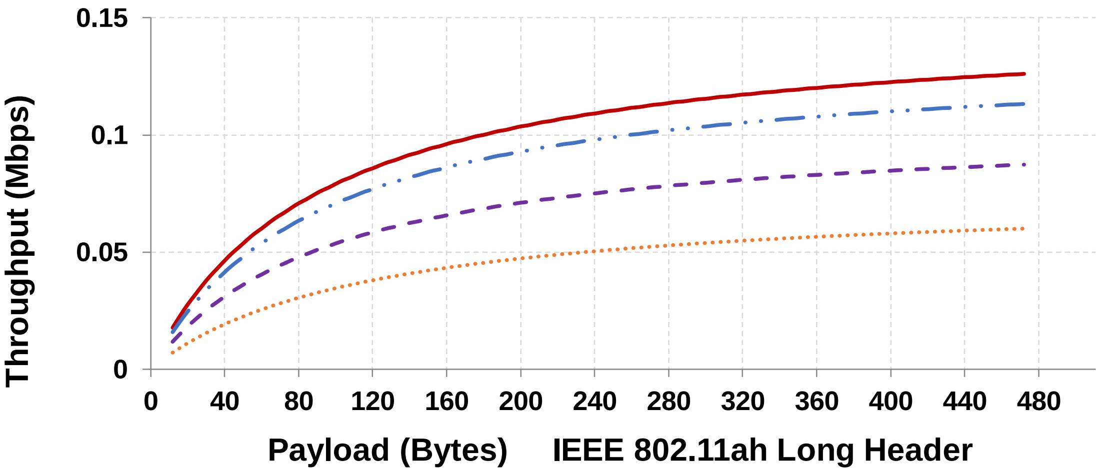

Figure 10. Throughput vs Payload size for IEEE 802.11ah (long MAC header and normal ACK).

IEEE 802.11ah allows a shorter MAC header to reduce overhead. However, we observed minimal throughput improvements (i.e. less than 1%) when short headers and NDP ACK were used. This is the reason why, in Figure 10, we plot the throughput results using long headers and normal ACK. It is clear that IEEE 802.11ah's most reliable link is much slower than employing other IEEE 802.11 technologies (150 kbps). Some of the characteristics that give 802.11ah the longest-range turn into a drawback when throughput is compared. Results denote a maximum throughput of 126 kbps (reduced to 60 kbps when PER = 50%) for 475 Bytes payload. With 12 Bytes, throughput varies from 17.6kbps (no errors) to 6.9 kbps (PER = 50%).

Notice, we consider the maximum data frames of size 1500 Bytes in IEEE 802.11n/ac. For IEEE 802.11ah, the data frames are limited to 511 Bytes at 1 MHz using MCS10 and 1 spatial stream [4](including preamble and header) and thus, the maximum payload is 475 Bytes for long header case, and 485 Bytes for the short header case.

In Figure 11, the A-MPDU frame aggregation for IEEE 802.11ac and 11n provides a maximum throughput (PER = 0%) of 6.71 Mbps with 1500 Bytes (*K*=3, recall that *K* corresponds to the number of frames that form an A-MPDU) PER of 50% reduces it to 3.35 Mbps. With the shortest frame tested, i.e. 12 Bytes, we obtain 1.56 Mbps of throughput with 64 MPDUs (*K*=64) at 0% PER and 0.78 Mbps at 50% PER (x4, and x8 times the throughput with respect to the case without aggregation).

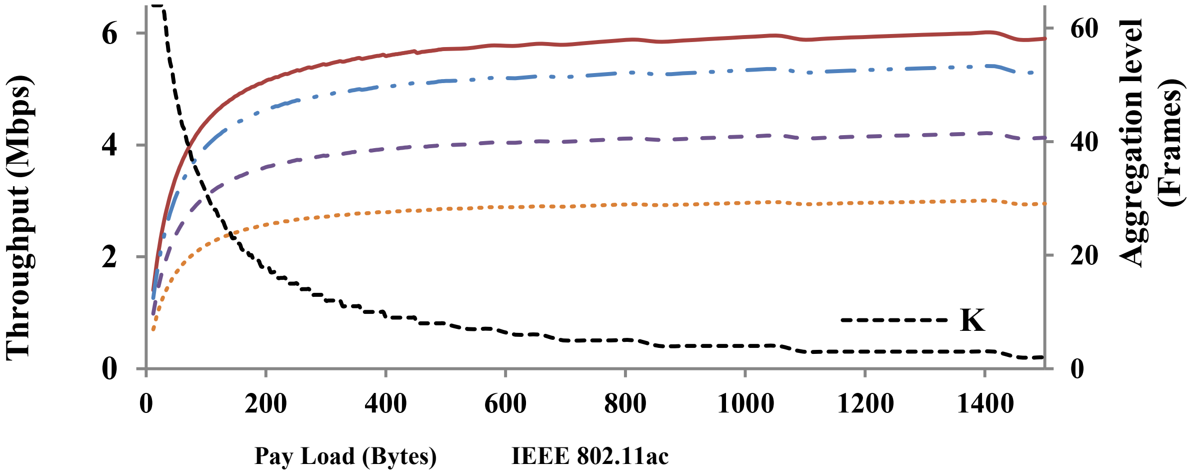

Figure 11. A-MPDU Throughput vs Payload size for IEEE802.11ac.

Considering IEEE 802.11ah and A-MPDU (Figure 12) with the minimum payload (12 Bytes of data), we achieve 36.9 kbps with 9 MPDUs (*K*=9) and PER equal to 0%. Note that using the maximum payload, i.e. 475 Bytes, there is no aggregation possible. Also, note that throughput vs. payload size lines break every time the number of aggregated frames is reduced in order not to exceed the maximum allowed physical frame [4] (i.e. fewer frames can be aggregated as we increase their size).

This thesis explores IEEE 802.11ah performance and provides a comparison between IEEE 802.11ah and current IEEE 802.11a/n/ac in terms of range and throughput. Detailed results indicate that IEEE 802.11ah benefits from the widest coverage, due to the lower frequency band, a narrower bandwidth, and a more robust coding scheme. It shows, at least, a fivefold increase with respect to the second-best range (IEEE 802.11a), and more than ten times improvement with regard to the worst case (IEEE 802.11n in the 2.4 GHz band).

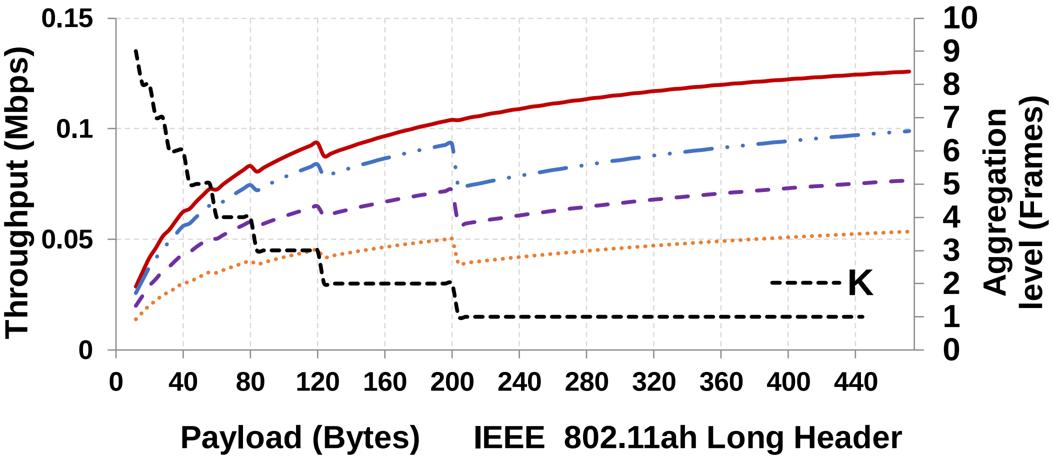

Figure 12. A-MPDU Throughput vs Payload size for IEEE802.11ah.

On the other hand, IEEE 802.11ah presents the lowest throughput, in comparison with other amendments, a maximum throughput of 144 kbps (reduced to 71 kbps when PER = 50%) can be achieved at the limits of its estimated coverage, which is enough for the use cases this technology is targeting.

Given the use case scenarios where the size of data frames is inherently small, the use of aggregation slightly mitigates the excess of overhead but its impact is limited by the low data rates that 802.11ah devices will support.

3.3 *Throughput and coverage range analysis under distinct PHY features*

In this subsection, distinct MCS, spatial streams and Channel Bandwidth (CBW) features are taken into account for the throughput and coverage range evaluation of IEEE 802.11ah against IEEE 802.11n and IEEE 802.11ac.

3.3.1 Throughput analytical model

For throughput calculation in this section, in order to enhance the model, the use of distinct MCS configurations, different CBW, and SS is performed. Besides, we follow Equation 17 presented in subsection 3.2.1. Notice that under ideal channel conditions (PER=0), we consider that $T_{BACKOFF}$ is CWmin/2 times the slot time (T_{Slot}); CWmin corresponds to the minimum CW (cf. Table 4). All frame sizes are given in Bytes and frame durations in μs.

T_{DATA} calculation for IEEE 802.11ah includes three different cases:

1. 1 MHz CBW case with short and long Guard Interval (GI) subcases, following Equations (21) and (22), respectively. Note that with 1 MHz CBW only one PHY preamble/header type applies (cf. Table 4).
2. Short preamble case for 2, 4, 8 and 16 MHz CBW with short and long GI subcases, which also follow Equations (21) and (22), respectively; in this case, a different value for the PHY preamble/header length should be used (cf. Table 4).
3. Long preamble case for 4, 8 and 16 MHz CBW with short and long GI subcases, following Equations (23) and (24), respectively:

$$T_{shortGI} = T_{Preamble\&Header} + 40 \times \ (N_{LTF} - 1) + T_{Syml} + T_{Syms} \times \left(N_{sym} - 1\right) \qquad (21)$$

$$T_{longGI} = T_{Preamble\&Header} + 40 \times (N_{LTF} - 1) + T_{Syml} \times N_{sym} \qquad (22)$$

$$T_{shortGI\ long_{preamble}} = T_{Preamble\&Header} + 40 \times N_{LTF} + T_{Syml} + T_{Syms} \times \left(N_{sym} - 1\right) \qquad (23)$$

$$T_{longGI\ long_{preamble}} = T_{Preamble\&Header} + 40 \times N_{LTF} + T_{Syml} \times N_{sym} \qquad (24)$$

where N_{LTF} corresponds to the number of long training symbols, T_{Syml} is the duration of a symbol with the long GI and T_{Syms} corresponds to the duration of a symbol with the short GI.

Now the number of symbols N_{sym} is as follows.

$$N_{symAH} = \left\lceil \frac{8+(6*N_{ES})+8*K*(L_{Header}+L_{data})+(K-1)*(L_{deli}*8)}{NDBPS} \right\rceil \qquad (25)$$

$$N_{\frac{symAC}{\frac{N2.4}{N5}}} = \left\lceil \frac{16+(6*N_{ES})+8*K*(L_{Header}+L_{data})+(K-1)*(L_{deli}*8)}{NDBPS} \right\rceil \qquad (26)$$

N_{ES} and N_{DBPS} depend on the MCS chosen and are fixed in the standard specification.

3.3.2 Evaluation results

We consider data frames with a maximum payload size of 1500 Bytes to build the MPDU aggregation A-MPDU. Up to 64 individual frames are allowed to assemble an A-MPDU. Note, however, that the standard enforces other restrictions that may reduce the number of aggregated frames carried by an A-MPDU. IEEE 802.11ah presents a maximum length for an A-MPDU of 511 symbols and a maximum duration of 27.930 ms. On the other hand, IEEE 802.11n allows up to 65,535 Bytes, whereas IEEE 802.11ac is able to deal with 1,048,575 Bytes of maximum length. In both amendments, the maximum frame duration is of 5.484 ms.

Different from Hazmi et al. [40], who utilizes a Bit Error Rate (BER) model for different MCS, we use the minimum receiver sensitivity established in the IEEE 802.11ah amendment [4]. That is, for each distance and propagation model considered, we assume the transmitter is using the fastest available MCS, the minimum sensitivity of which is larger than the received power at that distance. For that reason, Figures 13 to 20 show a stepped relationship between throughput and coverage range.

As expected, using the most robust MCS leads to increased coverage and to a more reliable communication. On the other hand, while employing higher-order MCS, the benefit of the higher data rate in the communication scenario can be observed in Figures 13 to 16 regarding the macro deployment scenarios, where the A-MPDU throughput versus coverage range in distinct IEEE 802.11ah technologies are highlighted. In the same way, results are presented in Figures 17 to 20, where the Indoor C scenarios (cf. Table 6) shows the A-MPDU throughput versus coverage range from different IEEE 802.11 standards.

The use of a sub 1 GHz frequency band, together with the new and more robust modulation that MCS10 provides benefit IEEE 802.11ah in achieving the long-range feature, i.e., IEEE 802.11ah amendment can operate under macro deployment scenario and can achieve a coverage range of up to 1500 m. The same PHY configuration can reach up to 900 to 1100 m in different indoor scenarios.

Hence, in terms of coverage, there is seven-fold improvement using IEEE 802.11ah with the most robust MCS with respect to best sub-6 GHz amendment result (IEEE 802.11ac, 20 MHz, with 1 Spatial Stream, SS).

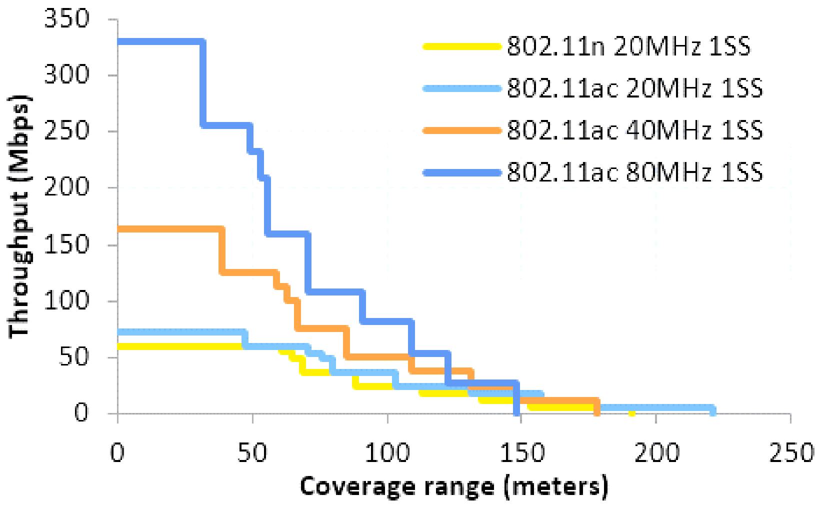

Figure 13. **Macro deployment A-MPDU throughput vs. coverage range using 1 SS for 802.11n and 802.11ac**

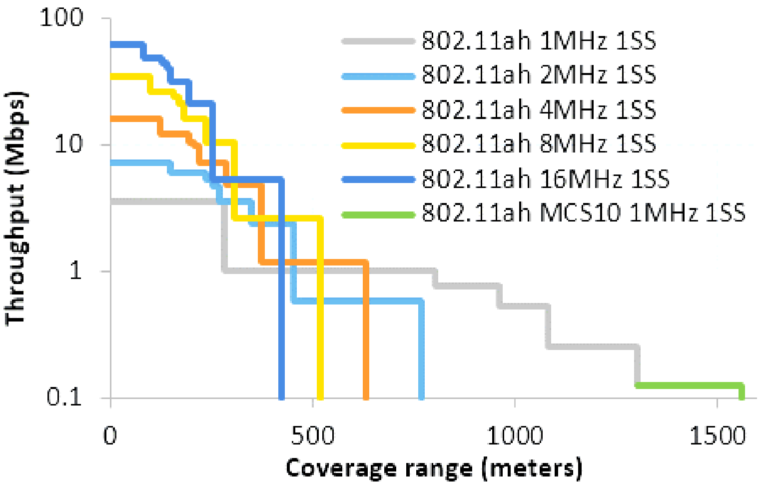

Figure 14. **Macro deployment A-MPDU throughput vs. coverage range for 802.11ah in 1, 2, 4, 8, 16 MHz CBW with 1 SS, highlighting the new MCS10 with 1 SS.**

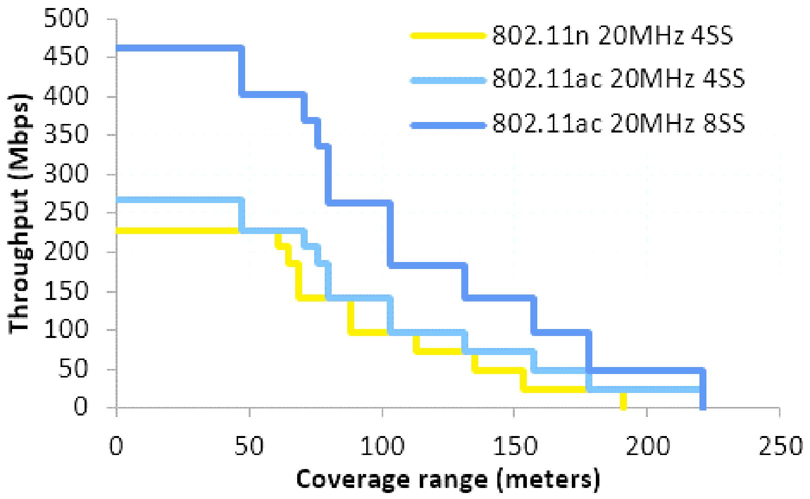

Figure 15. **Macro deployment A-MPDU throughput vs. coverage range using 4 and 8 SS for 802.11n and 802.11ac.**

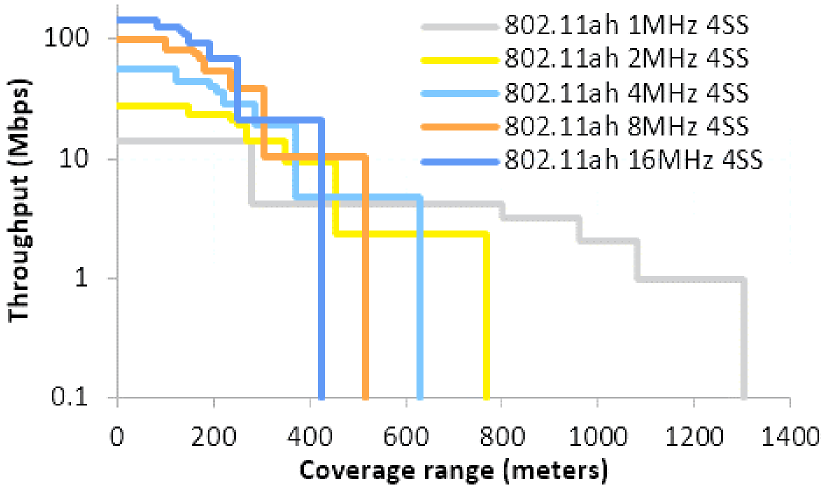

Figure 16. **Macro deployment A-MPDU throughput vs. coverage range for 802.11ah using 4 SS.**

Furthermore, the improvement obtained by the new MCS10 in the IEEE 802.11ah case is around 15% for distance reached in macro deployment in comparison with the lowest MCS (MCS 0) with 1 SS and around 20% in indoor cases. Besides, the use of more than 1 SS improves the throughput up to 95% when employing four SS, but in turn reduces the coverage range considerably. It is also important to highlight the fact that improving the range results in a throughput performance decrease. However, the throughput achieved by the IEEE 802.11ah in the limit of its coverage can still reach the 100 kbps, which can be sufficient for most of IoT applications.

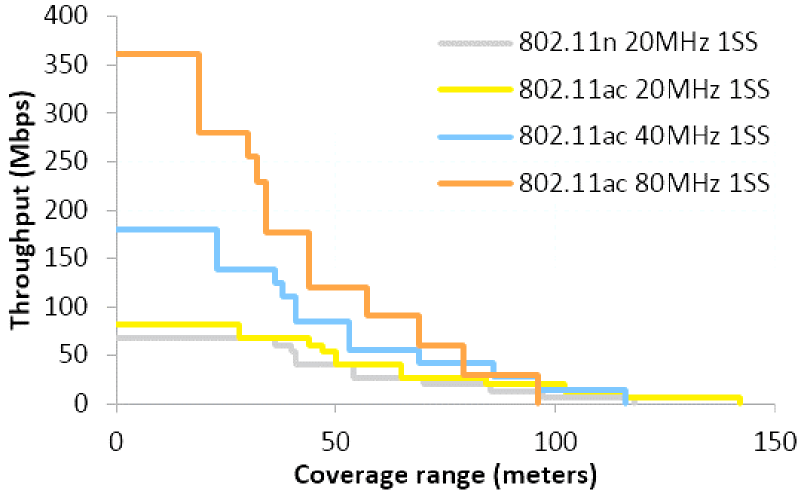

Figure 17. Indoor A-MPDU Throughput vs. coverage range in IEEE 802.11 using 1 SS for 802.11n and 802.11ac.

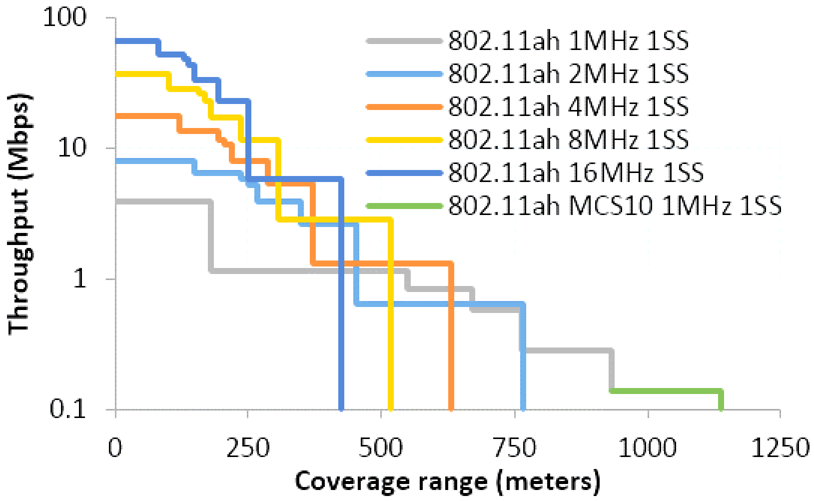

Figure 18. Indoor A-MPDU Throughput vs coverage range for 802.11ah in 1, 2, 4, 8, 16 MHz CBW with 1 SS.

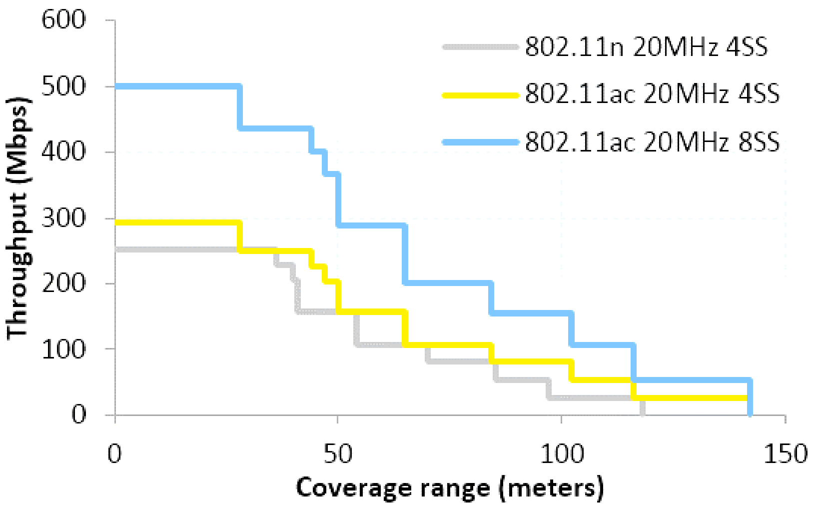

Figure 19. **Indoor A-MPDU Throughput vs coverage range using 4 and 8 SS for 802.11n and 802.11ac.**

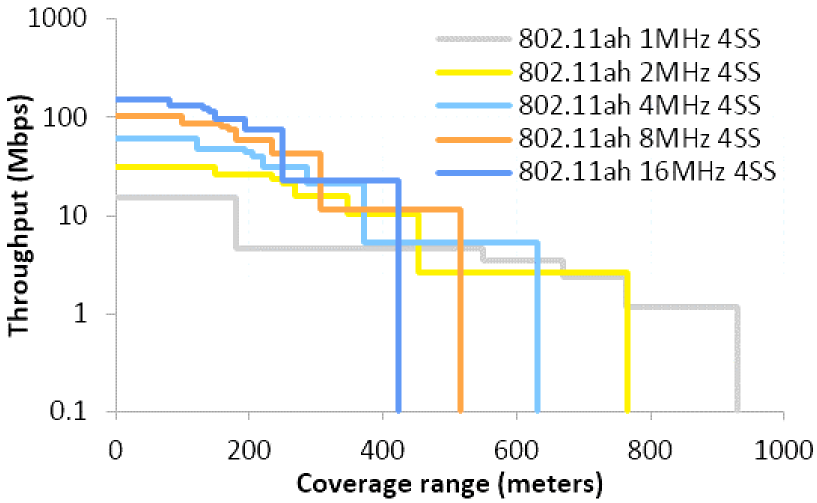

Figure 20. **Indoor A-MPDU Throughput vs coverage range for 802.11ah using 4 SS.**

It is also worth mentioning that a higher throughput performance can be obtained for IEEE 802.11ah employing two 8 MHz or four 4 MHz channels instead of one 16 MHz channel. First, note that the use of larger Channel Band Width (CBW) improves the transmission efficiency, since it allows the use of a larger proportion of data subcarriers (pilot, guard subcarriers are the same regardless of the CBW used).

However, the required receiver minimum input sensitivity also increases by using larger CBW, thus a better signal quality is needed at the receiver to complete a successful reception. In this way, for long distances, it results in a more profitable practice to use, for example, 16 channels of 1 MHz CBW instead of 1 channel of 16 MHz CBW; with high signal quality in reception, the larger bandwidth becomes a better option due to the better proportion of data/pilot OFDM carriers.

3.4 Summary

In this chapter, we provide an evaluation between IEEE 802.11ah and IEEE 802.11a, IEEE 802.11n, and IEEE 802.11ac in terms of range and throughput. Detailed results in Subchapter 3.2 demonstrate Wi-Fi HaLow is beneficiated for the lower frequency band, narrower bandwidth, and the robust coding scheme, giving the widest coverage in the results. IEEE 802.11ah surpassed the IEEE 802.11 standards compared (IEEE 802.11a/n/ac), showing more than five times range improvement concerning the second scored competitor (IEEE 802.11a).

Regarding the throughput, IEEE 802.11ah presents the lowest results. Notice that when the frame size is small, the aggregation mechanism does not improve as much as with a big frame size. Hence, the excess of overhead impact is limited by the low data rates that IEEE 802.11ah devices will support.

Evaluations performed in Subchapter 3.3 highlight the potential coverage at reasonably high rates exhibited by IEEE 802.11ah. This fact makes this technology an attractive alternative in fulfilling the needs of future IoT communications. The analysis of the results presents IEEE 802.11ah with more than 8 times improvement in coverage range against any other IEEE 802.11-based amendment and shows that it can provide throughput close to 100kbps in the worst case, which is enough to cover most IoT applications.

4. IEEE 802.11ah as a technology to face the IoT challenge

Once that the IEEE 802.11ah standard fundamentals were exposed in Chapter 2, additionally with the performance evaluation on throughput and coverage range of Wi-Fi HaLow presented in Chapter 3, in this chapter, we characterize distinct IoT applications in different areas. The IoT communications challenges are presented, following with the evaluation of the results of the study of IoT applications requirements against IEEE 802.11ah capabilities, and finishing with the CAPEX and OPEX evaluation.

After exposing the capabilities of the IEEE 802.11ah standard in supporting different IoT applications together with the characteristics and enhancements of the amendment, a thorough analysis, and evaluation was required to show the capabilities of IEEE 802.11ah standard. Furthermore, we provide numerical results showing how the IEEE 802.11ah specification offers the features required by IoT communications, thus putting forward IEEE 802.11ah as a technology to cater to the needs of the Internet of Things paradigm. Notice that part of this work has been published in [20].

4.1 IoT communications challenges

In order to visualize the challenges within IoT communications, we can distinguish the typical requirements such as a large number of autonomous devices sending traffic (simultaneously or in deferred times), low power consumption, and long sleep period. In this section, we provide an overview of the mechanisms used by IEEE 802.11ah to tackle these challenges.

4.1.1 Coverage range

Some of the IoT applications require more than 1 km of coverage for their desired operation. Besides the fact that it is using a lower frequency band (sub-1 GHz) with better propagation characteristics, in IEEE 802.11ah, the extended range requirement is fulfilled by introducing 1 MHz wide transmission and by using a new MCS index (MCS10, cf. Subchapter 3.1).

This scheme is effectively MCS0 (BPSK 1/2) with the addition of 2x repetition. Along with 1 MHz CBW, IEEE 802.11ah also supports 2, 4, 8, and 16 MHz (it is expected that early commercial devices support up to 4 MHz). These narrower bandwidths entail a larger symbol duration than legacy IEEE 802.11. With longer symbols (and guard intervals), IEEE 802.11ah transmissions are more robust to inter-symbol interference found in longer links and outdoor scenarios (large delay spread).

By supporting MIMO, IEEE 802.11ah benefits from spatial diversity, which improves the received signal quality and, hence, makes longer links possible. The specification also considers multi-hop operation with relays or mesh networking to extend coverage.

4.1.2 Time and frequency resources

Many technologies concurrently operate in the overcrowded frequency band of 2.4 GHz (IEEE 802.15.4e, BLE, IEEE 802.11, among others), where they suffer of a lot of interference, which seriously degrades the performance of the networks. With the advent of IoT, and the increase in the number of devices implementing these technologies, the fate of this band does not look promising; on the contrary, communications problems, such as the co-channel interference, which is especially harmful in Carrier Sense Multiple Access (CSMA)-like access schemes, will be exacerbating.

However, the IEEE 802.11ah amendment is intended to operate below 1 GHz, which, besides improved coverage, faces less interference. This characteristic of the IEEE 802.11ah seems particularly appealing for IoT applications, where hundreds or thousands of devices are expected to coexist.

4.1.3 Support of large number of IoT devices

IoT networks have the main characteristic of being formed by a large number of autonomous devices (typically ranging from hundreds to a few thousands). This is because many of the applications are expected to operate over large areas. However, collisions occur frequently when a large number of devices try to communicate simultaneously. Excessive collisions result in reduced overall throughput in the network and thus, finding appropriate methods to reduce collisions is one of the main challenges for the IoT.

The IEEE 802.11ah defines the optional new contention channel access mechanism RAW. This access method is designed to reduce collisions by improving channel efficiency by dividing stations into different groups and restricting channel access only to a group at a particular time period (cf. subchapter 6.1).

Legacy IEEE 802.11 supports up to 2007 associated stations per AP, due to the limited number of available AIDs that can be assigned to each associated station. In order to increase the number of supported stations by AP, IEEE 802.11ah utilizes a novel hierarchical AID structure. The new AID consists of 13 bits and thus the number of supported stations increases to $2^{13} - 1$ (= 8,191). AID structure consists of four hierarchical levels (i.e., page, block, sub-block, and station's index in sub-block). IEEE 802.11ah employs the aforementioned structure to group stations based on similar characteristics (e.g., traffic pattern, location, battery level, etc.).

4.1.4 Low power consumption

Considering the fact that many IoT devices are battery driven and are meant to operate for days, weeks, months, or even years (depending on the application), the low power consumption becomes a crucial aspect to increase battery life. IoT devices are equipped with embedded Network Interface Card (NIC) and thus have the ability to communicate autonomously within the network they belong.

The wireless NIC represents a large portion of the energy consumed by the device and thus, the definition of efficient power management for the NIC is of paramount importance. This can be achieved by employing different wake-up and doze timers.

In legacy IEEE 802.11, the specified maximum idle period allows any station to maintain its association state for up to 18.64 hours of inactivity, while IEEE 802.11ah aims to utilize different periods for different applications, up to a year scale.

Many new features introduced by the IEEE 802.11ah are intended to achieve more efficient transmissions, thus allowing energy saving. For example, the reduced overhead due to shorter headers and mechanisms, such as the implicit ACK control frames (not required in some cases), the speed frame exchange (method that allows exchanging a bidirectional sequence of frames during a reserved TxOP, cf. Subchapter 2.6), extending the battery life of STAs by shortening transmission time, keeping them awake for shorter periods.

Besides, there is the TWT mechanism, which allows an AP to set up a specific time or set of times for each STA to access the medium. For further information, please refer to the subchapter 2.5.6.

4.2 Notable technologies contenders for IoT

Recently we have witnessed an exponential growth in the evolution and development of different communication technologies addressed to support the IoT. As a consequence of this evolution, new applications have been triggered that require innovative connectivity solutions and new ways of sharing data among different devices and networks as the IoT [41].

In related literature, a collection of new terms has been coined in an attempt to clarify the new scenario of connected applications. The IoE [42] appears as a concept that contains both the IoT and IoH, including the capability to share data between each other (IoT and IoH) or among themselves using M2M [43] or M2H communications [44]. Following a similar approach, we could shape the IoT definition to include two different concepts: industrial IoT (iIoT) [45] and consumer IoT (cIoT), exhibiting new scenarios that will dominate the world's communications in the near future, at least in terms of the number of participating devices.

The upcoming IoT applications are enablers of innovative concepts such as smart cities [46], smart/e-health [47], smart metering [48], and the smart things [49], among others. Each of these applications has particular requirements, i.e., different data rates, low power consumption, low cost of implementation, large number of supported devices, and the capability to cover different distance ranges.

This massive implementation of the IoT paradigm will bring changes to many aspects of our lives. The debate on which technology should lead this revolution has not been settled yet. Over the years, there were multiple contenders, while Wi-Fi seemed to be observing from the bench, until the release of the IEEE 802.11ah, which is one of the most prominent technologies in the wireless networks communications field.

It is well known that IEEE 802.11 specifies the mechanisms corresponding to MAC and PHY layers. On the other hand, the Internet Engineering Task Force (IETF) [50] is in charge of the Internet standards development, being responsible for the first reference protocol stack for the IoT after a decade of work, which includes the adaptation layer 6LoWPAN [51] to support IPv6 over IEEE 802.15.4 and IEEE 802.11ah [52] networks.

IEEE 802.11ah is not the only technology trying to cover the requirements of IoT communications. IEEE 802.11 will have to contend against other technologies that are already established in the IoT arena, such as ZigBee/IEEE 802.15.4e, BLE [53] and different Low Power Wide Area Network proprietary technologies. In Table 7, we briefly summarize the most notable characteristics of the aforementioned technologies, pointed out in subchapter 1.4.

Each technology presented in Table 7 has particular features that are attractive to different IoT scenarios. ZigBee/IEEE 802.15.4e [54] has been used in most of the WSN [55] due to its low implementation cost, its large number of supported devices, the offered data rates (i.e., 20 to 250 kbps) and the low power consumption, which makes it appealing for some IoT short-range low-rate applications. Notice that in contrast to IEEE 802.11ah, the data rate where ZigBee/802.15.4e reaches a maximum of 250 kbps against the maximum IEEE 802.11ah data rate of 346 Mbps. Similarly happens with the coverage where ZigBee/802.15.4e longest coverage range is 100 meters in contrast with IEEE 802.11ah, which reaches up to 1.5 km coverage range.

Similarly, BLE is focused on low energy consumption and short-range low-rate communication. Observe that in contrast to IEEE 802.11ah, the coverage range is limited for the BLE, due to the longest coverage range of Wi-Fi HaLow (up to 1.5 km). The same happens with the data rate where BLE reaches a maximum of 1 Mbps against the maximum IEEE 802.11ah data rate of 346 Mbps.

3rd Generation Partnership Project through MTC [56] technology is also making an effort to standardize M2M communications offering features such as QoS, mobility and roaming support based on cellular technologies.

In addition to the higher frequency bands used in 3GPP MTC, the refarming of the licensed GSM spectrum brings the possibility to use sub 1 GHz frequencies. 3GPP MTC, (release 12 and 13) and will be further developed in future releases, presents the largest coverage feature and the highest number of supported devices in comparison to the other aforementioned technologies but operates in a licensed spectrum.

3GPP has also introduced Narrowband Internet of Things [57], which allows operators to use a minimal portion of the available spectrum (LTE [58], or GSM networks) to target ultra-low-end IoT applications. However, NB-IoT suffers from not being fully backward compatible with existing 3GPP devices .

In addition, in the past few years, LPWAN solutions have appeared in competition to conquer the IoT market. Probably, the most outstanding solutions nowadays are LoRa [59] and SigFox [60] which present long coverage ranges (less than 3GPP MTC) and an increased number of supported devices.

4.3 IoT applications evaluation in IEEE 802.11ah

The use of ICT as an enabler for smart cities creates the concept called Urban Automation Networks (UANs), which allows a wide spectrum of applications focused in smart cities, such as garbage collection, lighting control, green zone management, environmental control, parking availability, street traffic, utility infrastructure, and security, among other uses. All aforementioned applications can be included within the IoT applications framework.

In addition, there are many other important applications available for IoT, such as multimedia and smart/e-health applications, smart metering, smart green, and integrated transport [61], home automation, consumer services, smart grids [62], smart automotive and transit, smart logistic and supply chain, smart oil, gas manufacturing and, industrial applications.

Building home automation consists on the automatic centralized control of a building in areas such as Heating, Ventilating, and Air-Conditioning (HVAC), lighting, safety, and security systems, among others. Moreover, smart metering applications are focused on smart grids, including on demand and periodical meter reading, load management and electric service pre-payments.

Multimedia (audio and video devices), is not commonly considered within the IoT, but it can be used as sensors/actuators for smart/e-health applications, which include phone conversations and video transmissions for emergency notification, transference of high-resolution images, and smart monitoring on biometrical signals, such as electroencephalography (EEG), electrocardiography (ECG) and blood pressure (BP), among others.

Table 7. Notable technologies contenders for IoT

Feature	IEEE 802.11 (n/ac)	IEEE 802.11ah	ZigBee /802.15.4e	BLE	3GPP MTC	LPWAN		
						LoRaWAN	SigFox	NB-IoT
Frequency band (GHz)	Unlicensed 2.4, 5 GHz	Unlicensed 900 MHz	Unlicensed 868/915 MHz 2.4 GHz	Unlicensed 2.4 GHz	Licensed <5 GHz	Unlicensed 867–928 MHz	Unlicensed 868–902 MHz	Licensed <180 kHz
Data Rate	6.5–6933 Mbps	150 kbps–346 Mbps	<250 kbps	<1 Mbps	<1 Mbps	<25 kbps	<1 kbps	<159 kbps
Coverage range	< 200 m	<1.5 km	<100 m	<50 m	<100 km	<20 km	< 40 km	<35 km
Power consumption	Medium	Low	Low	Low	Low	Low	Low	Low
Number of devices supported	2007	8000	65,000	Unlimited*	>100,000	>100,000	>1,000,000	>52500

4.3.1 Accomplishing the requirements of IoT applications

We present an analytical study to evaluate the viability of IEEE 802.11ah as the basis of different IoT applications by confronting the application requirements and the IEEE 802.11ah capabilities. We collect a selection of typical IoT applications, classifying them into smart applications and multimedia and smart/e-Health applications.

Smart applications are divided further into two categories according to their time-related requirements: permanent connectivity and event-based applications (highlighted in Table 8). Multimedia and smart/e-Health applications (signified in Table 9 are classified by type, namely audio, video, data, and biometrics). Tables 8 and 9 show the minimum number (i.e., worst case) of STAs each IEEE 802.11ah AP can support while meeting the requirements of different IoT applications.

In all of the aforementioned IoT applications, we expose the expected number of devices that an IEEE 802.11ah standard AP can support over different distances (i.e., less than 1 km, 500 mts, and 250 mts). In order to do that, we consider the typical data size and aggregated data rate requirements for different applications found in the literature (e.g., [63], [64]). In each case, we also assume the fastest MCS (among the set of mandatory MCS) that can be reached at those distances, according to the minimum receiver sensitivity set in the IEEE 802.11ah specification [4] . This explains why larger cells admit fewer users; larger distances require more robustness and therefore, slower modulations.

Our evaluation scenarios are conformed by multiple IEEE 802.11ah transmitters or STAs and one receiver (AP). In order to set a reliable lower bound, we assume the most demanding case; which is, all STAs are active and willing to transmit at the same time (i.e., saturation conditions). We start the evaluation with one STA and then we keep adding new STAs until the provided layer-2 throughput ceases to meet the requirements of the application, i.e., the obtained throughput per station is below the data rate required by the application.

The throughput as a function of the number of contending STAs is computed according to the well-known Bianchi's analytical model, which is a model that provides the saturation throughput in IEEE 802.11 networks [65] and considering IEEE 802.11ah basic access parameters.

The value of the average data rate is calculated as follows: first we have carried out a study of the state of the art on the different IoT applications such as permanent connectivity and event-based applications, multimedia and smart / e-Health applications, among others in order to determine a typical payload required for each one of them [63], [64].

Furthermore, we have taken into account the time in which they regularly send data (seconds, minutes, hours, or days) depending on the particular needs of each application. In addition, the Bianchi model is used to find the maximum number of simultaneous STAs that would produce an average throughput per station equal to or greater than the one required by that application (depending on its packet size and the frequency of data packets to send), in the calculation we use different MCSs (slow/fast) which allow us reaching typical distances of IoT applications (<1k, <500m, <250m).

Note that the specific use of IEEE 802.11ah mechanisms, such as RAW (cf. Subchapter 2.5.4), will improve the efficiency in the radio channel access, thus allowing an increase in device density and in the number of STAs served by one AP.

Also note that we are not considering any multiplexing gain when, for most applications, it is unlikely that all associated STAs are active simultaneously. As a rule of thumb, the total number of associated devices supported could be obtained by dividing the number of devices reported in Tables 8 and 9 by the expected duty cycle of the application, measured during the hours of maximal activity.

In many applications where the duty cycle is very small (e.g., few transmissions per hour or per day), the limit in the number of supported devices is actually determined by the AID field (i.e., near 8200 devices per AP) and not by the achieved throughput. For the sake of example, we can assume that the distribution automation application requires each connected device to transmit 600 Bytes (4 frames with a payload of 150 Bytes each, (cf. Table 8) every 5 seconds.

The resulting duty cycle, considering the slowest bit rate (i.e., 150 kbps at MCS10,) is <1.3%. According to Table 8, the maximum number of simultaneous transmitters at the largest distance is 55 and, therefore, we could admit up to 4200 associated devices; however, note that with 4200 transmitters, the probability of having 56 or more simultaneous contestants (i.e., probability of having congestion) is relatively high, at 30%.

Therefore, in order to reduce congestion, we suggest that the number of admitted stations is reduced to 80% or less (e.g., 3300); in such case, the probability of congestion is less than 2%. Assuming that stations behave as independent ON-OFF state machines, the number of simultaneous transmitters and congestion probability can be obtained by treating the system as an *M/M/C*, where *C* corresponds to the number of supported devices reported in Tables 8 and 9.

It is also apparent, how in circumscribed cases (backhaul, firmware, EHR, video, and image applications), the use of frame aggregation is a key enabler, necessary to meet throughput requirements. In order to visualize it, and as a part of Table 8, the use of aggregation is explained accordingly to each case.

The numbers of the backhaul application (* in Table 8) are provided assuming frame aggregation, with which IEEE 802.11ah is capable of meeting the minimum throughput requirements of the backhaul application. Note that the wireless backhaul application consists of a network of point-to-point links, where the required number of supported STAs per link is 1 (plus the AP). A number of STAs X>1 means that X/2 bidirectional links can coexist in the same channel and still meet the throughput requirements. Also note that, in this particular application, we can safely assume MxM MIMO capable nodes, which have the potential to multiply by M the throughput obtained (M≤4). The firmware application (+ in Table 8) also needs the use of the frame aggregation feature to allow higher throughput for timely bulk data transfer of, typically, 400-2000 kbps.

The similar explanation as before is provided to highlight the use of the aggregation in Table 9. Bulk data transfer applications (+ in Table 9) will benefit from the use of frame aggregation. For example, with frame aggregation, IEEE 802.11ah could support is up to 10 simultaneous EHR users at 600 m whereas, without aggregation, the available throughput only leaves room for one user meeting the required quality. Video 2 (* in Table 9) and IMG 2 (** in Table 9) applications will also benefit from the use of frame aggregation and of more than 1 SS; however, IEEE 802.11ah is able to transmit typical quality images and video files needed for most applications.

Table 8. **Number of supported STAs per IEEE 802.11ah AP for different smart applications.**

	Application	Description	Average Payload Size (Bytes)	Average Aggregate Data Rate (Kbps)	Supported Device at <1 km (Outdoor	Supported Devices at < 500 m (Outdoor)	Supported Devices at < 250 m (Indoor)
Permanent connectivity applications	Home/Building automation	Sensitive delay applications, including services to manage different commodity infrastructure, remote control of industrial facilities, smart cities applications, etc.	100	15–30	1250	2100	2500
	On-demand meter reading		100	40–180	250	1000	1200
	Distribution Automation		150	60–480	55	300	400
	Electric service prepayment		50–150	30–90	725	2000	2100
	Service on/off switch		25	5–10	1600	2400	2600
	Security (sensors, alarms).		100	40–180	250	1050	1150
	Backhaul/core/metro networks*		1500	240–4100	1	6	17
	Parking Availability		100	40–180	250	1050	1150
	Street traffic		100	40–180	250	1050	1150
Event-based applications	Multi-interval meter reading	Delay-tolerant where data is collected infrequently (multiple times per day) applications, including all non-critical applications not requiring permanent connectivity such as scheduled reporting of bulk measurements.	100	<1	4200	5000	5300
	Firmware Updates+		1500	45–250	400	1800	2500
	Garbage Collection		100	<1	4200	5000	5300
	Lighting Control		100	<1	4200	5000	5300
	Green zone management		100	<1	4200	5000	5300
	Environmental Control		64	<1	4200	5000	5300
	Utility infrastructure		100	<1	4200	5000	5300

Table 9. Number of supported STAs per IEEE 802.11ah AP for different multimedia and smart/e-health applications.

Application		Description	Average Payload Size (Bytes)	Average Aggregate Data Rate (kbps)	Supported Devices at <1 km	Supported Devices at < 500 m	Supported Devices at < 250 m
Audio	Audio 1 Codec G723.1 Rate 6.4 kbps	In these applications, a variety of codecs is available depending on the audio quality required.	100	80–600	5	15	30
	Audio 2 Codec AMRx Rate 12.2 kbps		120	70–650	5	20	35
Video	Video 1 Codec H.264 Rate 500 kbps	In these applications, different codecs are needed depending on the quality of the video required.	1500	500–4000	1	3	7
	Video 2* Codec H.264 Rate 8 Mbits/s		1500	8000–25000	-	1	3
Data	Electronic Health Record (EHR) +	Applications involving the transmission of large files in the context of smart/e-health.	1000	1000–10000	1	5	10
	IMG 1 Low resolution lossless compression, 1024 × 768 px 24 bits/px		1500	450–2000	3	9	12
	IMG 2** High resolution lossless compression, 4096 × 4096 px 24 bits/px		1500	3500–20000	1	2	6
Biometrics	Electroencephalography EEG	Applications where data is collected from the electrical signals in the human body to get representative information in the evolution of vital signs.	100	100–400	1	2	3
	Electrocardiography ECG		50	50–300	1	5	10
	Blood pressure (BP)/Pulse Oximeter (SpO ^{2})		400	80–1100	25	140	320

Finally, notice the fact that most of the technologies presented in Table 7, do not meet throughput requirements of most of the IoT applications considered in this chapter when providing enough coverage and supported users, or fail to provide a decent coverage when meeting throughput requirements.

Note that, in comparison with other notable technologies contenders for IoT, which offer data rates from 1 kbps up to 1 Mbps, IEEE 802.11ah presents a wider range of available operating rates, which go from 150 kbps up to 346 Mbps a clear example is provided with multimedia applications.

The multimedia term has not been usually associated with the IoT paradigm due to the lack of capacity of traditional IoT solutions for supporting the required bit rates. With the exposed analysis, we show that IEEE 802.11ah enables the IoT to adopt new use cases involving the transmission of multimedia data (i.e., audio/video), thus making the link between multimedia and IoT applications now possible.

4.4 Application and infrastructure costs evaluation

In order to provide a more complete view of the viability of an IEEE 802.11ah-based IoT infrastructure, in this subchapter we give an approximation of its costs. We assume a highly dense scenario of 1 km^2 populated by 10,000 IoT devices, i.e., sensors/actuators connected together in the same area. We calculate the total infrastructural cost to cover both 6 and 12 years of operation for short and medium term-operations.

We focus this analysis on the costs of the radio interfaces, disregarding the costs of the site (placement and installation of the APs) and the cost of the device, which will be comparable regardless of the wireless technology chosen.

A typical scenario based on legacy IEEE 802.11 technology, would require, at least, 50 APs: first, we assume enterprise-level APs supporting up to 200 connected devices per AP and an effective coverage radius of 80 m to serve the whole 1 km^2 area. Secondly, we consider 20 USD per radio interface and 500 USD per AP.

The investment in the aforementioned assets falls under the denominated Capital Expenditure (CAPEX), which is the investment needed to acquire the elements conforming to the infrastructure on a project. The Operation Expenditure (OPEX) is the investment that will be needed to maintain the installations in working conditions, and it can be estimated as 10% of the CAPEX plus the salaries of the IT staff who will operate and manage the network. Noting that the OPEX is calculated per year, the project generates a total outlay of 740,000 USD in a six-year project and an investment of 1,200,000 USD in a twelve-year project.

On the other hand, we analyze the same scenario based on IEEE 802.11ah technology with the caveat that there are still no IEEE 802.11ah products available in the market and, therefore, precise price ranges cannot be given. We assume the same requirements presented previously.

In terms of coverage, just two IEEE 802.11ah APs would be enough. However, in order to guarantee a good service to 10,000 IoT devices, four APs are recommended, each of which can cover a radius of less than 300 m. The IEEE 802.11ah APs can reach more than 1 km in typical outdoor deployments, cf. Subchapter 3.1 and it can serve 2500 devices (the maximum number of devices allowed in IEEE 802.11ah AP is ~8000).

As explained, the sensor/actuator hardware will cost the same amount as in the previous case. However, IEEE 802.11ah NICs are expected to be cheaper since they are intended to be integrated into low-cost small devices (assume 15 USD per radio interface); on the other hand, APs are more expensive (assume 1,000 USD per AP). With the same criteria to assess the OPEX, the total cost for a six-year project with IEEE 802.11ah would be 540,000 USD in a six-year project and 940,000 USD in a twelve-year project (near to 25% cheaper).

In the same scenario, we estimate the deployment costs of other IoT communication alternatives, such as the proprietary solutions LoRaWAN or SigFox. In this case, a sensor radio costs around 10 USD. Three base stations are going to be needed to support 10,000 devices, with an approximate price of 6000 USD each. Thus, following the same rules for OPEX computation, the total cost would be around 484,000 USD for a six-year project and around 850,000 USD for a twelve-year project. These alternatives offer lower implementation costs in comparison to IEEE 802.11ah technology, but the higher complexity of LoRaWAN/SigFox interconnection and the limited available bandwidth is the biggest limitations holding back a wider adoption in these IoT technologies.

In addition, with regard to the IoT scenario based on cellular technologies, each sensor radio that is going to be connected to the operator infrastructure has an approximate cost of 50 USD. In this case, for the OPEX computation, 20% of the CAPEX is usually considered, due to the addition of data plane maintenance costs. Thus, the estimated OPEX would be around 1,100,000 USD for a six-year project and around 2,300,000 USD for a twelve-year project, thus making cellular technology the most expensive approach.

4.5 Summary

The potential coverage at reasonably high rates exhibited by IEEE 802.11ah makes it an attractive alternative in fulfilling the needs of future IoT communications. In this chapter, we provide a comparison between different technologies contending to cover the IoT communications framework, and thus indicate IEEE 802.11 technology as one of the strongest contenders.

We give a thorough analysis of the requirements of many typical IoT applications (classified as permanent connectivity, event-based applications, audio, video, data and biometrics), assessing the number of supported devices per AP, with up to 1 km of coverage. In the cases where the required coverage distance is larger than 1 km, IEEE 802.11ah can be used to build a multi-hop distribution system.

We also provide an analysis of the implementation and infrastructure costs that make IEEE 802.11ah very attractive in front of other IEEE 802.11 specifications and the competing wireless technologies. Overall, the expected performance of IEEE 802.11ah asks for a remarkable place in the IoT landscape.

5. Simulation environment

The present chapter is dedicated to the introduction of the ns-3 network simulator, used for the analysis and evaluations of distinct features throughout the work developed in this thesis. This chapter also includes the aforementioned model settings, environment, and the changes made to the ns-3's IEEE 802.11ah model to adapt it to our purposes.

The current scenario, where new technologies are emerging with different specifications and features, demands the use of networks simulators, aiming to evaluate the performance of these new technologies against legacy features, in order to support the detection and or correctness of future problems in the implementation and deploying of scenarios that can be expensive to implement physically. After each successfully well-modeled network, simulators can achieve meaningful insights over a modeled network, allowing the use of different scenarios, parameters, etc. to study different behaviors of those networks.

As mentioned before and in order to mimic a real system's behavior, distinct parameters are tested particularly in PHY and MAC layers, which is mainly the object of study in this thesis. With the ongoing network communications importance on the IoT scenarios, the apparition of network simulators is increased, being probably OMNet++ [66], OPNET [67], ns-2 and ns-3 [68] the more prominent ones. From our point of view, and in in order to support the analysis and evaluation of different features, ns-3 discrete-event network simulator is the best option to perform these duties. Notice that ns-3 has specified models for IEEE 802.11ah developed by researchers from the University of Antwerp [69].

To sum up, the next subchapter will introduce ns-3. Following, the simulation model´s settings are exposed, as well as the IEEE 802.11ah adaptation is performed until the summary in subchapter 5.4

5.1 ns-3 structure for IEEE 802.11-based simulations

The ns-3 implementation is modular and provides the following sublayers. First, the PHY layer models. Second, the MAC low models, where functions, such as medium access DCF, EDCA, Request To Send (RTS)/CTS, and ACK are modeled. Finally, with the MAC high model, also known as upper MAC, includes models for the non-time-critical processes as the MAC-level beacon generation, rate control algorithms, probing, and association state.

An important part of the evaluations carried out in this thesis is obtained by means of simulations using the ns-3 discrete-event, event-based network simulator, licensed under the GNU GPLv2 license. ns-3's IEEE 802.11ah models were developed by researchers from the University of Antwerp [69].

An overview of the ns-3 model is performed in this chapter. Firstly, we have to mention that ns-3's basic abstraction element is the ***Node***, which can be conceived as a host or, more generally, a computer. ***Nodes*** are connected to a network through ***NetDevice*** objects, which cover both the software driver and the simulated hardware. ***NetDevices*** can represent NICs, implementing, for example, the behavior of Ethernet, Wi-Fi, Bluetooth, etc. Hence, ***Nodes*** must have a ***NetDevice*** "installed", and in this way, the ***nodes*** can communicate among them in simulation via ***Channels*** (class in charge of managing communication and connecting ***Nodes*** to them). Additionally, as in real network transmissions, a ***Node*** can be able to be connected (using multiple ***NetDevices***) to more than one ***Channel***. Secondly, focusing on the Wi-Fi-model, ns-3 utilizes the ***WifiNetDevice*** to create a model of 802.11-based infrastructure and ad-hoc networks.

The objective of ns-3's 802.11 models is to provide an accurate MAC-level implementation of the IEEE 802.11 specification including a packet-level abstraction for distinct PHYs. Regarding the ***WifiNetDevic***e models for wireless networks based on IEEE 802.11 standard, the ns-3 supports the following IEEE 802.11 features:

- The PHY layer of IEEE 802.11a, IEEE 802.11b, and IEEE 802.11g.
- The PHY layer (including both 2.4 GHz and 5 GHz bands) for IEEE 802.11n, IEEE 802.11ac, and IEEE 802.11ax.
- Infrastructure and ad-hoc modes with basic 802.11 DCF.
- MSDU aggregation technique and MPDU aggregation extensions for IEEE 802.11n.
- IEEE 802.11e QoS-based EDCA and queueing extensions.
- IEEE 802.11s mesh and IEEE 802.11p and WAVE models.
- Various rate control algorithms such as Constant rate, Minstrel, etc.
- Distinct propagation delay models

Overall, ns-3 ***nodes*** can have multiple ***WifiNetDevices*** on separate ***Channels*** and they can coexist with other device types/network technologies.

5.2 ns-3 IEEE 802.11ah adaptation

As mentioned before, researchers from the University of Antwerp developed the ns-3 models for IEEE 802.11ah used in this thesis [69]. This implementation provides the models for the Wi-Fi channel including the propagation loss model and delay model. Regarding the MAC low layer mechanism, the model includes techniques such as DCATxOP/EDCATxOP, implements part of the RAW mechanism, packet queues, fragmentation, retransmission, and rate control.

Additionally, the MAC high module implements management functions such as beacon generation, fast association, probing, and another part of the RAW. Note that on an extension of their work in [70], they included support to RAW with an interface for dynamic configuration based on their model [71]. Besides, it includes TIM segmentation and energy consumption model and an adaptative MCS model.

However, some relevant IEEE 802.11ah's mechanisms are not implemented, such as the BSS color mechanism, and heterogeneous RAW configurations with the use of different MCS, payloads, group size. Moreover, we should take into account the use of distinct characteristics IEEE 802.11, such as control frame formats, Sub-Channel Selective Transmission, and the TWT for future development, among others.

Notice that to the best of our knowledge, there was a lacking of validation of the ns-3's IEEE 802.11ah model against an analytical model.

5.3 Simulation model's settings

In preceding chapter 3, we expose an analytical model, which was the base to validate our simulation-based study with the IEEE 802.11ah ns-3 version. We perform a throughput evaluation of the IEEE 802.11ah standard taking into account two distinct setups, one using the long header frame format and the short header MAC configurations (cf, Table 10). Refer to Table 4 for a complete PHY and MAC parameter set. Thus, results including the effects of frame aggregation technique (A-MPDU) are shown in subchapter 3.2 and 3.3 and, in chapter 6, those results regarding the e-model applied to RAW strategies evaluation.

A set of tests has been designed with the aim to evaluate the reliability of the e-model and ns-3's IEEE 802.11ah models for a simple scenario implementing EDCA, in order to configure the IEEE 802.11ah ns-3 module to adapt it to our experimentation settings. Set up includes 1 MHz channel bandwidth, 1 SS, utilizing three different MCS (MCS 10 at 150 kbps, MCS 4 at 1.8 Mbps, and MCS 9 at 4 Mbps) and packet sizes of 100 Bytes. The ns-3 simulator results are obtained averaging over a large number of different simulations, where the STAs are randomly placed within a 50 meters radius from the AP.

We have to note that ns-3's capture effect implementation (the effects of which have not been evaluated yet in the new IEEE 802.11ah radios) was disabled, providing a fairer comparison with the mathematical models used in the development of this thesis; recall that the modeled throughput with and without A-MPDU considers all collided packets are effectively lost. Confidence intervals are very small and therefore are not shown in the figure in order to facilitate the reading of Figure 21.

Depicted in Figure 21, Bianchi's model shows a difference within the ±5%, on average, on all the cases tested, in comparison with the ns-3 results under the same scenario configuration. In the case of 20 stations using the MCS 4 at 1.8 Mbps, the model shows a throughput of 0.276 Mbps, while the simulation result was of 0.270 Mbps, showing a difference of 2.275%. In contrast, in the case of 36 STAs, the Bianchi's model shows a 0.261 Mbps throughput, while the simulation provides 0.247 Mbps, resulting in the largest average difference observed, of almost 5%.

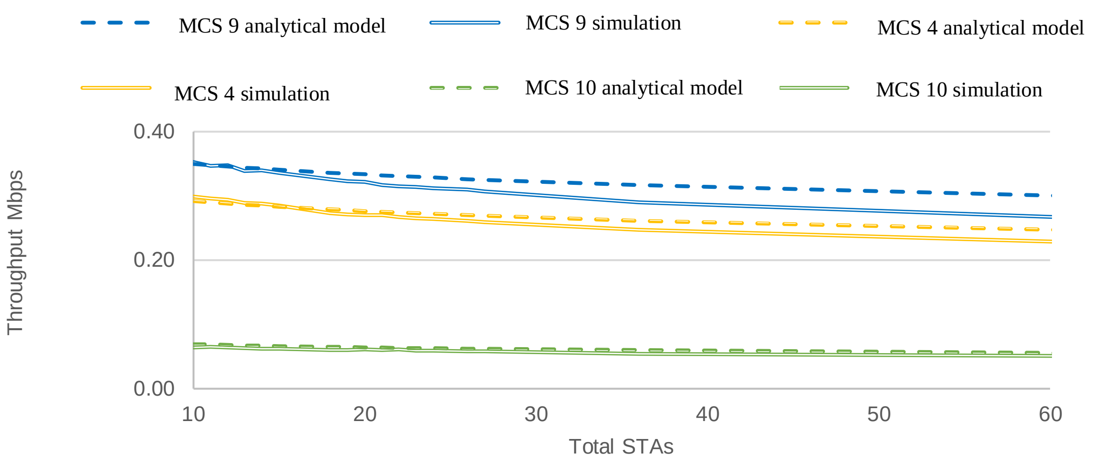

Figure 21. IEEE 802.11ah EDCA analytical model vs ns-3 simulation results.

Similarly, in the case of MCS 9 (4 Mbps), where, for example, 15 stations give an analytical throughput of 0.340 against the simulation result of 0.335, a difference of 1.46%. In the case of 27 STAs with 0.325 Mbps obtained with the analytical model throughput versus the 0.307 Mbps simulation throughput shows a difference of 5%.

The novel MCS 10 in IEEE 802.11ah, with 150 kbps, shows 0.068 Mbps vs 0.065 Mbps for analytical model and simulation results, respectively (5% difference) in the case of 11 STAs. As well, the 22 STAs case gives an e-model throughput of 0.063 Mbps against the 0.060 Mbps with an average divergence of 4%

For larger groups, the divergence increases, resulting in a difference of more than 10% in some cases. However, note that in order to reduce the number of competing STAs, the use of grouping with RAW is intended, so that slots grant access only to a few STAs, a domain in which both simulation and model provide very similar results.

Table 10. Simulation parameters

NDBPS	*6*
NES	1
NLTF	1
TIM us	200000
SLOT us	52
SIFS/uS	160
DIFS/uS	264
Tpreamble/header(us)	560
Short Lheader/Bytes	26
Long Lheader/Bytes	36

The presented evaluation highlights the validation of the analytical model against the ns-3 simulation results for IEEE 802.11ah with 3 different PHY rates (low, medium, and high). These results constitute a benchmark for saturation models in IEEE 802.11ah for homogeneous scenarios. In the following Chapter 6, we evaluate the performance of heterogeneous scenarios.

5.4 Summary

In a broader view through the development of this dissertation, we perform the study and evaluation of main IEEE 802.11ah standard features by means of its throughput with and without A-MPDU, and with multiple different configurations to evaluate it in outdoor and indoor scenarios.

Moreover, we validate the ns-3's IEEE 802.11ah model against known analytical models for IEEE 802.11ah, with the development of the e-model in chapter 6, which, to the best of our knowledge, was the first time that the IEEE 802.11ah ns-3 version is validated.

The success of the ns-3 as a tool for computer network research is undoubtedly due to the fact that it allows the researcher to perform analysis for multiple network technologies, such as 3GPP specifications, IEEE 802.11 standards, among others, avoiding the cost of implementing a hardware-based scenario for evaluation.

6. RAW grouping strategies

IEEE 802.11ah is an Internet of Things enabling technology, where the efficient management of thousands of devices is a key function. To this aim, IEEE 802.11ah provides the RAW mechanism, which reduces contention by enabling transmissions for small groups of stations.

An optimal grouping of RAW stations requires an evaluation of many possible configurations. In this chapter, we propose an analytical model (named *e-model*) that provides an evaluation of the RAW configuration performance, allowing a fast adaptation of RAW grouping policies, in accordance to varying channel conditions.

We base the e-model in known saturation models, which we adapted to include the IEEE 802.11ah's PHY and MAC layer modifications and to support different bitrates and packet sizes. As a proof of concept, we use the proposed model to compare the performance of different grouping strategies, showing that the e-model is a useful analysis tool in RAW-enabled scenarios. Notice that part of this work has been accepted for presentation and publication at the IEEE GLOBECOM 2020.

6.1 Random access window

A new contention-free channel access period called RAW [4] is included in the IEEE 802.11ah standard. RAW is defined and designed to reduce collisions and improving channel efficiency by splitting stations into different groups and delimiting channel access only to a reduced group during a particular time period.

Notice that the channel airtime is divided into multiple intervals, some of these are assigned for RAW groups, and alternatively, other periods are shared and can be accessed by all non-RAW stations using the legacy IEEE 802.11 EDCA.

The RAW Parameter Set (RPS), transmitted at fixed intervals within beacon frames, is used to announce the RAW configuration, specifying which stations belong to each group using AID, duration, and group start time. A given RAW is further divided into slots of equal duration. Within a RAW, the stations are distributed among slots following a round-robin assignment (cf. Figure 22).

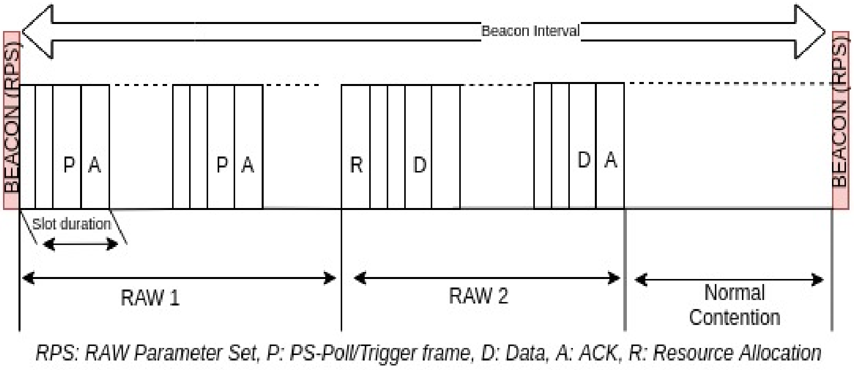

Figure 22. Restricted Access window structure.

The RAW mechanism splits STAs into groups by using the AID. Additionally, RAW splits channel access into time slots to reduce collision probability, at the same time that it assigns slots to groups where the AP indicates through its beacons the slot assignments and RAW allocation. Hence, STAs are only allowed to transmit on their group's assigned slot period.

Thus, each RAW can be divided into up to $N_{RAW} < 64$ RAW slots of equal duration, which corresponds to each STA.

$$T_{slot} = \frac{T_{RAW}}{N_{RAW}} \tag{27}$$

For the calculation of the assigned slot number to an STA we follow:

$$i_{slot} = \left(x + N_{offset} \right) mod\ N_{RAW} \tag{28}$$

where x is the position in the list of the admitted STA and the N_{offset} is a pseudo-random value used to increase fairness. Inside the RAW slot, channel access is performed by the STAs using EDCA with CSMA/CA. Hence, the STA senses the medium before the transmission is started, but waits to transmit until the medium is idle.

Furthermore, two independent back-off rules are used, one back-off state for EDCA and the second for each RAW slot, continuing the EDCA back-off when the RAW slot is finished. Take into account, that distinct backoff rules can be applied due to the different contention conditions. In order to reduce collisions probability at the moment where the medium is sensed idle, EDCA performs a backoff, this new backoff initializes a counter when the station RAW slot begins. This counter is set up with random integer uniformly drawn from [0, $CW_{min} - 1$] interval. Consequently, the STA reduces the backoff counter each time that the channel is sensed idle for its backoff slot. On the contrary, that is the case when the channel is busy; the counter is stopped and resumed when the medium is sensed idle again.

Furthermore, an STA transmits a data frame each time the backoff counter reaches 0, thus, the protocol to follow in order to transmit for the first time a new data frame starts when an STA initializes the counter again with a random integer from [0, $CW_{min} - 1$] interval. In this scenario for transmission attempt i, the new STA backoff value is over the [0, $CW_{i-1} - 1$] interval, every transmission attempt CW_{i-1} is doubled until CW_{max}.

Moreover, if the Cross-Slot Boundary feature is enabled, STAs are allowed to complete the ongoing transmission, even if they need some time beyond its assigned RAW. The STAs are as well allowed to sleep during another group's slot. On the other hand, if the Cross-Slot Boundary is disabled, an STA wakes up after the beginning of its slot; it may use only the physical channel sense to determine if the channel is free.

As mentioned previously, a particular characteristic in IEEE 802.11a is the use of two backoff periods, where the inside and outside RAW backoff are not equal. The outside RAW backoff is suspended at the moment in which RAW transmission occurs, and after the RAW duration ends the outside, RAW backoff is resumed.

The standard procedure for the inside RAW backoff, initiates at the start of each RAW. A new backoff function is generated in an STA by setting up the $CW = CW_{min}$ and the backoff time from [0, $CW_{min} - 1$], by doing it this way, the previous RAW backoff counter ends, thereby it will not overpass the new RAW backoff, achieving implementation of the fairness feature with this procedure.

6.1.1 RAW grouping

Notice that the number of groups and their duration have a big impact on the RAW optimal configuration as the authors in [72] highlight. New approaches have been studied since IEEE 802.11ah's RAW mechanism was defined, outstanding related works based on Markovian Chains presented in [73] and [74].

A new grouping scheme is proposed in [75], in which STAs are allocated by the AP to each time slot during a RAW, taking into account geographic positions in an attempt to reduce the collision probability and to decrease the hidden-node problem. In those cases, and, as other studies suggest, each RAW slot has the same duration in the entire RAW period. However, in [76], authors debate that the duration of each slot should be chosen according to the size of the group to enhance the saturation throughput for a uniform grouping scheme in IEEE 802.11ah.

In [77], an AID shuffle mechanism that works with any slot size is proposed for each STA to find, in a distributed way, a different and distinct temporary AID in each RAW to address the fixed subgroup problem. Authors in [72] determine the optimal RAW parameters as a function of the network's conditions with the aim to achieve optimal performance in terms of throughput, latency and energy-efficiency using a network simulator (ns-3), where the sub-1 GHz model and IEEE 802.11ah MAC protocol are implemented [69].

Authors in [78] present a mathematical model, which allows estimating throughput and energy consumption based on two slot based model with slot boundary crossing option enabled. A surrogate model that predicts RAW performance given specific network conditions and RAW configuration parameters is presented in [71]. Notice that the surrogate model needs an initial set-up configuration to determine the RAW parameters. The optimization of the surrogate model for IEEE 802.11ah in heterogeneous networks is presented in [79].

A sector-based device grouping scheme for fast and efficient channel access in IEEE 802.11ah is proposed by [80]; the performance of this scheme is compared with the conventional DCF and IEEE 802.11ah. MAC layer performance metric of differentiated QoS IoT nodes in IEEE 802.11ah RAW mechanism is presented in [81] .

In [82] authors study an energy-efficient RAW optimization in IEEE 802.11ah-based uplink communications, by identifying the number of slots in each RAW for different group scales and a retransmission scheme to reuse the empty slots. An algorithm based on Markov chain and probability theory is presented in [83]; the optimal solution is derived by applying a gradient descent approach aiming to reduce delay through RAW control and maximizing uplink energy efficiency.

The use of relay-based IEEE 802.11ah networks method is used in [84] to estimate the RAW size based on traffic loads, to provide relay node support for stations to use different MCSs, and to measure the suitability of IEEE 802.11ah based network in covering a wide area of a smart city.

6.2 Analytical model for the RAW evaluation

This study applies and adapts Ergen’s model, as adapted by E. Lopez-Aguilera et all. [85] On IEEE 802.11ah RAW slots, where the saturation throughput is calculated taking into account the average collision time and the average successful transmission time for the new IEEE 802.11ah standard with a single AP, one spatial stream, and a varying number of devices, as described in each strategy (cf. subchapter 6.3).

Ergen's model is an extension of the known Bianchi's model [65] to allow heterogeneous scenarios with multi-rate STAs. We modify current Ergen's model to obtain throughputs in saturation by including the IEEE 802.11ah's PHY and MAC layer modifications and to support different packet sizes. We also assume that the STAs within each RAW group show the same traffic pattern (all stations are in saturation). Note that this assumption does not necessarily mean stations are saturated all the time, which is not realistic in a practical IoT scenario; we consider that, at least during their assigned slot, the stations always have frames pending to be delivered. Under these circumstances, we argue that it is safe to consider the expression for the normalized saturation throughput of each STA operating at a given PHY rate based on the aforementioned model [85].

The bit rate of the stations involved, along with their packet size, is a major characteristic that determines the duration of a successful transmission and collision. For a multi-rate scenario, it is the value for the average duration of a successful transmission, similarly, stands for the average of values (i.e., duration of a collision). Note that the duration of a collision is determined by the STA with the longest transmission time, which depends on the packet size and the transmission rate used. In our e-model, we compute and per each slot. Within each slot, N STAs compete; and G different packet transmission times are observed, where represents the number of STAs in group $j \in (1, \mathrm{G})$:

$$\overline{T_c} = \sum_{i=1}^{N-1} \sum_{j=1}^{G} \sum_{k=1}^{N_j} \binom{N - k - \sum_{l=1}^{j-1} N_l}{i} * T_{cj} \tau^{i+1} (1-\tau)^{N-1-i} \tag{29}$$

$$\overline{T_s} = \sum_{j=1}^{G} N_j T_{sj} P_{sj} = \tau(1-\tau)^{N-1} \sum_{j=1}^{G} N_j T_{sj} \tag{30}$$

where P_{sj} is the probability, in each group j, that exactly only one station transmits in a randomly chosen slot time, and this transmission is successful, τ is the probability that a station transmits in a randomly chosen slot time. T_{sj} corresponds to the total time required by a STA in group j to successfully transmit a frame (including inter-frame space and corresponding ACK control frame).

Note that Bianchi already defines T_c and T_s (cf. [65]), and Ergen explains how to obtain $\overline{T_c}$ and $\overline{T_s}$ for multi-rate scenarios [85], which we adapted to also support multiple packet sizes. Please, refer to [65] and [85] for more details.

For the calculations of $\overline{T_c}$, consider that a given STA's transmission collides if i other stations also attempt transmission, $i \in (0, \mathrm{N} - 1)$. The duration of a collision is determined by the STA with the largest transmission time (i.e., largest T_{cj}), thus, the order in which the G groups are considered is important: j = 1 stands for the group of stations with the largest transmissions, and j = G for the fastest. Observe that $\overline{T_c}$ expression applies when $N \geq 2$ and $G \geq 2$.

The e-model's per-RAW slot aggregate saturation throughput is then calculated as:

$$S_{slot} = \sum_{j=1}^{G} N_j S_j = \frac{\tau(1-\tau)^{N-1} E_p}{E_s} * N \tag{31}$$

Using the e-model, E_p consists in the average data frame payload size and, according to Bianchi's definition, E_s, the average duration of a slot (Bianchi's slot definition), where a transmission event, collision or absence of transmission at a given instant, not to be confused with a RAW slot (i.e. divisions of a RAW), is as follows*:*

$$E_s = P_\sigma \sigma + \overline{T}_s + \overline{T}_c \tag{32}$$

where P_σ consists in the probability that the slot time is empty, and σ is the duration of an empty slot (cf. [65]).

The total throughput, considering all R RAW groups, each one consisting of K_r RAW slots, is computed as follows:

$$S_{total} = \sum_{r=1}^{R} \frac{d_r * \sum_{k=1}^{K_r} \frac{S_{slot_k}}{K_r}}{d_{total}} \tag{33}$$

where d_r is the duration of the *rth* RAW and d_{total} is the total duration of all *R* RAWs.

6.2.2 Performance evaluation of the e-model

The evaluation is carried out by means of simulations using the ns-3 simulator presented in Chapter 5. A variable number of STAs using EDCA forms the following performance evaluation scenario presented. Three different types of STAs are present (i.e., *G*=3), each group defined by the use of a given MCS and a given packet size; the number of STAs in each group is the same (i.e., = *N*/3 for *j* = 1, 2 and 3).

EDCA multi-rate analytical model comparison against the EDCA multi-rate ns-3 simulation is depicted in Figure 23. The difference between the model and the simulation varies from 0.113 Mbps versus 0.112 Mbps throughput with a total of 39 STAs (<0.2%), to 0.094 Mbps versus 0.090 Mbps in the case of 90 STAs (~4%).

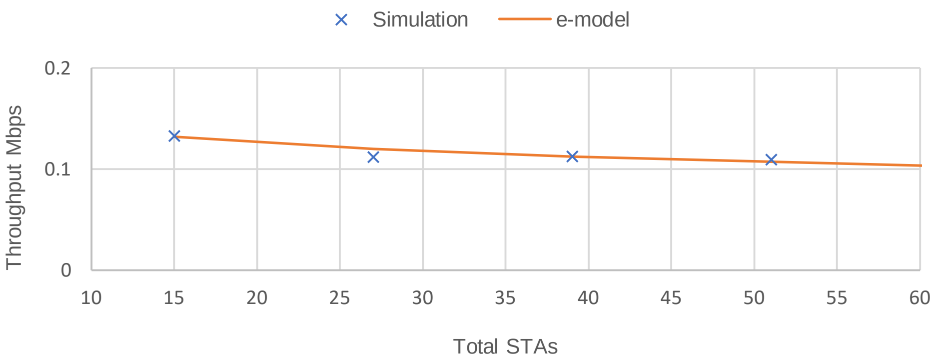

Figure 23. IEEE 802.11ah EDCA multi-rate analytical model vs ns-3 simulation results.

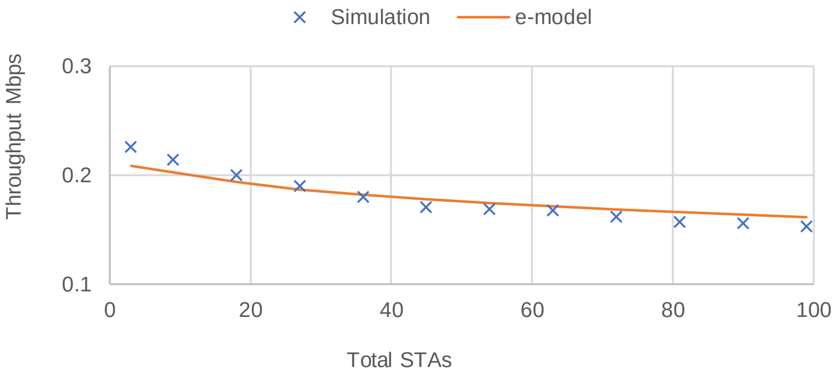

Figure 24. IEEE 802.11ah RAW feature with two groups, analytical model vs ns-3 simulation results.

Lastly, Figure 24 depicts the use of the RAW feature considering two RAW groups, each one of them with one slot. The first RAW group is composed of fast STAs employing MCS 9 (4 Mbps), and the second RAW group includes slow stations operating with MCS 4 and 10 (1.8 and 0.15 Mbps). The same trend is observed as shown in Figures 21 and 23, with a difference within ±5% between the results of the e-model and the simulator.

Taking as sample the simulation throughput with 36 stations, a simulation result of 0.180 Mbps against the e-model throughput of 0.182 Mbps can be observed, with an average 1.09% difference. With 72 stations, a simulation throughput of 0.162 Mbps is obtained in front of the e-model throughput of 0.168 Mbps, showing an average difference of 3.5%.

All of the above results validate the functionality of the proposed e-model and make it particularly valuable for predicting the performance of a given RAW configuration, thus making the e-model a useful analysis tool in RAW-enabled scenarios.

6.3 Applicability and grouping strategies of the model

In this section, we show a simple e-model-based grouping is capable of enhancing the RAW performance by evaluating different strategies with different RAW configurations, and selecting the best strategy to use in each case. To that aim, we present a timeline (seconds), where RAW grouping is enabled and different stations (with different PHY rate) become active or inactive dynamically. We evaluate the scenario using different baseline RAW grouping strategies, as described below.

All the strategies presented below are evaluated in the same scenario with the same configuration (100 Bytes of payload, 1 MHz channel bandwidth, 1 spatial stream), and three different MCS available (MCS 4, 9 and 10), where each strategy combines a different number of STAs with fast MCSs or slow MCSs. The number of STAs and their MCS is varying constantly as the transmission evolves.

a) *Strategy 1:* legacy EDCA mode (i.e., no RAW in use).

b) *Strategy 2:* three RAW groups defined, one per each MCS (i.e., STAs with different MCS are not mixed). This strategy is focused on medium contention reduction because it divides STAs into smaller groups and reduces the performance anomaly [86] (i.e., performance degradation in the presence of slow STAs).

c) *Strategy 3*: STAs are split into three RAW groups, equally distributing fast and slow STAs (i.e., mixed MCSs). This strategy aims to reduce contention while keeping fairness among groups.

d) *Strategy 4*: two RAW groups, one for the fastest transmission MCSs (1.8 Mbps and 4 Mbps), and a second group where all the stations use the slowest MCS 10 (150 kbps). This strategy maximizes the throughput of the fast STAs by avoiding the performance anomaly; it also reduces contention.

e) *Strategy 5:* same as strategy 2 (i.e., three groups, no mixed MCS), but in this case, the RAW duration depends on the number of STAs in each group.

f) *Strategy 6 (e-model)*: computes the expected saturation throughput in the current network state for all the above strategies, following the model described in Subchapter 6.2 and selects the one providing the best throughput.

Considering the aforementioned strategies for the RAW configuration in IEEE 802.11ah, the evaluation performed, as shown in Figure 25, highlights that the e-model strategy is capable of identifying the best grouping strategy, provided that the number of stations with pending frames, their packet size and their MCS are known.

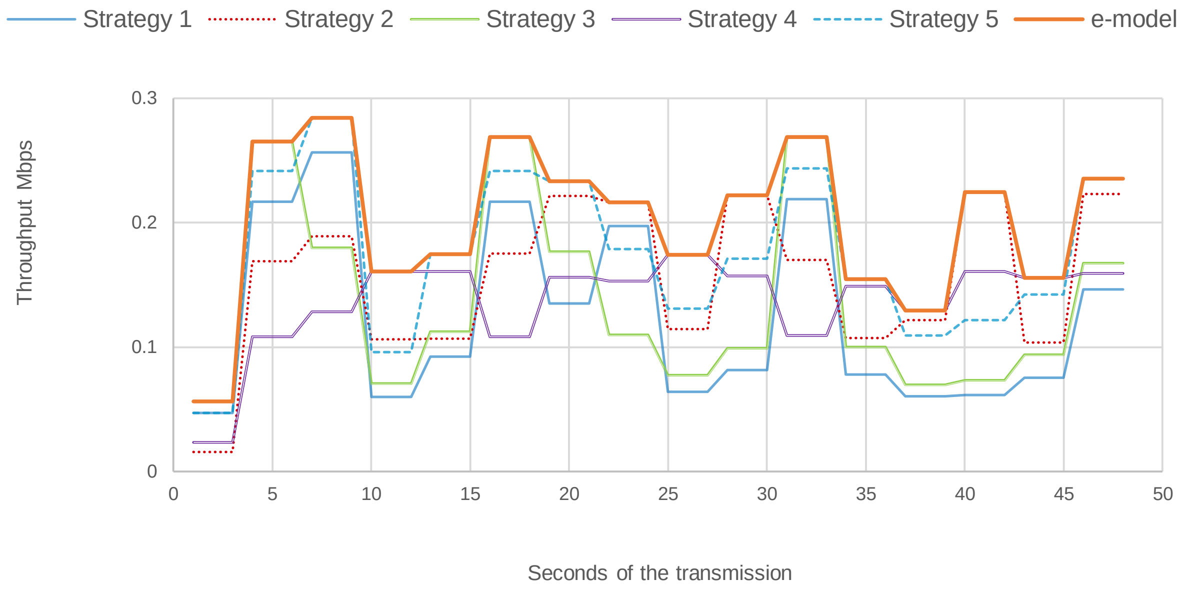

Figure 25. Different RAW grouping strategies against the e-model.

Note that different strategies perform better than others in different scenarios. For example, the network configuration after 10 seconds is better managed by strategy 4, with 0.1608 Mbps throughput, thus defeating the other strategies; the same applies at 26 seconds time with a maximum throughput of 0.1734 Mbps. Note that strategy 4 also wins at instant 45 seconds reaching a throughput of 0.1559 Mbps.

A different scenario happened in seconds 9, 15, 21, and 48, where strategy 5 shows the best performance, giving throughputs of 0.2843, 0.1748, 0.2335, and 0.2352 Mbps, respectively. Strategy 3 is the best option in seconds 1, 18, 33, showing a throughput of 0.0565, 0.269 and 0.2689 Mbps, respectively. In all cases, the best performing strategy was properly identified by the e-model and, therefore, strategy 6 was able to match the best performance among the other strategies.

These results validate the utility of the e-model as a tool for any strategy in order to assess the performance of a given RAW configuration, set for a given network scenario.

6.4 Summary

New standards and mechanisms are needed to solve the massive number of stations expected to be supported by IoT networks using multiple applications, each one of them with different requirements, such as QoS, latency, energy consumption and throughput.

In the present work, we propose an analytical tool (e-model), altogether with the ns-3 simulator with specific modifications to RAW mechanism, for evaluating heterogeneous RAW configurations.

Additionally, the e-model is used to validate the simulations results obtained in ns-3, being this, to the best of our knowledge, the first time that ns-3's IEEE 802.11ah models are compared to analytical models. For the sake of clarity, the IEEE 802.11ah evaluation is performed by employing 3 different PHY rates (low, medium, high).

These results constitute a benchmark for saturation models in IEEE 802.11ah for homogeneous scenarios, where all STAs are using the same MCS, and for heterogeneous scenarios, with STAs operating at different PHY rates.

RAW performance is evaluated by using distinct strategies with different RAW configurations, and the e-model is thus shown to be a useful tool to assess the best RAW performance for a given network scenario.

7. Final Discussion

The overwhelming appearance of the Internet of Everything is present every day and it is becoming an important part of modern life in all of its forms, as the Internet of Humans and the Internet of Things. Those are the main drivers that are shaping our future in the mid and long term, along with the researchers' skills and abilities to interconnect the digital and the real world through the Internet.

Tactile Internet concept was born in the past years [87] with the main aim to provide 'latency zero' in all the applications with similar needs. e.g., autonomous cars, smart cities, telemedicine, tele-surgery, distant robot operations, among others.

In the near future, we will be experiencing new forms of interaction with objects, applications, platforms, and even complete digital systems that will be able to predict our choices and our likes or dislikes, due to machine learning and artificial intelligence, technologies that are under development nowadays. The integration of IoE, machine learning algorithms as a part of Artificial Intelligence (AI) applications, or Big Data analysis will open the new requirements for services, applications, and needs that will enhance the wellness of citizens.

In a broader view, it is clear that IoE brings numerous benefits in many scenarios. Smart Cities, Industry 4.0, and Vehicular Ad-hoc Networks (VANETs) have a shared key feature to success in their fundamental applications that is the latency.

As a consequence of the IoT concept, there are new scenarios with ultra-dense networks like Smart Cities, and there are massive devices deployments using wireless networks in diverse environments (e.g., homes, offices, streets, campuses, industry, farms, warehouses, among others), where different devices (e.g., sensors, smartphones, computers, wearables, and more) have to compete to gain communication resources and, at the same time, cooperate to enforce a global interconnection.

IEEE based WLANs (due to their ease of deployment and cost-efficiency) could be used as a viable alternative technology for IoT environments if the restrictions of high-power consumption and the limited number of associated stations are overcome.

There is a need to adopt universally accepted, cost effective, and scalable communication technology within IoT framework. IEEE based WLANs (due to their ease of deployment and cost efficiency) could be used as viable alternative technology for these aforementioned scenarios, with the IEEE 802.11ah standard.

At this point, it is important to mention that the top of the IoT communications networks is undeniably going to be the 3GPP 5G networks [88], the next generation of cellular wireless communications. Due to the above reason, both interoperability and integration with Wi-Fi networks are going to be key features to fulfill the requirements of the future scenarios in the coming years.

In the case of cellular technology implementation, we have to take into account what this technology has to offer for IoT use-cases. Note that for multiple use cases and scenarios, the use of the Wi-Fi networks is going to be needed in order to have an interconnected network to perform quality services with low latency for indoor and outdoor scenarios around the globe.

The focus of this thesis has been to study the IEEE 802.11ah standard as one of the paramount technologies to IoT scenarios-based Wi-Fi networks. In order to tackle the IoT scenarios challenges, for proper operation in IoT scenarios, IEEE 802.11ah defines the operation of license-exempt wireless networks 1 GHz frequency bands and below.

Wi-Fi HaLow was developed with the ability to operate in outdoor scenarios (not excluding indoors) and with the characteristic to support point to multipoint applications. The mode of operation in the PHY layer ensures transmission range up to 1 km if needed and typical data rates from 100 kbps, designing a new MAC layer to support up to 8000 connected devices.

In a broader view, the PHY mode operation transmitting in sub 1 GHz improves propagation and penetration for large coverage area in the license-exempt frequency, improving the reliability of the communications with a high sensitivity and link margin, adding diversity frequency, time, and space, giving the improvement in longer battery energy life due to the short data transmission.

The MAC layer reduces overhead by using short MAC headers removing the duration, QoS, HT, and sequence control fields. Moreover, the NDP in the PHY header concentrates control frames information. In addition, sending beacon frames with a lower frequency rate, and not using ACK transmissions when employing the BDT mechanism, decreases battery consumption and increases the channel efficiency.

The IEEE 802.11ah protocol includes the hierarchical AID mechanism, a new structure that allows distinct STAs grouping to be capable of differentiating them according to multiple heterogeneous features. Additionally, the support of thousands of STAs associated to the same AP is improved by using the RAW feature, which consists in splitting into time slots the channel access, and dividing STAs into groups (AID).

The standard definition allows a configurable bandwidth with channel bonding of 1 MHz and 2 MHz (mandatory bandwidths). Following this, each country defined their own frequency bands and transmission power allowed between the limits of the IEEE 802.11ah specification. The standard specifies PHY rates from 150 kbps (using MCS10, one stream at 1 MHz frequency with long GI) to 347 Mbps (with MCS 9, along with 4 streams at 16 MHz and using short GI).

In the present dissertation, we evaluate the main characteristics and benefits provided in terms of throughput and transmission range by the most notable IEEE 802.11 specifications compared to the IEEE 802.11ah amendment. Detailed results indicate that IEEE 802.11ah benefits from the widest coverage with more than 8 times improvement against any other IEEE 802.11-based amendment, due to the lower frequency band, a narrower bandwidth, and a more robust coding scheme.

After all, the analysis of the results presents IEEE 802.11ah and shows that it can provide throughput close to 100kbps in the worst case, which is enough to cover most IoT applications.

IEEE 802.11ah shows, at least, a fivefold increase with respect to the second-best range (IEEE 802.11a), and more than ten times improvement with regard to the worst case (IEEE 802.11n in the 2.4GHz band). On the other hand, IEEE 802.11ah presents the lowest throughput, in comparison with other amendments, a maximum throughput of 144 kbps (reduced to 71 kbps when PER = 50%) can be achieved at the limits of its estimated coverage, which is enough for the use cases this technology is targeting. Giving the use case scenarios, where the size of data frames is inherently small, the use of aggregation slightly mitigates the excess of overhead, but its impact is limited by the low data rates that 802.11ah devices will support.

The potential coverage at reasonably high rates exhibited by IEEE 802.11ah makes it a very appealing alternative in fulfilling the needs of future IoT communications. Among the characterization of IEEE 802.11ah performed in this dissertation, we provide a comparison between different technologies contending to cover the IoT communications framework, and thus indicate IEEE 802.11 technology as one of the strongest contenders.

We give a thorough analysis of the requirements of many typical IoT applications (classified as permanent connectivity, event-based applications, audio, video, data and biometrics), assessing the number of supported devices per AP, with up to 1 km of coverage. In the cases where the required coverage distance is larger than 1 km, IEEE 802.11ah can be used to build a multi-hop distribution system.

We also provide an analysis of the implementation and infrastructure costs that make IEEE 802.11ah very appealing against other IEEE 802.11 specifications and competing wireless technologies. Overall, the expected performance of IEEE 802.11ah asks for a remarkable place in the IoT landscape.

New standards and mechanisms are needed to solve the expected massive number of stations supported by IoT networks using multiple applications with different requirements, such as QoS, latency, energy consumption and throughput.

In the present work, we propose an analytical tool (e-model), together with the ns-3 simulator with specific modifications to RAW mechanism, for evaluating heterogeneous RAW configurations. Additionally, this e-model is used to validate the simulations results obtained in ns-3; being this, to the best of our knowledge, the first time that ns-3's IEEE 802.11ah models are compared to analytical models.

For the sake of clarity, the IEEE 802.11ah evaluation is performed by employing 3 different PHY rates (low, medium, high). These results constitute a benchmark for saturation models in IEEE 802.11ah for homogeneous scenarios, where all STAs are using the same MCS, and for heterogeneous scenarios, with STAs operating at different PHY rates. RAW performance is evaluated by using distinct strategies with different RAW configurations, and the e-model is thus shown to be a useful tool to assess the best RAW performance for a given network scenario.

Additionally, to the achievements obtained in the development of this Ph.D. Thesis, it is proper to mention by the contributions of this work and the journal publications, we have inspired other researchers' works, knowing this by the citations in other investigators´ publications.

Besides the previous achievements, we acquired the experience to have studied and worked with the IEEE 802.11ah standard from the envisioning of the TGah until the release of the aforementioned standard and to get the knowledge about IEEE 802.11 standardization development. All of the above accomplishments form part of the experience obtained as a researcher.

As a part of our future work, to continue this research work, we consider the possibility to enhance the e-model developed in Chapter 6 with some machine learning techniques, like with the use of a genetic algorithm or a reinforcement algorithm in the IEEE 802.11ah RAW feature. In this scenario, the proposed e-model could be cataloged as a tool that allows us to select the best grouping strategy at different times in a time period

Thus, this e-model behavior can be used as an input of a genetic algorithm that consists in the search of a heuristic based on the theory of natural evolution by Charles Darwin. This theory is based on reflecting the process of natural selection, in this proposed optimization, the e-model is used to predict/select the finest grouping strategy available in an IEEE 802.11ah wireless network. As a result, we could get the best working configuration across distinct stations operating each of them at different MCS to enhance the RAW mechanism.

On the other hand, the use of a reinforcement-learning algorithm in a simplistic concept could use the experience to set up initial model transitions and outcomes in the environment based on the e-model selected strategies, where the right actions are chosen by searching or planning in this model according to the desired RAW configurations.

Following the previous assumptions, the same opportunity to future work is open to interact with the cloud and edge computing with or without the addition of artificial intelligence capabilities. These are some of the other branches that can be used as target research topics to continue the work presented in this thesis.

To sum up, cloud-computing applications require high throughputs and regular latency, over interconnected networks with QoS requirements. In order to fulfill the requirements of the aforementioned scenarios requirements, IEEE 802.11ah can be used as a viable connectivity option in specific applications, where its characteristics (long coverage range, data rate, and the number of stations supported) can give a better approach than other IoT technologies, and at the same time, fulfill the QoS required for this kind of applications.

Moreover, the edge computing scenarios could be another path to continue the future work of this research, where M2M networks communications are used typically as sensors, actuators, and machines that are computing and using network resources in the middle of the path between data sources and cloud data centers.

Furthermore, edge-computing applications require network communications with both regular throughputs and rapid responses with low latency, including the possibility that a machine learning algorithm would be capable to differentiate the needs of each STAs according to priority requirements at a specific moment of the transmission and execution of the application across the compute continuum.

IEEE 802.11ah could be the principal technology to cover edge computing connectivity requirements by using it as a backbone between wireless sensor networks and the cloud data centers in order to satisfy edge computing scenarios. On the other hand, through this dissertation, IEEE 802.11ah has demonstrated its capabilities to support and fulfill IoT application requirements. Since both edge computing and the IoT use-cases scenarios have similar communications requirements, they look to fulfill the same goals, the aim to improve human wellbeing.

Publications

[P1] *V. Banos, M. S. Afaqui, E. Lopez, and E. Garcia, "Throughput and Range Characterization of IEEE 802.11ah," IEEE Lat. Am. Trans., vol. 15, no. 9, pp. 1621–1628, 2017*[19].

Journal Impact Factor: 0.502, quartile: Q4, published in 2017 Area: Computer Science, Information Systems

[P2] *V. Baños-Gonzalez, M. S. Afaqui, E. Lopez-Aguilera, and E. Garcia-Villegas, "IEEE 802.11ah: A technology to face the IoT challenge," Sensors (Switzerland), vol. 16, no. 11, p. 1960, Nov. 20 16*[20].

Journal Impact Factor: 2.677, quartile: Q1, published in 2016 Area: Instruments & Instrumentation

[P3] *V. Baños-Gonzalez, E. Lopez-Aguilera, and E. Garcia-Villegas, "E-model : An analytical tool for fast adaptation of IEEE 802 . 11ah RAW grouping strategies."*

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