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WLAN as an offloading solution for mobile cellular networks

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Abstract:

The impact that WiFi networks have on today's society has been growing significantly during recent years. As a consequence, the number of devices and systems that give support to this technology nowadays is increasing exponentially. Only a limited number of investigations have been carried out on pushing forward the limits of WiFi. Nevertheless, mobile operators have started envisioning WiFi as a system which may give support to the mobile cellular networks as an offloading solution for part of the traffic they have to deal with.

This work focuses on evaluating WiFi performance and behavior in medium and large scale deployments. Furthermore, we propose an algorithm for dynamic channel selection that can improve WiFi performance in congested areas. Results show an improvement in networks where dynamic channel selection is used.

Preface

This report aims at documenting investigations of realistic Wireless LAN networks in medium/large scale deployments. The project has been carried out in cooperation with Nokia Siemens Networks, Aalborg site. It consists of the following chapters: 1. Introduction; 2. IEEE 802.11 WLAN; 3. Large scale deployment for IEEE 802.11; 4. Dynamic channel selection; 5. Conclusions. References, Bibliography and Appendixes are included in the end of the report.

Simulations were run on a proprietary Nokia Siemens Networks simulator. Note that all the information relative to the simulator is strictly confidential.

Matlab has been used to give support to different calculations.

The authors would like to acknowledge Gustavo W.O. Costa and Andrea F. Cattoni for their assistance during the whole project work time.

Francisco Galvañ Penalva

Luis Felipe Díaz López

Aalborg University, 31st May, 2011

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We would also like to make a special mention to our supervisors, Gustavo W.O. Costa and Andrea F. Cattoni for their support and their help during the whole project.

From this point, we would like to split our personal acknowledgements.

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Primero que todo, agradezco a mi familia que siempre ha estado ahí apoyándome en las buenas y en las malas. Todo lo que he logrado hoy en día ha sido por ese espíritu luchador y positivo que siempre me han enseñado. Gracias Tomas, Marta y Titi.

Thanks to all my friends that made special my student life and also special thanks from those that I learned.

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It is something to remark the way all my colleagues, professors and friends helped me through my university years to reach the point where I am now. Particularly Nuria, she was always there during the good and the bad times.

I would like to give my special thanks to my Aalborg family, Sara, Lucas, Javier, Marta, Ignacio, Carlos, Pablo and Mario for making my stay in Denmark a wonderful experience and for making me feel like at home.

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haber alcanzado los objetivos marcados y haberme convertido en la persona que soy hoy en día.

‘A problem cannot be solved thinking in the same way that when it was formulated’

Albert Einstein

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Abbreviations and acronyms

ACK	Acknowledgment.
AIFS	Arbitration Interframe Space.
AP	Access Point.
BPSK	Binary Phase-Shift Keying.
BS	Base Station.
BSA	Basic Service Area.
BSS	Basic Service Set.
BSSID	Basic Service Set Identification.
CCA	Clear Channel Assessment.
CCK	Complementary Code Keying.
CDF	Cumulative Distribution Function.
CR	Collision Rate.
CRC	Cyclic Redundancy Code.
CS	Carrier Sense.
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance.
CTS	Clear To Send.
CW	Contention Window.
DA	Destination address.
DCF	Distributed Coordination Function.
DCS	Dynamic Channel Selection.
DIFS	Distributed Interframe Space.

DR	Deployment Ratio.
DS	Distribution System.
DSSS	Direct Sequence Spread Spectrum.
EDCA	Enhanced Distributed Channel Access.
EIFS	Extended Interframe Space.
ERP	Extended Rate PHY.
ESS	Extended Service Set.
FCS	Frame Check Sequence.
HCCA	HCF Controlled Channel Access.
HCF	Hybrid Coordination Function.
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers.
IFS	Interframe Space.
ISI	Intersymbol Interference.
ISM	Industrial Scientific Medical
LAN	Local Area Network.
LTE	Long Term Evolution.
MAC	Medium Access Control.
MPDU	MAC Protocol Data Unit.
NAV	Network Allocation Vector.
OFDM	Orthogonal Frequency Division Multiplexing.
PC	Point Coordinator.
PCF	Point Coordination Function.
PIFS	Point Interframe Space.
PLCP	Physical Layer Convergence Procedure.
PMD	Physical Medium Dependent.
PPDU	PLCP Protocol Data Unit.

PSK	Phase Shift keying.
QAM	Quadrature Amplitude Modulation.
QoS	Quality of Service.
QPSK	Quadrature Phase Shift keying.
RA	Receiver Address.
RTS	Request To Send.
SA	Source Address.
SAP	Service Access Point.
SIFS	Short Interframe Space.
SSID	Service Set Identifier.
STA	Station.
TA	Transmitter Address.
UML	Unified Modeling Language
VCS	Virtual Carrier Sensing.
VoIP	Voice over Internet Protocol.
WiFi	Wireless Fidelity.
WLAN	Wireless Local Area Network.
WM	Wireless Medium.

Chapter 1

Introduction

1.1 Wireless Local Area Networks

Over the past few years, the world has become increasingly mobile. Wireless LANs are ideal for environments such as homes, offices, and public places because it supports users mobility, it is easy to install and it is not expensive. Mobility is one of the most obvious advantages of wireless communications, making the users life easier.

The most successful Wireless LAN technology has been IEEE 802.11 (WiFi) allowing wireless connection in local area network environments by using the unlicensed frequency bands of 2.4GHz or 5GHz. This technology is growing quickly. [10] Predicts that for 2012 the number of electronics devices with WiFi will likely reach 1 billion. Now, the challenge is in how to supply a good wireless connectivity with the resources available.

Furthermore, not only WiFi devices are sharing the wireless medium, lot of new devices appear in today's life, devices such as new mobile phones that are able to support more and more applications[1] with their corresponding needs of bandwidth and with their corresponding need to achieve high data rates. [12] Explains and illustrates in some studies that the demand for data traffic in mobile cellular networks is around 500 exabytes; and it is predicted to reach the 4000 exabytes by the year 2014.

This project provides a study of the IEEE 802.11 WLANs performance and a proposal improvement of it based in a frequency spectrum allocation technique.

[1] Flash videos on the internet and streamed television programming are the major contributors of today data traffic.

1.2 Motivation for the WiFi studies

Conversely to common sense, an efficient Wireless LAN is not the one which has a larger coverage area; it is the one that gives the correct throughput for data and multimedia applications. Nowadays Wireless LANs have a big challenge to provide the necessary throughput required by today's applications in order to give the best quality possible to the final user as the demand capacity is increasing more and more.

Lately, there are great discussions about the deployment of small base stations (BS), so called Femto BS, in connection with the next mobile communication generation (4G). Femto BS could be used to provide coverage and capacity in local areas as a complement to the existing macro and micro BS networks. Femto BSs are expected to provide high performance but the problem is the spectrum allocation and the inclusion within the operator's core network.

Alternatively, the IEEE 802.11 WLANs can also be used to be an offloading solution for mobile cellular networks.

Due to the fact that IEEE 802.11 WLANs are widely deployed and it uses an unlicensed band of the frequency spectrum (an advantage due to the fact that there is no need to spent money in buying frequencies), the main motivation for this project is to investigate to what extent WiFi networks performance can be improved to be used as an offloading solution.

Can be improved the IEEE 802.11 network performance with a dynamic channel selection mechanism?

1.3 Definition of the problem and scope of the thesis

There are few studies about to which extent IEEE 802.11 WLANs can work properly with the quality demanded by the users in hot-spot areas where there is a high user and networks density. Some of these studies have proved that IEEE 802.11 WLANs have a mutual impact in their performance when different networks are in close proximity to each other. In particular, [3] found that cumulative throughput can decrease around 50% with four networks sharing the same channel while it can be keeping its robustness with over one hundred users connected to an isolated network (associated to one access point).

The lack of studies for large scale deployments due to the fact that until now there was not a real interest in this kind of networks, lead us to a great challenge where to find a solid base study for how IEEE 802.11 WLANs behave in large scale deployments. To achieve this we go through a great amount of simulations and scenarios comparisons in order to obtain a better understanding of how exactly WLANs behave in these large scale deployments.

Furthermore, once obtained the necessary knowledge and a solid base study of this, our goal is to provide recommendation for offloading purpose on the WiFi networks deployment as well as an improvement to WiFi with the dynamic channel selection mechanism.

1.4 Outline

The thesis is structured as follows:

Chapter one gives a short overview about which are the motivations, the goals of the project, a brief introduction to WLANs and a section where abbreviations and acronyms are explained.

Chapter two explains the main theoretic information and knowledge required to understand what the IEEE 802.11 WLANs are, how they are structured, which architecture they have and more important of all, how they work.

Chapter three presents the problem of having a great network density in a certain area. Large scale deployments studies are done, where simulations and their corresponding results provide an idea of how networks perform in this kind of scenarios.

Chapter four is the core of the project where it is explained how our dynamic channel selection algorithm can improve the performance of a network base on the results obtained in chapter three.

Chapter five will addressed the conclusions about the project.

Finally, references, bibliography and several appendixes are in the end of the report, where it is also shown the models that support our studies.

Chapter 2

IEEE 802.11 WLANs

2.1 Introduction

The IEEE 802.11 Wireless LAN is known by the most people as WiFi is composed by a standard and several amendments in order to establish the rules, components and the architecture to follow for implementing this technology.

This technology works in the ISM band, more specific in the 2.4GHz and in the 5GHz bands. The big advantage of these bands is that they are unlicensed or free licensed bands all over the world which makes the WiFi technology a cheap one.

The most important versions nowadays are 802.11a, 802.11b, 802.11g and the amendment 802.11n; where 802.11a works in the 5 GHz band, the 802.11b and 802.11g work in the 2.4 GHz band and the 802.11n work in both bands. Table 2.1 summarizes the most relevant characteristics of these versions and amendment.

Standard/ amendment	802.11a	802.11b	802.11g	802.11n
Frequency Range	5.1 – 5.8 GHz	2.4 – 2.485 GHz	2.4 – 2.485GHz	2.4 – 2.485GHz 5.1GHz – 5.8GHz
PHY data rates	6, 9, 12, 18, 24, 36, 48, 54 (Mbps)	1, 2, 5.5, 11 (Mbps)	1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, 54 (Mbps)	802.11g data rates plus other 20 more up to 600 (Mbps)

Table 2.1 *IEEE 802.11 characteristics*

Apart from the differences in the physical layer, it is important to point out that all three versions and the amendment make use of the same protocol for accessing to the wireless medium. This is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which will be explained later in this chapter.

All three versions of the standard and the amendment can work in *infrastructure mode* or in *ad-hoc mode*. Also all of them allow the use of link adaptation techniques to improve the performance of the system by adapting the transmission rates depending on the channel conditions[2], but only in 802.11n the methodology has been specified.

2.2 Components and architecture

The 802.11 standards define an architecture and several components that interact with each other for giving to a WLAN communication and mobility in a proper way.

Figure 2.1 shows the most important components of a common used architecture (infrastructure mode) in which three users are associated to an access point in order to have access to the Internet through a WLAN.

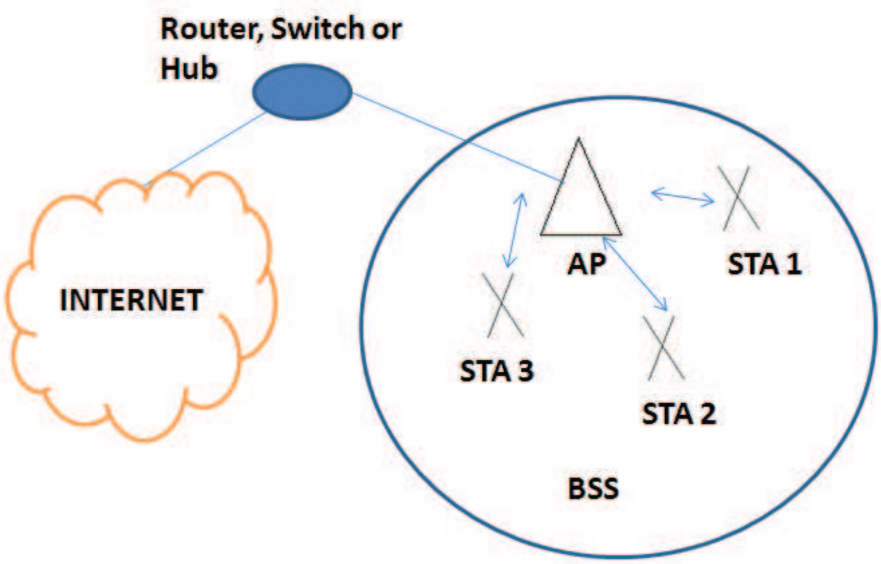

Figure 2.1 *802.11 WLAN architecture and components (infrastructure mode)*

[2] Not used in this project where only the maximum data rate is used due to the small coverage areas in consideration.

The BSS is the main block of an 802.11 LAN. In the Basic Service Set (BSS) there is a group of components such as stations that can be access points, client stations or both at the same time that communicates with each other.

The access point is any entity that gives access to the Distribution System (DS) through the wireless medium for the client stations that are associated.

The client station can be computers or devices with a wireless interface.

The distribution system is the component for interconnecting different BSSs and integrating LANs to create an Extended Service Set (ESS), which allows creating wireless networks of different size and complexity. This can be seen in figure 2.2.

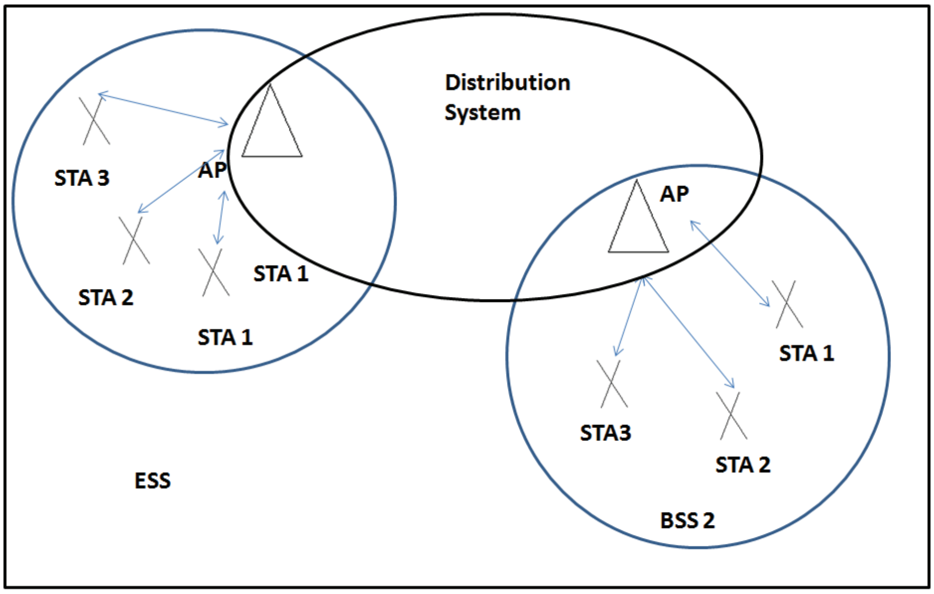

Figure 2.2 *Two BSSs connected through a distribution system forms an ESS*

2.3 Physical layer

There are several aspects that can be commented about the IEEE 802.11 physical layer, but we are going to focus in the ones that we have used for our studies (architecture, Orthogonal Frequency Division Multiplexing (OFDM), physical frame format and physical specifications). These are the ones for the IEEE std 802.11- 2007 [1]:

This standard specifies different types of modulations and coding such as direct sequence spread spectrum (DSSS), complementary code keying (CCK), orthogonal frequency division multiplexing (OFDM), and DSSS-OFDM in order to achieve the different data rates that are specified. The physical specifications will be explained later in section 2.3.4.

2.3.1 Architecture

The architecture of the physical layer consists on the Physical Layer Convergence Procedure (PLCP) sublayer and the Physical Medium Dependent (PMD) sublayer.

The first one is used in order that the IEEE 802.11 MAC layer works with the less dependence possible on the PMD sublayer. The MAC layer communicates with the PLCP sublayer via the service access point (SAP) through which MAC protocol data units (MPDUs) are accepted.

The PMD gives the means to send and receive data between stations.

Figure 2.3 shows the physical layer architecture.

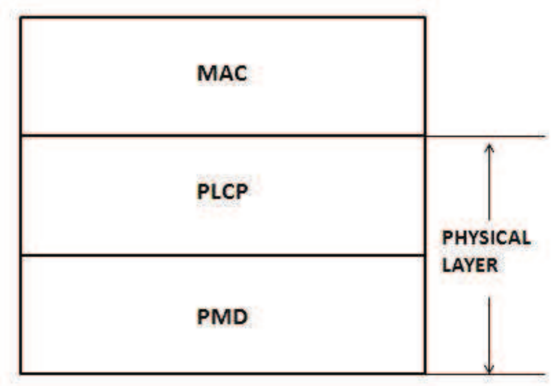

Figure 2.3 *Physical architecture*

2.3.2 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a multiplexing multicarrier technique where multiple subcarriers of low capacity are combined in order to achieve a higher capacity. The most important concept about OFDM is that the subcarriers are orthogonal among them having a separation in frequency of 1/T as a minimum requirement for the orthogonality, where T is the period of the signal. OFDM subcarriers can be seen in figure 2.4.

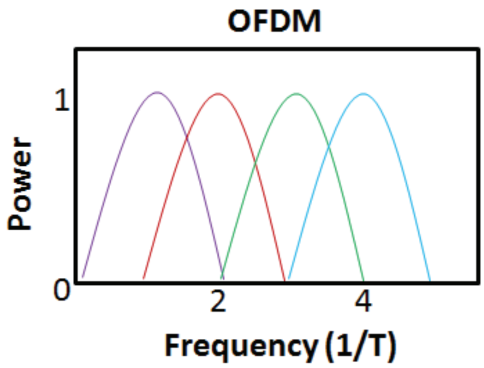

Figure 2.4 *OFDM signal*

The data for transmission is divided into several channels in parallel, using one of these channels for each subcarrier. Each subcarrier is modulated with a modulation technique such as QAM or PSK.

To point out one of the advantages of the OFDM is its capacity to deal with the frequency selective fading caused by multipath without complex equalizers and the possibility to eliminate the ISI because of the low symbol rate (compared to a single carrier signal with the same capacity) that makes affordable the use of a guard interval between symbols.

2.3.3 Physical Frame format

The physical frame is composed mainly by a preamble which is the responsible of timing and synchronization issues; the signal where it is specified characteristics as data rates, length and so on; and the data which is a field of variable length. To point out that the signal is modulated and coded in BPSK, r=1/2, while the data has a rate indicated in the rate subfield in signal.

This can be seen in figure 2.5.

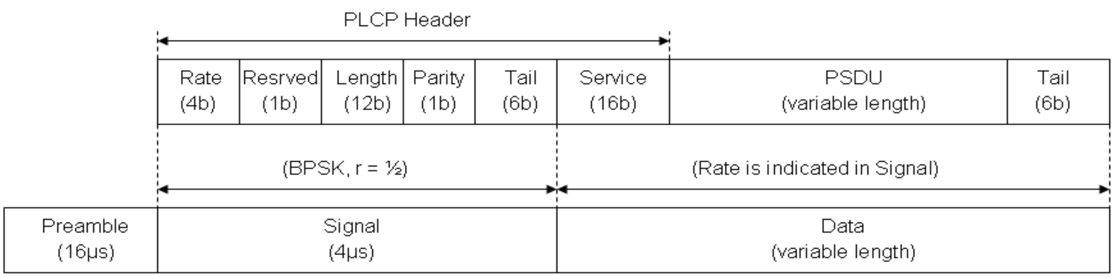

Figure 2.5 *IEEE 802.11 - 2007 PPDU Frame format (ERP-OFDM), where b refers to bits.*

2.3.4 Physical specifications

The IEEE std 802.11 – 2007 physical specifications can be summarized through different tables. These specifications refer to the extended rate phy (ERP) which defines all the possible combinations of modulation and coding rate to achieve all the data rates.

Table 2.2 shows the IEEE std 802.11 – 2007 modulation, coding characteristics and data rates.

Modulation	Coding rate	Coded bits per subcarrier	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	½	1	48	24	6
BPSK	¾	1	48	36	9
QPSK	½	2	96	48	12
QPSK	¾	2	96	72	18
16-QAM	½	4	192	96	24
16-QAM	¾	4	192	144	36
64-QAM	2/3	6	288	192	48
64-QAM	¾	6	288	216	54

Table 2.2 *Data rates (modulation and coding)*

Table 2.3 shows all the possible data rates defined by the standard in order to have backward compatibility with legacy stations, where the mandatory and optional modulations are specified.

Data rate (Mbps)	Mandatory modulation	Optional modulation
1	DSSS	
2	DSSS	
5.5	CCK	PBCC
6	OFDM	DSSS – OFDM
9		OFDM, DSSS – OFDM
11	CCK	PBCC
12	OFDM	DSSS – OFDM
18		OFDM, DSSS – OFDM
22		PBCC
24	OFDM	DSSS – OFDM
33		PBCC
36		OFDM, DSSS – OFDM
48		OFDM, DSSS – OFDM
54		OFDM, DSSS – OFDM

Table 2.3 *All possible data rates and modulations*

Table 2.4 shows the most common parameters defined by the standard.

Parameter	Value
Slot time	Long = 20 µs Short = 9 µs
SIFS time	10 µs
CCA time	< 15 µs for long Slot time and < 4 µs for short Slot time
DIFS time	50 µs for long Slot time and 28 µs for short
CWmin	15
CWmax	1023
Air propagation time	< 1µs
Preamble length	16 µs
MPDU max length	4095 bytes
ACK timeout	55 µs

Table 2.4 *IEEE 802.11 - 2007 Parameters (ERP-OFDM)*

2.4 Medium Access Control Layer (MAC)

2.4.1 Architecture

The MAC layer architecture can be described easily by using figure 2.6. Here it is shown the Point Coordination Function (PCF) and the Hybrid Coordination Function (HCF) via the services of the Distribution Coordination Function (DCF), knowing that in no Quality of Service (QoS) stations, HCF is not present and in QoS stations, both HCF and DCF are present. For all the stations, PCF is an optional feature.

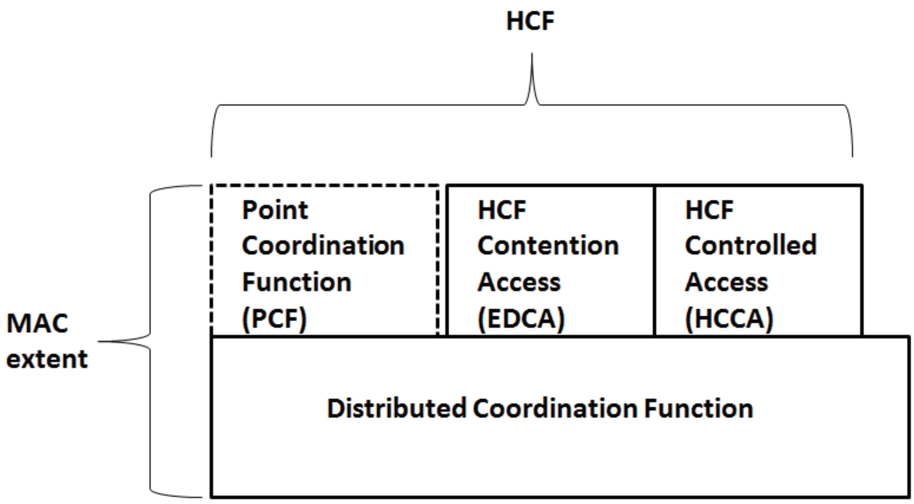

Figure 2.6 *MAC architecture*

The DCF is the main access method of the IEEE 802.11 MAC layer known as CSMA/CA. This access method is implemented in all the stations and it is used in IBSS and infrastructure networks. This will be further explained in section 2.5 of this chapter.

The PCF is an optional access method for the IEEE 802.11 which is only used in infrastructure networks. The main characteristic of this access method is that makes use of a Point Coordinator (PC) at the access point of the BSS in order to determine which station is the one which is going to transmit. The PCF gives the information within the beacon management frames for setting the Network Allocation Vector (NAV) in the stations so it can obtain the control of the medium. It uses the VCS mechanism (explained in section 2.5.1).

Beacon management frames are used by the access point for announcing its presence and for transmitting information that will help the stations to work well in a BSS. It is sent periodically and the information in this frame can be used for different purposes such as the data rates available in the BSS, the SSID and timestamp.

The HCF is an extra coordination function mechanism used only in QoS networks. It is called hybrid because it combines functions from the PCF and the DCF with some improvements. It uses two access channel methods. The Enhanced Distributed Channel Access (EDCA) and the HCF Control Channel Access (HCCA). The first one is a contention based channel access and the second one is a controlled channel access.

2.5 Distributed Coordination Function

The IEEE standard 802.11 defines a distributed coordination function based on the CSMA/CA protocol in order to share the wireless medium.

The stations listen to the channel before transmitting in order to determine whether other station is transmitting or not. To reduce the probability of collisions[3], stations use a random backoff time following a busy medium condition. In addition, the destination station in order to confirm the successful packet reception transmits a positive acknowledgement. If the acknowledgement is not received the sender station schedules a retransmission.

Other access technique defined by DCF is the RTS/CTS access mechanism (explained in section 2.5.4.2).

2.5.1 Carrier sensing mechanism

Carrier sensing determine if the medium is idle or busy. 802.11 define two types of carrier sensing functions to determine the state of the medium: physical carrier sensing provided by the physical layer and virtual carrier sensing provided by the MAC layer.

Physical carrier sensing detects activity in the radio interface. Before transmitting a frame, the station senses the medium and it attempts its transmission if the channel is sensed idle or it defers its transmission if the channel is sensed as busy. The channel is sensed idle if the strength of the received signal do not exceeds the CS threshold; otherwise, the channel is sensed as busy.

Virtual carrier sensing is based in the network allocation vector (NAV). The duration field of frames can be used as a NAV to reserve the channel for a fixed amount of time. The stations calculate the amount of time they expect to use the channel and set it to the NAV. The stations which receive this information,

[3] A collision in WLAN is the fact that two frames collide because two or more stations have transmitted at the same time.

defer in accessing the medium for the NAV time. When the NAV timer expires the virtual carrier sensing function indicate that the channel is idle.

By using the virtual carrier sensing, RTS/CTS mechanism solve the problem of "hidden terminals" which is explained in Section 2.5.4.2.

Physical carrier sensing works in combination with the NAV state. During the NAV countdown the physical carrier sensing is off. When the NAV reaches 0 the physical carrier sensing determine the idle or busy state of the medium for future transmissions.

2.5.2 Interframe Space

The time between frames, IFS, plays an important role providing different priorities levels for access to the transmission medium. By using the carrier sensing a station determine the state of the medium during the interval specified. The IEEE standard 802.11 - 2007 defines five different IFSs. We are only taking into account the three ones that we have used in our studies. Figure 2.7 shows the relationship between IFS.

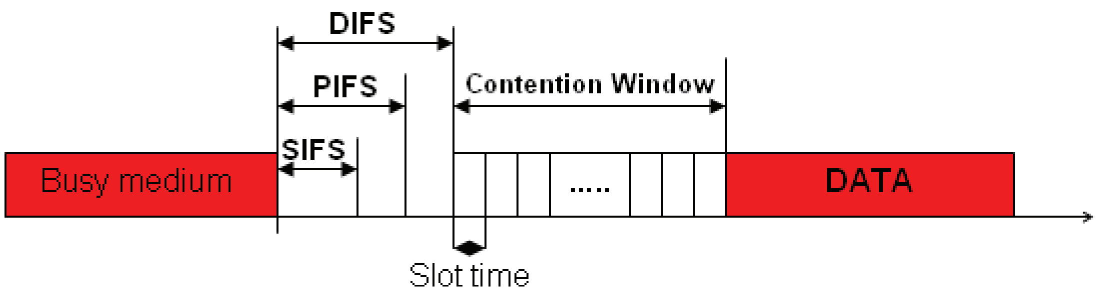

Figure 2.7 *Interframe Spacing relationships*

Once the medium becomes idle, high-priority frames does not have to wait as long as low priority frames. Varying the time interval between frames can be created different priority levels for different kind of traffic. The interframe space is a fixed amount of time, which is independent of the station data rate. The IFS values are specified by the physical layer. The five different IFSs are:

Short interframe space (SIFS)

The SIFS is the shortest of the IFSs for the IEEE 802.11 - 2007; it is used for high-priority transmissions such as ACK frames and CTS frames. Once the transmissions begin after a SIFS the medium becomes busy, so the stations which are waiting for the medium to be idle for a longer interframe space shall defer until the end of the current transmission.

PCF interframe space (PIFS)

The PIFS is used by the PCF to gain priority over the medium during the contention free operation. The PIFS shall be used also by stations to transmit a Channel Switch Announcement Frame (see chapter 4).

DCF interframe space (DIFS)

The DIFS is used by the DCF and is the minimum medium idle time which the stations should wait for the transmission of data frames and management frames.

The other two IFSs (EIFS and AIFS) defined by IEEE std 802.11 - 2007 are not relevant in the study of this project.

2.5.3 Random backoff time

The collision avoidance feature of the CSMA protocol is the random backoff interval.

After a transmission of a frame has been completed and the medium is sensed as idle for a period of time equal to DIFS, stations may generate a random backoff interval using the equation 2.1 for an additional deferral time before transmitting. The interval generated is divided into slots. The medium is sensed every backoff slot. If the medium is sensed idle for a particular backoff slot, then the backoff time is decremented in one slot. Otherwise if the medium is sensed busy the backoff procedure is suspended and the backoff time is not decremented. When the medium become idle again for a DIFS time, the backoff procedure is resumed. When the backoff timer reaches zero the transmission shall commence.

$$BackoffTime = Random() \times SlotTime \qquad (2.1)$$

Where

Random() = For each packet transmission is generated a random value in the range [0,CW]. The value CW is called contention window. The contention window depends on the number of retransmissions. For the first transmission attempt, the value of CW is equal to CWmin, the initial contention window. After for each retransmission, the range [0, CW] is doubled, up to the maximum value CWmax. CW is represented with the following notation: $CW = (2^i \cdot (CW_{\min} + 1)) - 1$, where '$i$' depends on the maximum contention window.

Note: The value of CWmin and CWmax are specified in the standard and depends on the physical layer.

SlotTime = depends on the Physical layer. The time needed to detect transmissions from any other station.

2.5.4 Access Procedure

DCF defines two access techniques based in CSMA/CA, these are: basic access mode and the optional RTS/CTS access mechanism.

2.5.4.1 Basic Access mode

A station before attempting to transmit data frames, checks whether the medium is idle. If the medium is sensed to be free for a period of time equal to DIFS, the station transmits. Otherwise, if the medium is sensed busy, the station defers its transmission and waits until the medium becomes idle for a DIFS and generates the random backoff time (explained in section 2.5.3) for an additional deferral time before transmitting. The backoff timer decreases as long as the medium is sensed as idle and is frozen when a transmission is sensed on the medium. When the medium becomes idle again for a DIFS, the timer is resumed. Once the backoff time reaches zero the station transmits.

The destination station transmits a positive acknowledgement to confirm a successful packet reception. If the acknowledgement is not received within the ACK timeout, the sender station schedules a retransmission and the contention window is doubled. Once the packet is transmitted successfully the contention window is reset to its default value, CW_{min}. Figure 2.8 shows an example of the basic access mode.

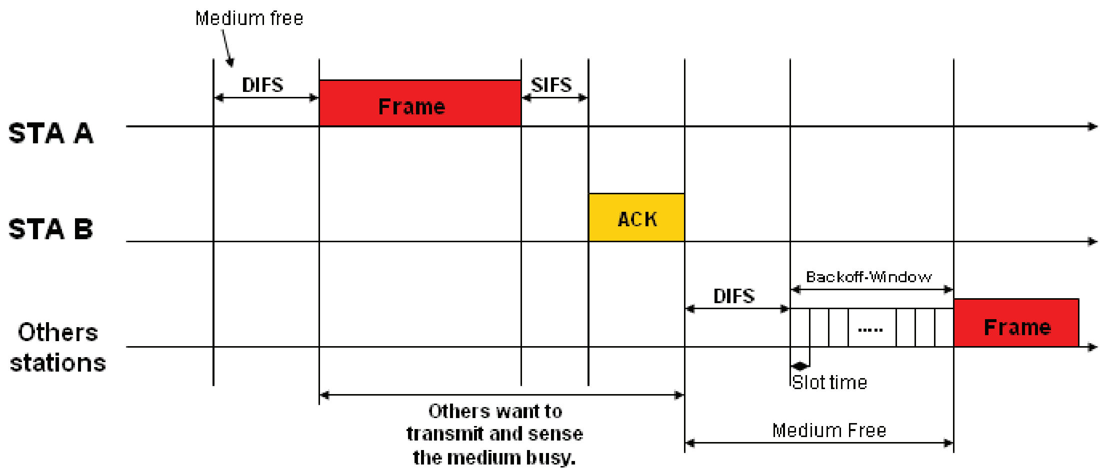

Figure 2.8 *Example of basic access mode*

One of the disadvantages of the basic access mode is the “hidden terminal” problem. Due to the position of a station in a network, sometimes the stations are not able to communicate with every other station from the network, as shown in Figure 2.9.

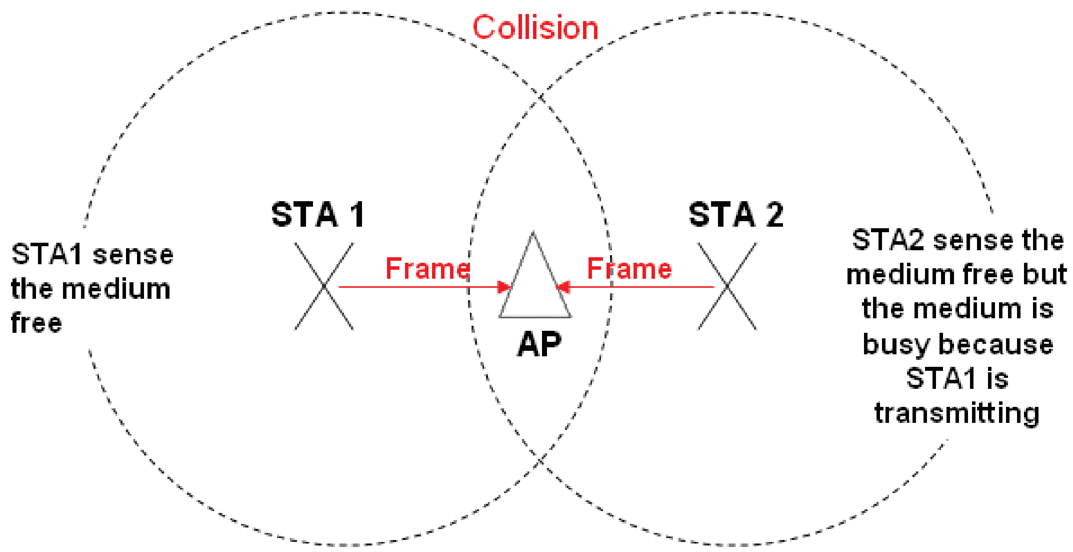

Figure 2.9 *Hidden terminal problem*

In the figure, both stations have to retransmit the frame due to a collision. The time wasted in collisions due to the “hidden terminal” is huge, affecting this the network efficiency. The solution for the “hidden terminal” problem is described in the next section.

2.5.4.2 RTS/CTS access mode

The RTS/CTS access mode is an optional function of the 802.11 standard to control the access to the medium.

RTS/CTS access mode is used to guarantee the reservation of the medium.

The RTS frame is first transmitted when there is a data frame or a management frame ready to be transmitted by a station. The station sets the NAV in its RTS frame and sends it after a successful contention for the channel. All stations that receive the RTS frame except the destination station, read the Duration field in order to update their NAV. Then, the destination station responses with a CTS frame after a SIFS. All the stations that receive the CTS frame read the duration field and update their NAV. Upon successful reception of the CTS frame, the source station is able to transmit its frame knowing that the channel is reserved for a transmission. If the sender station within a CTS timeout does not receive the CTS frame, the RTS frame is retransmitted after a successful contention of the channel.

Figure 2.10 shows the RTS/CTS mechanism. Note that the NAV maintains a prediction of medium busy time. The NAV (CTS) is calculated by the destination station, once the RTS frame is received, as the NAV (RTS) minus the duration of the CTS frame minus one SIFS.

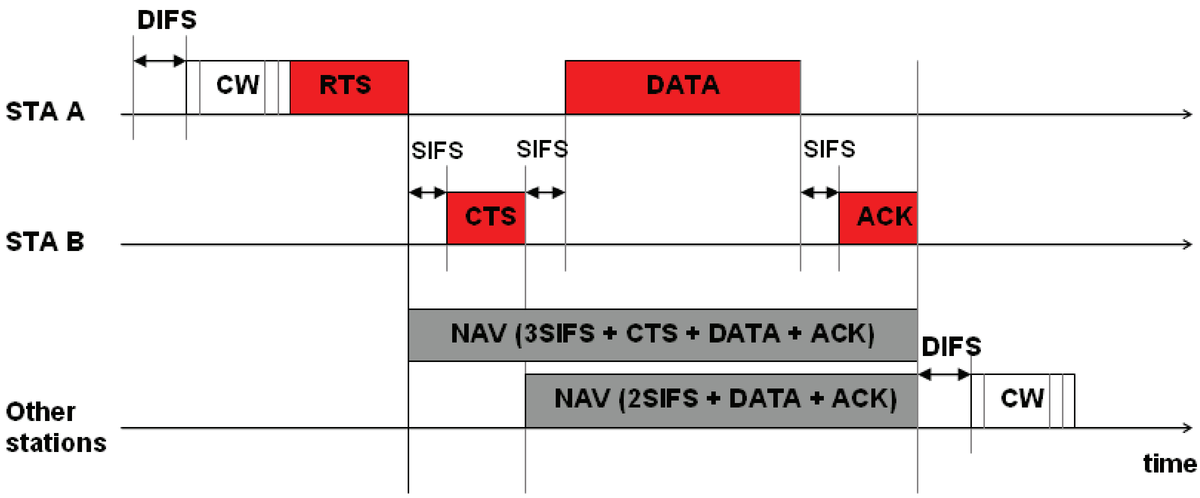

***Figure 2.10** RTS/CTS mechanism.*

RTS/CTS access mechanism solves the “hidden terminal” problem described in Section 2.5.4.1. The stations that may not be able to receive the RTS frame from the sending station are able to receive the CTS frame from the destination station. The reservation mechanism of the channel works across the BSA boundaries. Figure 2.11 shows how the RTS/CTS mechanism solves the “hidden terminal” problem. Note that station1 and station2 are out of range from each other.

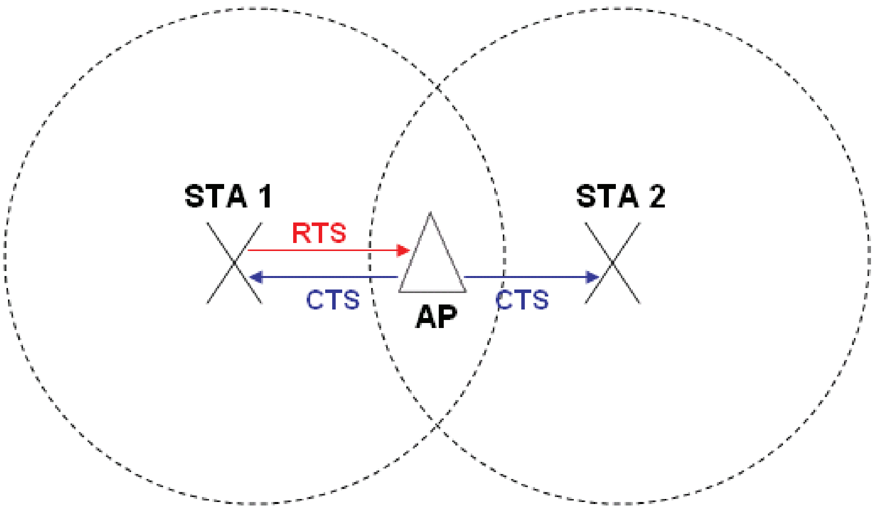

***Figure 2.11** Solution of the hidden terminal problem.*

RTS/CTS mechanism increases the overhead due to the addition of two frames per each data transmission. In other hand, it reduces the time wasted in collisions. RTS and CTS frames are relatively small (RTS is 20 octets and CTS is 14 octets) compared to the maximum data frame size. Depending on the network size and on the packet size, activate the RTS/CTS access mechanism is convenient or not (In Appendix III is explained how to determine this).

Chapter 3

Large scale deployments for IEEE 802.11

3.1 Introduction

This Chapter describes the consequences of overlapping coverage on large scale unplanned deployments for IEEE 802.11 Wireless LANs[4].

Nowadays, WLANs are being widely deployed all over the world. Moreover, a lot of different kind of wireless devices such as mobile phones, printers and laptops are entering in everyday life in a way that even some studies predict that the number of mobile phones with WiFi technology will reach 520 million by the year 2014 [11]. This reflects the fact that WiFi technology is growing exponentially driving us to a congested WiFi future.

This leads to a place where networks are surrounded by other networks and devices may compete for the same resources as can be the WiFi channels (spectrum frequency), producing degradation in the performance of a network. Some studies have obtained that in an area with coverage working in the industrial, scientific and medical (ISM) band (2450MHz), up to 80 access points can be found and more than the 40% of them working in channel number 6 and only the 14% of them using the remaining two non-overlapping channels, the rest of them are using the overlapping channels [4]. This channel is one of the three available non-overlapping channel (1, 6 and 11), meaning that there are only three channels available where a network can be deployed without competing for the same resource with other networks.

Several techniques such as power transmission control or carrier sensitivity adjustment in the receiver have been studied in order to cope with this undesirable lack of resources, but there are more factors that make the avoidance of this problem a great feat. To start with, the lack of coordination between users who deploy the networks in close proximity drives to

[4] In the study, we are interested in the behavior and performance of the IEEE 802.11-2007 Wireless LANs. In consequence, the use of the term 'WLAN' through the chapter refers to IEEE 802.11-2007 WLANs.

overcrowded channel utilization, in general, unbalanced allocation between networks in different channels.

Operators of mobile cellular networks are managing to solve this lack of resources by implementing femto cells in order to offload part of the traffic that a macro cell has. But, why do not try to offload all this traffic through the IEEE 802.11 WLANs? This is a technology which is widely extended and implemented. And it is thought that the next WiFi generation networks will be able to support a great amount of traffic with high data rates up to a theoretical maximum physical throughput of 1Gbps [7].

Furthermore, many studies have been made about the IEEE 802.11 MAC protocol scalability [2] in an isolated network, but system scalability in an unplanned multi network area is still something that needs further investigation. In [3] it is investigated how an increase of the number of access points strongly decreases the performance of a network, in this case, VoIP performance (but only up to four access points).

Larger scenarios with more than four access points and even more than fifty access points for throughput comparison is something that it is addressed through this chapter in order to study how these scenarios behaves in an unplanned network deployment.

This leads us to focus our studies in large scale unplanned deployments which represent today's real life.

Thus, Section 3.2 gives a description of the large scale scenarios to analyze, starting from an isolated network and finalizing with 16 networks placed in very close proximity. Finally, the simulations outputs of these large scale unplanned deployments are analyzed in Section 3.3. Concluding remarks are given in Section 3.4.

3.2 Large scale deployment scenarios

In this section, it is exposed the problem of having an IEEE 802.11 network in an area surrounded by other networks of the same type, all in close proximity, meaning that they have to share the resources, in this case, the same wireless medium.

To address this study, several simulations have been done in order to prove that in a crowded area the performance of a network decreases significantly.

To begin with, to propose an appropriate study of a large scale deployment, we define a scenario composed by 16 networks where we propose different configurations.

The first one is a scenario with one access point per network, 16 in total; with one client station per network, 16 in total. This means that at first we have 32 stations in the scenario. All the stations work in saturation condition meaning this that they always have a frame to transmit (transmission queues always full). Each network represents a house in which there is an IEEE 802.11g network deployed in there. The position of the access points and the client stations in the networks are randomly deployed by the simulator. Figure 3.1 shows the 16 network scenario.

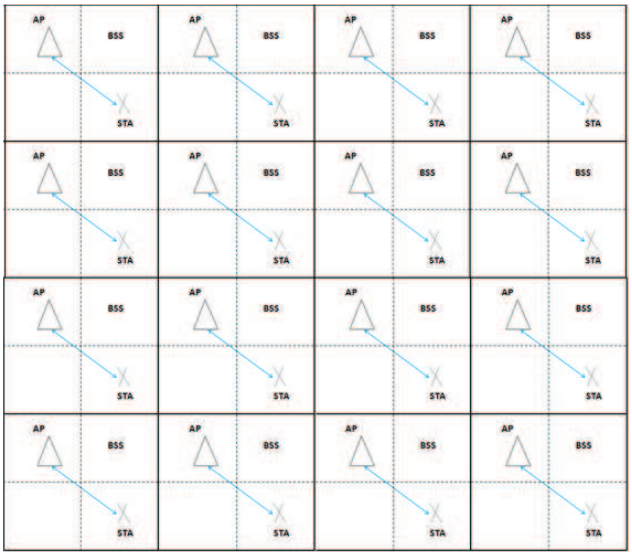

Figure 3.1 *Scenario with 16 networks, 16 access points and 16 client stations.*

Then, we move to other configurations where up to 160 stations are deployed in the scenario (16 access points and 144 client stations). We also study a more realistic case where in a crowded area do not necessary have to be a network deployed in every house. To achieve this, we have made used of a parameter called deployment ratio. This is defined as a uniform probability that represents the probability that a network can be deployed in a specific house of a scenario or not. It has a range of values from 0 to 1 (0% - 100%), meaning that a value of 0 represents that a network is not going to be deployed and a value of 1 assures the presence of a network in a house.

3.3 Simulations and results

This section documents the main simulation results for large scale deployments of IEEE 802.11g networks in terms of MAC throughput per user and average collision rate per network. The scenarios of the simulations have been explained in section 3.2 and the basic parameters employed are summarized in Table 3.1. The values of the parameters are chosen based in the IEEE std 802.11- 2007 in order to simulate IEEE 802.11g networks.

Parameter	Value
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
PIFS	30 μs
CWmin	15
CWmax	1023
Data rate	54 Mbps
MPDU	4095 bytes
ACK timeout	55 μs
RTS/CTS	Deactivated
Beacon interval	100 ms
Preamble time	16 μs

Table 3.1 *IEEE 802.11 - 2007 parameters used for the simulations.*

Before going in detail to the simulation results, we want to define briefly some terms in order to get a better understanding of what it is studied.

Throughput

The throughput is defined as the amount of data (in bits) successfully transmitted from node to node in a specific amount of time.

The focus of the study is the average throughput per user and per BSS in the medium access control layer Service Access Point (SAP). [2] Presents an analytical model to compute the saturation throughput performance of the IEEE 802.11 DCF which we used to validate our simulation model. Unfortunately, it is only valid if all the stations hear each other.

The following assumptions have been made. Management frames have not been taken into account. Fixed number of stations, each of them operate in saturation conditions; this means that the transmission queues are assumed to be never empty, as mentioned in section 3.2. The propagation delay is not considered.

Throughput Results

The following results show the Cumulative Distribution Functions of the MAC throughput (downstream, throughput received per each station) per user obtained for the scenario explained in section 3.2 (16 networks).

Figure 3.2 shows the CDFs of the MAC throughput of the 16 networks scenario, two stations per network. In this figure it is shown how the scenario behaves with different deployment ratios.

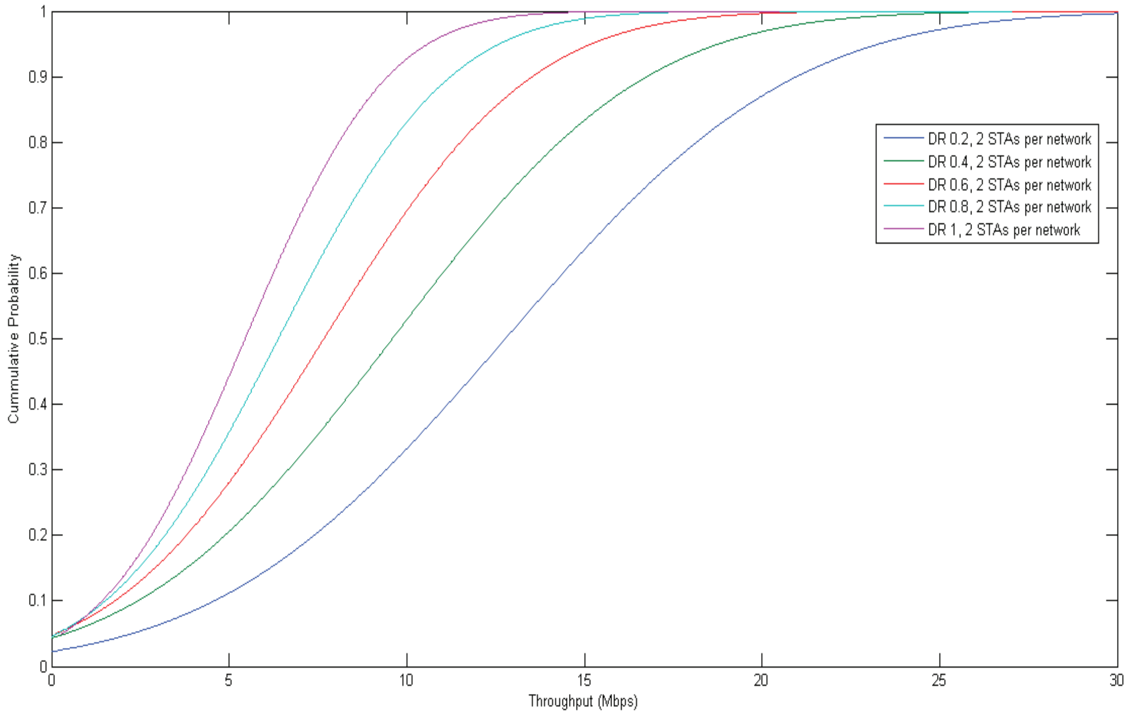

Figure 3.2 *Cumulative Distribution Function of throughput. 16 network scenario, two stations per network.*

As illustrated in figure 3.2, the collected throughput is representative, and it behaves as expected for the reason that at the same time that the deployment ratio increases (there is more probability that a network can be deployed in the scenario), the throughput decreases as a consequence of being in a more congested scenario.

As higher the congestion in the scenario is, more stations are without transmitting and they are getting a value of 0Mbps for their throughput. This effect is also produced by the fact that some stations do not gain access to the wireless medium within the simulation time.

To follow with the study, we present figure 3.3 which shows the CDFs of the MAC throughput of one scenario, which is composed by 16 networks with six stations per each network. Here, we want to see to what extent the increasing number of stations affects the throughput.

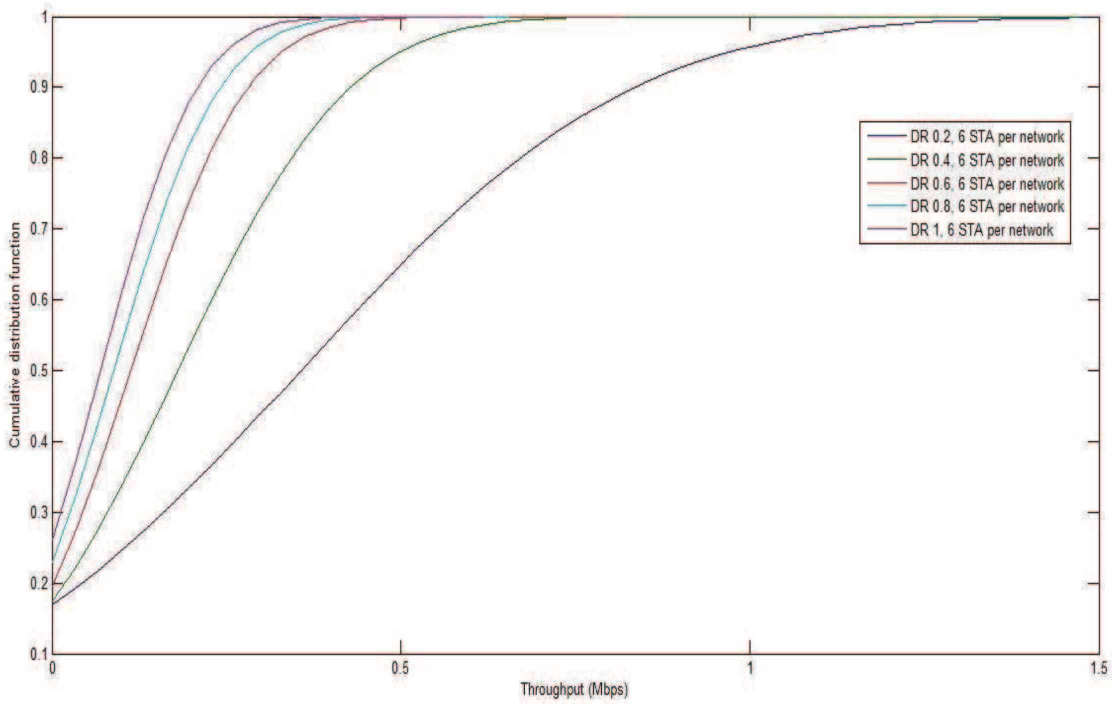

Figure 3.3 *Cumulative Distribution Function of throughput. 16 network scenario, six stations per network.*

As illustrated in figure 3.3, the scenario behaves as expected where the increasing numbers of stations produce degradation in terms of throughput per user due to the fact that now six stations per network are competing for the channel.

Here can be seen the same degradation in the throughput than in the figure 3.2, when the number of nearby networks increase. The best throughput is obtained when the deployment ratio is equal to 0.2. In this case the number of deployed networks quite likely is small, but in some cases this networks are located in close proximity been it the reason of having more spread throughput values. Comparing with the figure 3.2 this behavior is not exactly the same because of the different number of stations per network.

Furthermore, we present figure 3.4 which shows the CDFs of the MAC throughput of one scenario, which is composed by 16 networks with ten stations per each network. Here, we want to see again to what extent the increasing number of stations affects the throughput.

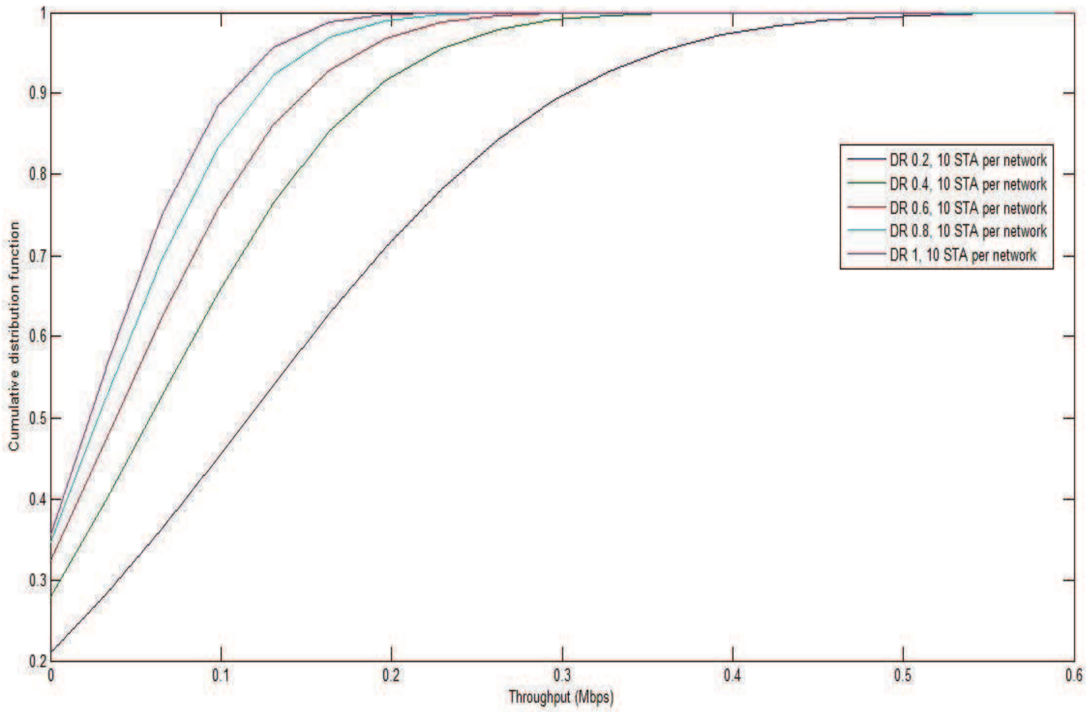

Figure 3.4 *Cumulative Distribution Function of throughput. 16 network scenario, ten stations per network.*

It can be seen in figure 3.4 that the scenario behaves as expected where the increasing numbers of stations produce degradation in terms of throughput per user in comparison with the figure 3.3 and 3.2. In general the behavior is the same, increasing the number of networks deployed the throughput degrades significantly.

More results for medium and large scale deployments can be seen in appendix V where different kinds of scenarios show the performance in terms of user throughput.

Collision rate

When at least two stations are attempting to transmit a packet and their backoff time (explained in section 2.6.3) expires at the same time, collision occurs.

The collision rate (CR) is defined as the average number of collided transmissions per each successful transmission. [2] and [5] provide a probabilistic approximation of the collision rate based on the number of stations sharing the channel, the initial contention window and the backoff stage.

Collision rate results

Figure 3.5 shows the number of frames collided per successful transmission. It is a comparison between the behavior of one network and two networks when there is an increase of the number of stations per network.

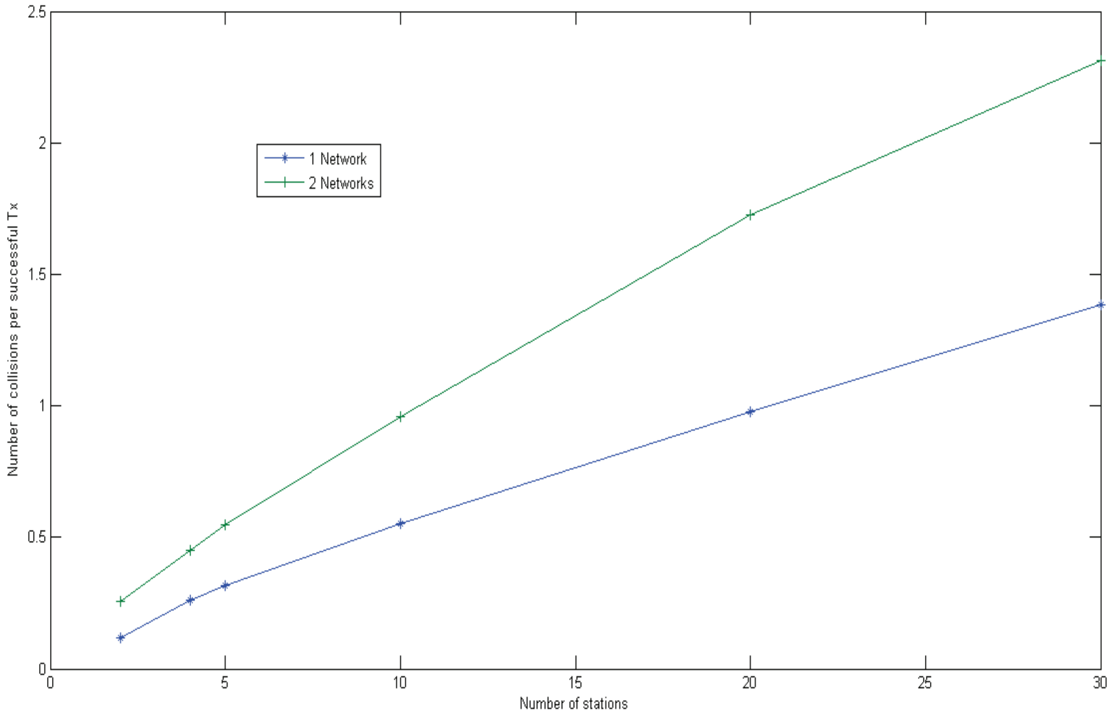

Figure 3.5 *Comparison collision rate between one network and two networks with variable number of STAs (2, 4, 5, 10, 20 and 30).*

With respect to figure 3.5, it can be said that the frames that collide in a network increase while the number of stations increases and also when the number of networks increases, being the effect of increasing the number of networks more harmful in terms of collisions than increasing the number of stations. This is due to the fact that an increase on the number of access points affects more the performance of a network than an increase of the number of stations as it is shown in [**3**].

It is also illustrated that the only addition of one network produces a significant increase of this effect. With these results, the throughput obtained is barely sufficient for having a good performance in a network. This leads us to a place where trying to achieve a low collision rate can be critical to obtain a great performance in a network (chapter 4).

3.4 Comments

In this chapter, we have investigated the performance of large scale unplanned deployment scenarios for IEEE 802.11g WLANs. The simulation results show that when increasing the number of BSSs on the same channel, the performance of the network is highly affected.

We have shown that the throughput degrades significantly by increasing the number of networks sharing the same channel. The CDFs show that when increasing the deployment ratio, the throughput also degrades significantly as a consequence of the increasing number of networks deployed.

Also shown that the number of collisions per successful transmission have a significantly increment by increasing the number of networks sharing the same channel. In chapter 4 is carried out a deeper investigation about automatic and dynamic channel allocation based in this ratio in order to achieve a better performance for the IEEE 802.11g networks.

Finally, we also want to remark what we have explained in the previous section about the behavior of some stations in big scenarios where they do not have a chance to access to the wireless medium because the simulation time is less than the time required for these stations to gain access to the channel.

Chapter 4

Dynamic channel selection for WiFi systems

4.1 Introduction

Talking about WiFi technology we understand as dynamic channel selection all the schemes or algorithms that permit to certain entities, access point in this case, to automatically select and switch to a new channel where the performance of its network can be improved. This dynamic channel selection can be based on different parameters which have to be studied in detail for obtaining the best channel possible. These parameters can be a study of how the throughput is affected in a network because of the load of the channel, due to others BSSs.

It can be seen in the results from chapter 3 that when there are many networks together the probability of having collisions in a specific BSS increases. As was also said in chapter 3, WiFi networks are being deployed in most of the cases without a previous study of the impact that this could have in the networks nearby or even in the impact that other networks can have in the network deployed. One example of this can be the problem that has to face cities in large where the great number of access points per area is becoming an issue.

For this reason, this chapter tries to explain how good it would be to have a dynamic channel selection in large scale deployments for WiFi systems, where the final user does not have to be aware or to have the knowledge for making a channel switch in his network.

4.2 Core of the concept

The proposed dynamic channel selection is based on the collision rate[5] that a certain BSS estimated due to the number of associated stations and affected by others BSSs sharing the same channel.

[5] Collision rate (CR) refers to the average number of collided transmissions per each successful transmission in a certain amount of time.

For channel selection we have eleven 22 MHz-wide channels defined in the IEEE 802.11 std 2007 in the 2.4 GHz band [1]. The separation between channels is 5 MHz, Starting at 2.412 GHz through 2.462 GHz.

For dynamic channel selection we are going to use the three non-overlapping channels available: 1, 6 and 11, shows in the Figure 4.1.

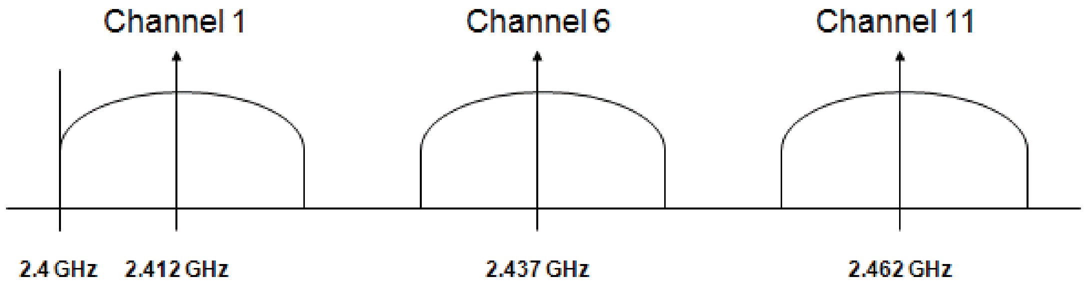

Figure 4.1 *IEEE 802.11 standard 2007, China and North America channel selection-nonoverlapping.*

4.3 Assumptions

The channel selection is only for the non-overlapping channels.

For deciding if a channel switch is needed, it is calculated a threshold value for the theoretical collision rate in the network over which is convenient the channel switch. This threshold depends on the number of associated client stations to the access point.

Each station, independently, makes the real collision rate measurements.

The inputs for our algorithm are the number of stations in a BSS (client stations + access point).

4.4 General Procedure

This section describes in details the general procedure of the dynamic channel selection. How the communication between the network entities is, how they cooperate with each other to change the channel allocation and which the channel selection algorithm is.

First of all, each station calculates the threshold value for the theoretical collision rate in the network over which is convenient a channel switch. Reference [2] gives a theoretical calculation collision rate for an isolated saturated network from where we calculate the threshold. This threshold depends on the number of associated client stations to the access point, information that it is available in the beacon frames (see Appendix VI for the beacon frame format). The real collision rate is calculated periodically per each station and it is compared with the threshold.

Figure 4.2 shows a comparison between the calculated thresholds and the results obtained by simulations of the real collision rate varying the number of associated stations for an isolated network, and for two networks sharing the channel. Note that the parameters used for the simulations are described in Table 3.1 (chapter 3).

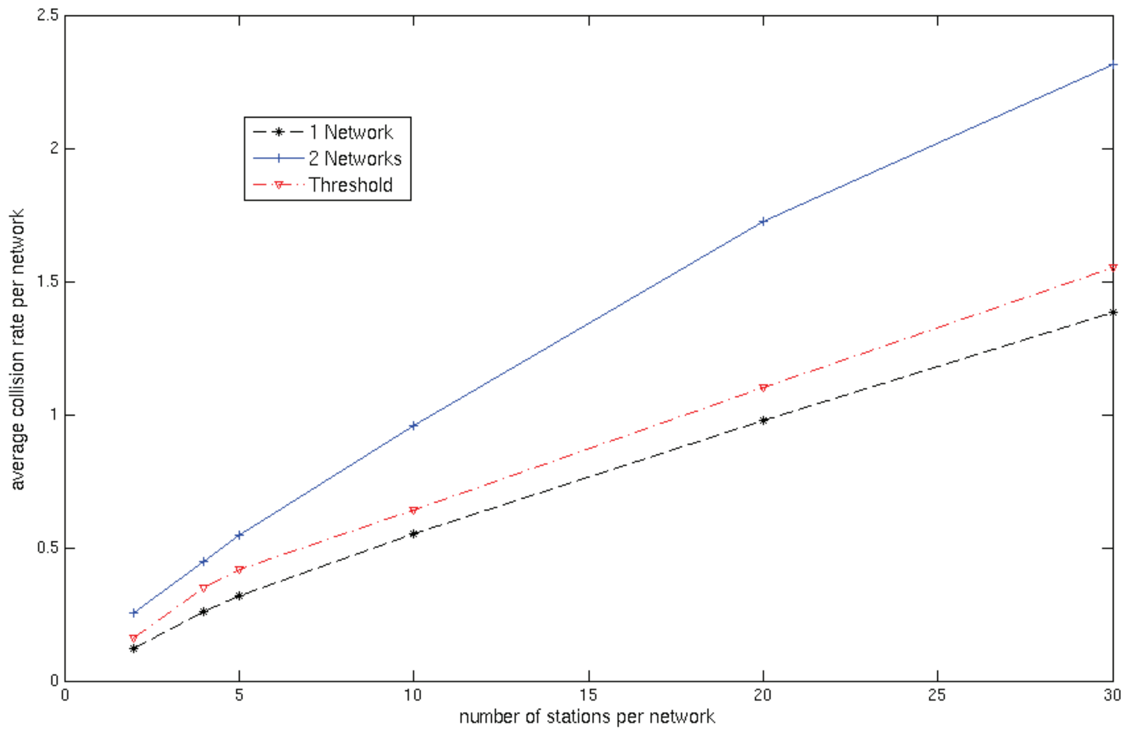

Figure 4.2 *Comparison collision rate.*

So, if the client station perceives the collision rate above the threshold it sends a *change request* frame (see Appendix IV for details about the frame format). If the number of stations requesting a channel switch including the access point is higher than half of the associated to the BSS plus one (to start with, more than the 50%), the RTS/CTS mechanism is activated (see Figure 4.3) in order to protect the network from the hidden terminal problem and for trying to reduce the number of collisions in the BSS. Once this mechanism is activated, the collision rate is calculated again per each client station[6].

[6] The measurements of the collision rate are done by the stations every beacon reception. This can also be modified depending on the number of stations associated to the access point (information known from the beacon frame). More stations mean more time interval for making the measurements.

Figure 4.3 shows an example of one BSS composed of one access point and two client stations in which STA1 and STA2 request a channel change. Due to the fact that it is the first channel change required, RTS/CTS mechanism is activated.

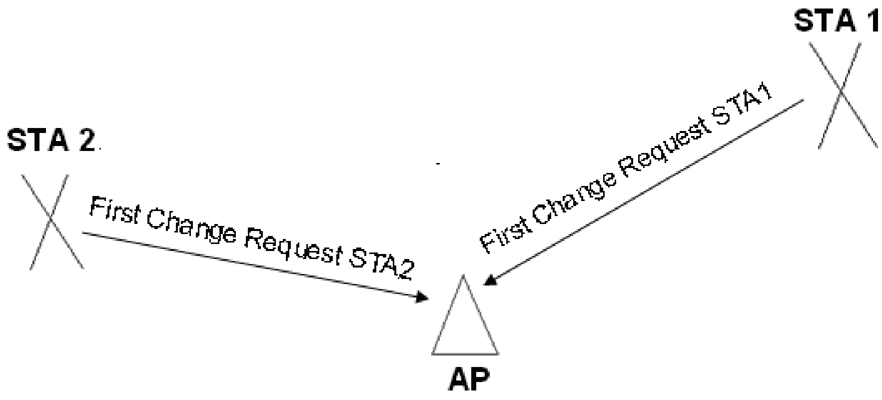

Figure 4.3 *First channel change request by the client stations.*

Figure 4.4 shows an example of the change request procedure. STA A and STA B are client stations associated to the AP. These two stations perceive a collision rate above the threshold. Change request transmission time represents the time spent in the transmission of one change request frame.

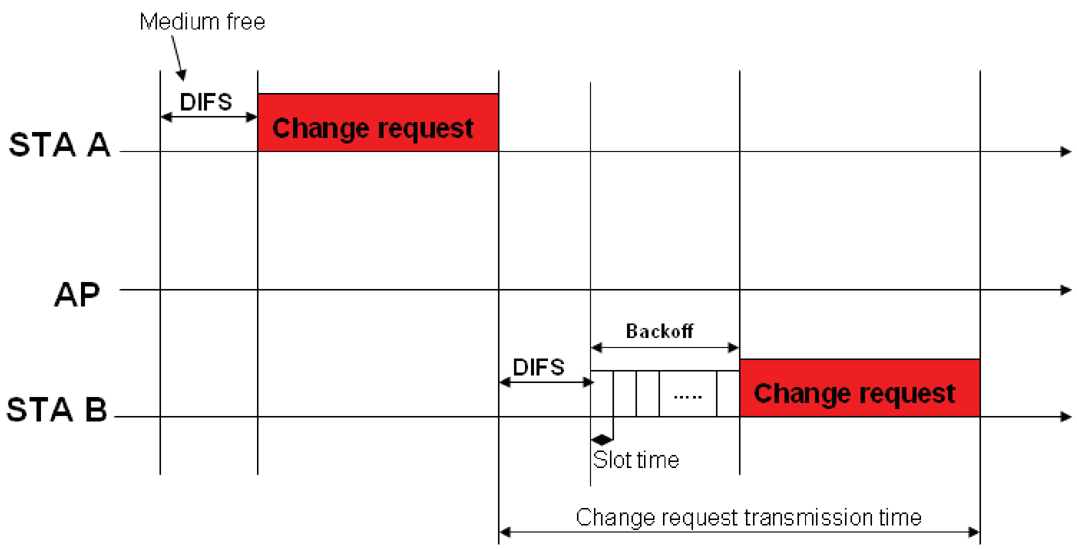

Figure 4.4 *Change request procedure.*

Now, if the client station still perceives the collision rate above the threshold it sends again the change request frame (see Figure 4.5). If the number of stations requesting a channel switch is still being more than half of the associated to the BSS plus one, the access point checks if it is convenient[7] to keep the RTS/CTS mechanism activated or if it should be deactivated before the access point informs to all the client stations in the BSS that a channel switch is needed.

The channel switch is done by sending the information in a frame called *Channel Switch Announcement* (see Appendix IV for details about the frame format) where it is said that a channel change is needed and to which channel the client stations should jump. Then, the client stations confirm to the access point the correct reception of this frame with a *Channel Switch Announcement Response* frame (see Figure 4.6). There is a possibility that this response frame collides and the access point does not receive it. For this reason once the access point receives a channel switch announcement response, it transmits a positive acknowledgement[8] to the sender station. If the CSA response ACK is not received within the timeout, the channel switch announcement response frame is retransmitted. Once the ACK is received the client station proceeds with the channel switch.

Once the access point receives all the response frames, it will proceed with the channel switch. If a timeout expires and there is any response frame missing, the access point will send the Channel Switch Announcement frame again. This timeout starts when the channel switch announcement frame is transmitted and the duration is equal to the time spent in a successful transmission of one channel switch announcement response (see this successful time in figure 4.7) multiplied by the number of associated stations.

Figure 4.5 shows an example of one BSS composed by one access point and two client stations in which STA1 and STA2 request a channel change. Due to the fact that it is the second channel change required, the access point begins the channel change procedure.

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[7] Depending on the number of associated stations to the access point and on the MSDU size, the RTS/CTS mechanism improve or affect the performance of the network, even if the hidden terminals problem is solved. Reference [**Bianchi**] describes when the RTS/CTS mechanism is convenient depending on these two parameters.

[8] The subtype of this acknowledgement is different than the subtype of the ACK defined in the IEEE std 802.11 - 2007. The channel switch ACK frame is only transmitted by the access points to confirm the correct reception of the channel switch announcement response frame.

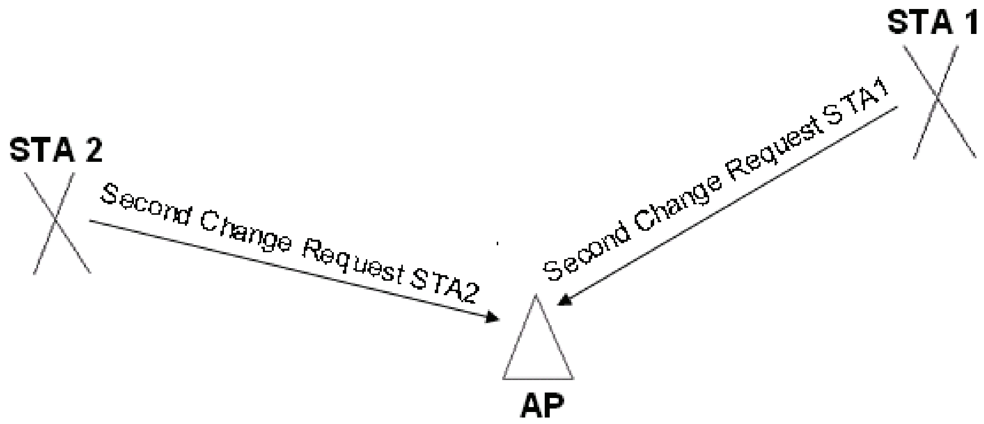

Figure 4.5 *Second channel change request by the client stations.*

Figure 4.6 shows an example of one BSS composed of one access point and two client stations in which the AP informs to all the client stations associated that a channel switch is needed. The numbers 1, 2 and 3 represent the order in which the frames are transmitted.

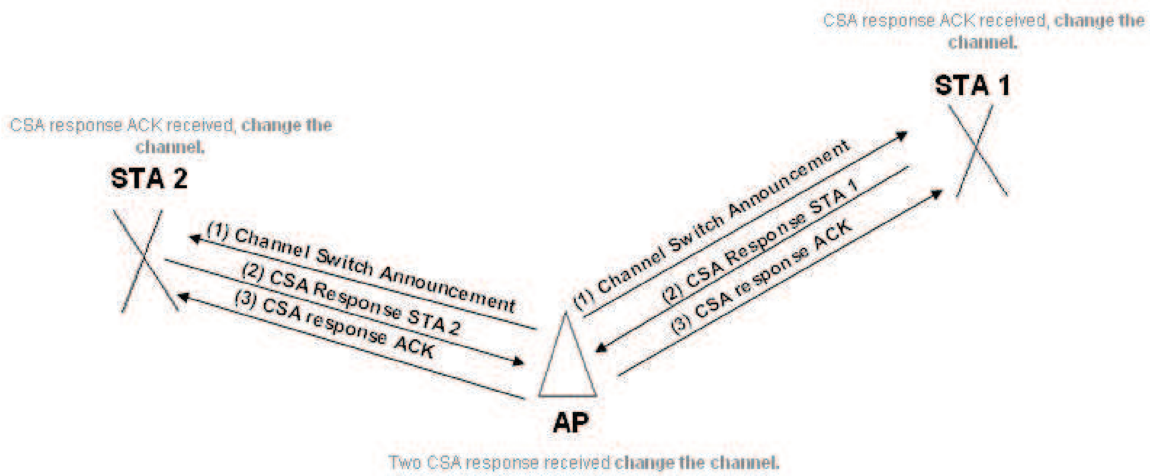

Figure 4.6 *Channel switch announcement by the access point.*

Figure 4.7 shows the channel switch procedure. STA A and STA B are client stations associated to the AP. Note that the channel switch announcement request frame is transmitted as a high priority after a PIFS time. The Successful CSA response transmission time represents the time spent in a successful transmission of one channel switch announcement response.

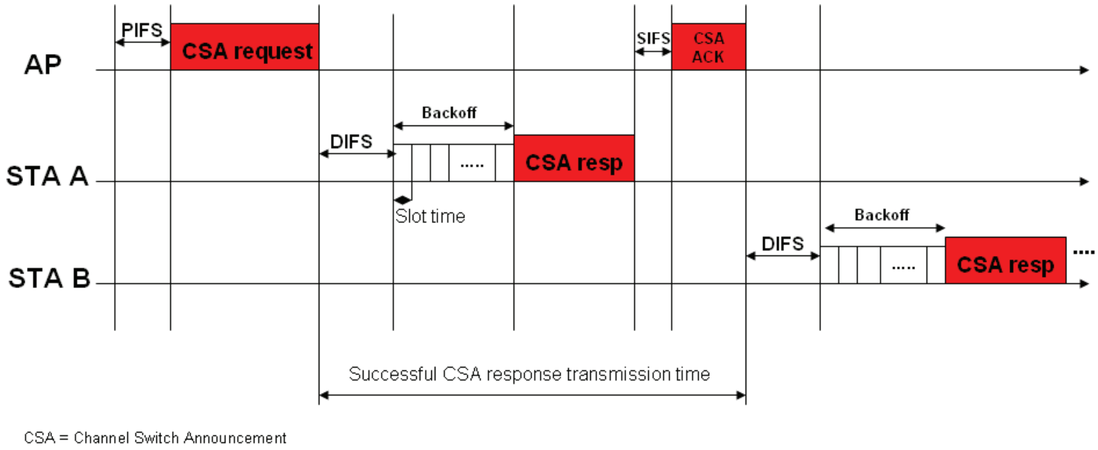

Figure 4.7 *Channel switch announcement procedure.*

Once the stations are allocated in a new channel, the first beacon frame received represents the starting point of transmissions, as it is shown in Figure 4.8.

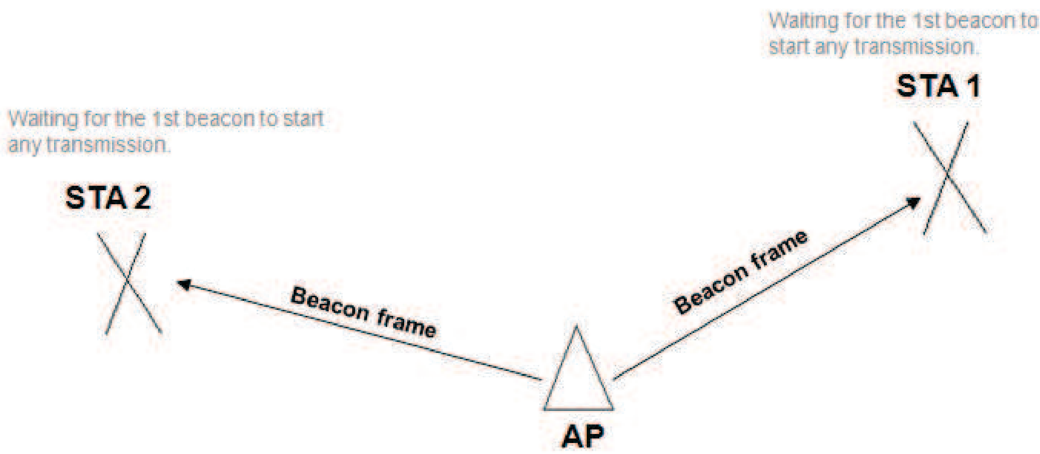

Figure 4.8 *Start transmissions in the new channel after 1st beacon received.*

For obtaining the collision rate, the access point and the client stations associated are the ones who carry out the task of taking samples from time to time. There will be set a time window where the client stations are able to recollect the number of ACK frames received and the number of frames retransmitted by them, in order to be able to calculate the collision rate (number of data frames retransmitted divided into the number of ACK frames received). The access point calculates the collision rate before of every beacon transmission.

This is a kind of decentralization of the network, giving some intelligence to the client stations and not all the responsibility to the access point.

Now, we face another question. Which is the appropriate number of stations affected by the collision rate that has to determine if the RTS/CTS mechanism is needed or if a channel switch is needed?

Furthermore, it can happen that only few stations in the BSS are affected significantly by the collision rate while, most of the others may be not affected. Moreover, it can also happen that most of the stations in the BSS perceive a high collision rate.

For solving this problem, we have to decide which the way of procedure is going to be. Changing to another channel because a few percentages of the stations are affected? Not changing even if these clients are losing most of their transmissions?

So, for this purpose, we have decided that if more than the 50% of the stations in the network need a channel switch, then the access point will start the procedure for changing the channel. Only the client stations with a collision rate above the threshold are the ones informing the access point that they need a channel switch. The access point is the one that checks if more than the 50% of the stations (including the AP) are requesting a channel change within a time interval which depends on the number of associated client stations. This time interval starts when the first channel change frame is received and the duration is equal to the time spent in the transmission of one change request frame multiplied by the number of associated client stations.

Figure 4.9 shows an example of two BSSs sharing the same channel (channel 6), where one of the BSS decides to change to another channel (channel 11) because the number of stations that perceive the collision rate above the threshold is higher than the 50%.

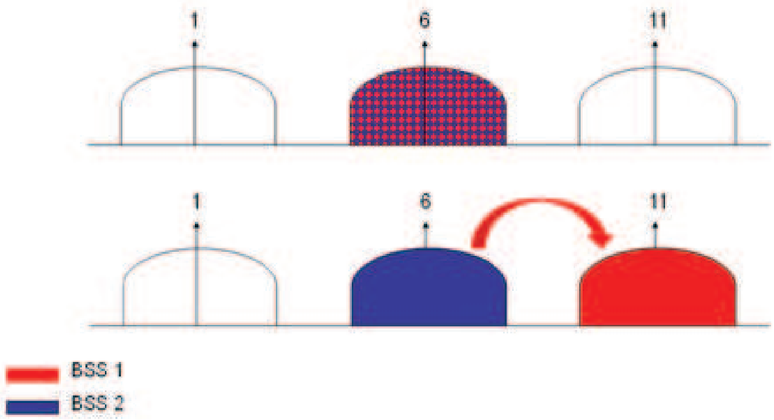

Figure 4.9 *The channel change*

In the case that there are multiple BSSs in different channels, the access point has to decide to which channel is better to jump in order to obtain a lower collision rate.

As a first idea, every time that the channel is changed the access point calculates an average collision rate of the stations that require a channel change and save this in a buffer. If the BSS has already jumped to all the available channels, the access point selects from the buffer the one in which the average collision rate obtained was smaller and change to this channel if this is not the current one. In this case, the dynamic channel selection is turned off for some time[9] due to the congestion of all the available channels.

Figure 4.10 represents an example of a dynamic channel selection process of one BSS when all the available channels are congested. Starting from channel 6, it changes to channel 11 where a change is also needed to channel 1. The BSS jumps to all the available channels and all of them are congested, so the access point selects the one in which the average collision rate was smaller, in this case, channel number 11.

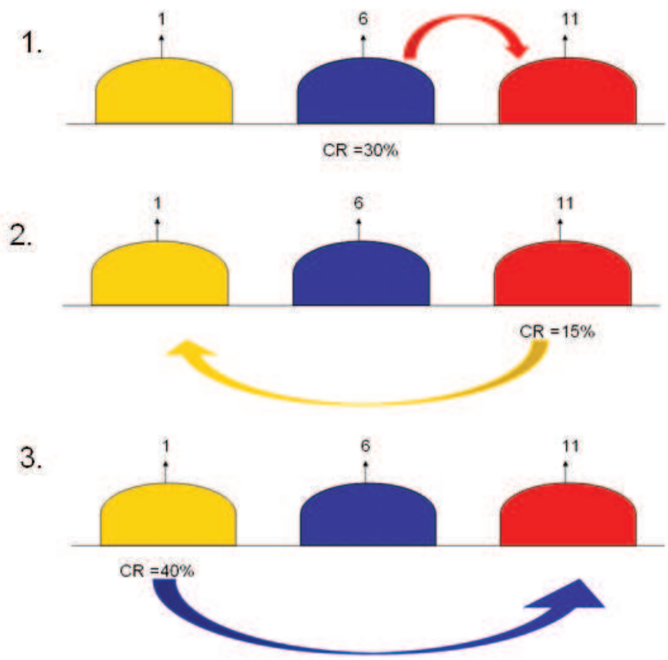

Figure 4.10 *Selection of the better channel available*

The number of stations that are competing in the channels is enough information to select the better one. [5] Shows mechanisms to determine the

[9] If all the channels are congested for a long time and the same process is repeated, the time that the dynamic channel selection is turned off is doubled.

average number of competing terminals based on run-time measurements by a selected station. Using this mechanism, it is possible to choose the best channel without having to jump and check all the available ones.

4.4.1 Client station procedure

As was explained in section 4.5, the client station follows an independently procedure to determine if the channel change is needed. The focus here is in the steps that the client stations have to follow to make the dynamic channel selection work properly. For this reason we have designed the following flowcharts that describe this procedure.

Figure 4.11 represents the flowchart of client stations measurements procedure. The collision rate is calculated and compared with the threshold. If this calculated value is higher than the threshold the client station informs the access point that a channel switch is needed. Otherwise, the procedure starts again in the next beacon reception.

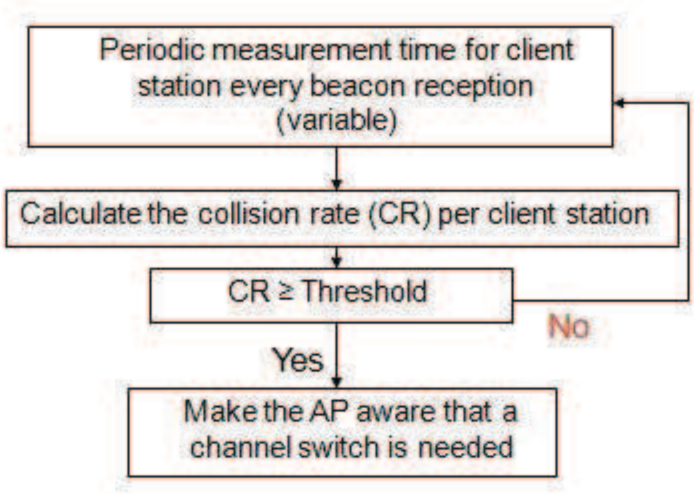

Figure 4.11 *Client stations measurements process flowchart (I).*

Figure 4.12 represents the channel switch procedure by the client stations. Once the Channel Switch Announcement frame is received correctly, the client station transmits the confirmation of it to the access point and it starts waiting for the acknowledgement of this transmission. If the client station receives the ACK, it changes the channel; otherwise the channel switch announcement response is retransmitted.

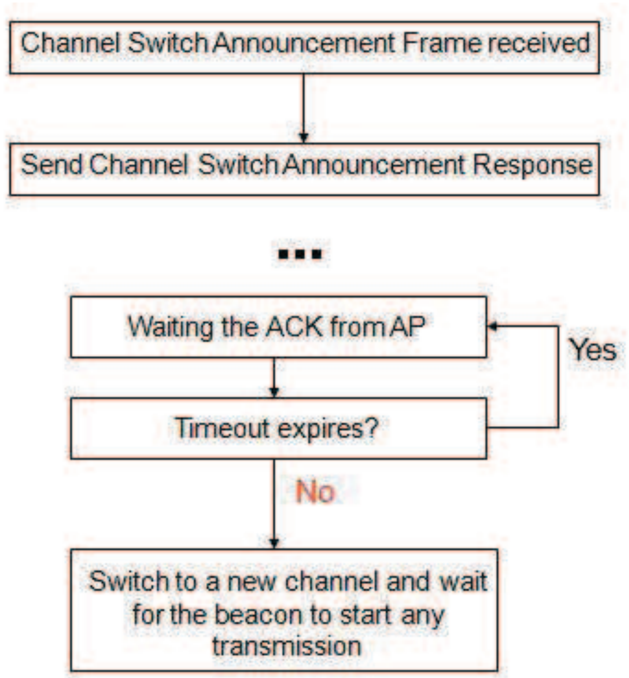

Figure 4.12 *Client stations channel switch flowchart (II).*

4.4.2 Access point procedure

The access point is who take the decisions in the dynamic channel selection mechanism. Depending on the percentage of stations in the BSS requiring a channel change, the access point is who decides in a fairly manner how to proceed. The focus here is the steps that the access point has to follow to make the dynamic channel selection work properly. For this reason we have designed the following flowcharts that describe this procedure.

Figure 4.13 represents the flowchart of how the access point manages the dynamic channel selection depending on the needs of the network. If within a time interval (explained in section 4.5) more than 50% of the stations require a channel change, the access point proceeds checking if RTS/CTS mechanism is activated. If this is not activated the next step is only switch on the RTS/CTS mechanism. Otherwise, the access point checks if it is convenient to keep it activated or switch it off and it proceeds selecting the new channel allocation. Once the new channel is selected this is set in the channel switch announcement frame and it is transmitted. When this transmission ends, the channel switch announcement response timeout starts (explained in section 4.5).

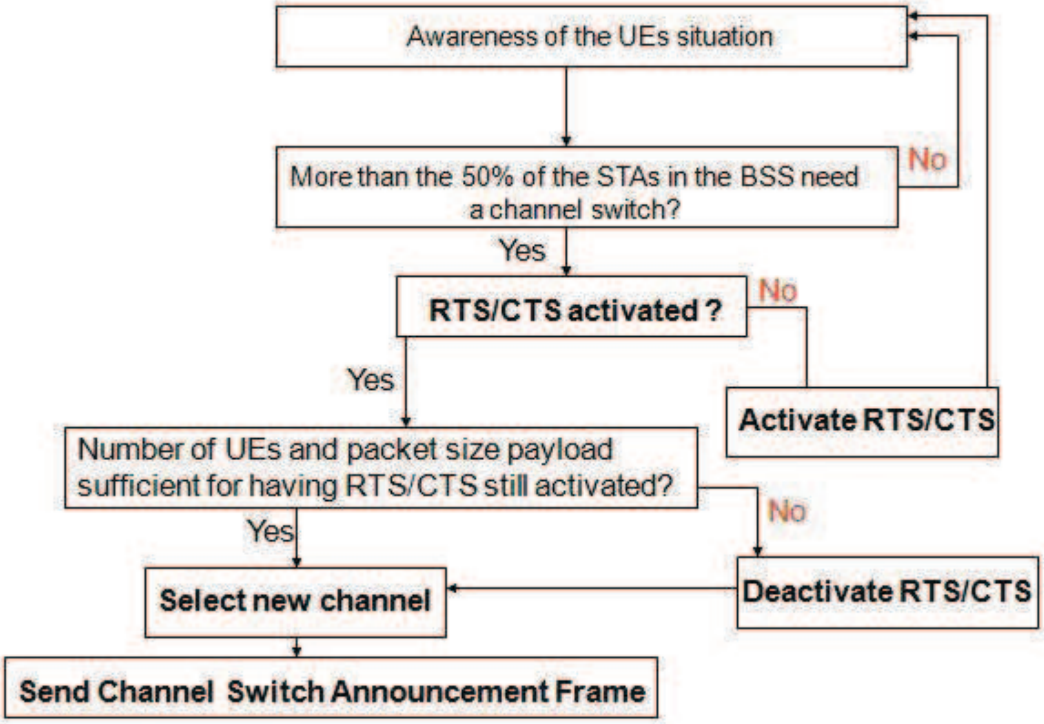

Figure 4.13 *Access point procedure flowchart (I).*

Figure 4.14 represents the channel switch procedure by the access point. If the channel switch announcement response frames from all the associated stations are not received within the timeout the announcement frame is retransmitted. If all the response frames are received the access point changes the channel.

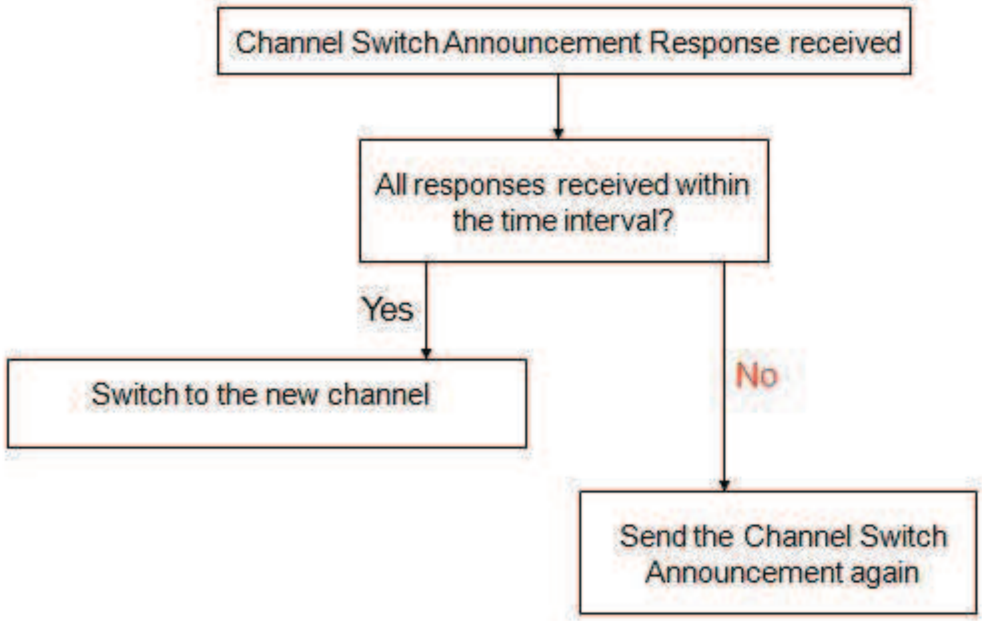

Figure 4.14 *Access point channel switch flowchart (II).*

4.5 Simulator implementation assumptions

The dynamic channel selection was implemented taken into account some simulation assumptions, these are:

- Each station operates in saturation condition. This means that the transmission queue of each station always contains at least a packet to be transmitted.
- All the stations in the networks are working based in the same IEEE 802.11- 2007 standard (WiFi g version), no mixing modes.
- The client stations and the access points do not move during the simulation. But the initial positions are random. .
- At the beginning the RTS/CTS mechanism will be deactivated.
- The measurements starting point of the networks are randomized between 0s and 1s.
- The measurements of average collision rate of the network are done every 100ms. If the channel is changed ten times (all the channels are congested) the dynamic channel selection is turned off for 15 seconds.
- The threshold is variable, depends on the number of the client stations associated to the access point. These values were estimated from simulation results (validated in Appendix III).
- All the BSSs have the same initial channel (channel 6).
- The channel selection is random. It means that when the access point select a new channel this could be one of the non-overlapped channels with equal probability for each of them.
- If the average collision rate of the network is above the threshold, there is 50% of probability of changing the channel.

For the first implementation (see figure 4.15), the time spent in the transmissions of channel change frame, channel switch announcement and channel switch announcement response is not taken into account. The measurements of the collision rate per station are done in a computational time.

As outputs for the simulator, we obtain the number of transmitted frames, specifically the number of successful frames (ACK frames received), the number of frames retransmitted, the average throughput per station and per network, the cumulative distribution function (CDF) of the throughput and the collision rate per station and per BSS.

Figure 4.15 represents the Unified Modeling Language (UML) for the first implementation of the dynamic channel selection.

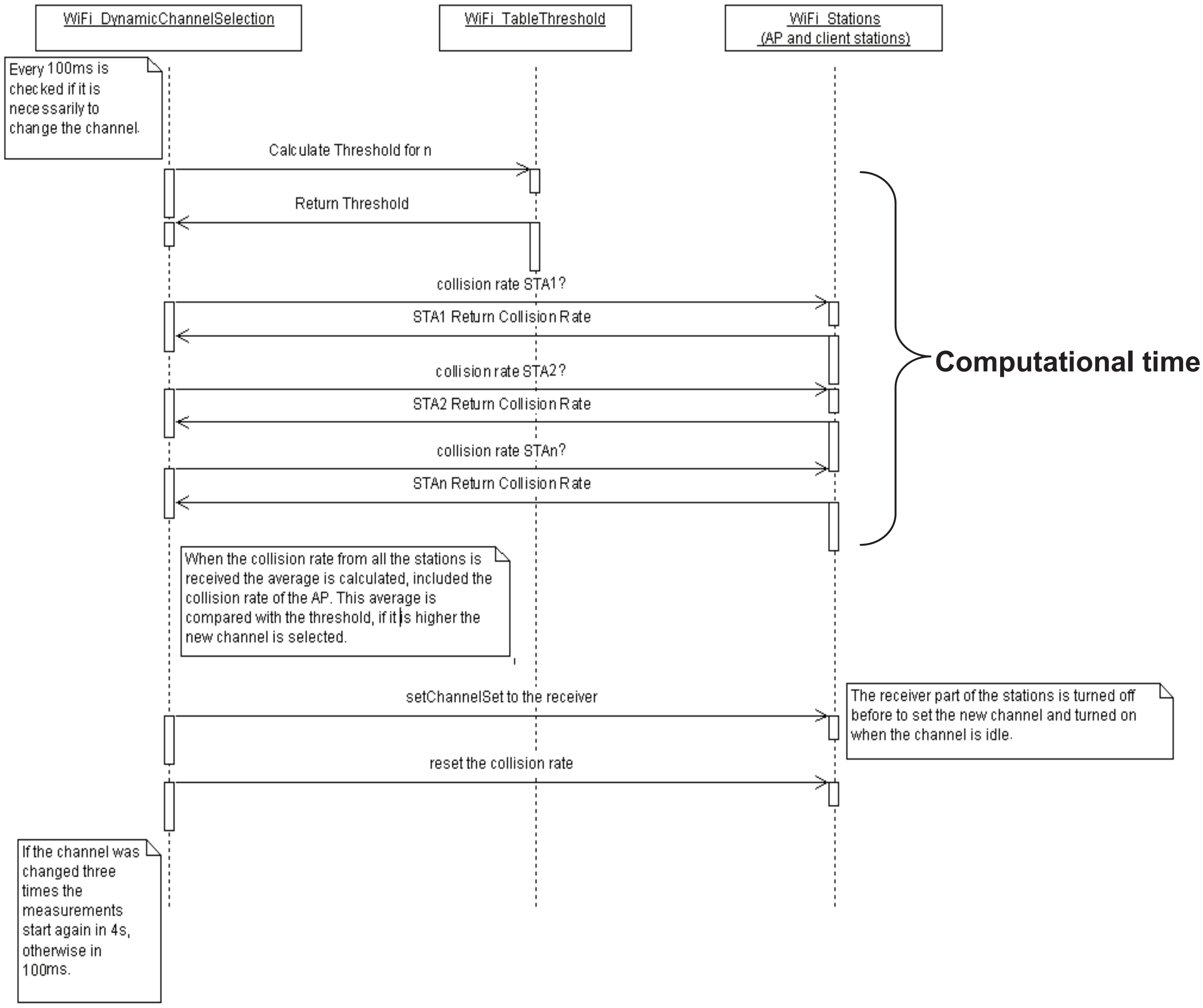

Figure 4.15 *UML of the first DCS implementation.*

In the figure, WiFi_DynamicChannelSelection is an object which manages all the dynamic channel selection process interacting with the WiFi_Stations and the WiFi_TableThreshold.

The object WiFi_TableThreshold has only one method that returns the threshold depending on the number of stations.

In the next section are shown the simulation results obtained from the first implementation of the dynamic channel selection for WiFi systems.

4.6. Simulation results

In this section are exposed the simulation results for the dynamic channel selection. It is compared the behavior of a scenario with two different type of spectrum allocation techniques[10]. These are the following: fixed spectrum allocation and the dynamic channel selection.

The fixed spectrum allocation means that all the BSSs in the scenario have the same channel when they are deployed. The dynamic channel selection refers to our proposal, the technique explained through chapter 4 where each BSS decides which the better channel is in order to be allocated.

The simulation results obtained in this section are based on a scenario with two BSSs with two stations per network that compete for the wireless medium. The simulation time used is ten seconds.

Figure 4.16 shows the comparison results of the CDF MAC throughput per user with the different spectrum allocation techniques.

In the simulator there is a parameter that can be used to choose when to start collecting throughput. In the figure below, there is a CDF that represents the throughput from the whole simulation time and one that starts collecting throughput in the second number five.

We choose to start collecting throughput in the second number five because after this time (explained in section 4.5), the networks have been allocated in the best channel possible by the DCS mechanism. On the other hand, when it is computed from 0 to 10 seconds, what happen is that the throughput obtained has lower values because during the first seconds of the simulation there are networks that could still be sharing the channel and they are not already allocated in the best channel.

[10] In wireless networks, these techniques are required to allocate bandwidth and communication channels to the components of a wireless system.

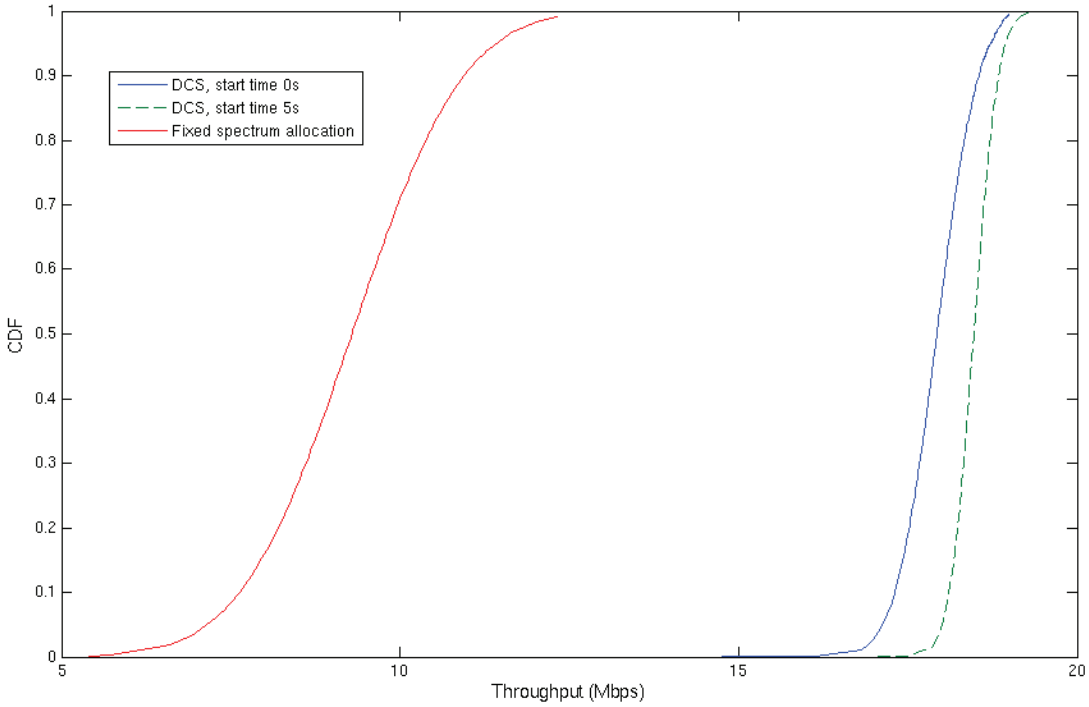

Figure 4.16 *Throughput comparison between fixed spectrum allocation and dynamic channel selection.*

From the results illustrated in figure 4.16 we can make the following analysis: the best performance obtained with the spectrum allocation techniques is achieved with the DCS mechanism. Comparing the curves that represents the throughput obtained using the DCS mechanism, it can be seen that when the collection of throughput starts in the second number five, at this time the networks are already allocated in the best channel possible. The BSS can change the channel 10 times before selecting the best channel and turn off the DCS mechanism for 15s. The 10 channel changes are done in less than 5s.

As can be seen, in the average throughput in the case of the fixed spectrum allocation is approximately 50% lower than the one obtained using the dynamic channel selection mechanism. Most of the stations achieve throughput between 8Mbps and 11Mbps. The reason is because the networks deployed are always sharing the same channel, as was explained in chapter 3.

4.8 Conclusions

Some conclusions that can be extracted from the results obtained are the followings:

- With DCS mechanism it is possible to find a balanced situation with the networks deployed where the stations achieve the throughput expected as if there were no more networks in the channel (two networks with three channels available).
- For larger scenarios with more networks than channels available, the DCS is still working but with less performance compared with the case with more channels than networks as there are less resources to share.
- The DCS can be a good mechanism to be used in the 5GHz band where the number of channels is greater compared to the 2.4GHz band, meaning that there are more resources where to allocate the networks and in consequence a better performance for each network can be achieved (to be studied in the future).
- The DCS mechanism begins with the networks deployed in the same channel and then tries to allocate them in the best balanced situation possible. A better performance can be achieved if the networks are deployed in a random way through the channels available from the very beginning and then using the DCS to find the best performance (to be studied in the future).

Given all these conclusions, it should be remarked that these results are only a first approach for the DCS mechanism. With future studies, a better understanding in how the mechanism will affect the performance of a network can be achieved.

Chapter 5

Conclusions

During this project we have studied the IEEE 802.11g performance for unplanned large scale deployments. The results obtained confirm the need of the proposed dynamic channel selection.

We have also explored the potential benefits that the dynamic channel selection mechanism has in unplanned deployments for WiFi systems, where the number of channels available is greater than the number of networks to be deployed in a congested area. For this purpose, a representative scenario was selected, consisting of two BSSs and two stations per each BSS (two access points and two client stations).

It is also remarkable that the DCS is still working for larger scenarios with more networks than channels available, but with worse performance compared with the case where there are more resources (channels) to share than networks deployed.

To be aware of, these results are only a first approach for the DCS mechanism, and further studies have to be carried out in order to validate the whole mechanism for the WiFi systems. These further studies may be focus on:

- Studying the efficiency of the DCS mechanism in the 5GHz band where there are more channels available compared to the 2.4GHz band.

- How to improve the DCS mechanism estimating the average stations in all the available channels based on run-time measurements by a selected station.

- Studying the behavior of the DCS mechanism for future WiFi versions such as IEEE 802.11ac.

Finally, to conclude the studies done during this project, IEEE 802.11 is a technology that can be improved in terms of throughput making use of a spectrum allocation technique such as DCS for medium and large scale deployments.

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Appendix I

Simulator architecture

The GRACE++ is a system level simulator developed in c++ language by Aalborg University and Nokia Siemens Networks.

The simulator current basic model is represented in the figure below.

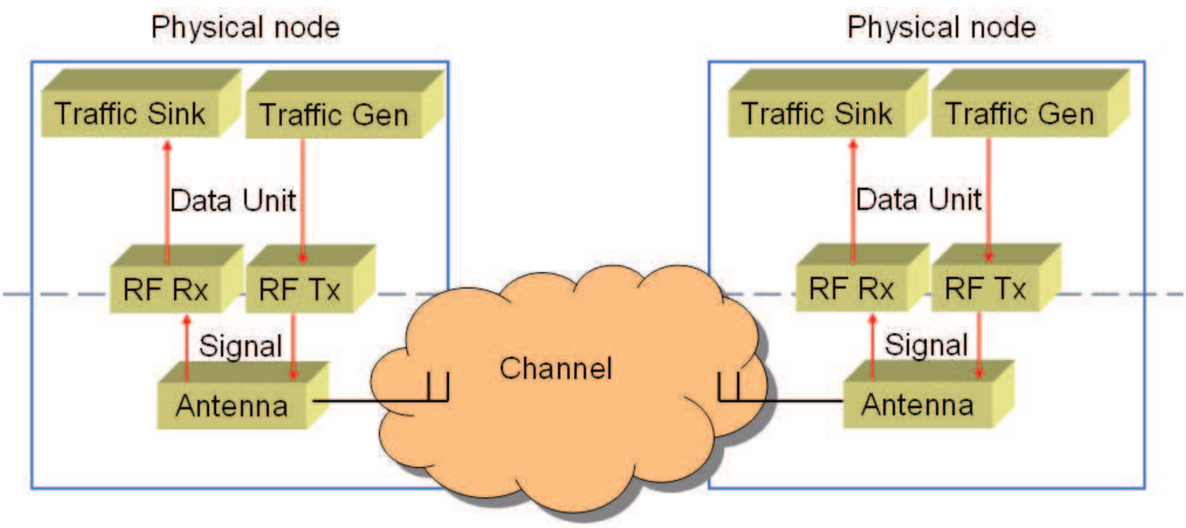


Figure A1.1 *Simulator current basic model.*

Each of the boxes from figure A1.1, are classes that interact with each other forming a physical node station. The current basic model is generally explained as follows:

- When a signal is detected in the channel, this is passed to the RF receiver where depending on the SINR is decoded or not. If the signal is decoded and the receiver address of the frame is the ID of the node that is receiving, the MSDU is passed to the Traffic Sink.
- When a data unit is generated by the Traffic Gen this is passed to the RF Transmitter where depending on the state of the station (receiving, scheduling other transmission, etc) this is stored in a data unit buffer or not. Before to transmit the frame the receiver has to certify that the

channel is idle making use of the CSMA/CA. If the channel is idle the signal is transmitted.

The simulator was developed to study the effect of the interference of different systems working in the same or near bandwidth. For this project, the aim was in the implementation of the WiFi system based in the IEEE 802.11g.

The classes named *"RF Tx"* and *"RF Rx"* internally has the follow architecture:

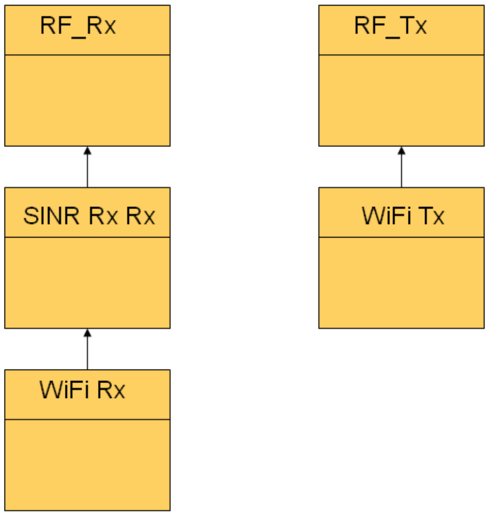


Figure A1.2 *Internal model of RF Tx and RF Rx*

To be more specific, most of the implementations during this project were done in the WiFi Rx and the WiFi Tx. The different frames implemented (see appendix II), the timeouts and the frames queues are in the WiFi Transmitter. While the CSMA/CA mechanism, the processing of the signals and the carrier sensing mechanism are in the WiFi receiver.

The CSMA/CA procedure and the carrier sensing mechanism for transmissions and receptions of frames are implemented in the simulator as a state machine. The state machine allows synchronization between transmissions and receptions of frames achieving a real behavior of the WiFi system in the simulator.

Figure A1.3 shows the state machine implemented the receiver part of the GRACE++ simulator.

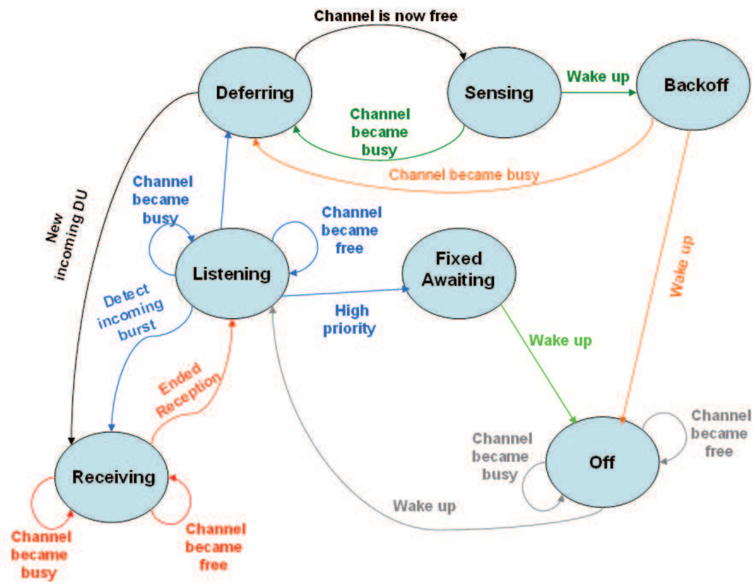


Figure A1.3 *WiFi state machine.*

In the figure A1.3 the blue circles represents the states and the name on the arrows represents methods that can change the state or keep the current one.

Appendix II

Simulator implementations

This appendix explains the implementations done in the GRACE++ simulator. For each feature implemented is explained the theoretical definition (based in IEEE 802.11 standard), assumptions, the model and some simulation results.

A2. Implementations

A2.1. Contention window

Contention window was implemented in the GRACE++ simulator based in IEEE 802.11 std 2007.

In the simulator, every time that a station has a data packet to transmit and the medium is sensed as idle for a period of time equal to DIFS, it may generate a random backoff interval (between 0 and the value of contention window) for an additional deferral time, in which the channel has to be idle, before transmitting. The theoretical detailed explanation of contention window is explained in chapter 2, section 2.6.3. Appendix III shows some simulation results of the WiFi performance influences, due to the initial value of the contention window.

A2.2. Encapsulation and de-encapsulation

Encapsulation and de-encapsulation was implemented in the GRACE++ simulator based in the IEEE 802.11 std 2007, specifically in the extended rate phy (ERP) PPDU frame format. Figure A2.1 shows the PPDU frame format used.

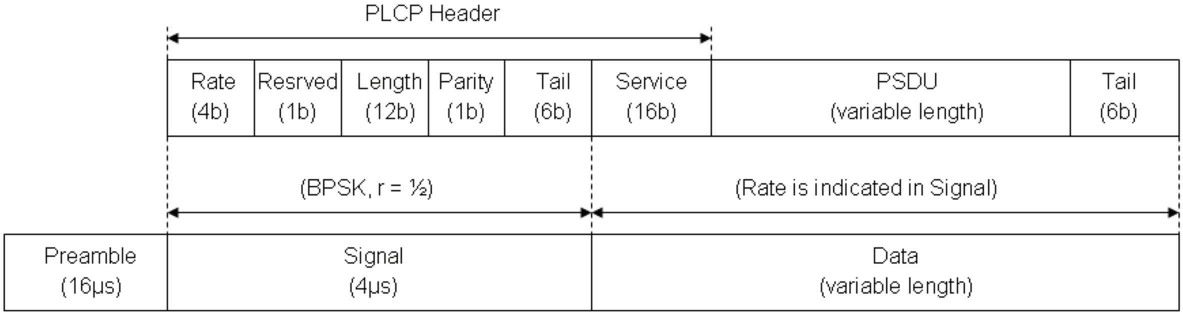


Figure A2.1. *IEEE 802.11 - 2007 PPDU Frame format (ERP-OFDM), where b refers to bits.*

For all the frames the PPDU frame format is the same. The MAC header is variable and depends of the type and subtype of frame (see the MAC frame formats in chapter 2).

In the simulator, every frame is encapsulated before to be transmitted and de-encapsulated for the receiver station following the IEEE 802.11 std specifications.

A2.3. ACK

A2.3.1 Introduction

When having a successful reception of a frame that requires an acknowledgement, an ACK frame should be generated by the destination station. This frame is to be transmitted when the destination station successfully receives a unicast frame but not if it receives a broadcast or multicast frame, even if that frame is a type that requires an ACK frame. After the reception of a frame which requires an ACK frame, the transmission of this frame should start after a SIFS time, without taking into account the busy or idle state of the medium.

A2.3.2 ACK frame format

The ACK frame format used for the implementation is explained in chapter 2 in section 2.5.1 control frames.

A2.3.3 ACK mechanism

After a source station has transmitted a frame which requires an acknowledgement, it should wait for an ACK time out interval. Within this time the source station cannot transmit any type of frames. This period of time has a value of a SIFS time + a slot time + a physical delay (10us + 20us + 25us). If the ACK frame arrives within the ACK time out interval and the frame is successfully received, this means that the frame sent by the source station has been received correctly and a successful transmission and reception has taken place. On the other hand, if the ACK frame is not received within the ACK time out interval or if the ACK frame is corrupted, the source station should do a retransmission of the frame which was sent at the beginning. The ACK mechanism is mandatory and it is part of the distribution coordination function which is based on CSMA/CA.

The conceptual design of ACK is explained in the figure bellow:

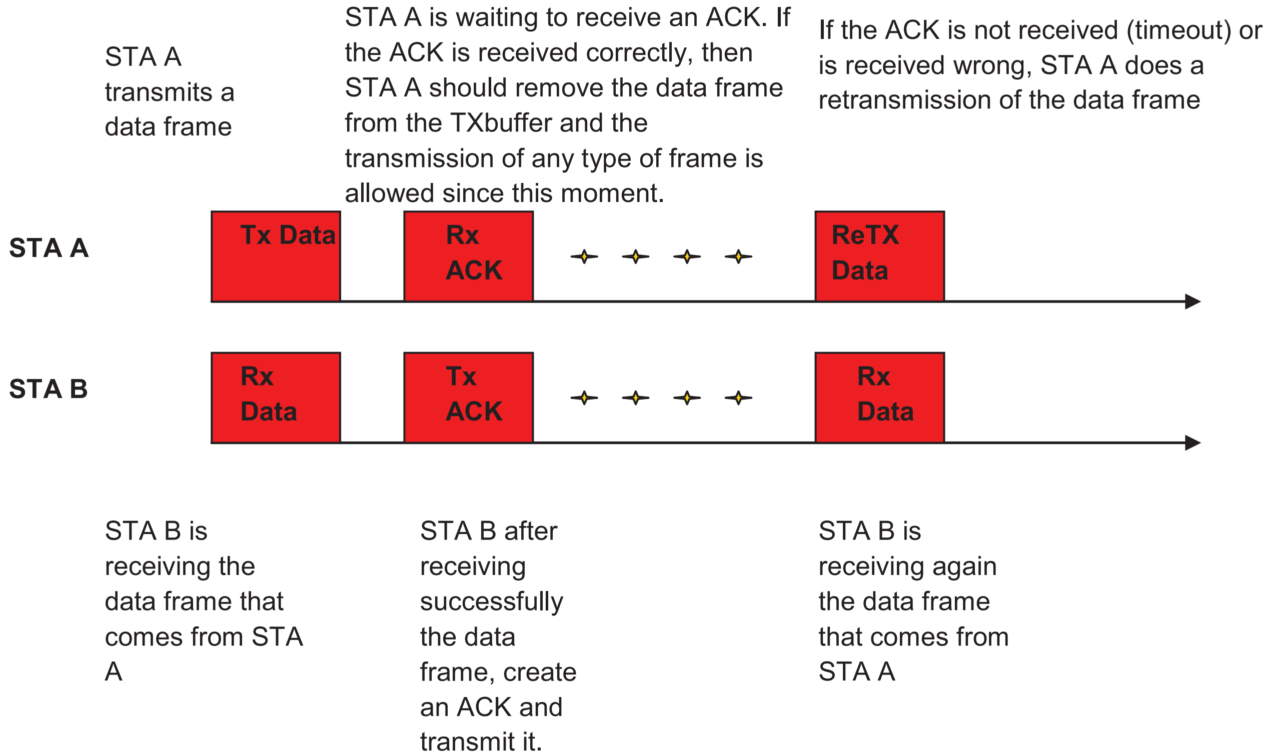


Figure A2.2 *ACK conceptual design.*

A2.3.4 ACK timeout

During the ACK time out it is supposed to be only in the channel the transmission of the ACK frame, but can happen that an AP has a beacon transmission scheduled (see section A2.5 for beacon implementation). In this case, we can think about different situations that can appear in the channel. The main cases are differentiated if the beacon is transmitted during the ACK timeout or not.

In the simulator was implemented a parameter named "disableBeaconWithinTimeOut" to enable or disable the transmission of beacons within the timeout.

A2.3.4.1 Beacon not transmitted within the ACK time out

Setting as true the parameter before mentioned the beacons cannot be transmitted within the ACK timeout. Some examples are explained below:

A2.3.4.1.1 Beacon generated within the ACK time out

In this case, the beacon frame is generated within the ACK time out and its transmission is delayed until the time out expires in order to cause no interference with the ACK frame that is supposed to be received during this time. So, once this time passes, the beacon frame will be transmitted after a PIFS time.

Figure A2.3, A2.4 and A2.5 show examples of beacon frame transmission deferred because of the ACK timeout.

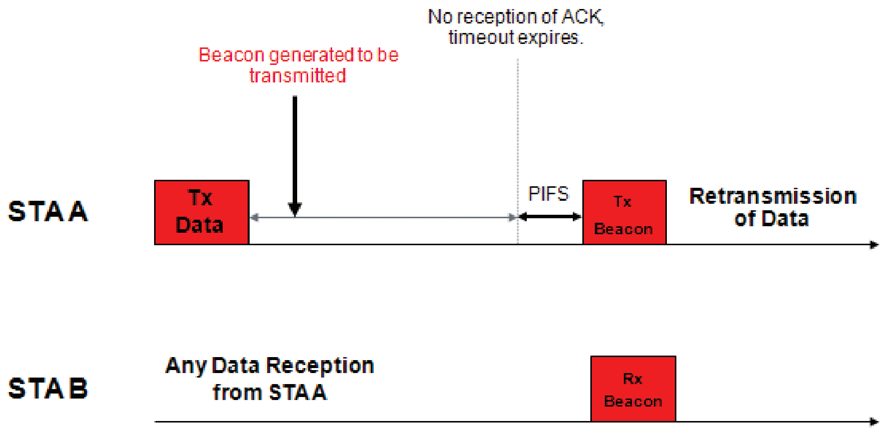


Figure A2.3 *Beacon generated within the ACK timeout and deferred, ACK not received.*

A2.3.4.1.2 Beacon generated within the current data transmission

Here, the situation is the same as the previous one but with the only difference is that now; the beacon frame is generated during the current data transmission, as is shown in figure A2.4.

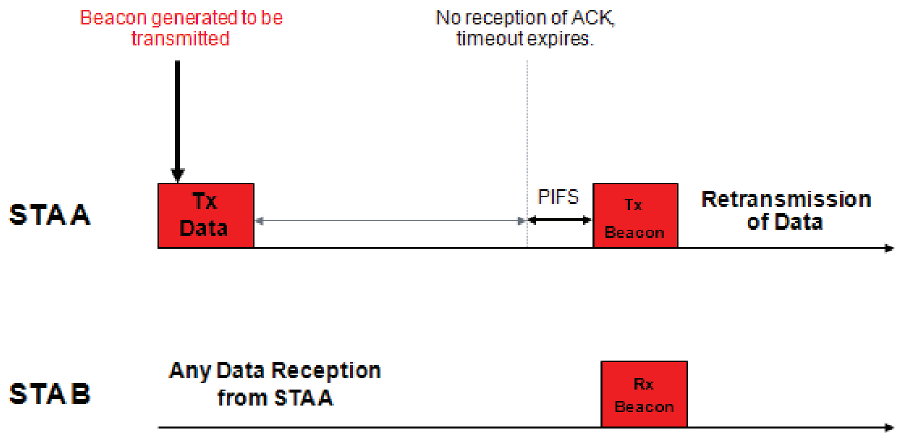


Figure A2.4 *Beacon generated within the current data transmission and deferred, ACK not received.*

A2.3.4.1.3 ACK received within the ACK time out and beacon generated within data transmission

In this case, the beacon is generated during the data transmission and ready to be transmitted. Once the ACK is received and therefore the ACK time out cancelled, the beacon frame is transmitted just after the ACK when a PIFS time passes.

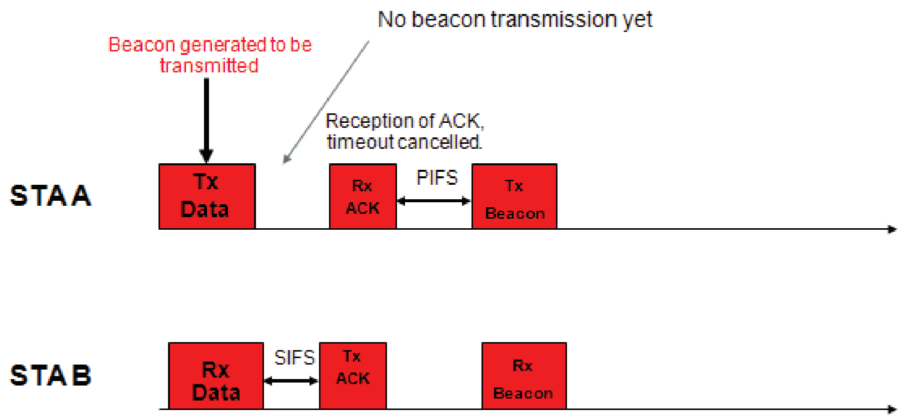


Figure A2.5 *Beacon generated within the current data transmission, ACK received.*

A2.3.4.2 Beacon is transmitted within the ACK timeout

Setting as false the parameter before mentioned the beacons can be transmitted within the ACK timeout. Some examples are explained below:

A2.3.4.2.1 Beacon generated within the ACK timeout

In this case the beacon is generated and transmitted after a PIFS time within the ACK timeout. If there was a collision on the data frame to be acknowledged, there is going to be no ACK in response within the ACK timeout, so the beacon will be transmitted and received by the other stations if this frame is not lost.

Figure A2.6, A2.7 and A2.8 show examples of beacon frame transmission within the ACK timeout.

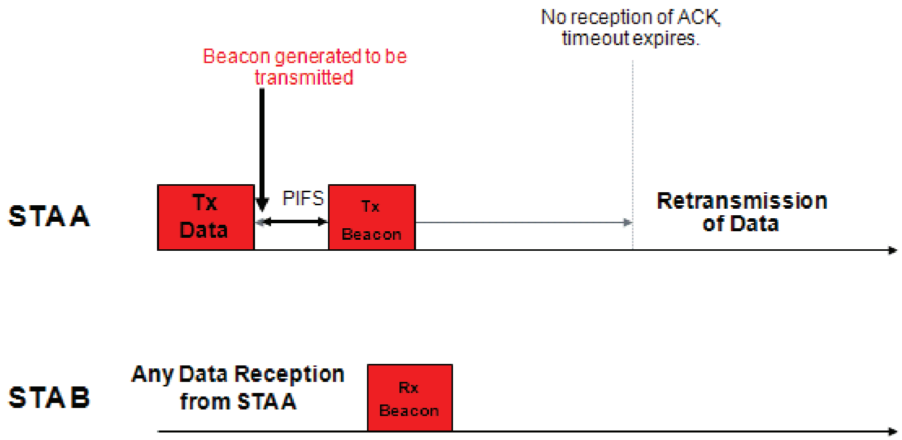


Figure A2.6 *Beacon generated and transmitted within the ACK timeout, ACK not received.*

A2.3.4.2.2 Beacon generated within the data transmission

This case is the same as the previous one but with the difference that the beacon frame is generated within the data transmission.

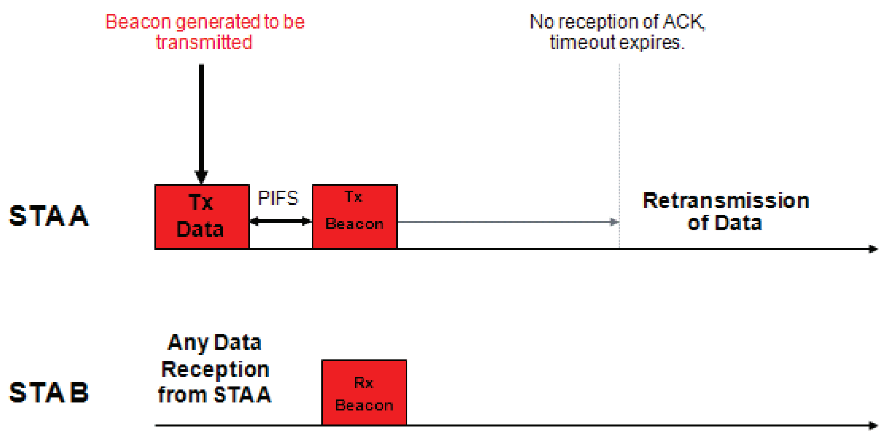


Figure A2.7 *Beacon generated during the current data transmission and transmitted within the ACK timeout, ACK not received.*

A2.3.4.2.3 ACK received within the timeout and beacon generated within the Data transmission

In this case, the ACK frame is received within the ACK time out while the beacon is also ready to be transmitted within this timeout as it was generated during the data transmission. So, as the ACK has a higher priority than the Beacon (SIFS<PIFS), the ACK frame is going to be received and after that, the beacon frame is going to be transmitted after a PIFS time.

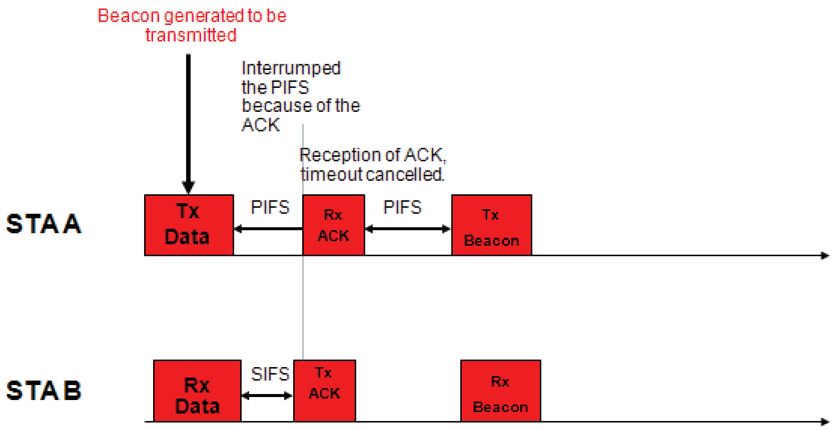


Figure A2.8 *Beacon generated during the current data transmission, ACK received within the timeout and beacon transmitted after the ACK reception.*

A2.3.5 ACK implementation in the GRACE simulator

For implementing the ACK in the simulator we divided the task in two different parts. The first one for managing the reception of a frame that needs to be acknowledged and creating the corresponding ACK frame, and the second one, to manage the transmission of the ACK frame knowing that this frame has a higher priority compare to data frames and has to be sent after a SIFS time.

A2.3.5.1 ACK UML diagram

We have two different diagrams where we distinguish between the case where the ACK frame is received correctly and the case where it is not.

A2.3.5.1.1 ACK frame received correctly within the ACK timeout

In this is a case, a Data frame is transmitted from Station 1 to Station 2 and received correctly. An ACK frame is generated in Station 2 and it is transmitted to Station1. After checked the correct reception of the ACK frame the Data frame stored in the Data Unit Buffer is deleted.

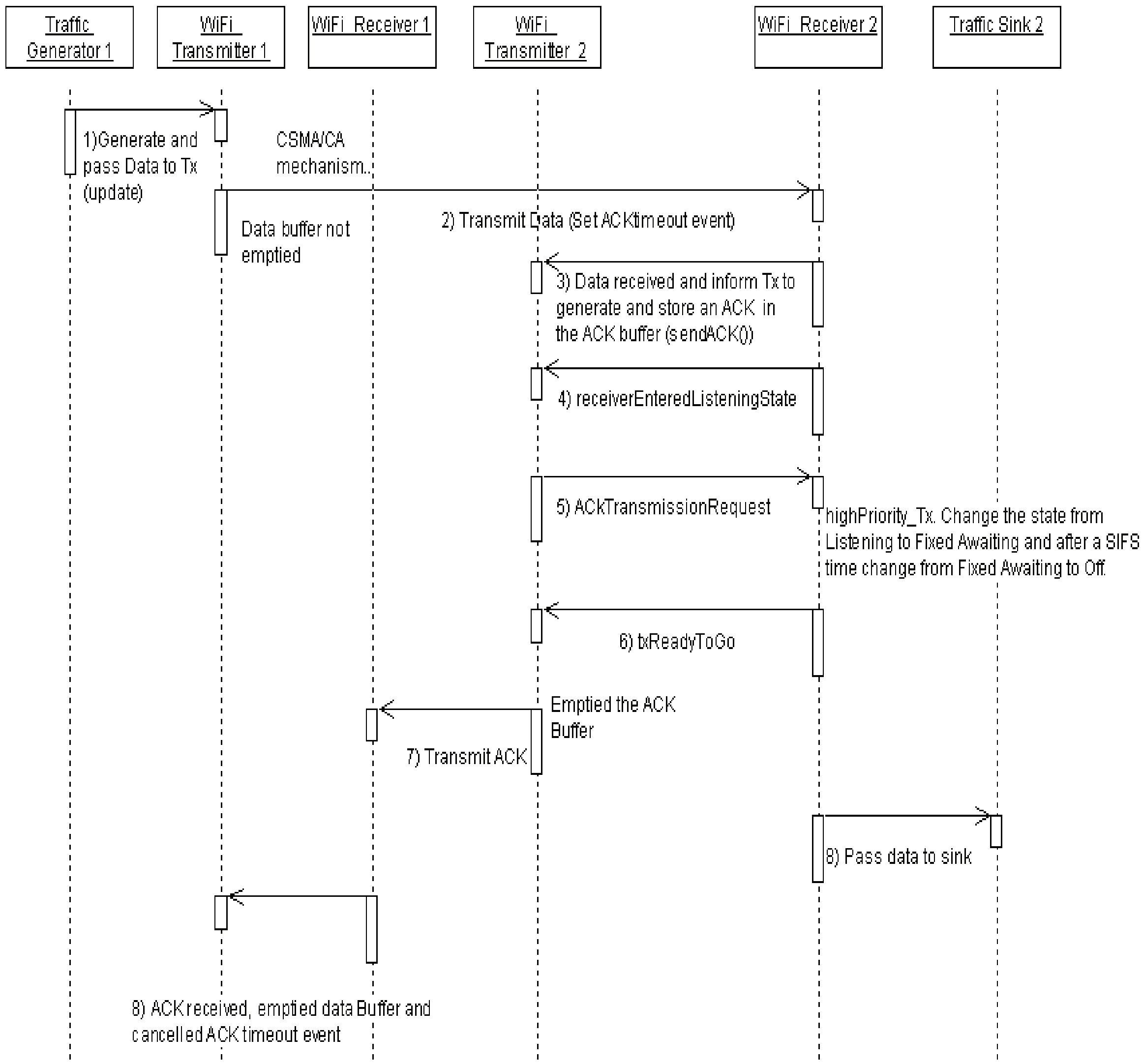


Figure A2.9 *ACK UML. Correct reception of ACK within the timeout.*

Tx1, Rx1, Traffic Generator1, Tx2, Rx2, Traffic Sinck2 are objects. The first 3 objects are part of a WiFi Station 1(STA 1) and the last 3 objects are part of a WiFi Station 2 (STA 2).

A2.3.5.1.2 ACK frame not received correctly within the ACK timeout

This case shows a Data frame sent from Station 1 to Station 2 and this is not received. Since the moment when the Data frame is transmitted, in Tx1 starts an ACK timeout (54µs). Within this timeout the Station 1 cannot transmit any type of frames. The ACK timeout expires and retransmission is processed.

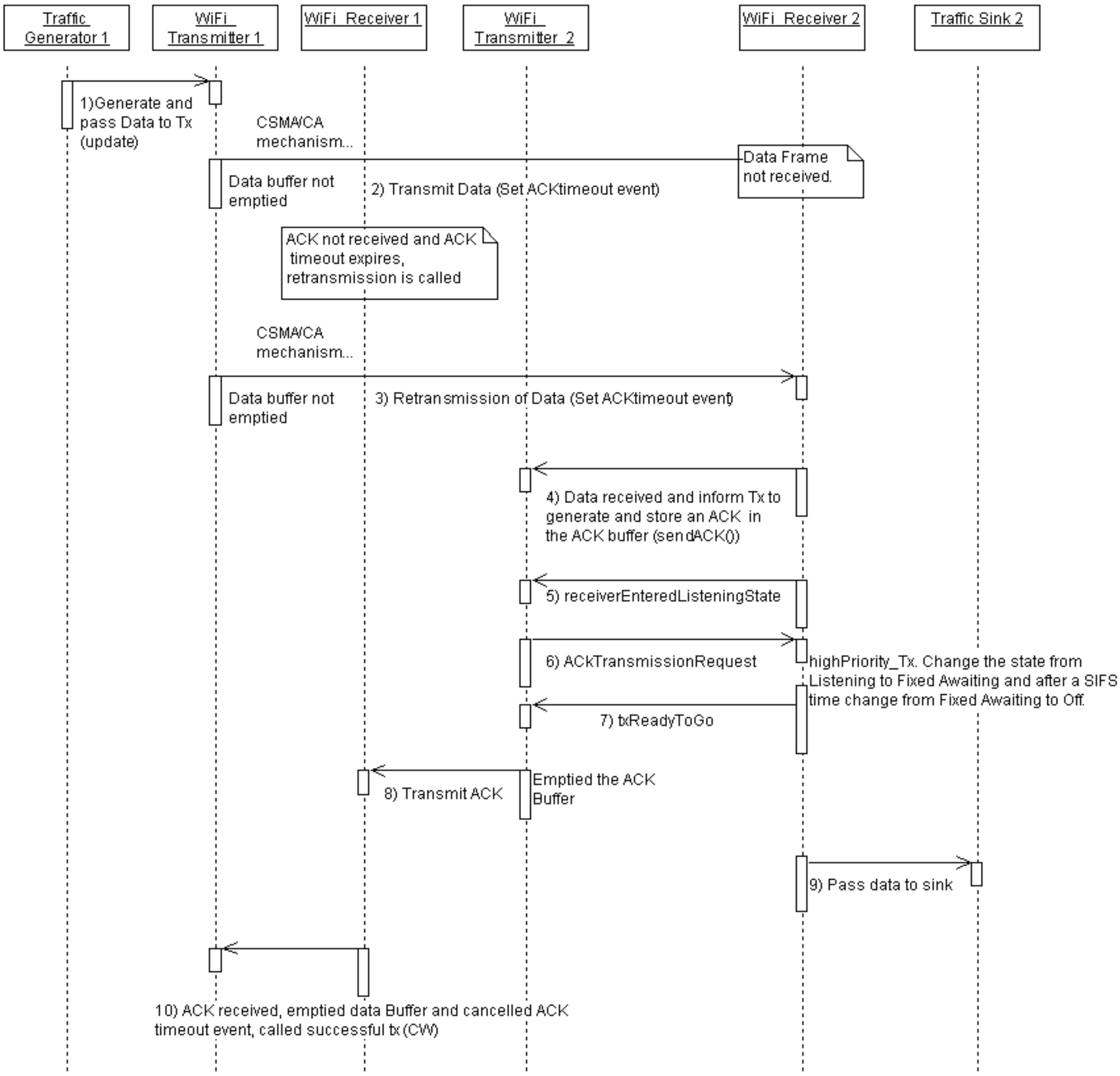


***Figure A2.10** ACK UML. Not reception of ACK within the timeout.*

A2.4. RTS/CTS

A2.4. 1 Introduction

In this section is explained the implementation of RTS/CTS mechanism in the GRACE++ simulator. The procedure of the mechanism and the description of the "hidden terminals" problem can be seen in details in chapter 2.

A2.4.2 Frame format

The RTS and CTS frame formats used for the implementation are explained in chapter 2 in section 2.5.1 control frames.

A2.4.2 RTS/CTS procedure

The RTS frame is first transmitted when there is a data frame or a management frame ready to be transmitted by a station. The RTS is sent after a successful contention for the channel. All the stations in range in the BSS will hear the RTS frame and read the duration field in order to set their NAV. Then, the destination station response with a CTS frame after a SIFS time has elapsed. All the stations hearing the CTS frame will also read the duration field and update their NAV. Upon successful reception of the CTS frame, the source station is able to transmit its frame knowing that the channel is reserved for a successful transmission. Figure A2.11 shows the RTS/CTS procedure.

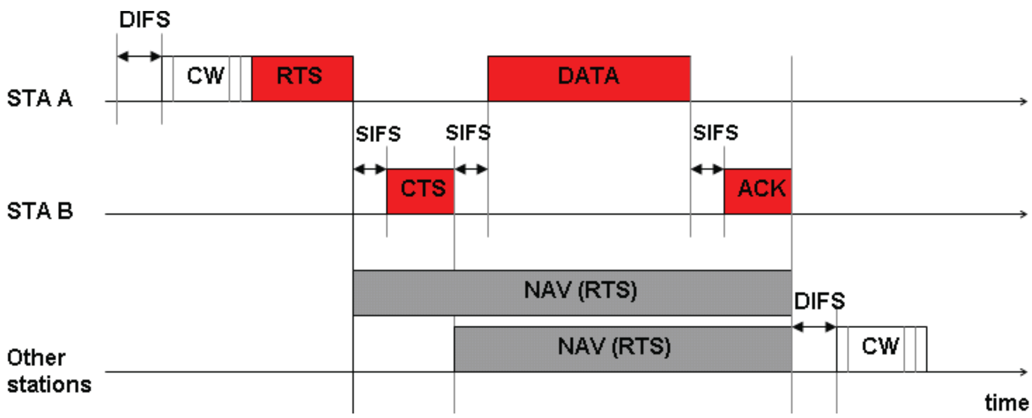


Figure A2.11 *RTS/CTS procedure.*

Collisions only occur on RTS frames or on CTS frames if a hidden node that has not heard the RTS frame transmits before receiving the CTS frame. In this case, the station which has sent the RTS frame retransmits this after a CTS time out has passed. This timeout has the same value as the one used for the ACK because both frames, CTS and ACK, have the same length, priority and are transmitted after a SIFS time. So, CTS time out is 55μs. The main problem we find here is that if a CTS frame is lost, all the stations that have already updated their NAV because of the RTS frame will not be able to contend for the channel until their NAV expires, being this a kind of wasted time and efficiency loss in the network.

Another important aspect is that the RTS/CTS mechanism can be used as a protection mechanism in networks that have legacy stations. The transmission rate of these frames depends on which types of legacy stations are associated to a BSS. For example, if there are 802.11b and 802.11g devices, the 802.11b rates are used to transmit the protection frames since the 802.11g stations can decode those frames.

Furthermore, this mechanism can be also an advantage in an area where there is overlapping of multiple BSSs using the same channel, because the reservation mechanism of the channel works across the BSA boundaries.

Chapter 2 explains how RTS/CTS mechanism reserves the channel, solving the hidden terminals problem.

A2.4.3 RTS/CTS threshold

Stations can be set to never use the RTS/CTS, use it whenever the MSDU exceeds a certain packet size threshold value or always use it.

This packet size threshold is a value from which it is convenient to switch to RTS/CTS mechanism. Depending on the payload packet size, the mechanism is useful or not. This threshold depends in the number of associated stations to the access point. Is logical that increasing the number of associated stations, the threshold decrease. The reason is because for large networks sizes the probability of collisions is high. Appendix III presents a comparison between the threshold obtained by simulations and the theoretical threshold based in [2].

Although this mechanism reduces the bandwidth wasted in collisions, in a not too loaded channel, additional delay can appear due to the overhead of the RTS/CTS frames.

The RTS/CTS mechanism cannot be used for transmitting MPDUs with broadcast or multicast destination. This will incur in a multiple concurrent senders of the CTS frame in response to the RTS.

Even if a station is not using the RTS/CTS mechanism, this station shall update its virtual carrier sensing mechanism with the duration in a received RTS or CTS frame. Moreover, the station shall response to an RTS frame which is addressed to it with a CTS frame if allowed by the medium access rules.

A2.4.4 RTS/CTS UML diagram

A2.4.4.1 Successful transmission of data frame with RTS/CTS

The model implementation of the RTS/CTS mechanism is shown in figure A2.12. This UML represents a successful data transmission using RTS/CTS mechanism. The NAV is updated if a third station receive the RTS or the CTS frame. The figure represents the the communication between two stations.

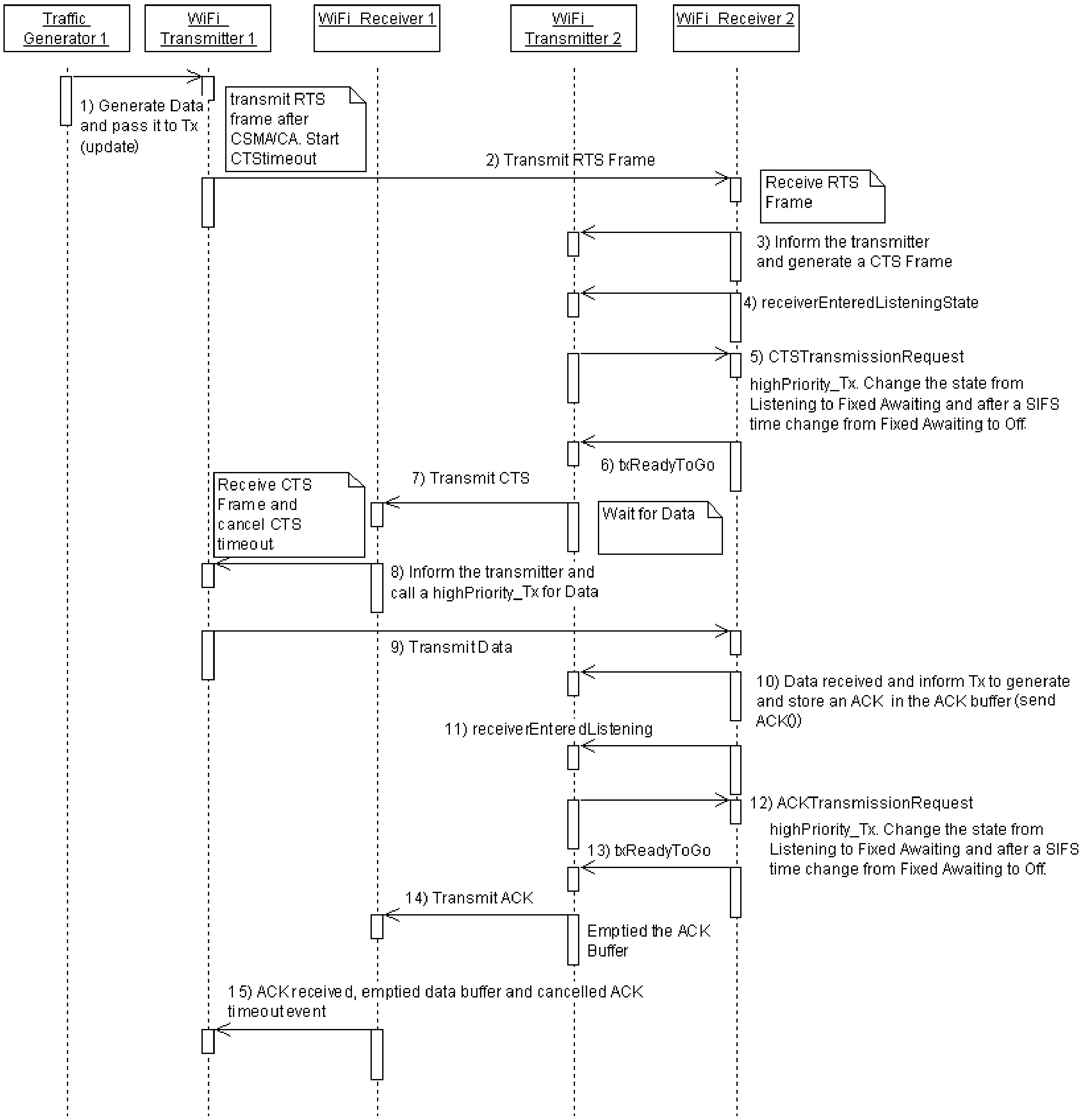


***Figure A2.12** RTS/CTS UML.*

A2.5. Beacon

A2.5.1 Introduction

This section explains in details the implementation of the beacon in the GRACE++ simulator. Following the detailed explanation of this implementation, some results are presented.

A2.5.2 Beacon frame

All the management frames have the same MAC header, no matter which subtype of frame is. The main difference relies on the frame body.

To start with, the beacon frame format is as follows:

Octets: 2	2	6	6	6	2	0 - 2312	4
Frame Control	Duration	Address 1 (DA)	SA	BSSID	Sequence Control	Frame Body	FCS

MAC Header

Figure A2.13 *Beacon frame format.*

Where the frame body is:

Octets:	2	2	2	2 - 34	3 - 10	7	3	0 - 8	6 - 256
	Timestamp	Beacon interval	Capability	SSID	Supported Rates	FH Parameter Set	DS Parameter Set	CF Parameter Set	TIM

4	8 - 256	7	20	3	4	8	10 - 255	3	3	36 - 256	3 - 257
IBSS Parameter Set	Country	BSS Load	EDCA Parameter Set	Power Constraint	TCP Report	Quiet	IBSS DFS	ERP information	QoS Capability	RSN	Extended Supported rates

3 - 257
Vender specific

Figure A2.14 *Beacon frame body.*

A2.5.2.2 Beacon frame model for implementation

In order to implement the beacon frame in the GRACE++ simulator, we had to take into account that there are several subfields in the frame body that are mandatory while others are not. The mandatory ones are: Timestamp, Beacon interval, Capability, **SSID** and Supported Rates. All the other subfields are optional depending on which kind of information we want to announce to the network. In our case, from now on, our frame body will be a payload of 432 bits: 16 bits (beacon interval) +80 bits (supported rates) + 48 bits (timestamp) + 16 bits (capability info) + 272 bits (SSID). This means, using the mandatory subfields.

From this, we can say that the amount of bits that we are going to transmit with a beacon frame is 676 bits: MAC header (192 bits= 16 bits (Frame control) +48 bits (RA) +48 bits (TA) +48 bits (**BSSID**) +16bits (sequence control)) + Frame body + Phy header (52 bits= 40 **PLCP** header + 16 bits preamble).

A2.5.3 Beacon procedure

The access point should define the synchronization time for the whole BSS by transmitting the beacon frames. The transmissions of the beacon frames are scheduled every beacon interval. If the medium is sensed as busy when the interval time expires, the transmission of this management frame is delayed until the medium becomes idle (see Figure A2.15).

Figure A2.6.3 shows an example of the beacon transmissions by the access point. The letter “B” refers to beacon, the letter “D” refers to busy medium and the time interval is 100ms. The beacon frame is delayed in some transmissions because the medium is sensed as busy when the time interval expires. In this case when the medium becomes idle the beacon is transmitted.

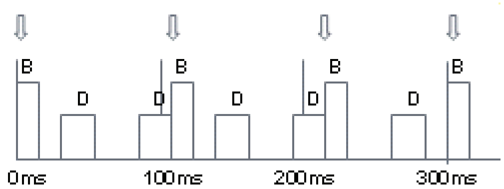


Figure A2.15 *Beacon transmissions.*

Based in the IEEE 802.11 standard, before transmitting a beacon frame, the channel has to be idle for a PIFS period of time. The Figure A2.16 shows an example of an access point attempting to transmit a beacon but the channel is sensed busy within the PIFS interval of time.

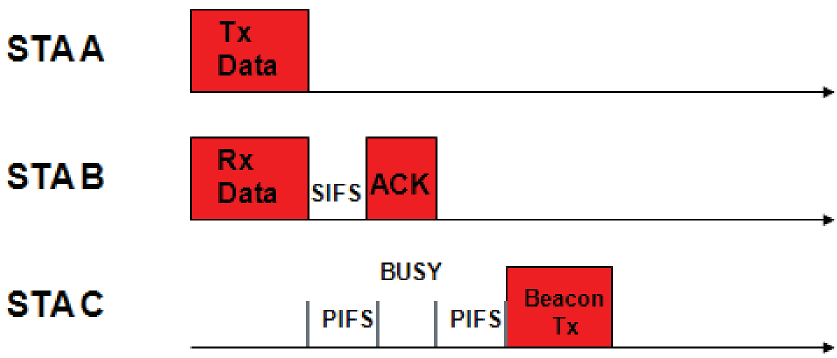


Figure A2.16 *Example of beacon transmission.*

A2.5.3.1 Beacon starting point

A problem to solve in our implementation of the beacon frames was achieving a randomization starting point. At the first implementation, all the access points started transmitting beacons at the same time, being this not realistic and causing many collisions. For this reason we implemented a uniform random time generator in the access point to get the time in which the first beacon transmission starts. This random time is a time between 0ms and 100ms which is also the time of the beacon interval.

Figure A2.17 shows an example of the beacon transmission starting point in a scenario composed for six networks. The access points start transmitting the first beacon in different times.

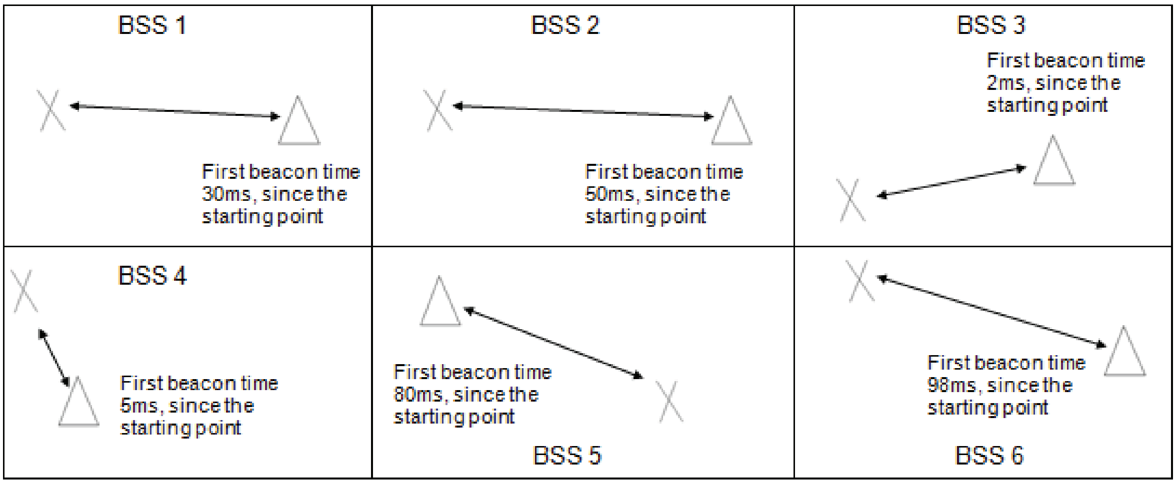


Figure A2.17 *Example of starting point of beacon transmissions.*

The beacon implementation is something that can be activated or deactivated in the simulator in order to simulate different behaviors in different kind of scenarios. The beacon interval is something that it is also added as a parameter in the simulator, so can be changed too.

A2.5.4 Beacon UML diagram

Using the sequence diagram of UML is possible to explain how the GRACE++ simulator works after the beacon implementation. This type of diagram has different elements for describing the behavior through time of the beacon implementation.

When we talk about states in this diagram, we are talking about the states which belong to a state machine implemented in the GRACE++ simulator

For the beacon implementation, we manage two different cases depending on when the beacon frame is generated.

A2.5.4.1 actual state not listening

In the first case, the actual state is not in listening (It is any other state, meaning that the station is receiving a signal or scheduling other transmission or transmitting), so the beacon transmission is delayed until the state returns to listening.

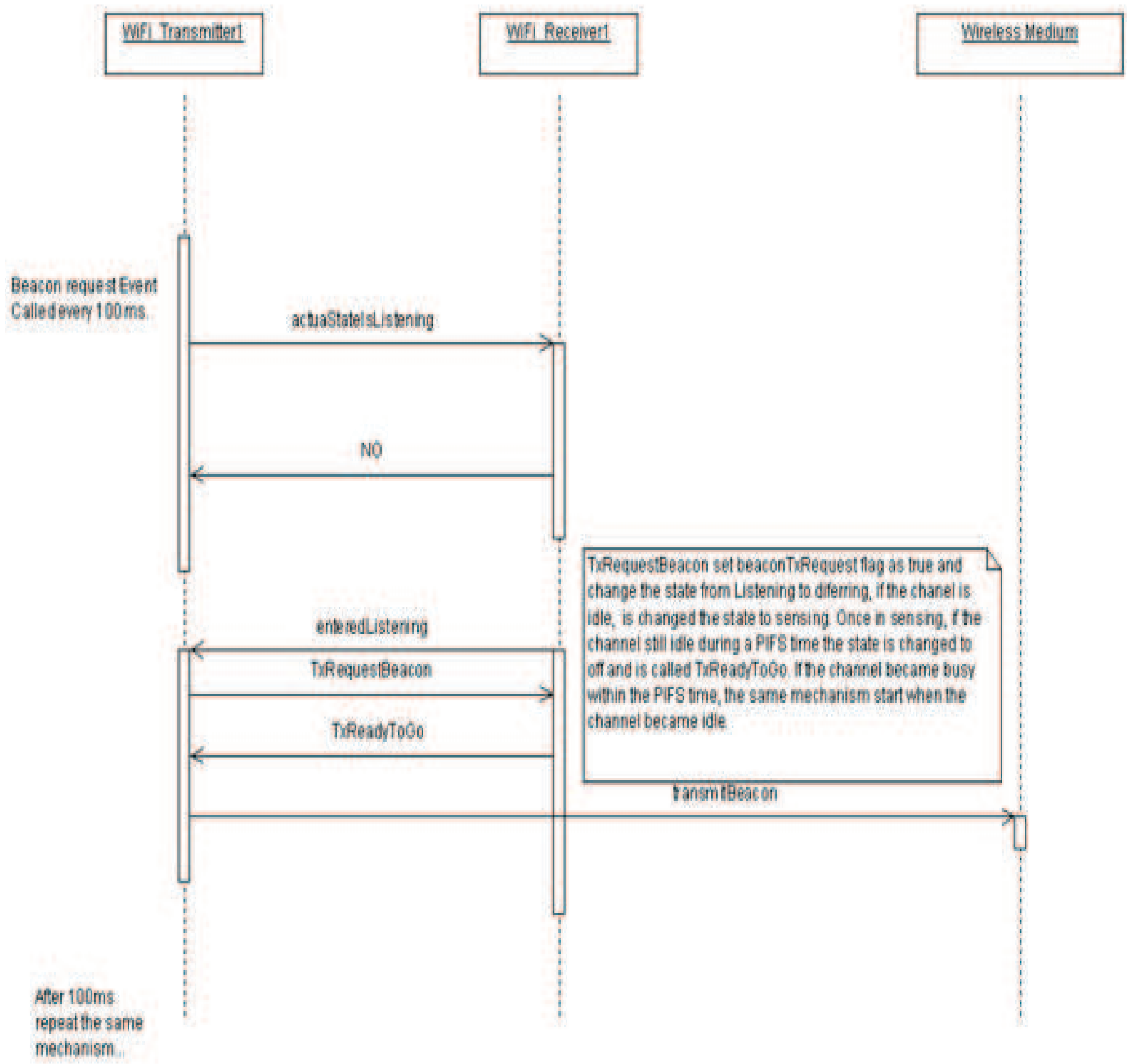


Figure A2.18 *Beacon UML. Actual state is not listening.*

A2.5.4.2 Actual state listening

In this second case, the actual state is listening so, the beacon is directly transmitted because the channel is idle.

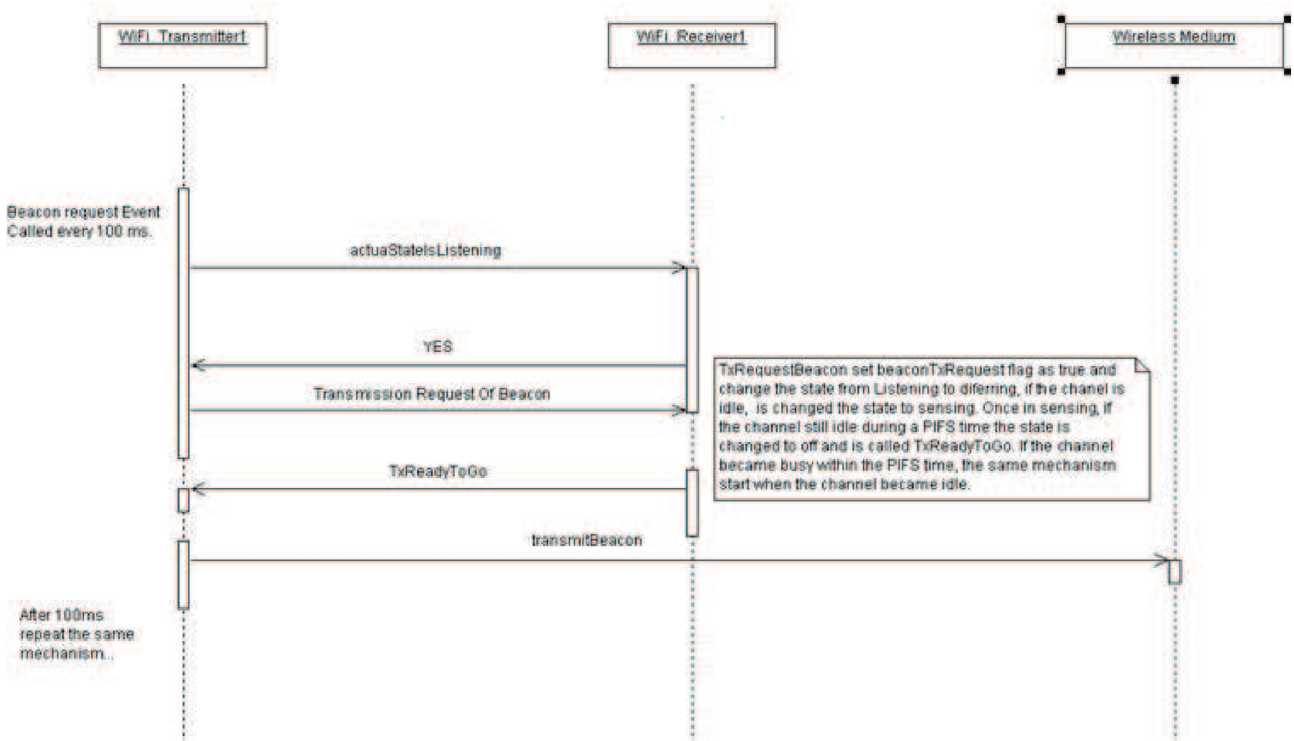


Figure A2.19 *Beacon UML. Actual state is listening.*

A2.5.5 Simulation results

This section documents the main simulation results of the influences of the beacon frame transmission every 100ms in the performance of the network. The basic parameters employed are summarized in Table A2.1. The general assumptions for the simulations are the same exposed in chapter 3; the only different is the activation of the beacon and the simulation time that here was set to10s.

Parameter	Value
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
PIFS	30 μs
CWmin	15
CWmax	1023
Data rate	54 Mbps
MPDU	4095 bytes
ACK timeout	55 μs
RTS/CTS	Deactivated
Beacon interval	100 ms
Preamble time	16 μs

Table A.2.1 *IEEE 802.11g parameters used for the simulations.*

Figure A2.20 shows the cumulative distribution function (CDF) of the throughput per user when beacon is activated and when it is not. The number of associated client stations to the access point is equal to one.

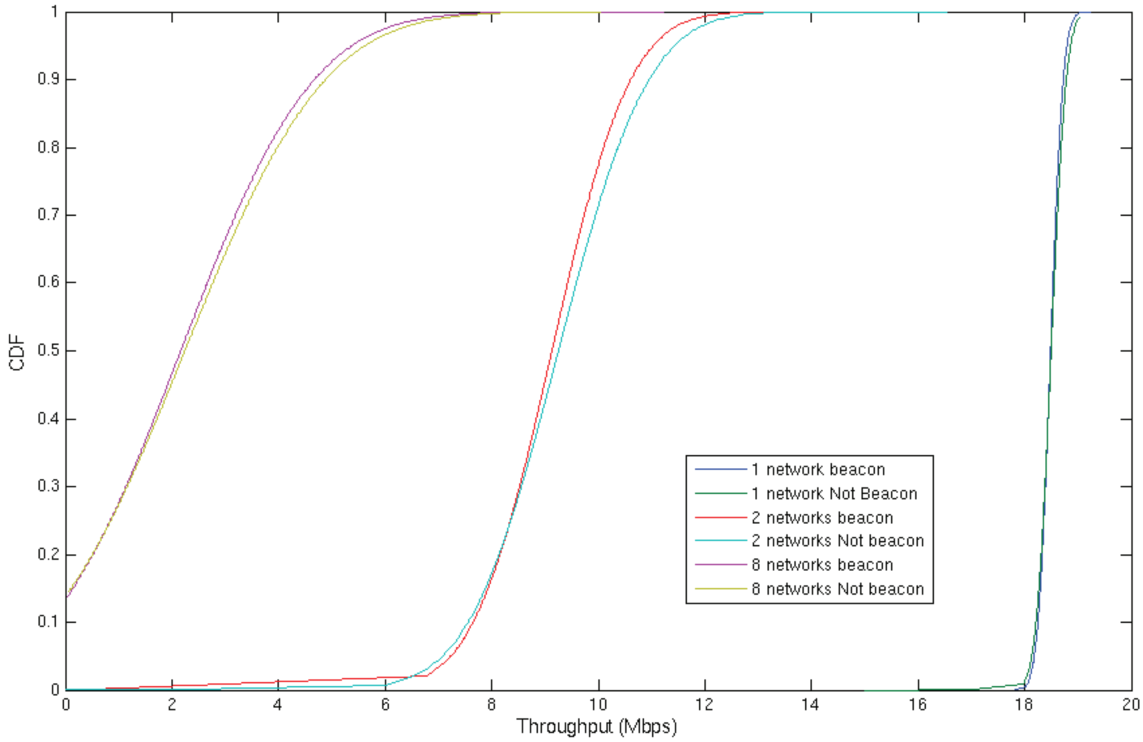


***Figure A2.20** Effect of beacon in throughput.*

With respect to the figure, in the networks with beacon activated the throughput degrades a bit, as was expected. The reason is, because every 100ms, in the case of one network scenario, the medium is occupied for this management frame. Increasing the number of networks, the medium busy time due to the beacon frames also increase, affecting it more the throughput per user.

A2.6. Power ramp on

The transmitted power on ramp for the 10% to 90% of the maximum transmission power may be no more than 2 us.

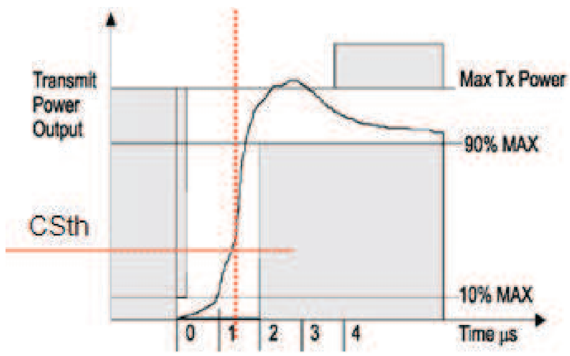


***Figure A2.21** Power ramp on. IEEE 802.11 std 2007.*

In order to model this behavior we divide the 2 us in two parts, the first one until the power reaches 10% of the maximum and the second one when the power is between the 10% and the 90% of the maximum. The implementation of the power ramp on was done as follow:

The first microsecond, the transmission power is fixed to zero. Seen the figure A2.21 the power within this interval of time is below the 10% of the maximum transmission power.

The second microsecond, the transmission power increases with more slope. The figure A2.21 shows that in some point (variable) this transmission power reach the carrier sense threshold of a specific station.

In order to detect the signal in a station, the signal should be above a threshold, in this case the carrier sense threshold. This detection will be held after a time that we have named time below threshold (*tbelow_th*). This time will be between 1us and 2us and therefore, the total time below threshold is 1us plus time below threshold (Totaltbelow_th= 1us + tbelow_th). Later, we will explain the mathematical calculation of this value.

The power ramp on was divided in two parts to make it easier and logical the implementation in the simulator. Figure A2.22 shows that the first microsecond of power ramp on was implemented in the transmitter part and the second variable microsecond in the receiver part.

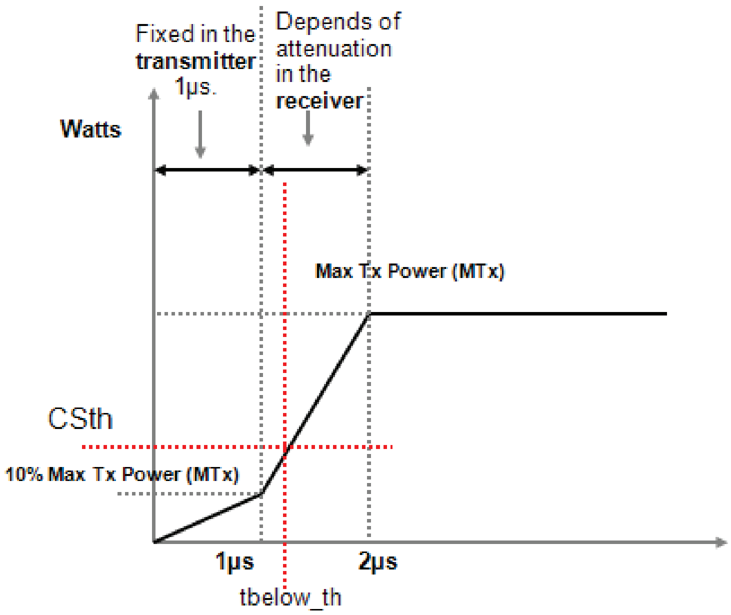
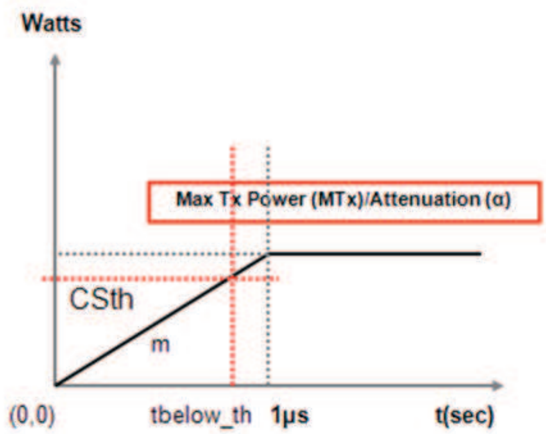


Figure A2.22 *Power ramp on model implemented.*

Once the signal reaches the destination station, the model is the same but taking into account the attenuation of the channel. We do not take into account the delay which suffered the signal because is much less than 1us, something not relevant in this case. The figure below explains how the time below threshold is calculated when an IEEE 802.11 signal is received.



$$m = \frac{MTx}{(1\mu s * \alpha)}$$

$$m = \frac{CSth}{tbelow\_th} = \frac{MTx}{(1\mu s * \alpha)}$$

$$tbelow\_th = \frac{(1\mu s * \alpha) * CSth}{MTx}$$

Figure A2.23 *Power ramp on mathematical calculation of the time below the carrier sensing threshold.*

Where *MTx* = 100mW; *CSth* = -76dbm = 2.51e-11W, *m* is the slope and α is the attenuation (variable). The value of attenuation is obtained from the received signal. The received signals in the simulator are objects that can return the attenuation suffered from a specific method. Every time that an IEEE 802.11 signal is sensed in the channel, the reception is delayed for the time below the threshold.

This implementation makes more realistic the GRACE++ simulator. The delay obtained with the power ramp on in the reception of signals increases the number of collisions per each successful transmission.

Appendix III

Bianchi's model validation

A3.1 Introduction

Once implemented in the simulator the features explained in Appendix II the next step was validate our code. To compare with, we made use of the Bianchi's model paper [2] which provides an analytical model to compute the 802.11 DCF throughput, in assumptions of finite number of stations and ideal conditions (for example, no hidden terminals).

Through the paper is explained how to calculate the packet transmission probability[11] based in a Markov Chain model for the backoff window size. From this probability are calculated the following statistics:

- The probability *Ps* that a transmission occurring on the channel is successful.
- The probability *Ptr* that there is at least one transmission in the considered slot time.

These probabilities are used to compute the system throughput, defined as the fraction of time the channel is used to successfully of payload bits transmission.

The system throughput depends on the initial contention window, the backoff stage and the number of stations.

In the paper, once is explained how to calculate the throughput, based in the statistics, this is compared this with some simulation results. Our validation was done with some of these comparisons, which are:

- Saturation throughput versus initial contention window size for the basic access mechanism.

[11] The packet transmission probability is defined as the probability that a station transmits in a randomly chosen slot time.

- Saturation throughput versus initial contention window size for the RTS/CTS mechanism.
- Number of collisions per each successful data transmission (collision rate) versus number of stations.
- Packet payload threshold over which the RTS/CTS mechanism is advantageous.

A3.2 Comparison of the results

This section presents the comparison between the results obtained in the simulator and the Bianchi's model. The assumptions are the same than in the model, saturation conditions, ideal channel conditions, fixed number of stations and the parameters used are from IEEE 802.11g version.

A3.2.1 Saturation throughput versus initial contention window

As was mentioned before, the throughput depends of the initial contention window, the number of stations, the backoff stage and the access technique. Increasing the initial contention window directly reduces the probability of collisions, being it advantageous if the network is composed for many stations.

Figure A3.1, A3.2 and A3.3 show the dependences of the throughput on the initial contention window, on the number of stations and on the access technique.

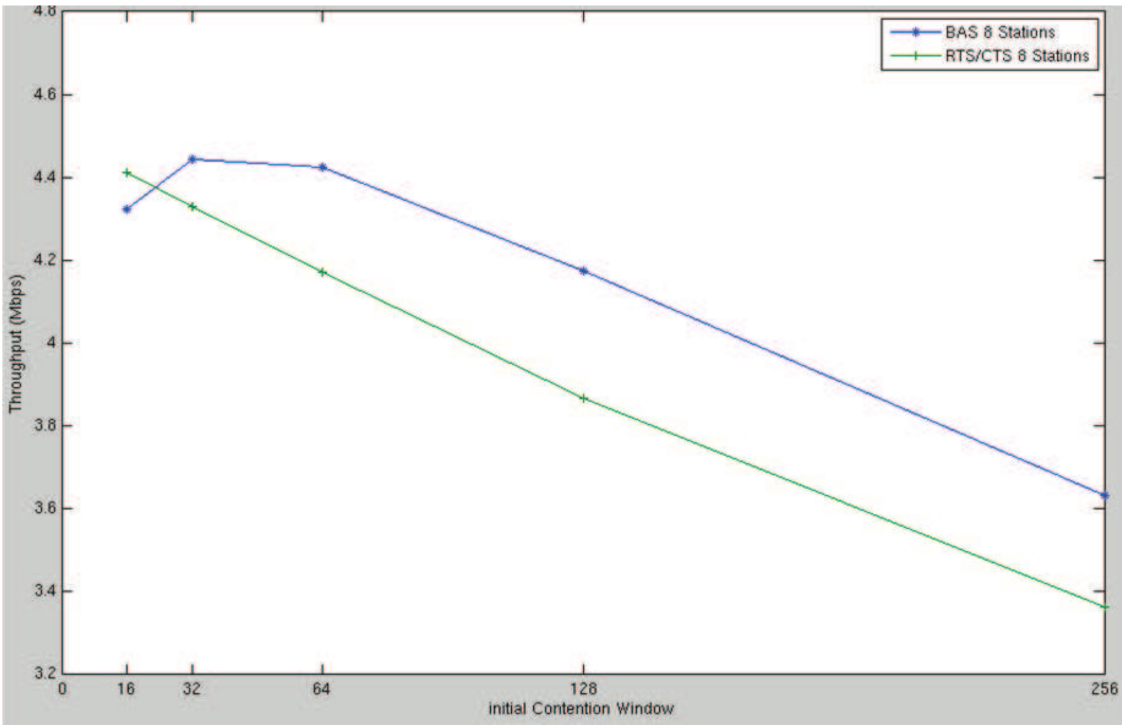


Figure A3.1 *Saturation throughput versus initial contention window. 8 stations.*

In the figure A3.1 can be seen that for the basic access method the highest throughput is obtained when the initial contention window is set to 32. But in case of RTS/CTS mechanism the throughput decrease when the initial contention window increase. RTS/CTS mechanism is useful for large networks sizes, due to the fact that the probability of collision is very high and the time wasted in collisions using this mechanism is smaller than using the basic access method (in the paper is deduced the collision time for both access techniques). Compared with the Bianchi's model the behavior is the expected.

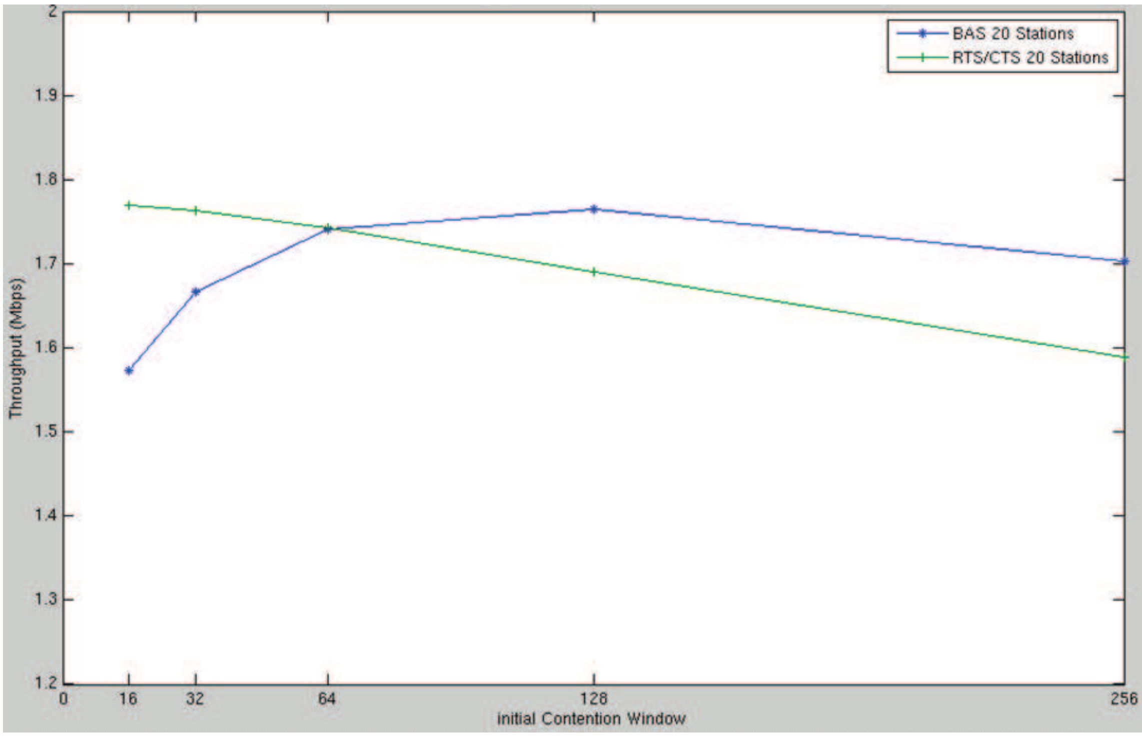


Figure A3.2 *Saturation throughput versus initial contention window. 20 stations.*

In the figure A3.2 can be seen that the throughput behavior in case of RTS/CTS mechanism is similar than in the figure A3.1. In the case of the basic access method the highest throughput is obtained when the initial contention window is set to 128. In this figure can be seen the dependences of the throughput in the number of stations and on the initial contention window. Comparing the curves between this figure and the figure A3.1 we can conclude that increasing the number of stations the optimal throughput is reached for higher initial contention window.

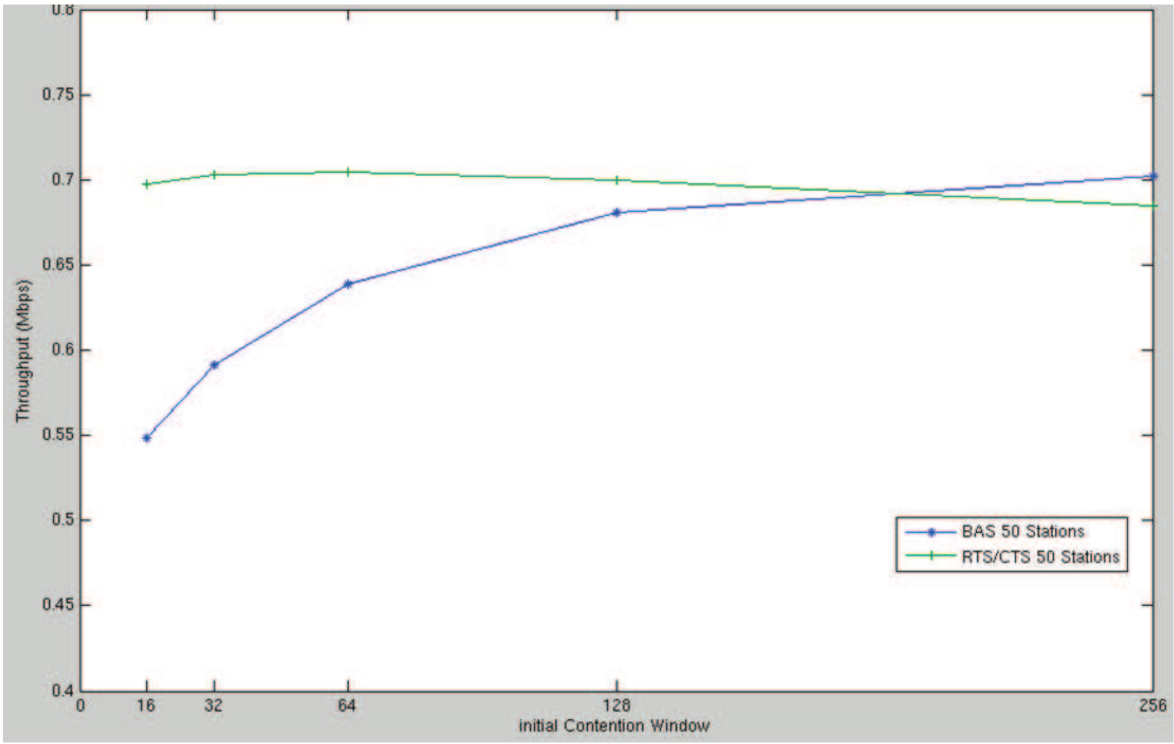


Figure A3.3 *Saturation throughput versus initial contention window. 50 stations.*

Finally, the figure A3.3 follows the same behavior before explained for the basic access method. The optimal throughput is obtained when the contention window is set to 256.

As a general conclusion of the results, the access technique is useful depending on the initial contention window.

A3.2.2 Collision rate versus initial contention window

The collision rate strongly depends on the initial contention window. As was explained in sub-section A.3.2.1 higher sizes of the initial contention window reduces the collision rate. The reason is because the probability that the stations transmit at the same time is lower for higher initial contention window.

This sub-section presents a comparison collision rate between the theoretical calculation with Bianchi's model and our simulation results obtained. The collision rate is defined as the number of collisions per each successful data transmission.

Figure A3.4 shows a comparison of the probability of collision between the results obtained in the GRACE++ simulator and the theoretical calculation obtained from Bianchi's model. The results from the simulator are very similar than the calculated in the model. As was explained before, the behavior of the probability of collision is the expected.

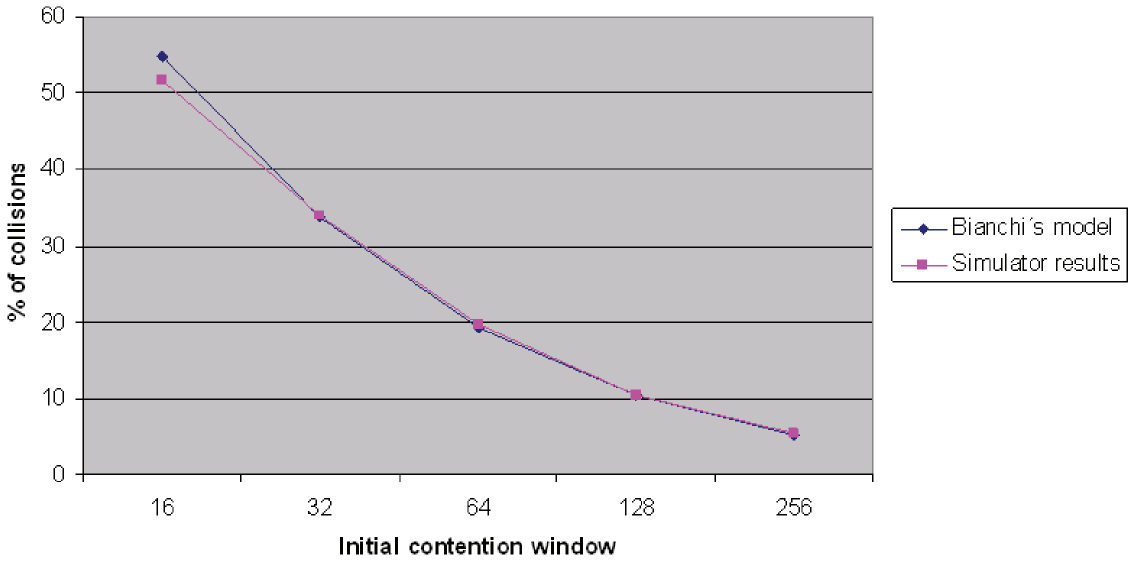


***Figure A3.4** Collision rate versus initial contention window.*

A3.2.3 Comparison collision rate versus number of stations

The collision rate is a parameter that can define how load are the channels. The dynamic channel selection explained in chapter 4 is based in this. For higher networks sizes the collision rate is also higher depending it in the number of stations.

Figure A3.5 shows a comparison of the collision rate between the results obtained in the GRACE++ simulator and the theoretical calculation obtained from Bianchi's model. This comparison is done between five different numbers of stations (2, 4, 8, 10 and 18).

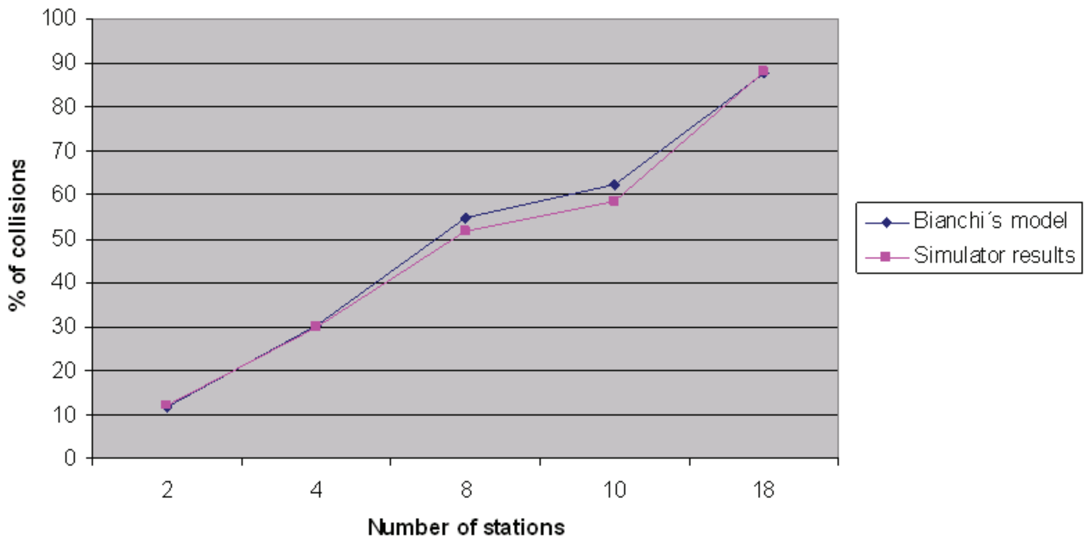


***Figure A3.5** Collision rate versus number of stations.*

A3.2.4 RTS/CTS threshold

The RTS/CTS mechanism is convenient depending of the MSDU size and the number of stations in the network. In the Bianchi's model is defined a payload size threshold over which is convenient to switch to RTS/CTS mechanism. This threshold is calculated mathematically from the throughput equation assuming basic access method and the equation assuming RTS/CTS mechanism.

For the validation of the RTS/CTS implementation in the GRACE++ simulator, were compared the results obtained for the two access techniques varying the MSDU size for three different scenarios (2, 10 and 50 stations).

Figure A3.6, A3.7 and A3.8 show the throughput versus the MSDU size. Each of them represents different scenarios with different number of stations. The Table A3.1 shows the threshold comparison between the values obtained from the simulations and the calculated from the model. Note: the MSDU threshold in the figure is in the intersection between the curves.

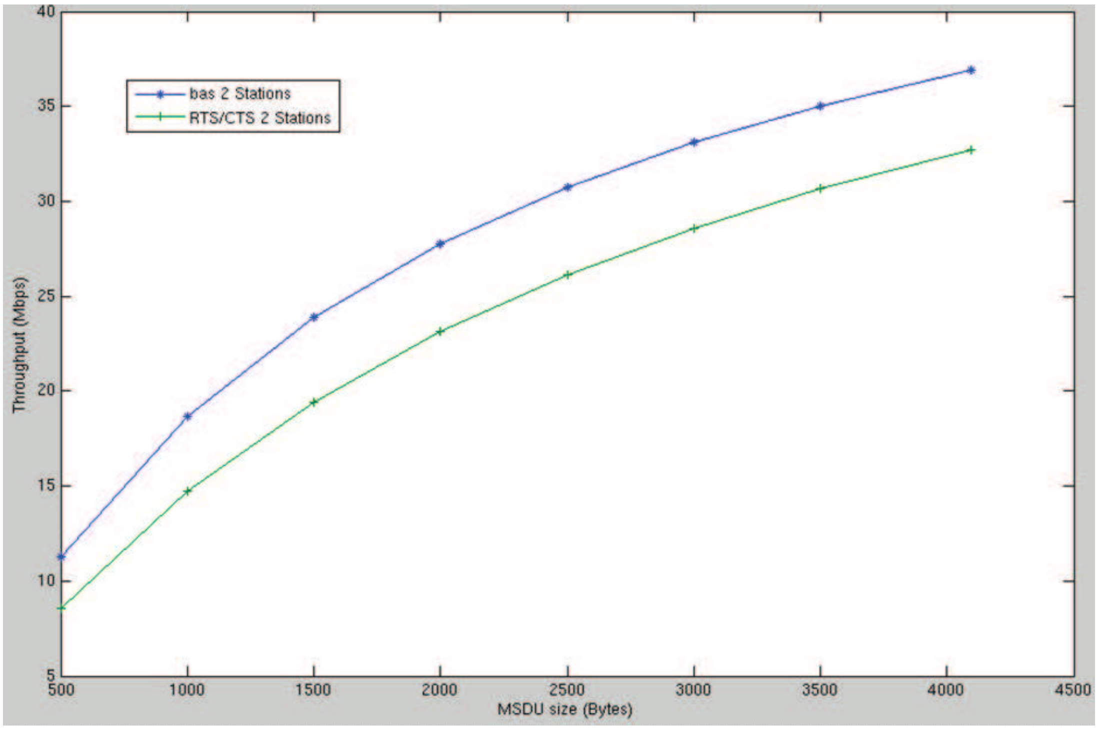


Figure A3.6 *Throughput versus MSDU size. 2 stations.*

In the case of two stations (figure A3.7) the RTS/CTS is never convenient. The reason is because the probability of collision is very small for this scenario and what the RTS/CTS mechanism is doing is introducing more overhead because of the RTS and CTS frames.

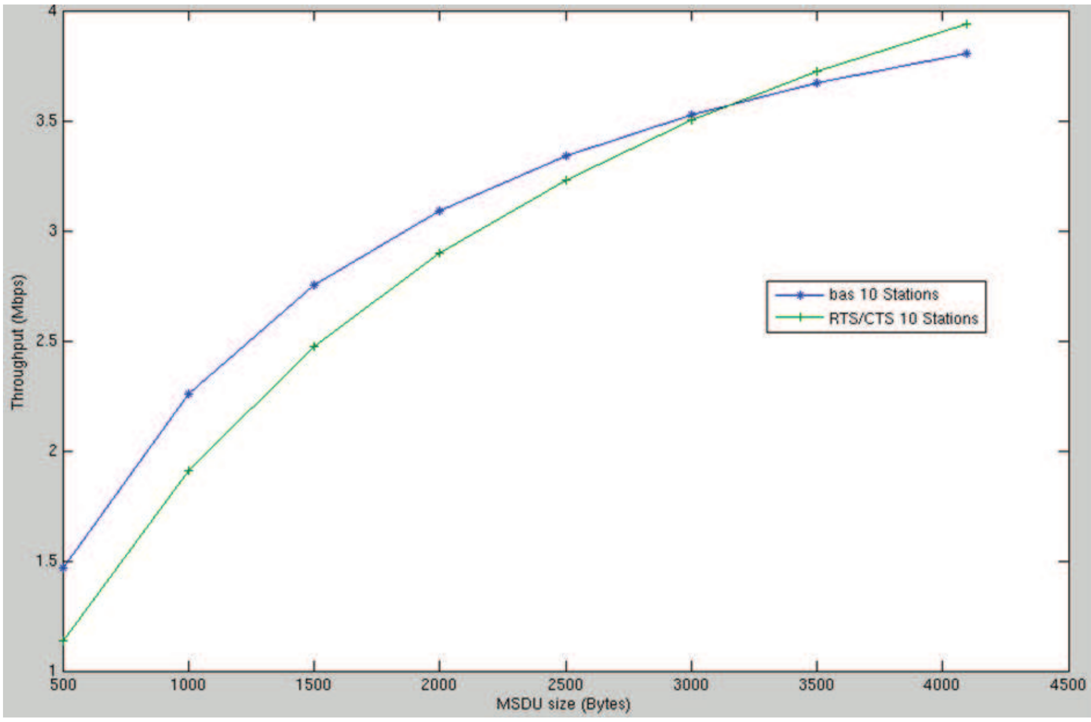


Figure A3.7 *Throughput versus MSDU size. 10 stations.*

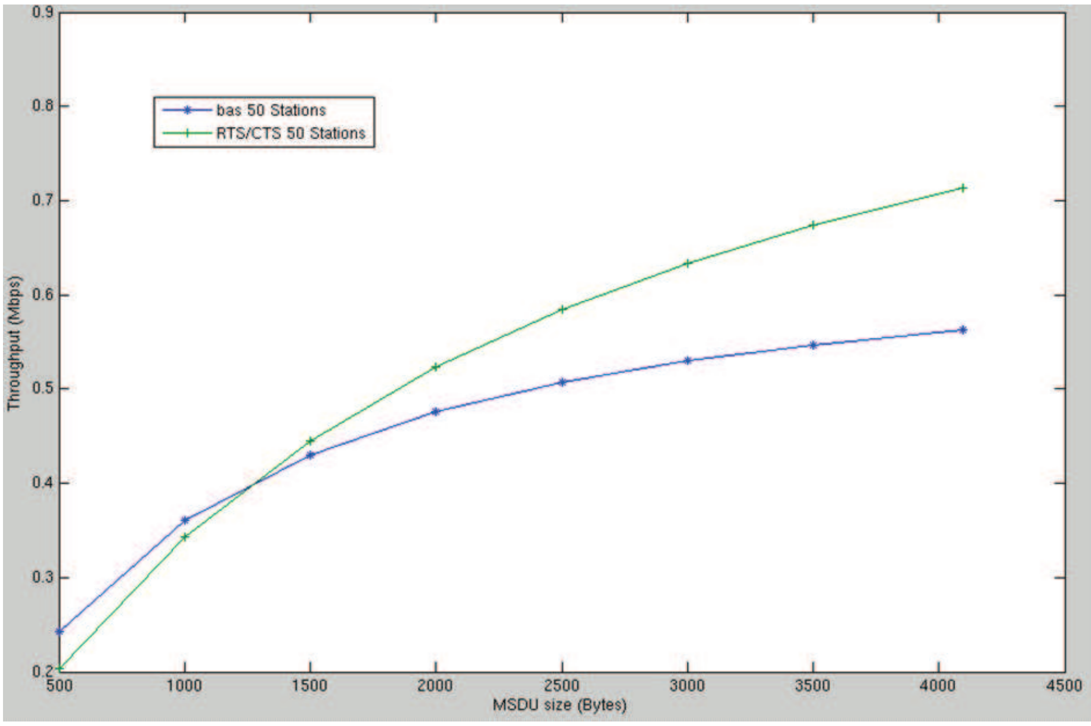


Figure A3.8 *Throughput versus MSDU size. 50 stations.*

Increasing the number of stations can be seen in the figures above, that RTS/CTS mechanisms become convenient from over a certain MSDU size. For

10 stations the threshold is approximately 3000 Bytes and for 50 stations it is approximately 1300 Bytes.

Table A3.1 represents a comparison between the MSDU threshold obtained from the simulator and the MSDU threshold obtained from the Bianchi's model. Note: the standardized configuration parameters used for the simulations and for the mathematical calculations are from IEEE 802.11g version.

Theoretical threshold (Bianchi's model)	Simulation threshold
P_2 > 13163 bytes	P_2 > More than the maximum packet size 4095 bytes
P_{10} > 2785 bytes	P_{10} > 3000 bytes
P_{50} > 1374 bytes	P_{50} > 1300 bytes

Table A3.1_Comparison threshold simulator results versus theoretical calculation._

Appendix IV

Dynamic channel selection

The format of the MAC frames used in the DCS is specified in this appendix. These frames were designed for us based in the IEEE 802.11 standard MAC frame formats.

The usefulness of these frames is explained in chapter 4. The table below shows the name, type and subtype of these frames.

Type value	Type description	Subtype value	Subtype description
00	Management	One of the reserved	Channel Switch Announcement (CSA)
00	Management	One of the reserved	Channel Switch Announcement response (CSA response)
00	Management	One of the reserved	Change request
01	Control	One of the reserved	CSA response ACK

Table A4.1 *types and subtypes of DCS frames designed.*

The type and subtype together identify the function of the frame. CSA, CSA response and Change request are management frames and CSA response ACK is a control frame. The subtype value is different for each frame and has to be one defined as reserved by the IEEE 802.11 std.

The frames formats designed are:

Channel Switch Announcement

This management frame is transmitted by the access point to all the associated stations in order to communicate that the channel change is needed and to which channel the stations have to change.

The frame format for the CSA frame is as defined in the figure A4.1.

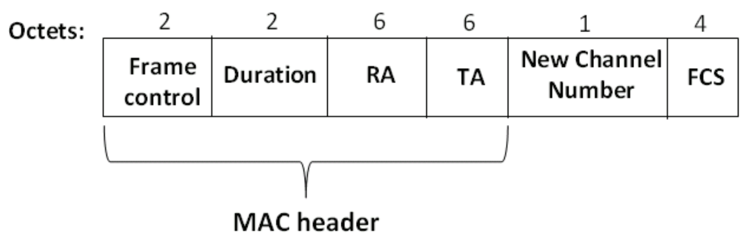


Figure A4.1 *Channel Switch Announcement frame format.*

New Channel Number field is the number of channel to which the client stations have to change (1, 6 or 11) once the CSA response ACK frame is received. The type and subtype of the frame are subfields of the Frame control field. Frame control, Duration, RA, TA and FCS are defined in the IEEE 802.11 standard.

Channel Switch Announcement response

This management frame is transmitted by the client stations as a confirmation of a correct reception of the CSA.

The frame format for the CSA response frame is as defined in the figure A4.2.

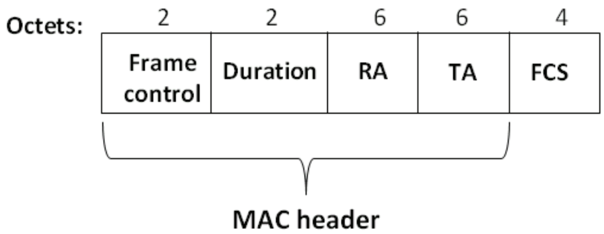


Figure A4.2 *Channel Switch Announcement response frame format.*

Frame control, Duration, RA, TA and FCS are defined in the IEEE 802.11 standard.

Change request

This management frame is transmitted by the client station if the collision rate perceived in a certain moment is above the threshold (see chapter 4). This collision rate perceived by the station is set in the change request frame (in collision rate field) allowing that the access point calculates the average as was explained in chapter 4.

The frame format for the change request frame is as defined in the figure A4.3.

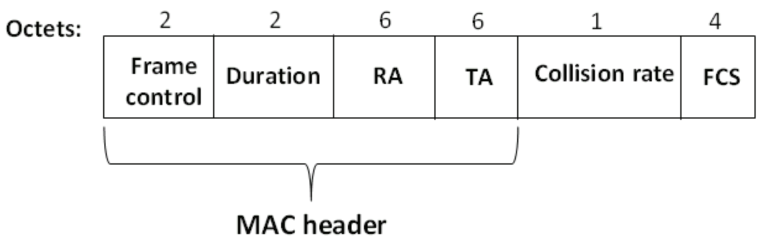


Figure A4.3 *Change request frame format.*

Frame control, Duration, RA, TA and FCS are defined in the IEEE 802.11 standard.

CSA response ACK

This control frame is transmitted by the access point as a confirmation of a correct reception of the CSA response.

The frame format for the CSA response ACK frame is as defined in the figure A4.3.

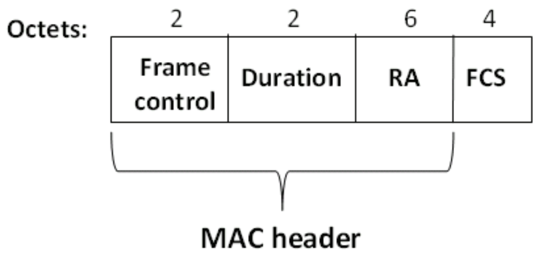


Figure A4.4 *CSA response ACK frame format.*

Frame control, Duration, RA, TA and FCS are defined in the IEEE 802.11 standard.

Note: the only difference between CSA response ACK and ACK is in the subtype of the frame.

Appendix V

Medium/Large scale deployment simulation results

This appendix presents some simulation results for medium/large scale deployments of IEEE 802.11g networks in terms of MAC throughput per user and average collision rate per network. The simulations assumptions are explained in chapter 3 and the basic parameters employed are summarized in Table A5.1.

Parameter	Value
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
PIFS	30 μs
CWmin	15
CWmax	1023
Data rate	54 Mbps
MPDU	4095 bytes
ACK timeout	55 μs
RTS/CTS	Deactivated
Beacon interval	100 ms
Preamble time	16 μs

Table A5.1. *IEEE 802.11 - 2007 parameters used for the simulations.*

The following results show the Cumulative Density Functions (CDF) of the upstream MAC throughput per user obtained for a fixed number of stations and variable number of BSSs sharing the same channel and located in very close proximity with each other.

Figure A5.1 shows the CDFs of the MAC throughput per user for four different scenarios. These scenarios are 1, 2, 3 and 4 nearby networks with two stations per network.

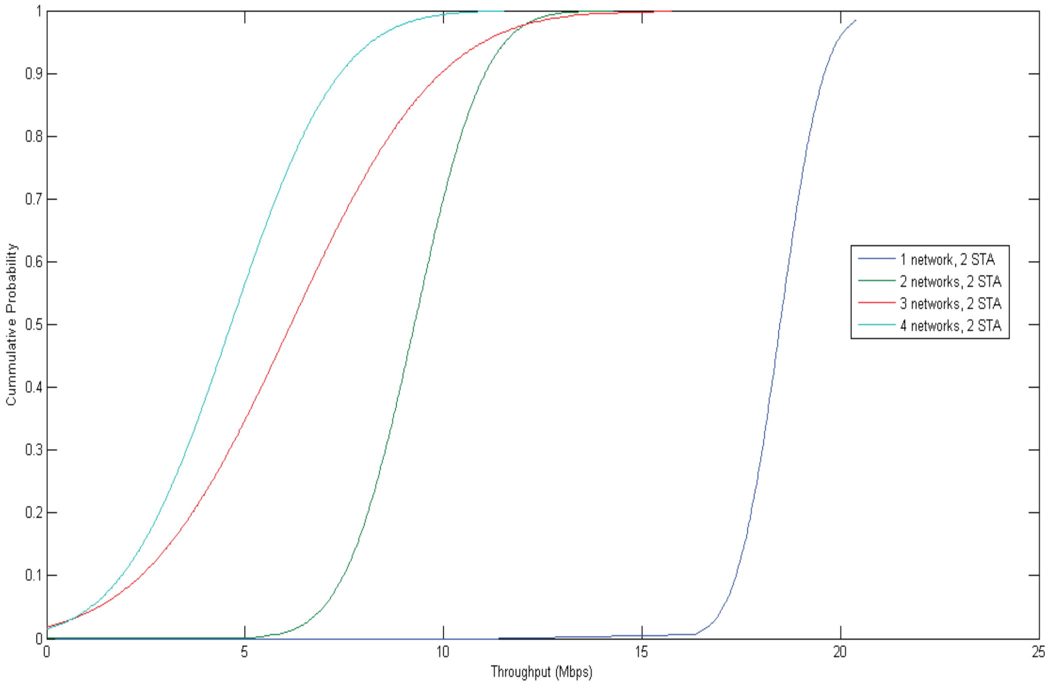


Figure A5.1. *Cumulative Density Function of throughput. Four different scenarios, two stations per network.*

With respect to Figure A5.1, an increase of the number of nearby networks in the same channel produces a significant degradation in the throughput. We can see that the slope of the CDF from the three networks scenario is a bit different compare to the other ones. This behavior is due to the fact in how the simulated scenarios are deployed[12].

Another aspect to comment is that as the number of networks and in consequence the numbers of stations are doubled, the throughput decreases to half its value.

The huge difference in throughput can be appreciated between the isolated network where 80% of the stations are between approximately 15Mbps and 18Mbps of throughput and the four networks scenario where the 80% are between 0Mbps and 6Mbps.

[12]The topology of the deployments is represented as number of networks located in the “x” axis and number of networks located in the “y” axis, i.e. four networks deployment is represented as 2 networks in the x axis and 2 networks in the y axis as a building with two floors, two apartments per floor and one network per apartment. The case of three networks deployment is represented as a building with 3 floors, one apartment per floor and one network per apartment, this topology leads to the network that is in the middle look more affected than those that are in the corners.

Figure A5.2 shows the CDFs of the MAC throughput per user of another four different scenarios. These are 1, 2, 3 and 4 nearby networks with four stations per network.

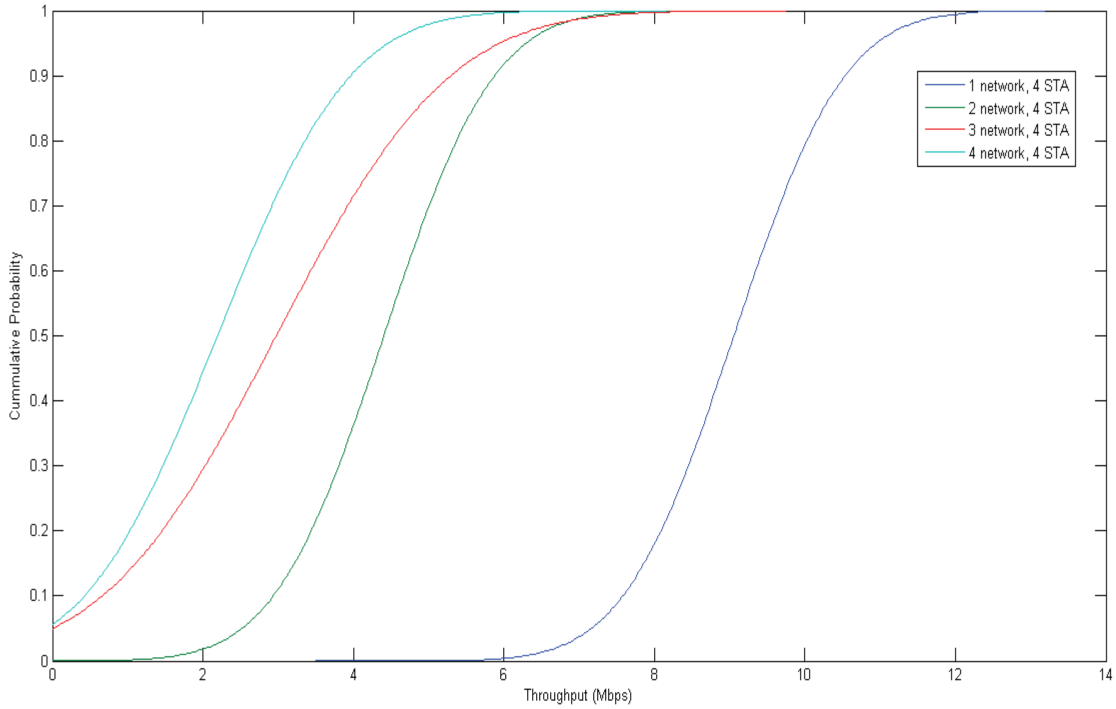


Figure A5.2. *Cumulative Density Function of throughput. Four different scenarios, four stations per network.*

About Figure A5.2, an increase of the number of nearby networks in the same channel produces a significantly degradation in the throughput. As expected, these networks have the same behavior as the ones presented in figure A5.1 but with the difference that there is less throughput (half the throughput, as expected) per network due to the fact that there are four stations per network instead of two. As in figure A5.1, can be also seen the different behavior in the CDF slope for the three network scenario.

For an isolated network the 80% of the stations are between 9Mbps and 10Mbps, and in a four networks scenario the 80% of the stations are between 0Mbps and 3Mbps.

Figure A5.3 shows the CDFs of the MAC throughput per user of another four different scenarios. These are 1, 2, 3 and 4 nearby networks with ten stations per network.

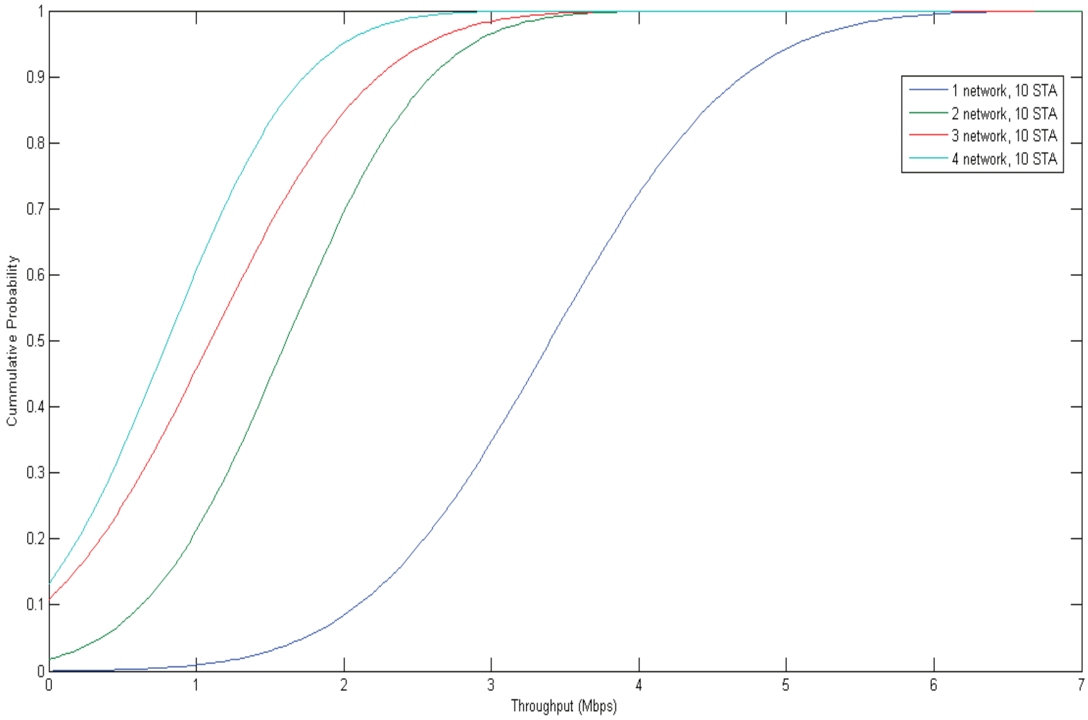


Figure A5.3. *Cumulative Density Function of throughput. Four different scenarios, ten stations per network.*

In figure A5.3 is illustrated the same behavior of the throughput per user as the ones shown in figure A5.1 and figure A5.2 but as mentioned before, with less throughput because the number of stations per network is higher.

In the isolated network the 80% of the stations are between 3Mbps and 4.5Mbps, and in a four networks scenario the 80% of the stations are between 0Mbps and 1.5Mbps.

Figure A5.1, figure A5.2 and figure A5.3 confirm again that the number of nearby access points (networks) on the same channel affects significantly the performance of the networks.

These results confirm again the necessity of the dynamic channel selection (chapter 4). Networks deployed in a close proximity and in the same channel allocation degrades in a high manner the throughput per user.

Appendix VI

MAC frame formats

The MAC frame formats are composed of different elements. These are:

1. MAC header, which consists of the frame control, duration, addresses, sequence control information, and for QoS data frames, QoS control information.
2. Frame body, which is of a variable length and contains different kinds of information depending on the type and subtype of the frame.
3. FCS, which has a 32 bit CRC.

This can be seen in figure A6.1.

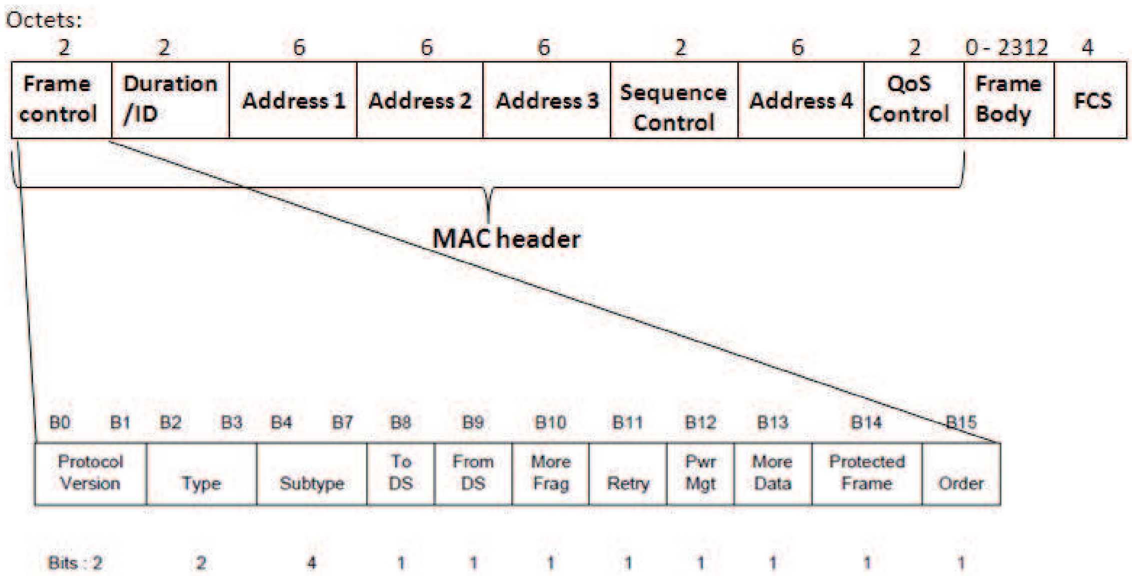


Figure A6.1 *MAC frame format*

The frame control is divided in several subfields as illustrated in figure A6.1. These subfields define the type (control, management and data) and subtype (association, beacon, authentication…) of the frames; which protocol are the frames using; if it has been used fragmentation or not; if the frame is a retransmission or not; if power saving mode is being used or not; etc.

The duration/ID field is used to update the NAV.

The addresses fields are used to specify the BSSID, the source address (SA), the destination address (DA), the transmitter address (TA) and the receiver address (RA).

The sequence control field is used to know which frame it is. And the QoS control field is only used in QoS data frames.

In the following section are described the different type of MAC frames.

A6.1 Control frames

This type of frames is used to assist the data frames transmission between stations. Control frames are composed by the MAC header and the FCS; there is no frame body in this kind of frames.

The most common ones are the following:

- **Acknowledgement frame (ACK)**. This frame is used to make a station aware that has sent a frame that the frame was received correctly. If after an ACK timeout the ACK frame is not received, the sending station will retransmit the frame. Figure A6.2 shows the ACK frame format.

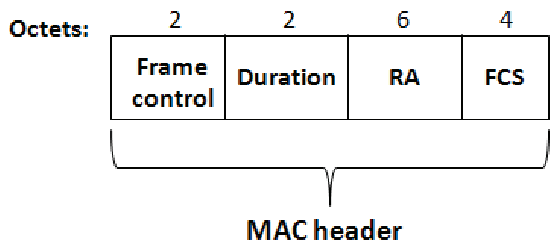


Figure A6.2 *ACK frame format*

- **Request to send frame (RTS)**. This frame is used in the first phase of a two way handshake in order to request permission for accessing the channel. It is used before a data frame transmission and this frame is replied by a CTS frame. It is sent in the RTS/CTS mechanism. Figure A6.3 shows the RTS frame format.

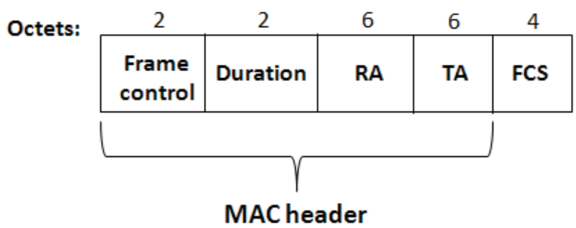


Figure A6.3 *RTS frame format*

- **Clear to send frame (CTS)**. This frame is used in response to a RTS frame to make the station that has sent the RTS frame know that it can transmit into the channel or in order to be used in the CTS to self mechanism where a CTS frame is sent to make aware the stations in the BSS that a transmission of a frame is going to occur. Figure A6.4 shows the CTS frame format.

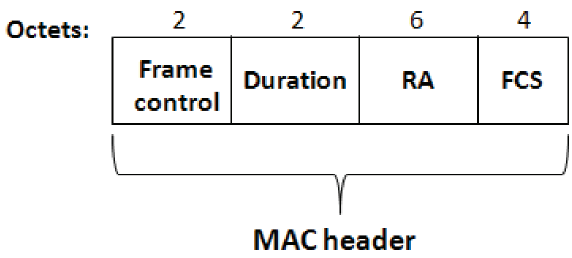


Figure A6.4 *CTS frame format*

A6.2 Management frames

This type of frames is used by the stations to establish and to keep communications. The most relevant management frame is the beacon frame.

- **Beacon frame.** This frame is used by the access point for announcing its presence and for transmitting information that will help the stations to work well in a BSS. It is sent periodically and the information in this frame can be used for different purposes such as the data rates available in the BSS, the SSID and timestamp. Users are listening for beacons in the channel from all the networks in range in order to associate to the best network possible or in order to obtain information about a network. Figure A6.5 shows the beacon frame format.

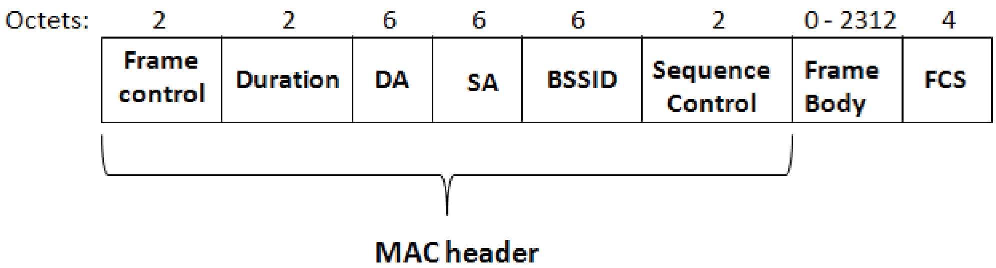


Figure A6.5 *Beacon frame format*

A6.3 Data frames

This type of frames is used to transmit packets from upper layers within the frame body, being this, the main purpose of a WLAN. Figure A6.6 shows the data frame format.

Octets: 2	2	6	6	6	2	6	2	0 - 2312	4
Frame control	**Duration /ID**	**Address 1**	**Address 2**	**Address 3**	**Sequence Control**	**Address 4**	**QoS Control**	**Frame Body**	**FCS**

MAC header

Figure A6.6 *Data frame format*

Appendix VII

Definitions

ACK Acknowledgment. A type of medium access control (MAC) control frame used in the IEEE 802.11 to make a sender station (STA) aware that its frame has been received correctly.

AIFS Arbitration Interframe Space. Time that has to pass between frames when a quality of service (QoS) station wants to transmit data frames, management frames or some control frames.

AP Access Point. Any entity that gives access to the distribution system (DS) through the wireless medium (WM) for the client stations that are associated.

BPSK Binary Phase-Shift Keying. A type of digital modulation based on phase. This is used in the IEEE 802.11 for low data rates in order to gain robustness.

BS Base Station. A wireless communication station which is in a fixed position and it is used to communicate as part of a wireless telephone system or radio system.

BSA Basic Service Area. The area where the stations associated to a basic service set or to other BSSs are.

BSS Basic Service Set. The main block of an 802.11 LAN. In the BSS there is a group of stations which can be access points, client stations or both at the same time.

BSSID Basic Service Set Identification. A field in the MAC frame which represents the identity of a BSS.

CCA Clear Channel Assessment. A logical function of the IEEE 802.11 physical layer used to determine the current state of the wireless medium (WM).

CCK Complementary Code Keying. A modulation scheme used in wireless networks.

CDF	Cumulative Distribution Function. The probability that a random variable with a given probability distribution will be found at a value equal or less than a certain value.
CR	Collision Rate. Defined as the average number of collided transmissions per each successful transmission.
CRC	Cyclic Redundancy Code. Type of function used to detect changes in a frame during a data transmission.
CS	Carrier Sense. A mechanism used to determine the state of the medium; busy or idle.
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance. Fundamental access method to the wireless medium of the IEEE 802.11.
CTS	Clear To Send. Type of MAC control frame used in response to a request to send frame (RTS) to make aware a sender station that the medium is idle and can be used. Also used as a self protection mechanism CTS-to self.
CW	Contention Window. A parameter of the IEEE 802.11 used in the calculation of the backoff time procedure.
DA	Destination address. A field in the MAC frame that indicates the address of the station where the data is going to be sent.
DCF	Distributed Coordination Function. The fundamental access method of the IEEE 802.11 MAC.
DCS	Dynamic Channel Selection. A channel allocation scheme used to allocate communication channels and bandwidth in order to achieve the maximum frequency reuse.
DIFS	Distributed Interframe Space. When working under the DCF, the time used by a station to transmit data or management frames.
DR	Deployment Ratio. Defined as an uniform probability that a network can be deployed in a specific house of a scenario. It has a range of values from 0 to 1 (0% - 100%), meaning that a value of 0 represents that a network is not going to be deployed and a value of 1 assures the presence of a network in a house.
DS	Distribution System. Component for interconnecting different BSSs which can be used because of the need of increasing the coverage of a network.

DSSS Direct Sequence Spread Spectrum. Modulation method for transmitting signals in spread spectrum.

EDCA Enhanced Distributed Channel Access. A CSMA/CA access mechanism with priority used by QoS stations in a QoS BSS.

EIFS Extended Interframe Space. The time that a station has to wait to transmit a frame when the medium is idle after the reception of a frame containing an error.

ERP Extended Rate PHY. Refers to all the data rates used in the IEEE std 802.11 2007.

ESS Extended Service Set. The union between the BSSs connected via the DS.

FCS Frame Check Sequence. Extra bits added to a frame for error detection and correction.

HCCA HCF Controlled Channel Access. Channel access mechanism used in hybrid coordination function (HCF) to coordinate contention free media use by QoS stations (STAs) transmissions.

HCF Hybrid Coordination Function. An extra coordination function mechanism used only in QoS networks.

IBSS Independent Basic Service Set. A type of BSS that can work as an ad-hoc network. This is the most basic 802.11 LAN as the minimum requirement is that a WLAN can be done with only two stations. This can be possible when the stations can communicate with each other directly.

IEEE Institute of Electrical and Electronics Engineers.

IFS Interframe Space. The time interval between frames in IEEE 802.11

ISI Intersymbol Interference. A kind of distortion in a signal due to a symbol that interferes with other symbols.

ISM Industrial Scientific Medical

LAN Local Area Network. A small area where there are several devices interconnected.

LTE Long Term Evolution. A new standard of the 3GPP

MAC Medium Access Control. A sublayer of the Data Link Layer specified in the OSI model (layer 2).

MPDU MAC Protocol Data Unit. The data unit exchanged between two MAC entities using the physical layer (PHY).

NAV Network Allocation Vector. An indicator, in each station, of the time during which a transmission is on the wireless medium and as a consequence, no other station can access the medium during this time.

OFDM Orthogonal Frequency Division Multiplexing. A frequency division multiplexing (FDM) scheme which is used as a digital multi carrier modulation method.

PC Point Coordinator. The entity in a station in an access point that performs the point coordination function (PCF).

PCF Point Coordination Function. A coordination function where the logic is active in only one station in BSS at any time that the network is working.

PIFS Point Interframe Space. Time between frames used by stations working under the PCF.

PLCP Physical Layer Convergence Procedure. Used in order that the IEEE 802.11 MAC layer works with the less dependence possible on the physical medium dependent (PMD) sublayer. The MAC layer communicates with the PLCP sublayer via the service access point (SAP) through which MPDUs are accepted.

PMD Physical Medium Dependent. A physical sublayer responsible for the transmission and reception of data on the physical medium.

PPDU PLCP Protocol Data Unit. It is the data unit form in the PLCP.

PSK Phase Shift keying. Digital modulation technique that transmits data by changing the phase of a reference signal.

QAM Quadrature Amplitude Modulation. One of the modulation scheme used in the IEEE 802.11.

QoS Quality of Service. To guarantee a certain level of performance to a user.

QPSK Quadrature Phase Shift keying. Digital modulation technique that transmits data by changing the phase of a reference signal.

RA Receiver Address. A field in the MAC frame that indicates the address of the station where the data is going to be sent.

RTS Request To Send. Type of MAC control frame used for requesting the WM in order to transmit a frame and so, all the other stations sharing the channel know that a transmission is going to be done.

SA Source Address. A field in the MAC frame that indicates the address of the station which is sending the data.

SAP Service Access Point. Conceptual location where one OSI layer requests the services of another OSI layer.

SIFS Short Interframe Space. Time between transmission of MAC control frames which have high priority compared to data frames or management frames.

SSID Service Set Identifier. Indicates the identity of an IBSS or an ESS.

STA Station. Any device that have an IEEE 802.11 MAC and PHY interface to the WM.

TA Transmitter Address. A field in the MAC frame that indicates the address of the station which is sending the data.

UE User Equipment. Computers or devices with a wireless interface.

VCS Virtual Carrier Sensing. A mechanism to sense the channel without any physical measurements.

VoIP Voice over Internet Protocol. Communication technology for transmitting voice over Internet protocol networks.

WiFi Wireless Fidelity. It is a trade of the WiFi alliance. The organization that tests and certifies that the devices meet the required 802.11 standards.

WLAN Wireless Local Area Network. A system that interconnects two or more devices using a wireless distribution method.

WM Wireless Medium. The medium used to transmit protocol data units between physical layer entities of a WLAN.