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On the Enhancement of IEEE 802.11 Overlapping APs Capacity Sharing

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Αφιερωμένο στους γονείς μου Ζουράμπ και Λαρίσα και στην αδερφή μου Μαρία.

Abstract

Wireless Local Area Network (WLAN) is in a period of great expansion and the usage of WLANs is rapidly increasing throughout the world. Basic Service Set (BSS) is the fundamental building block of an IEEE 802.11 WLAN. The Overlapping BSS (OBSS) problem refers to situations that two or more BSSs, unrelated to each other, are operating in the same channel and are close enough to hear each other physically. As it easily understood, the OBSS problem may severely degrade the network performance. Having in mind that the number of the OBSSs is growing rapidly due to both the expansion of the number of WLAN devices and increase channel bandwidth to 80 MHz in upcoming standards, the OBSS problem becomes an important research challenge.

In this thesis, significant focus has been given on the design of a novel approach to enhance the performance of overlapping Access Points (APs) in IEEE 802.11 WLANs regarding to the capacity sharing. After carrying out a thorough study of several related issues (such as distributed coordination of the nodes, management of power and frequencies, network-wise resource and path allocations), we discuss various proposed solutions for the OBSS problem. We then study certain characteristics of IEEE 802.11aa and in particular the third draft of this upcoming standard that targets to provide MAC performance enhancements for robust audio video streaming.

By utilizing the Quiet Element functionality that has been defined in the IEEE 802.11-2007 standard, we present our proposed enhanced algorithm for sharing the Access Points capacity during the overlapping period. We then explore the effectiveness of our proposed algorithm in overlapping and non-overlapping scenarios by utilizing the OPNET Modeller simulation software. The derived simulation results show that our proposed algorithm achieves a significantly enhanced throughput and delay performance in the overlapping scenarios.

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Chapter 1

Overview

1.1 Introduction

During the last years, the Wireless Local Area Networks (WLANs) based on the IEEE 802.11 standards family, have turned into one of the most promising and successful technologies. WLANs provide free wireless connectivity to end users, offering an easy and viable access to the network, mobility and flexibility with a relatively low cost to users. In addition, wireless technology is providing easier internet access to areas that are too difficult and expensive to reach utilizing traditional wired infrastructure. Wireless networks are superior to wired networks regarding to the installation and flexibility. However, they do suffer from lower bandwidth, higher delays and higher bit-error rates.

The wide spread of live stream video and voice applications increase the needs for more bandwidth capacity. Since these applications have different demands from the underlying network protocol suite, high bandwidth of internet connectivity has become a basic requirement for the success of these applications. Hence, to fulfil this requirement and to satisfy the end users the increase of the channel [Annex A] bandwidth came as a result. On the current activities (e.g. IEEE 802.11aa/ac), IEEE is planning to increase the channel bandwidth up to 80 MHz mandatory and up to 160 MHz optional.

Through the increase of the channel bandwidth there are some issues that arise like the OBSS one. The OBSS problem refers to situations that two or more BSSs, unrelated to each other, are operating in the same channel and are close enough to hear each other physically. This actually means that some stations (STAs) or an Access Point (AP) [Annex A] of one BSS are able to obtain frames from the neighboring BSS. Overlapping in coverage of multiple co-channel WLAN BSSs is an undesirable situation because members of both BSSs compete for channel access, which increases the contention level of wireless medium access and reduces overall system performance. Hence, the OBSS problem may degrade the network performance severely.

It is expected that the number of the OBSSs in upcoming standards (e.g. IEEE 802.11aa/ac) arises even as a problem more than legacy standards (e.g. IEEE 802.11a/b/g) due both of channel bandwidth extension and expansion of WLAN devices.

Due to the limited spectrum, the OBSS problem requires special attention and needs to be addressed. The current thesis presents our proposed enhanced algorithm based on Quiet Element that was defined in IEEE 802.11-2007, which targets to mitigating the interference and collisions that exist due to the OBSS problem and, thus, to achieve better network performance. By introducing the Quiet element in our algorithm, we achieve an interval of time during which no transmission shall occur in the current channel (the proposal is presented in detail in Chapter 5).

1.2 Scope

Initially, a literature study was carried out about the IEEE 802.11 2007 and IEEE 802.11e standards in order to understand the Medium Access Control (MAC) architectures. The next step after the initial study was the Deliverable Report 6 of FLAVIA (Flexible Architecture for Virtualizable wireless future Internet Access) project that I was familiar with during my placement within NEC. After these primary studies, we focused on Overlapping BSS problem, by performing thorough research for the state of the art on OBSS (e.g. IEEE 802.11aa Draft) as well as the related work whereas several proposed solutions were analyzed. Through the IEEE 802.11aa Draft the main studies were on the QLoad Report element, the HCCA TXOP Advertisement and on the Sharing Schemes (i.e. the Proportional Sharing and the On Demand Sharing). Once these studies were completed an enhanced algorithm was proposed for overlapping APs capacity sharing. The conception of enhanced algorithm was based on the Quiet element that first was introduced on IEEE 802.11 2007. In this thesis, simulations have been carried out by using the software called OPNET Modeler version 12.0. During the implementation of the proposed solution number of cases was evaluated with and without the enhanced algorithm. Finally, the simulation results (i.e. throughput and delay performance) were plotted using the Matlab mathematical software and were further analyzed.

1.3 Purpose

The primary purpose of this thesis is to study and analyze the importance of the OBSS problem. Following the study of theoretical background and the thorough research of the state of the art, the main goal is to propose an innovative method that enhances the overlapping APs capacity sharing.

1.4 Outline

The rest of this thesis is organized as follows. In Chapter 2, the theoretical background of WLANs and the IEEE 802.11 Standard Family are described. Chapter 3 presents the Problem Definition of this thesis and the importance of the OBSS problem. In Chapter 4, the state of the art (e.g. IEEE 802.11aa amendment) and the related work about the proposed solutions regarding to the OBSS problem are reviewed. Chapter 5 gives a brief introduction to the OPNET Modeler version 12.0 simulator and to the simulation environment, proposes enhancement with simulation results and the evaluation of the results. Finally, the Chapter 6 concludes the thesis and proposes future work.

Chapter 2

Theoretical Background

2.1 Introduction to IEEE

The Institute of Electrical and Electronics Engineers (IEEE) is the world's largest professional association dedicated to advancing technological innovation and excellence for the benefit of humanity. IEEE and its members inspire a global community through IEEE's highly cited publications, conferences, technology standards, and professional and educational activities. The IEEE promotes the engineering process of creating, developing, integrating, sharing, and applying knowledge about electro and information technologies and sciences for the benefit of humanity and the profession [1].

2.2 Overview to the IEEE 802 Family of Standards

The IEEE-802 Local Area Network (LAN) / Metropolitan Area Network (MAN) Standardization Committee (LMSC) develops LAN and MAN standards, mainly for the lower layers (MAC and PHY) of the reference model for Open Systems Interconnection (OSI). IEEE-802 coordinates with other national and international standards groups. IEEE-802 LMSC is organized into a number of Working Groups (WGs) and Technical Advisory Groups (TAGs) operating under the oversight of a sponsor Executive Committee (EC) [2]. In this section, an overview is given to the several wireless standards that are being developed within IEEE-802. The WGs on wireless technology are listed as follows: (these are also mapped in Figure 2.1 together with information about the data rate and mobility for each one of them).

802.11	Wireless LAN (WLAN) Working Group
802.15	Wireless Personal Area Network (WPAN) Working Group
802.16	Broadband Wireless Access (BWA) Working Group
802.20	Mobile Broadband Wireless Access Working Group
802.21	Media Independent Handover Working Group

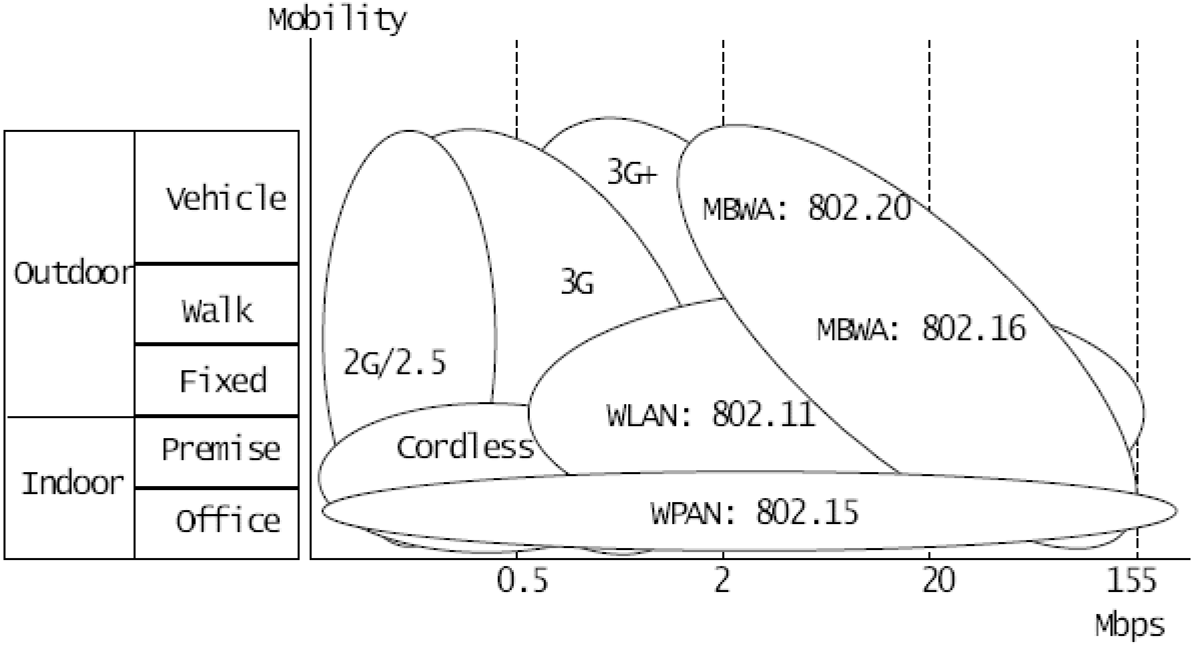

Figure 2.1 Standards, data rate, and mobility [3].

2.3 IEEE 802.11 Wireless LAN

In 1997, IEEE adopted IEEE Std. 802.11-1997, the first IEEE 802.11 WLAN standard. IEEE 802.11 defines one Medium Access Control (MAC) and several Physical layer (PHY) specifications for wireless connectivity for fixed and moving STAs within a local area [4]. The standard is similar in most respects to the IEEE 802.3 Ethernet standard and mapped to the OSI reference model as shown in Figure 2.2.

In particular, the IEEE 802.11 Wireless LAN, also known as Wireless Fidelity (Wi-Fi), provides wireless connectivity for two or more terminals, nodes or STAs (i.e. laptops, tablet PCs, servers, printers, etc.) that may be fixed or portable within a local area. It allows the users to communicate with each other without requiring a physical connection to the network.

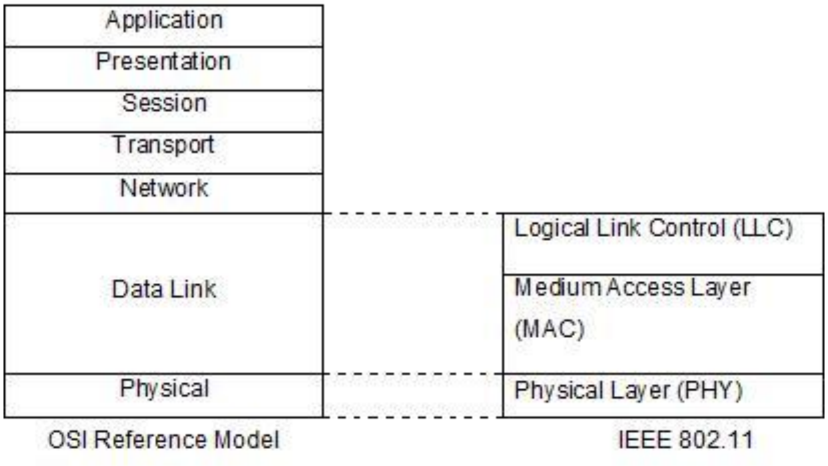

Figure 2.2 IEEE 802.11 standards mapped to the OSI reference model [4].

2.4 WLAN Components

The IEEE 802.11 architecture is comprised of several components that interact with each other, hence provide a WLAN [4].

2.4.1 Station (STA)

The STA is the most basic component of the wireless network. A STA is any device that contains the functionality IEEE 802.11-conformant, that being MAC, PHY interface to connect to the wireless medium [Annex A]. STAs may be mobile, portable or stationary (i.e. laptop PC, handheld device or an AP) and all STAs support the IEEE 802.11 services of authentication, de-authentication, privacy and data delivery. Typically, the IEEE 802.11 functions are implemented in the hardware and software of a Network Interface Card (NIC).

2.4.2 Basic Service Set (BSS)

The Basic Service Set (BSS) is the basic building block of an IEEE 802.11 wireless LAN and is a set of STAs that have successfully synchronized. Membership in a BSS does not imply that wireless communication with all other members of the BSS is possible [4]. Figure 2.3 shows two BSSs.

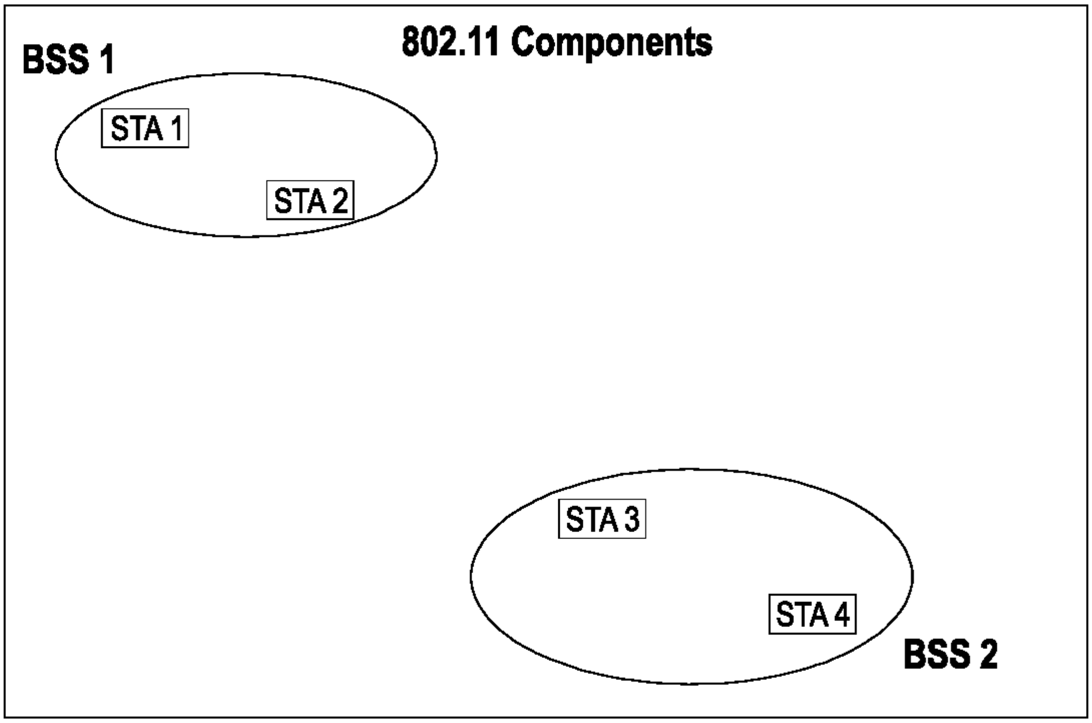

Figure 2.3 BSSs [4].

2.5 WLAN Architecture

IEEE 802.11 defines two different architectures, Infrastructure BSS and Independent Basic Service Set (IBSS).

2.5.1 Infrastructure BSS

In an Infrastructure BSS there is component called an Access Point (AP). The access point provides a local relay function for the BSS. The wireless STAs, are associated to an AP and all communications take place through the AP [5].

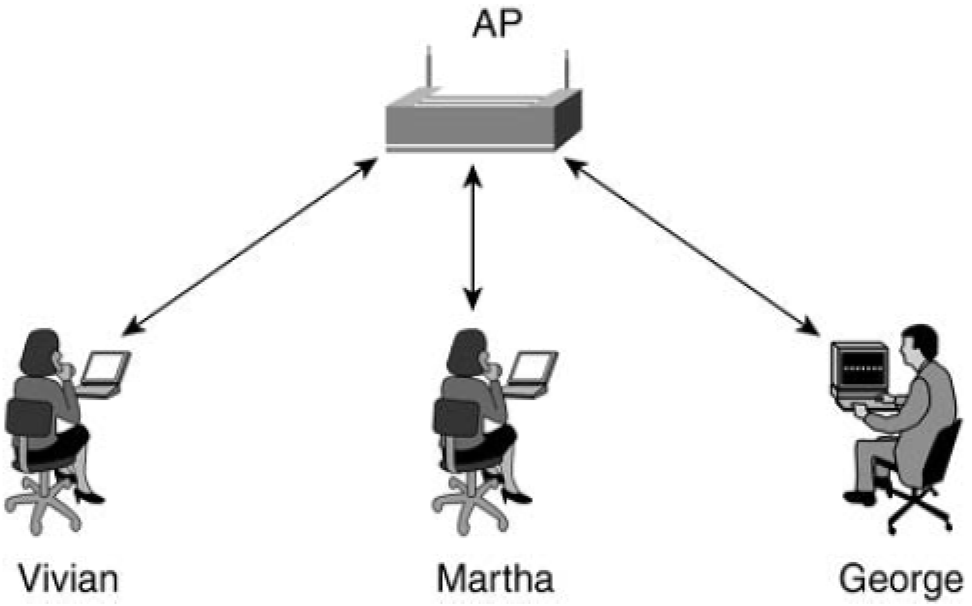

Figure 2.4 Infrastructure Basic Service Set [5].

Communication of among two STAs, for example Vivian and George, take place through the AP.

2.5.2 Independent BSS (IBSS)

In an Independent BSS, STAs can communicate directly to each other, providing that they are within each other’s transmission range. Every STA may not be able to communicate with any other STA due to the range limitations. There are no relay functions in an IBSS thus, all STAs need to be within range of each other and communicate directly. This architecture is facilitated to form a wireless ad-hoc network in absence of any network infrastructure [5].

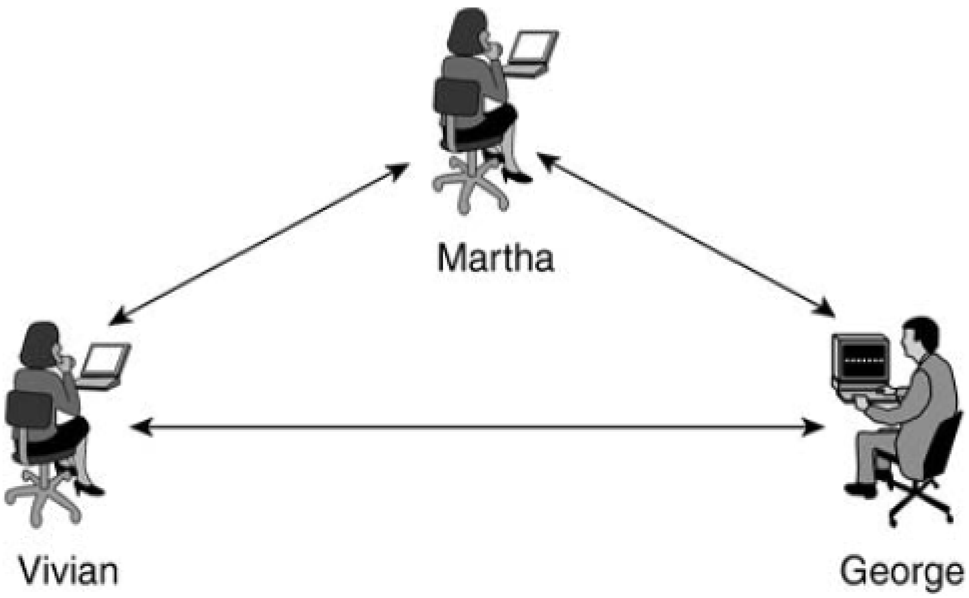

Figure 2.5 Independent Basic Service Set [5].

Communication of among two STAs, for example Vivian and George can take place directly. This type of IBSS is often called ad-hoc network.

2.5.3 Extended Service Set (ESS)

Several BSS can be connected together via some kind of backbone called Distribution System (DS) [Annex A]. The whole interconnected WLAN including the BSSs, their APs and STAs respectively and the DS form an extended network, called Extended Service Set (ESS) [5].

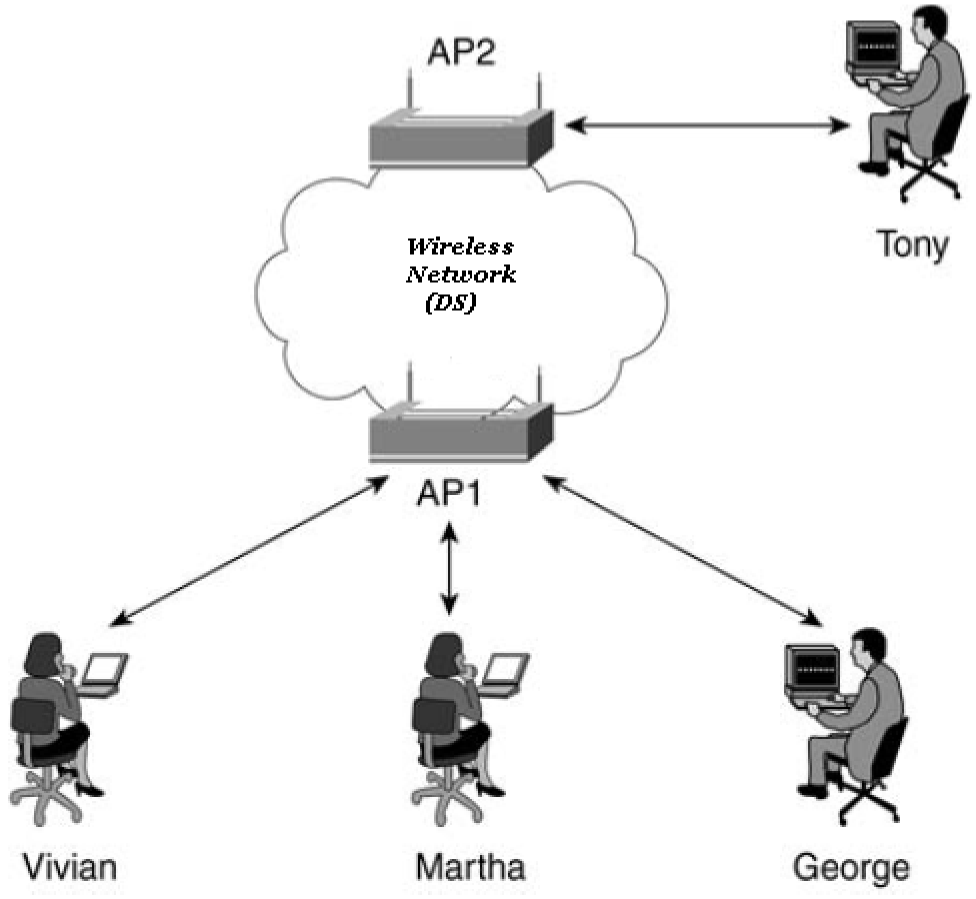

Figure 2.6 Extended Service Set [5].

2.6 IEEE 802.11 Media Access Control

The MAC is a sublayer of the Date Link Layer specified in the seven-layer OSI model (layer 2). The MAC layer provides, among other functions, channel access control that makes it possible for multiple STAs on a network to communicate within a multi-point network. The IEEE 802.11 MAC also supports shared access to the wireless medium through a technique called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which is similar to the original (shared medium) Ethernet's Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [6].

2.6.1 MAC Architecture

The MAC architecture is illustrated in Figure 2.7. The architecture of the MAC sublayer, includes the Distributed Coordination Function (DCF), the Point Coordination Function (PCF), the Hybrid Coordination Function (HCF), and their coexistence. These functions are described later on subchapters 2.6.2 (DCF), 2.6.3 (PCF), and 2.6.4 (HCF).

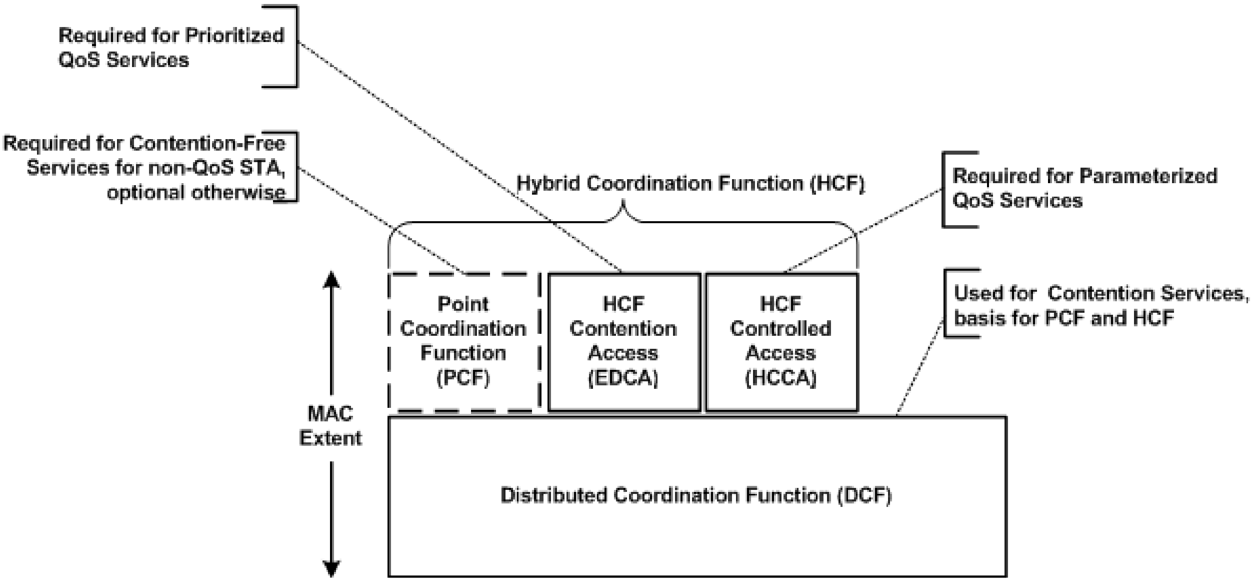

Figure 2.7 MAC architecture [4].

2.6.2 Distributed Coordination Function (DCF)

The fundamental access method of the IEEE 802.11 MAC is a DCF. The DCF method is implemented in all STAs, for use within both IBSS and infrastructure network configurations. [4].

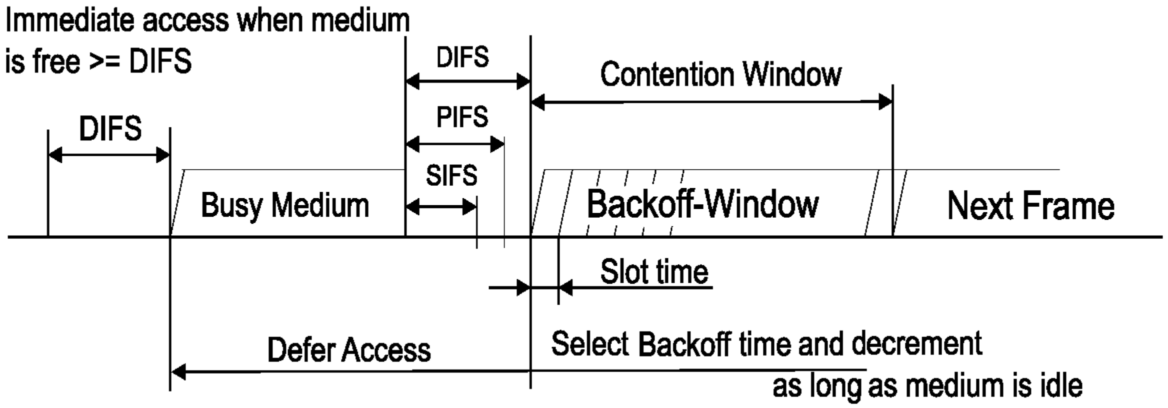

Figure 2.8 Distributed Coordination Function [4].

2.6.2.1 Carrier Sense Multiple Access (CSMA)

CSMA works by a "listen before talk scheme". This means that a STA wishing to transmits, first senses the radio channel to determine if another STA is transmitting. If the medium is sensed to be “idle,” the STA is permitted to transmit. If the medium is sensed to be “busy” then the STA defers its transmission.

There are two mechanisms that STAs use for sensing the medium the physical carrier sensing and virtual carrier sensing using the so-called Network Allocation Vector (NAV).

In the physical carrier sensing there is a channel sensing function that is called Clear Channel Assessment (CCA). CCA is an essential ingredient in wireless networks employing channel sensing as part of their medium access mechanism. While CCA itself is implemented at the PHY layer, the primary impact of its performance/complexity is on MAC metrics like throughput and energy efficiency. The channel status is determined by sensing the signal power level in the channel. If the STA finds that the power level in the STA is above a predefined threshold, the medium is considered to be busy, otherwise idle.

In a virtual carrier sensing the NAV is employed and logically it resides within the MAC. Virtual carrier sensing uses reservation information carried in the duration field of the MAC headers announcing impeding use of the medium. The NAV is the time duration that is included in MAC frame. Each MAC frame carries a duration field that is used to update the NAV of any STA. The duration field holds a time value that indicates the duration for which the sending STA expects the medium to be busy referenced from the end of the last symbol of the MAC frame. Thus, the received STAs are not allowed to transmit into the channel for the time duration of NAV.

2.6.2.2 Collision Avoidance (CA), Random Backoff Time & Contention Window

The Collision Avoidance (CA) mechanism reduces the probability of collisions among STAs sharing the medium, by which a STA utilize a random backoff time procedure before initiating a transmission. Every STA after detecting the medium as idle for minimum duration called DCF Inter-Frame Space (DIFS) [Annex C], STA keeps sensing the medium for an additional random time called the backoff time. The backoff timer is decremented by one for every slot time that the wireless medium is idle, as determined by the CS function. The STA will initiate its transmission only if it finds that the medium remains idle for the duration of DIFS and when this additional random backoff timer reaches zero on a STA. So, if the selected backoff value is 9, then the wireless medium must be idle for the duration of nine slot times before the STA can transmit a frame.

The duration of the Backoff Time is determined as a random function multiplied by multiple of slot time by every STA individually and the value changes randomly during each new transmission attempt [7].

Backoff Time = Random() × aSlotTime where:

- Random() = Pseudo-random integer drawn from a uniform distribution over the interval [0,CW], where Contention Window (CW) is an integer within the range of values of the PHY characteristics aCWmin and aCWmax, aCWmin ≤ CW ≤ aCWmax. It is important that designers recognize the need for statistical independence among the random number streams among STAs [4].
- aSlotTime = The value of the correspondingly named PHY characteristic.

CA mechanism cannot detect the transmissions by hidden STAs [Annex A] (hidden is a STA whose transmissions cannot be detected using carrier sense (CS) by a second STA).

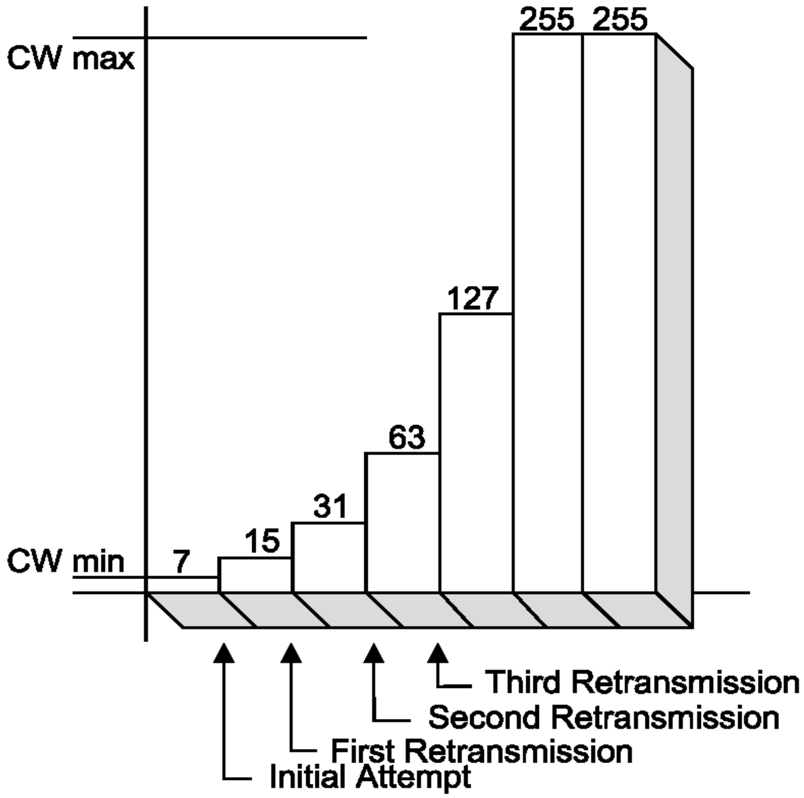

Figure 2.9 Incrementing the CW until it reaches aCWmax [4].

2.6.2.3 Request to Send (RTS) / Clear to Send (CTS) Frames

To minimize collision duration, the transmitting and receiving STA can exchange short control frames after determining that the medium is idle and after any deferrals or backoffs, prior to data transmission. A node wishing to send data initiates the process by sending a Request to Send frame (RTS). All STAs in the BSS, hearing the RTS packet, read the duration field and set their NAVs accordingly. The destination node responds to RTS after an SIFS idle period has elapsed with a Clear to Send frame (CTS). Any other node receiving the RTS or CTS frame should refrain from sending data for a given time of the frame. Upon successful reception of the CTS, the source STA is virtually assured that the medium is stable and reserved for successful transmission of a frame [3].

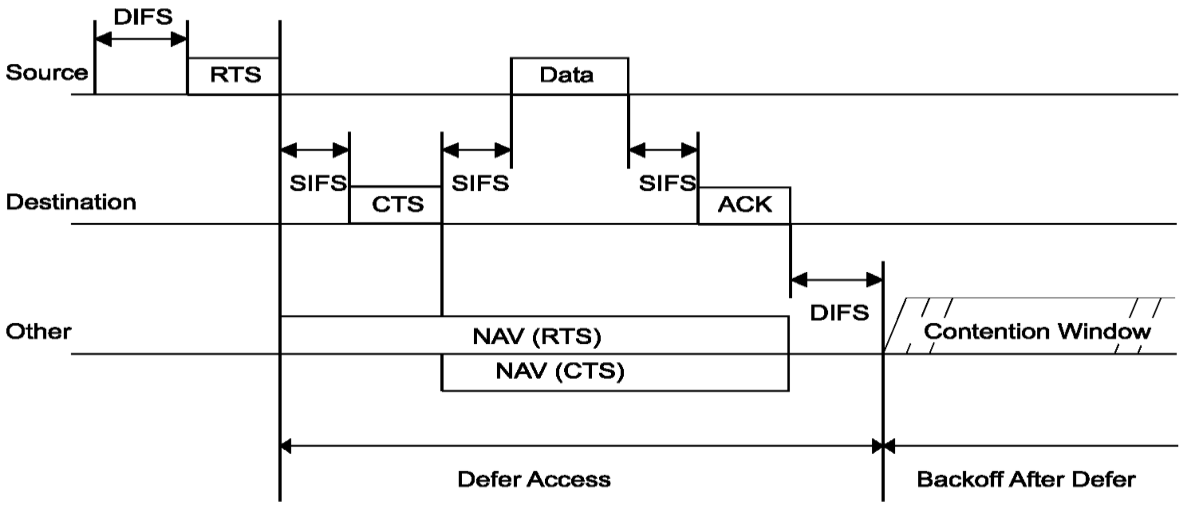

Figure 2.10 RTS/CTS/data/ACK and NAV [4].

2.6.3 Point Coordination Function (PCF)

The IEEE 802.11 MAC also defines an optional access method called PCF, which is employed for infrastructure network configurations. This access method uses a Point Coordinator (PC) [Annex A], which operates at the AP of the BSS, in order to determine which STA currently has the right to transmit and for how long. The operation utilizes polling, with the PC performing the role of the polling master.

The PCF uses a virtual Carrier Sense (CS) mechanism aided by an access priority mechanism. The PCF shall distribute information within Beacon management frames to gain control of the medium by setting the NAV in STAs. In addition, all frame transmissions under the PCF may use an Interframe Space (IFS) that is smaller than the DIFS for frames transmitted via the DCF. The use of smaller IFS implies that point-coordinated traffic will have priority access to the medium over STAs in overlapping BSSs operating under the DCF access method [4].

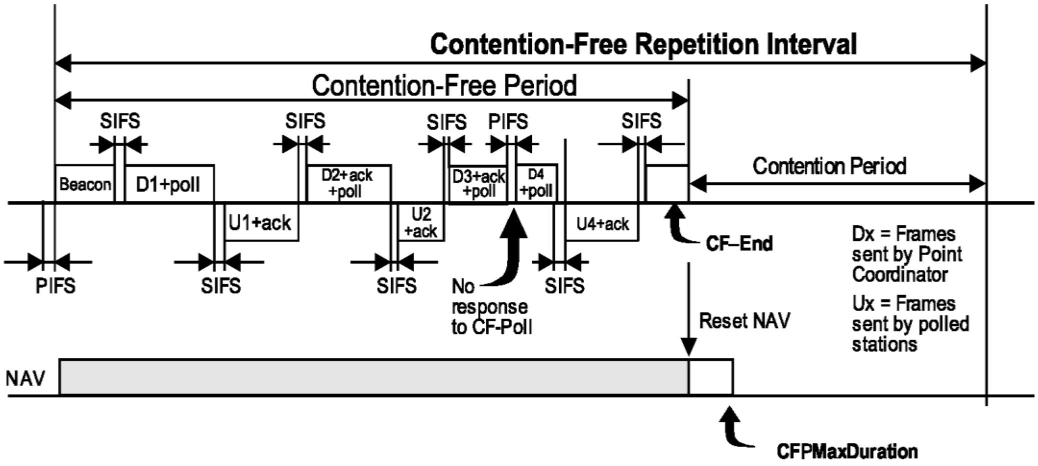

Figure 2.11 Point Coordination Function [4].

2.6.4 Hybrid Coordination Function (HCF)

The IEEE 802.11e medium access control protocol is an emerging standard for WLANs providing Quality of Service (QoS) [Annex A]. QoS is the ability to provide different priority to different applications and users. The extension of the legacy MAC, proposed by Task Group E (TGe), introduced a new mechanism to the MAC layer, namely HCF, enhancing QoS management and providing QoS guarantees to QoS aware applications. HCF is only usable in QoS network configurations and is implemented in all QoS STAs. The HCF combines functions from the DCF and PCF with some enhanced, QoS-specific mechanisms and frame subtypes to allow a uniform set of frame exchange sequences to be used for QoS data transfers during both the Contention Period (CP) [Annex A] and Contention Free Period (CFP) [Annex A]. The HCF uses both a contention-based channel access method, called the Enhanced Distributed Channel Access (EDCA) mechanism, and a contention-free channel access method referred to as the HCF controlled channel access (HCCA) mechanism [4].

2.6.4.1 HCF Contention Based Channel Access

The EDCA mechanism provides differentiated, distributed access to the wireless medium for STAs using eight different User Priorities (UPs). The EDCA mechanism defines four Access Categories (ACs) that provide support for the delivery of traffic with UPs to the STAs. See bellow on the Table 2.1 the mapping of UPs to the ACs.

Priority	UP (as 802.1D user priority)	802.1D designation	AC	Designation (informative)
Lowest	1	BK	AC_BK	Background
	2	-	AC_BK	Background
	0	BE	AC_BE	Best Effort
	3	EE	AC_BE	Best Effort
	4	CL	AC_VI	Video
	5	VI	AC_VI	Video
Highest	6	VO	AC_VO	Voice
	7	BC	AC_VO	Voice

Table 2.1 UP-to-AC mappings [4].

Every STA maintains four transmit queues one per AC as is illustrated in Figure 2.10. Each AC is an enhanced variant of DCF that contends to get the access to the medium by using the same principles (i.e. CSMA/CA, Backoff) in particular for Transmission Opportunity (TXOP) using ACnTable specified channel access parameters from the EDCA parameter set element or from the default values for the parameters when no EDCA parameter set element is received from the AP of the BSS with which the STA is associated.

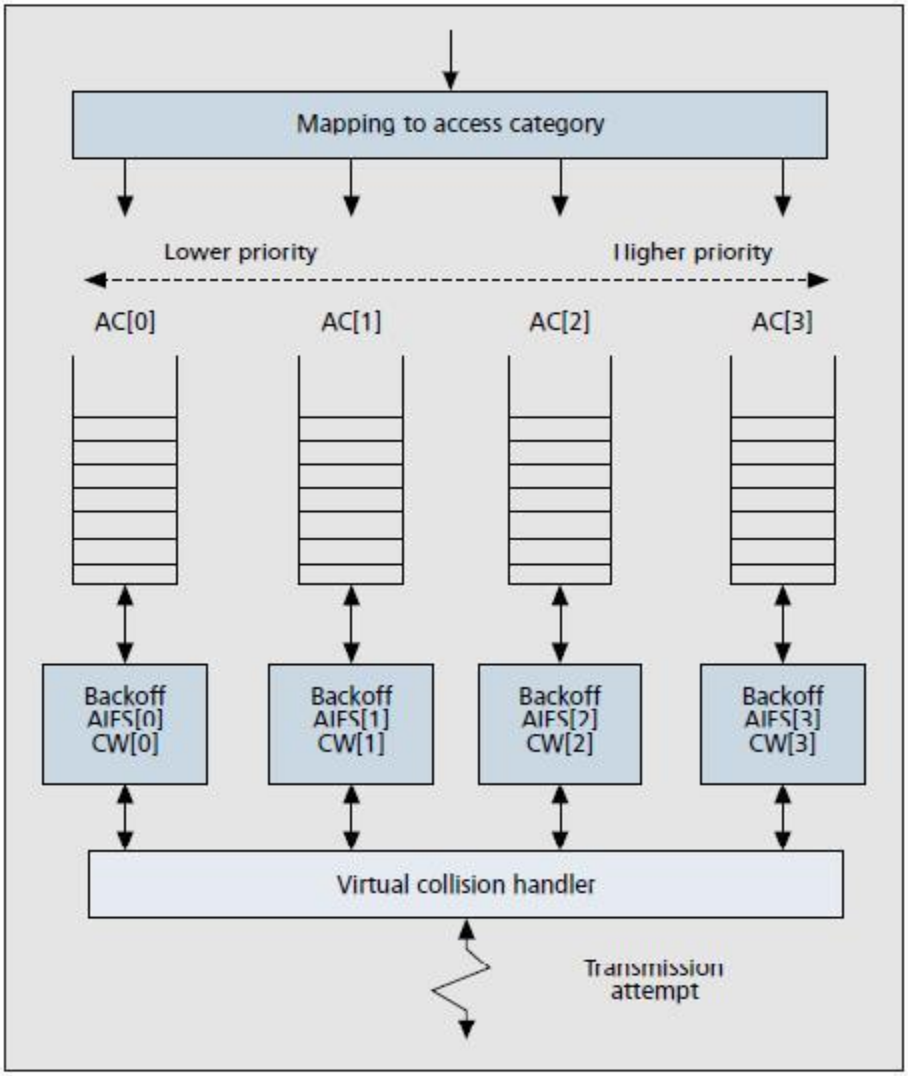

Figure 2.12 The four ACs, for each of them the Backoff, AIFS and CW [8].

Bellow is described in detail the EDCA parameter set [8]:

• Minimal CW value for a given AC (CWmin[AC]): CWmin can be different for different ACs. Assigning smaller values of CWmin to high priority classes can ensure that high-priority classes obtain more TXOPs than low-priority ones.

• Maximal CW value for a given AC (CWmax[AC]): Similar to CWmin, CWmax is also on a per AC basis.

• Arbitration Interframe Space (AIFS[AC]): Each AC starts its backoff procedure after the channel is idle for a period of AIFS[AC] instead of DIFS. The AIFS[AC] for a given AC should be equal to an Short Interframe Spacing (SIFS) plus multiple time slots (i.e., AIFS[AC] = aSIFSTime + AIFSN[AC]*aSlotTime). Considering DIFS = aSIFSTime + 2 * aSlotTime in legacy IEEE 802.11, AIFSN[AC] is typically set to not less than 2 such that the shortest waiting time is DIFS.

- TXOPlimit[AC]: TXOPs obtained via EDCA are referred as EDCA-TXOPs. During an EDCA-TXOP, a STA may be allowed to transmit multiple data frames from the same AC with a SIFS gap between an ACK and the subsequent data frame transmission. TXOPlimit[AC] gives the limit for such a consecutive transmission.

- Virtual collision: If the backoff counters of two or more collocated ACs in one STA elapse at the same time, a scheduler inside the STA treats the event as a virtual collision. The TXOP is given to the AC with the highest priority among the “colliding” ACs, and the other colliding ACs defer and try again later as if the collision occurred in the real medium.

AC	CWmin	CWmax	AIFSN	TXOP limit
AC_BK	aCWmin	aCWmax	7	0
AC_BE	aCWmin	aCWmax	3	0
AC_VI	(aCWmin+1)/2-1	aCWmin	2	3.008ms
AC_VO	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2	1.504ms

Table 2.2 Default EDCA Parameter Set element parameter values [4].

The QoS AP announces the EDCA parameter set element in all Beacon frames occurring within two or more Delivery Traffic Indication Message (DTIM) periods following a change in AC parameters to assure that all STAs are able to receive the updated EDCA parameters [4] and in all Probe response and (re) association response frames. If no such element is received, the STAs shall use the default values for the parameters.

2.6.4.2 HCF Controlled Channel Access (HCCA)

The HCCA mechanism is not mandatory for IEEE 802.11e APs. In fact, a few (if any) APs currently available are enabled for HCCA**.** The HCCA mechanism uses a QoS-aware centralized coordinator, called a Hybrid Coordinator (HC). During the HCCA the AP is typically the AP of the BSS thus, controls the access to the medium, for more detail see [Annex A]. HCCA allows CFP being initiated during a CP. This kind of CFP is called a Controlled Access Phase (CAP) in IEEE 802.11e. A CAP is initiated by the AP whenever it wants to send a frame to a STA or receive a frame from a STA in a contention-free manner. In fact, the CFP is a CAP too. The HCF protects the transmissions during each CAP using the virtual CS mechanism. HC operates concurrently with the EDCA thus, the HC traffic delivery and TXOP allocation may be scheduled during the CP and locally the CFP is generated.

A STA based on its requirements and sends requests to HC for TXOPs. Hence, the HC either accepts or rejects the request based on an admission control policy. If the request is accepted, the HC schedules TXOPs for both the AP and the STA. For transmissions from the STA, the HC polls the STAs based on the parameters supplied by the STA at the time of its request. For transmissions to the STA, the AP directly obtains TXOPs from the HC within the AP and delivers the buffered frames to the STA, again based on the parameters supplied by the STA.

2.7 IEEE 802.11 Physical Layer

The IEEE 802.11 Physical layer is the interface between the wireless medium and the MAC layer and defines the radio wave modulation and signaling characteristics for data transmission. In IEEE 802.11 the physical layer splits into Physical Layer Convergence Protocol (PLCP) and the Physical Medium Dependent (PMD) sub layers. The PLCP prepares frames for transmission and reception using various IEEE 802.11 media access techniques and directs to the PMD. The PMD performs the transmission/reception and modulation/demodulation of the frames by accessing directly to the air under the guidance of the PLCP.

Four different Physical layer specifications were defined, namely, Infrared (IR), Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), Complementary Code Keying (CCK), and Orthogonal Frequency-Division Multiplexing (OFDM).

2.7.1 Infrared (IR)

Infrared is mainly defined by IrDA (Infrared Data Association). Infrared light is part of electromagnetic spectrum that is shorter than radio waves but longer than visible light. Its frequency range is between 300 GHz and 400 THz. The IR relies on optical signals in the 800-900 nm band and direct detection of the optical signals to transmit data at 1 or 2 Mbps using the diffuse mode of propagation.

The modulation method that is adopted for this physical layer is Pulse Position Modulation (PPM). PPM was adopted because it is one of the most power efficient modulation methods, which is appropriate for a channel where the propagation losses are very high [9].

The use of infrared for WLAN has not been accepted by public, since there were no successful commercial implementations of IEEE 802.11 IR technologies.

2.7.2 Frequency Hopping Spread Spectrum (FHSS)

The frequency hopping was the first step in the evolution to the DSSS and more complex data transmission techniques. The idea is to transmit on a given frequency for a very short time and switch to another frequency according to a pre-defined frequency hopping pattern known to both transmitter and receiver. In FHSS, the whole frequency band is divided into a set of narrow channels thus, the STA jumps from one channel to another as a predefined cyclic pattern. IEEE 802.11 frequency hopping separates the whole 2.4 GHz band into channels that are spaced of 1 MHz. The transmitter has to change channels at least 2.5 times per second (every 400msec or less). The hopping patterns are described by 3 sets containing 26 hopping sequences each. The sets are defined in such way that the sequences in each set, when set up on different access points, provide minimum mutual interference.

The FHSS is quite stable to interference, cost effective and simple data transmission technique but it is not widely used nowadays for WLANs [10].

2.7.3 Direct Sequence Spread Spectrum (DSSS)

DSSS is one of the most successful data transmission techniques for today. The DSSS is used in cellular networks, Global Positioning Systems (GPS) and Wireless LANs. In IEEE 802.11, the DSSS is specified a 2 Mbps-peak data rate with optional fallback to 1 Mbps in very noisy environments. DSSS increases modulation rate. The idea is to multiply the data being transmitted to a pseudo random binary sequence of a higher bit rate, the STA uses the same center frequency but the signal is spread by multiplexing with different spreading codes to reduce the interference between signals and the background noise. The receiver then decodes the original signal using the same code used by the transmitter.

DSSS systems spread transmissions across a relatively wide band by artificially increasing the used bandwidth. A DSSS transmitter converts an incoming data stream into a symbol stream where each symbol represents a group of 1, 2, or more bits. Using a phase-varying modulation technique such as Quadrature Phase Shift Keying (QPSK), the DSSS transmitter modulates or multiplies each symbol with a pseudorandom sequence which is called a “chip” sequence. The multiplication operation in a DSSS transmitter artificially increases the used bandwidth based on the length of the chip sequence [10].

2.7.4 Complementary Code Keying (CCK)

CCK achieves 5.5 Mbps and 11 Mbps transmit rates. The IEEE adopted the CCK and released the IEEE 802.11b in 1999. The CCK modulation is based on the use of the polyphase complementary codes. The codes posses nearly orthogonal (close to zero autocorrelation if shift is not 0) properties. The polyphase complementary codes are complex codes. They are not binary.

2.7.5 Orthogonal Frequency-Division Multiplexing (OFDM)

The basic principle of OFDM is that a very high rate data stream is divided into multiple parallel low rate data streams that are transmitted simultaneously over a number of subcarriers. Each smaller data stream is then mapped to individual data sub-carrier and modulated using some sorts of Phase Shift Keying (PSK) (i.e. Binary PSK (BPSK)) or Quadrature Amplitude Modulation (QAM) (i.e. QPSK, 16-QAM, 64-QAM). The sub-carriers are closely spaced to each other without causing interference. Since the symbol duration increases for the lower rate parallel subcarriers, the effects of time dispersion caused by multipath delay spread are decreased. Intersymbol interference is eliminated almost completely by introducing a guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid intercarrier interference. This is possible because the frequencies (sub-carriers) are orthogonal meaning the peak of one sub-carrier coincides with the null of an adjacent sub-carrier [3].

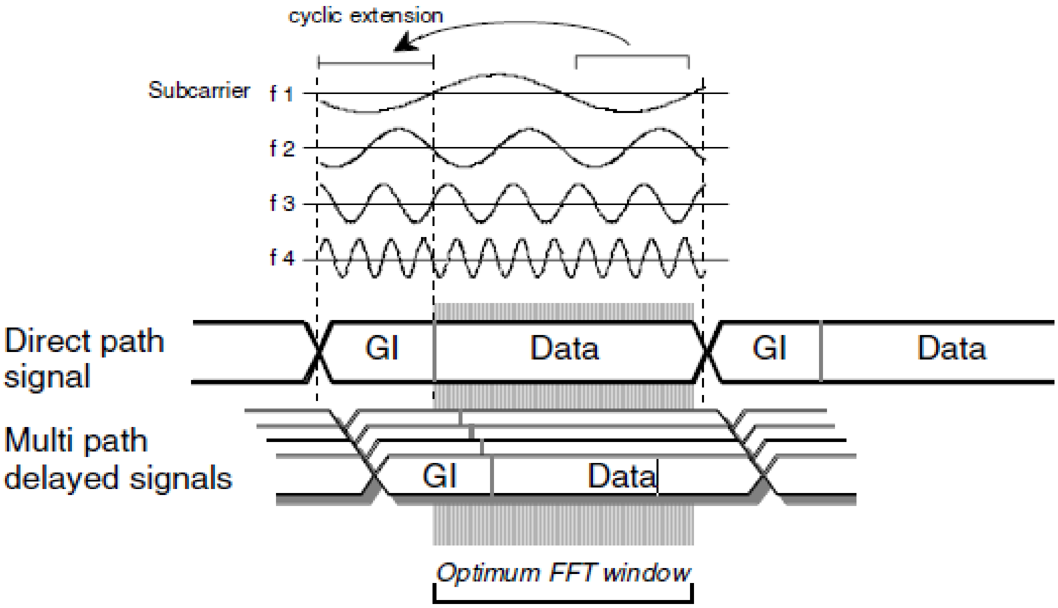

Figure 2.13 OFDM symbol with cyclic extension [3].

2.8 IEEE 802.11 Standards Family

The original version of the standard IEEE 802.11 was released in 1997. IEEE 802.11 supported a maximum network bandwidth of 2 Mbps - too slow for most applications. It specified three alternative physical layer technologies: diffuse infrared operating at 1 Mbps (IR remains a part of the standard but has no actual implementations), FHSS and DSSS operating at 1 Mbps or 2 Mbps. The latter two radio technologies used microwave transmission over the ISM frequency band at 2.4 GHz.

2.8.1 IEEE 802.11b

IEEE expanded on the original IEEE 802.11 standard in July 1999, creating the IEEE 802.11b specification and appeared on the market in early 2000. IEEE 802.11b uses a physical layer with DSSS and with the Complementary-Code Keying (CCK) modulation scheme, provides data rates up to 11 Mbps. However, because of the packet overheads the effective throughput was around 5 Mbps and this was insufficient for many applications such as video. The dramatic increase of throughput for IEEE 802.11b (compared to the original standard) along with simultaneous substantial price reductions led to the rapid acceptance of IEEE 802.11b as the definitive wireless LAN technology.

IEEE 802.11b devices suffer interference due the other products that operate in the 2.4 GHz band. Devices operating in the 2.4 GHz range include: microwave ovens, Bluetooth devices, baby monitors and cordless telephones. The interference may reduced by installing each of the devices in a reasonable distance from each other.

2.8.2 IEEE 802.11a

During the same year, IEEE created a second extension to the original IEEE 802.11 standard called IEEE 802.11a. Because IEEE 802.11b gained in popularity much faster than IEEE 802.11a did and due to its higher cost, IEEE 802.11a was planned to operate on business networks whereas IEEE 802.11b on the home market.

The IEEE 802.11a amendment uses the same data link layer protocol and frame format as the original standard but specifies the physical layer operating in the 5 GHz using a transmission scheme known as Orthogonal Frequency Division Multiplexing (OFDM) allowing data rates up to 54 Mbps. The higher frequency also means lower value on power transmission; hence signals have more difficulty penetrating walls and shortens the range of IEEE 802.11a compared to IEEE 802.11b.

2.8.3 IEEE 802.11e

IEEE 802.11e provides MAC enhancements supports WLAN applications with QoS requirements. The QoS enhancements are available to the QoS enhanced STAs (QSTAs) that are associated with a QoS enhanced Access Point (QAP) in a QoS enabled network. A subset of the QoS enhancements may be available for use between QSTAs. A QSTA may associate with a non-QoS AP in a non-QoS network and non-QoS STAs may associate with a QAP [3].

The IEEE 802.11e standard provides two mechanisms for the support of applications with QoS requirements. The first mechanism is EDCF, is based on the differentiating user priorities and access categories. The second mechanism is HCCA, allows for the reservation of transmission opportunities with the hybrid coordinator. A full description of EDCA and HCCA was given earlier in subchapters [2.6.4.1] and [2.6.4.2] respectively.

2.8.4 IEEE 802.11g

In June of 2003, a third modulation standard was ratified: IEEE 802.11g emerged on the market. The proposed IEEE 802.11g standard was rapidly adopted by consumers starting in January 2003, well before ratification, due both to the desire for higher data rates and to the reductions of WLAN devices in manufacturing costs. The IEEE 802.11g attempted to combine the best of both IEEE 802.11a and IEEE 802.11b. The IEEE 802.11g standard defines a physical layer with similar specifications as IEEE 802.11a (i.e. OFDM transmission scheme that supports bandwidth up to 54 Mbps) and it uses the 2.4 GHz frequency for greater range. IEEE 802.11g is backwards compatible with IEEE 802.11b, meaning that IEEE 802.11g access points will work with IEEE 802.11b wireless network adapters and vice versa. IEEE 802.11g devices suffer from interference due other products operating in the 2.4 GHz band as well.

2.8.5 IEEE 802.11n

In October of 2009, the newest IEEE standard in IEEE 802.11 category, IEEE 802.11n was published. It was designed to improve on IEEE 802.11g in the amount of bandwidth supported by utilizing multiple wireless signals and antennas called Multiple-Input Multiple-Output (MIMO) technology that uses techniques such as Spatial Division Multiplexing (SDM), transmitter beamforming and Space Time Block Coding (STBC) which also helps to improve the range of reception. The enhancements in both the physical and MAC layers and has the potential of offering higher data rates up to 200

Mbps based on the physical layer data rates up to 600 Mbps. IEEE 802.11n operates on both the 2.4 GHz and the lesser used 5 GHz bands.

2.8.6 Ongoing Standardization Activities

2.8.6.1 IEEE 802.11aa Draft

IEEE 802.11aa Draft is an upcoming standard of IEEE standardization committee currently under development which will provide very high throughput. The IEEE 802.11aa Task Group AA (TGaa) came into life on March 2008. This amendment specifies enhancements to the IEEE 802.11 MAC for robust audio video streaming. IEEE 802.11aa cooperates with TG Audio/Video Bridging (TGAVB) (802.1Qat, 802.1Qav, and 802.1AS) that develops the general principles for time-synchronized low-latency streaming services and to provide QoS guarantees for time-sensitive Audio Video (A/V) streams for IEEE 802.11 networks. The main services of the upcoming standard according to the current draft [11] are: Group Addressed Transmission Service, Intra-access category prioritization, Overlapping BSS, Stream Classification Service and Interworking with IEEE 802.1AVB.

The scope of this thesis is limited to the problem of Overlapping BSS problem that is described in detail in the following chapter.

2.8.6.2 IEEE 802.11ac Draft

IEEE 802.11ac is an upcoming standard that is developed by the IEEE standardization committee and is anticipated to be released by 2012. The main target of Task Group AC is to enhance the high throughput rates that achieved by IEEE 802.11n. The IEEE 802.11ac Gigabit standard utilizes a number of techniques that have been utilized within previous IEEE 802.11 standards and builds on these technologies, while adding some new techniques to ensure that the required throughput can be attained:

- OFDM: The IEEE 802.11ac standard utilizes OFDM that has been very successfully used in previous forms of IEEE 802.11. The use of OFDM is particularly applicable to wideband data transmission as it combats some of the problems with selective fading.

- MIMO and MU-MIMO: MU-MIMO enables the simultaneous transmission of different data frames to different clients. The use of MU-MIMO requires that equipment is able to utilize the spatial awareness of the different remote users. It also needs sophisticated queuing systems that can take advantage of opportunities to transmit to multiple clients when conditions are right.

- Increased channel bandwidth: The previous versions of IEEE 802.11 standards have typically used 20 MHz channels, although IEEE 802.11n used up to 40 MHz wide channels. The IEEE 802.11ac standard uses channel bandwidths up to 80 MHz. To achieve this, it is necessary to adapt automatic radio tuning capabilities so that higher-bandwidth channels are only used where necessary to conserve spectrum BSS problem is important in TGac because frequency channel shortage is expected. TGac is studying to use bandwidth of 160MHz and multi-channel transmission.

In [12], it is reported that the maximum multi STA throughput of at least 1Gbps and a maximum single link throughput of at least 500Mbps and that the operation is below of 6 GHz while ensuring backward compatibility and coexistence with legacy IEEE 802.11 devices in 5GHz unlicensed bands.

Chapter 3

Problem Definition

In this chapter, we will continue with the theoretical background, regarding to the problem definition (i.e. Overlapping BSS problem) of the current thesis.

3.1 Industrial, Scientific and Medical (ISM) Radio Bands

Industrial, Scientific and Medical (ISM) is a part of the radio spectrum that can be used without a license in most countries worldwide and is defined by the International Telecommunication Union Radiocommunication Sector (ITU-R). In the United States of America (U.S.A.), the 902-928, 2400-2484 and 5725-5850 MHz bands were initially used for machines that emitted radio frequencies, such as industrial heaters and microwave ovens but not for radio communications [13].

In 1985, the Federal Communications Commission (FCC), an independent federal regulatory agency in the U.S.A. responsible directly to Congress, opened up the ISM bands for Wireless LANs and Mobile Communications. In 1997, FCC added additional bands in the 5 GHz range known as the Unlicensed National Information Infrastructure (U-NII). Europe's HIPERLAN wireless LANs use the same 5 GHz band range, which are entitled the "Broadband Radio Access Network" [13].

3.1.1 2.4 GHz Wireless Band

IEEE 802.11 (IEEE 802.11b/g/n) divides these ISM bands into channels. Regarding to the 2.4000–2.484 MHz band, has 14 channels, not all of the channels are allowed in all countries; 11 are allowed by the FCC and used in what is often termed the North American domain, 13 are allowed in Europe where channels have been defined by European Telecommunications Standards Institute (ETSI) [14] and finally, in Japan are allowed all 14 channels [Table 2.1]. Each of channels has width of 22 MHz while the first channel is centered on 2.412 GHz and the “last” one (i.e. channel 13) on 2.472 GHz to which Japan adds a 14th channel 12 MHz above channel 13. The channels are spaced

5 MHz apart from the exception of 12 MHz spacing between the last two channels, as it is illustrated in Table 2.1 and Figure 3.1.

Channel	Center Frequency (MHz)	U.S. (FCC)	Europe (ETSI)	Japan
1	2 412	Yes	Yes	Yes
2	2 417	Yes	Yes	Yes
3	2 422	Yes	Yes	Yes
4	2 427	Yes	Yes	Yes
5	2 432	Yes	Yes	Yes
6	2 437	Yes	Yes	Yes
7	2 442	Yes	Yes	Yes
8	2 447	Yes	Yes	Yes
9	2 452	Yes	Yes	Yes
10	2 457	Yes	Yes	Yes
11	2 462	Yes	Yes	Yes
12	2 467	No	Yes	Yes
13	2 472	No	Yes	Yes
14	2 484	No	No	Only IEEE 802.11b

Table 3.1 WLAN channel frequencies in 2.4GHz and the availability per region

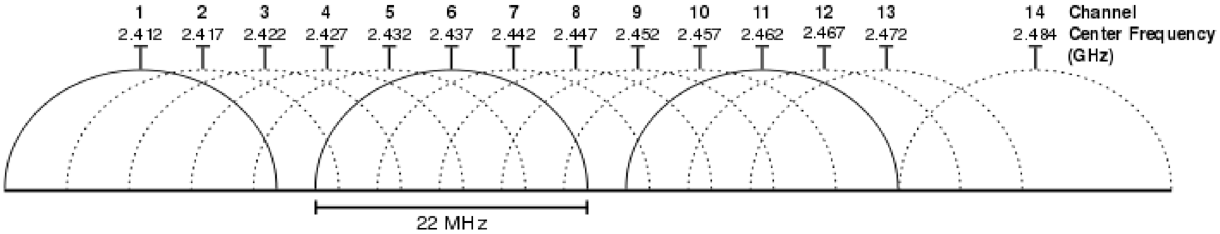

Figure 3.1 Channels of 22 MHz bandwidth in the 2.4 band

3.1.2 5 GHz Wireless Band

The 5 GHz band is utilized by IEEE 802.11a/n standards and is composed of four frequency bands: 5.150 - 5.250 MHz, 5.250 - 5.350 MHz, 5.470 - 5.725 MHz, and 5725-5850 MHz. The 5 GHz band has in total 24 channels in U.S. and 19 in Europe with 20 MHz bandwidth while 11 channels in U.S. and 9 in Europe with 40 MHz bandwidth. Table 2.2 below shows the frequency channels that are available in the 5 GHz bands.

Channel	Center Frequency (MHz)	U.S. (FCC)	Europe (ETSI)	Japan
34	5 170	No	No	Yes
36	5 180	Yes	Yes	Yes
38	5 190	No	No	Yes
40	5 200	Yes	Yes	Yes
42	5 210	No	No	Yes
44	5 220	Yes	Yes	Yes
46	5 230	No	No	Yes
48	5 240	Yes	Yes	Yes
52	5 260	Yes	Yes	Yes
56	5 280	Yes	Yes	Yes
60	5 300	Yes	Yes	Yes
64	5 320	Yes	Yes	Yes
100	5 500	Yes	Yes	Yes
104	5 520	Yes	Yes	Yes
108	5 540	Yes	Yes	Yes
112	5 560	Yes	Yes	Yes
116	5 580	Yes	Yes	Yes
120	5 600	No	Yes	Yes
124	5 620	No	Yes	Yes
128	5 640	No	Yes	Yes
132	5 660	No	Yes	Yes
136	5 680	Yes	Yes	Yes
140	5 700	Yes	Yes	Yes
149	5 745	Yes	No	No
153	5 765	Yes	No	No
157	5 785	Yes	No	No
161	5 805	Yes	No	No
165	5 825	Yes	No	No

Table 3.2 WLAN channel frequencies in 5GHz and the availability per region

3.2 The Overlapping BSS Problem

The Overlapping BSS (OBSS) problem refers to situations that two or more BSSs, unrelated to each other, are operating in the same channel and are close enough to hear each other physically [15], in particular when some STAs or AP from one BSS are able to receive frames from the other BSS. Hence, the transmissions by some STAs in one BSS will affect some STAs of other BSS. This is usually called the OBSS problem. The OBSS problem may degrade the overall network system performance severely for one or more reasons:

- Due to the doubling of the number of STAs, the medium contention level increases dramatically [16].
- The main reason of degradation of the network performance could be the interference that occurs during the OBSS. Interference makes it difficult for a wireless network to provide robust performance and lead to transient failures [17]. Hence, the STAs can not receive the frames correctly [18].
- The expansion of the hidden STAs in both BSSs due the OBSS increases severely the probability of collisions.

Below are some of the possible overlapping scenarios.

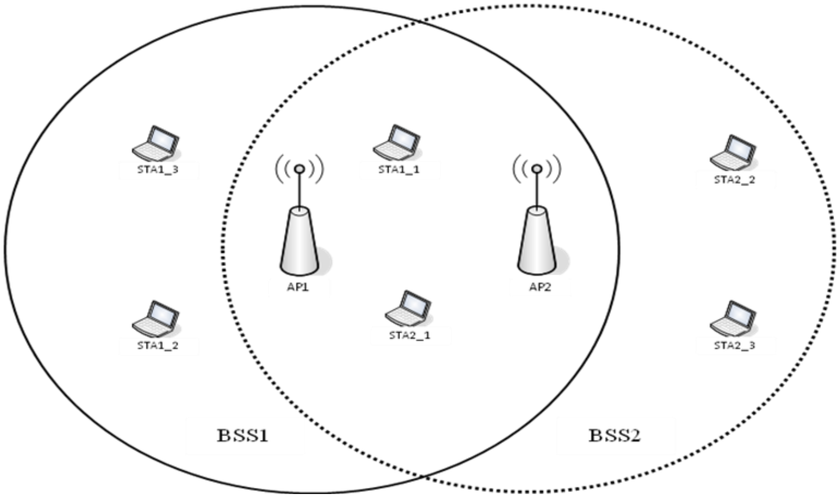

Figure 3.2 Scenario 1: Two OBSS, APs within range of each other [19].

Scenario 1 denotes an overlapping scenario where the AP1 and STAs from BSS1 are able to listen transmission of AP2 and of STAs from BSS2. Additionally, there are some STAs from both BSSs, so-called hidden nodes, which increase the collision probability.

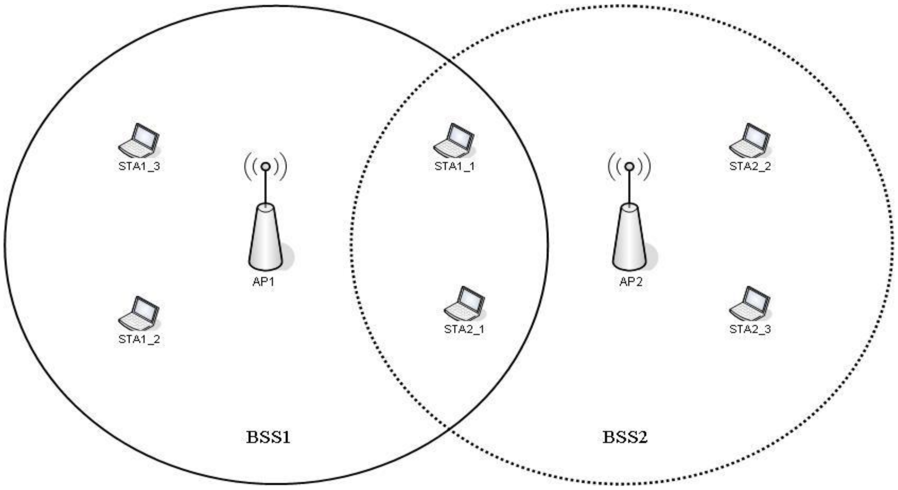

Figure 3.3 Scenario 2: Two OBSS, APs not within range of each other [19].

Scenario 2 illustrates two BSSs where the APs are not within the range of each other (Hidden APs), thus, the number of collisions may increase.

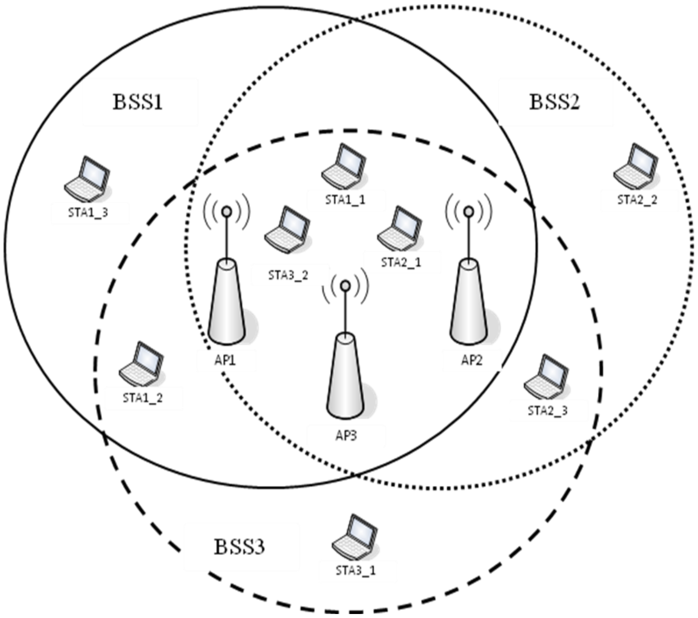

Figure 3.4 Scenario 3: Three OBSSs, APs within range of each other [19].

Scenario 3 shows an overlapping scenario of three OBSSs since there are three APs and some STAs of each BSS that are within the range of each other, thus they do listen each other physically. Some STAs of each BSS are hidden from each other thus, this scenario of three BSS has higher level of interference and collisions comparing to the two BSSs.

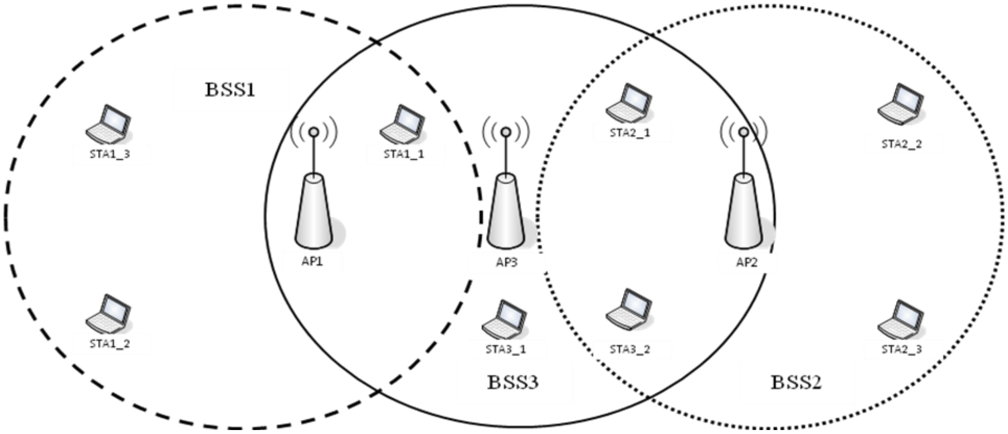

Figure 3.5 Scenario 4: Two OBSSs, one AP within range of two other [19].

Scenario 4 represents the case of “neighborhood capture effect” where there are three BSSs, one BSS is in between of two other BSSs that cannot hear each other thus, suffers a disproportionate degradation in throughput dependent upon the total traffic in all three BSSs. Hence, the two networks monopolize the wireless medium and the BSS in the middle is unable to get any traffic through.

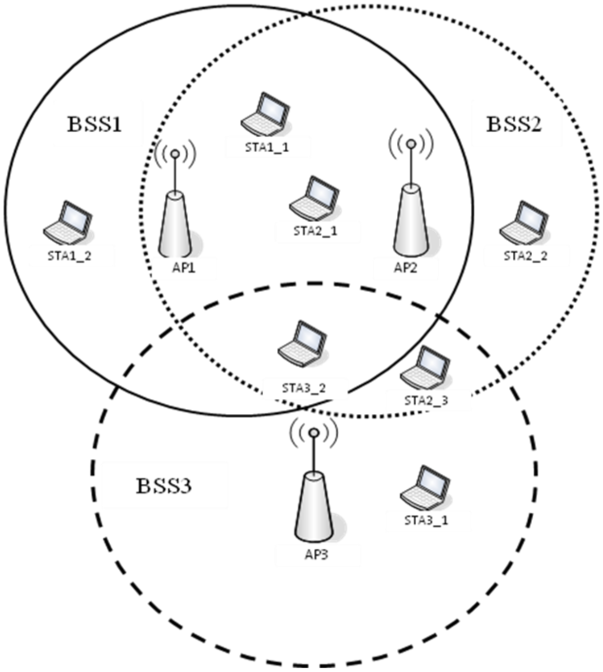

Figure 3.6 Scenario 5: Three OBSS, two APs within range of each other [19].

Scenario 5 depicts an overlapping scenario very similar to Scenario 3, with only deference, instead of three APs within the range there are two.

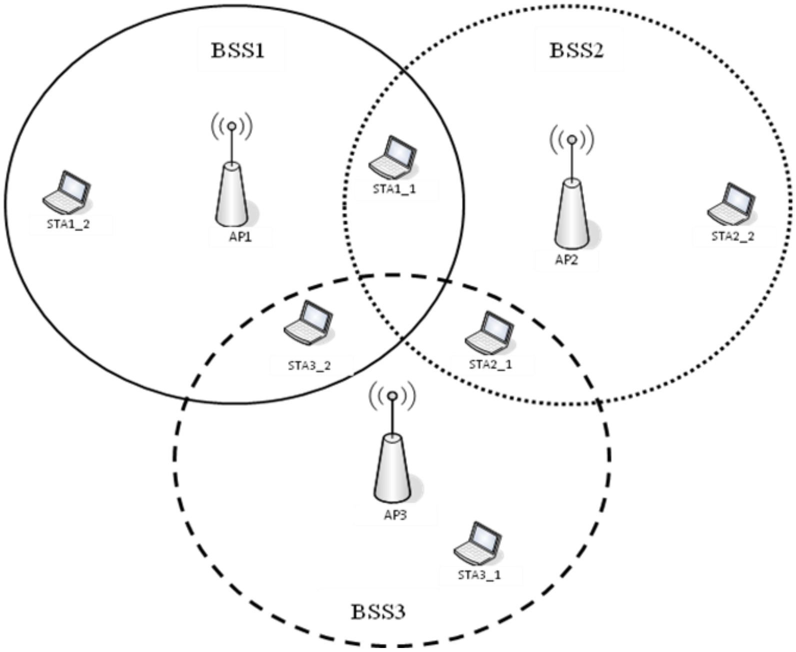

Figure 3.7 Scenario 6: Three OBSS, APs not within range of each other, shared STAs [19].

Scenario 6 illustrates an overlapping scenario of three OBSS where the three APs of each BSS are not within range of each other (hidden APs). There are STAs from each BSS that overlap.

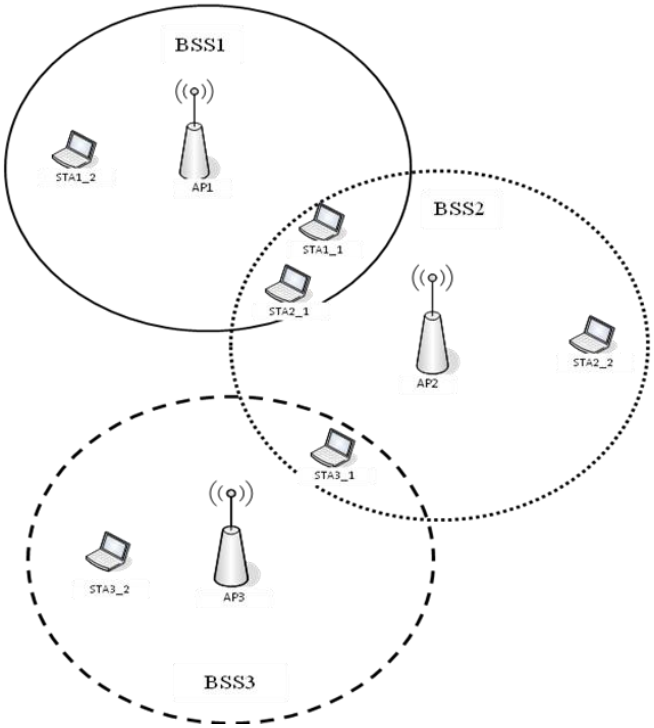

Figure 3.8 Scenario 7: Two OBSS, APs not within range of each other [19].

Scenario 7 depicts an overlapping scenario of two OBSS while there are three BSS. It is very similar with scenario of “neighborhood capture effect“ where one BSS is in between of other two. In this case, the APs of three BSSs are not within the range of each other, only some STAs from each BSS are overlapping.

3.3 Importance of the OBSS Problem

It is expected that the number of the OBSSs in IEEE 802.11aa/ac becomes more than in legacy standards (e.g. IEEE 802.11a/n) because of both frequency bandwidth extension and increase in the number of WLAN devices [20]. The 5 GHz band has in total 24 channels in U.S. with 20 MHz bandwidth where only twelve of them are non-overlapping and 11 channels with 40 MHz bandwidth. Since in IEEE 802.11aa/ac, 80 MHz of channel bandwidth is mandatory thus, there would be only the following five non-overlapping channels, 36-48, 52-64, 100-112, 116-128 and 149-161 plus a sixth, 132-144, with a regulatory change, as it is illustrated in Figure 3.9. With 160MHz of channel bandwidth which is the optional only two channels will be available.

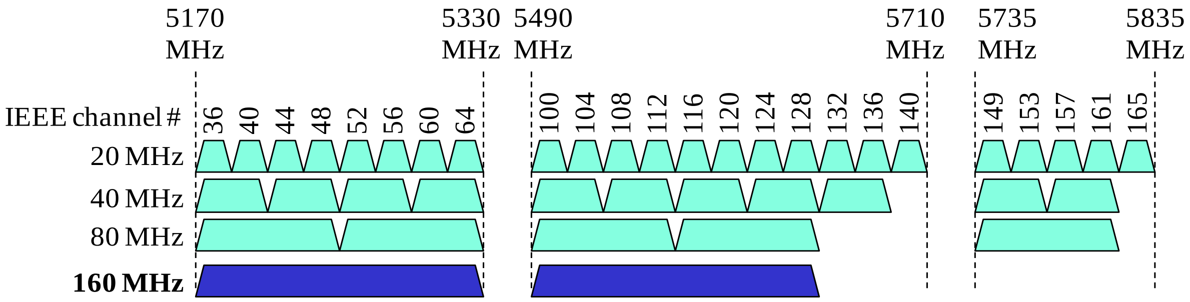

Figure 3.9 The non-overlapping channels in 5 GHz [21].

In [22], the authors present simulation results by using empirical propagation formula to present maximum potential number of overlapping networks, APs, for various residential scenarios (e.g. Apartment Block). As it is illustrated in Table 3.3, in case of apartments the potential of OBSS BSSs is very high.

Detached Houses	12
Terraced Houses	16
Townhouses	25
Single Layout Apartments	28
Double Layer Apartments	53

Table 3.3 Maximum potential number of overlapping per residential scenario [21].

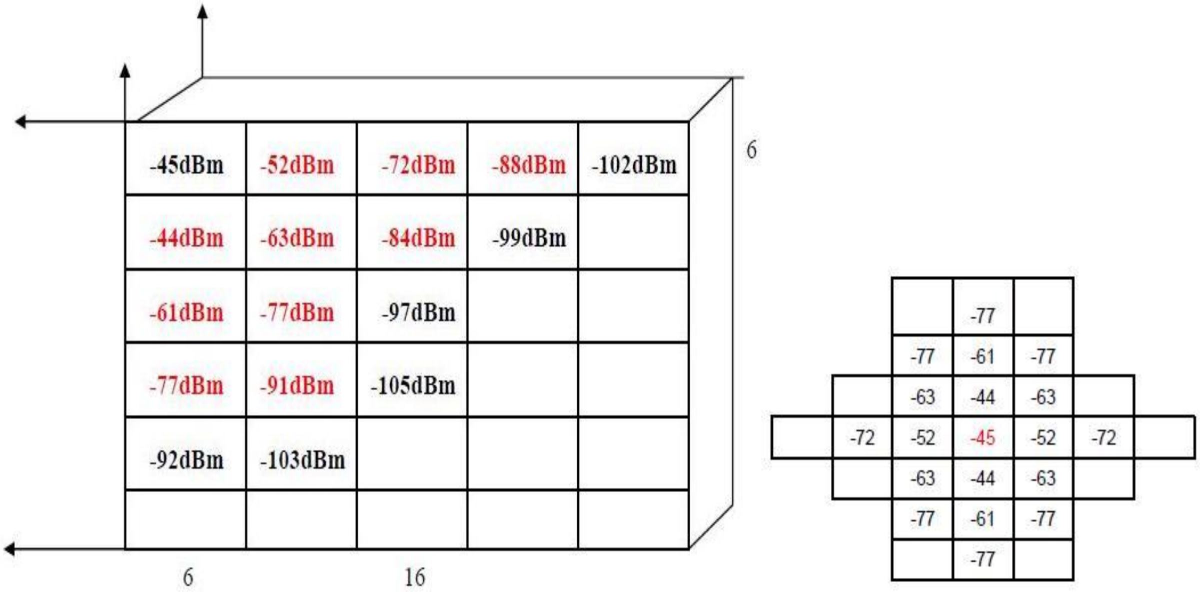

Figure 3.10 Apartment Block Single Layout [22]

Regarding to the 2.4 GHz band, there are only three non-overlapping channels with 22 MHz (i.e. channels 1, 6 and 11) and only two channels for with 40 MHz (i.e. channels 3 and 11). These non-overlapping channels of 2.4GHz band are illustrated in Figure 3.9. Since there is not enough non-overlapping channels in 2.4 GHz band for 80 MHz bandwidth thus, the IEEE 802.11aa/ac will operate in the 5 GHz band, which is a spectrum with less interference.

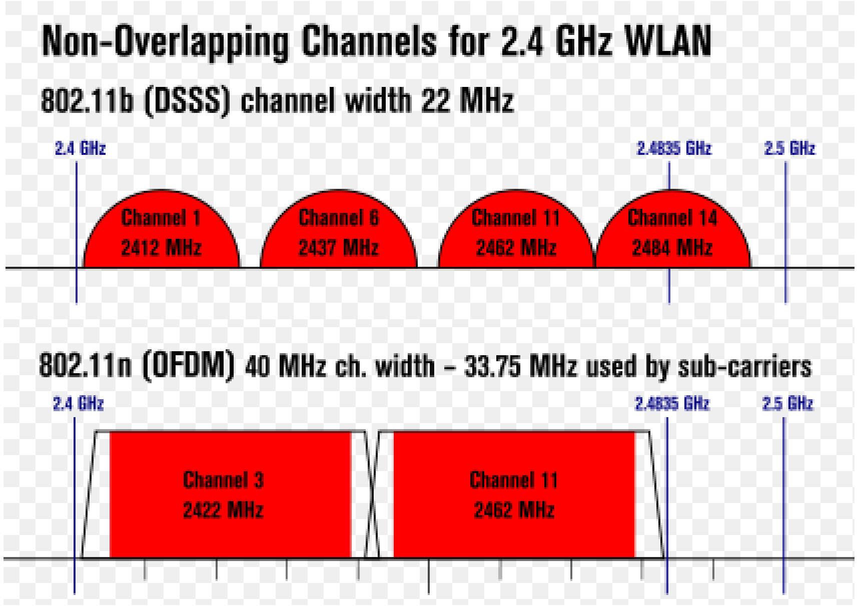

Figure 3.11 Non-overlapping channels in 2.4 GHz for 20/40 MHz.

The Task Groups for Very High Throughput (VHT) (e.g. TGac) agree that it is important to investigate the behavior of IEEE 802.11aa/ac devices in OBSS thus. The following chapter analyses the state of the art and the related work about the OBSS problem.

Chapter 4

State of the Art

In this chapter, we discuss and present a thorough analysis of state of the art and the related work that was carried out about the OBSS problem. Initially, we will present in detail the studies that we have done on IEEE 802.11aa draft and then we will describe all the mechanism that have been deployed in the past up to today that solve the problem of OBSS or enhance performance.

4.1 IEEE 802.11 TGaa Draft

4.1.1 Introduction in IEEE 802.11 TGaa Draft

The TGaa [11] is working on the IEEE 802.11aa that specifies a set of enhancements to the standard enabling the transportation of audio video streams with robustness and reliability while in the same time allowing the graceful and fair coexistence with other types of traffic. The TGaa has been working on the proposal since May 2008 and is nearing completion of the final draft, which is expected to be approved by the IEEE Standards Board by the beginning of 2012. The main services of the amendment are the following:

4.1.1.1 Group Addressed Transmission Service (GATS)

The Group Addressed Transmission Service (GATS) provides delivery of group addressed frames and Improvement for the multicast/broadcast mechanism of IEEE 802.11 to offer better link reliability and low jitter characteristics. GATS comprises the two services, Directed Multicast Service (DMS) and Groupcast with Retries (GCR).

4.1.1.1.1 Directed Multicast Service (DMS)

In the IEEE 802.11aa draft the DMS method can be used dynamically and switched with the other two policies. The DMS converts multicast traffic to unicast frames directed to each of the group recipients in a series. The transmission uses the normal acknowledgement policy and will be retransmitted until it is received correctly. This is the most reliable scheme but it also has the greater overhead and does not scale well to multicast groups with a large number of members.

4.1.1.1.2 Groupcast with Retries (GCR) [11]

GCR is a flexible service to improve the delivery of group addressed frames while optimizing for a range of criteria. GCR service may be provided by the AP to associated STAs in an infrastructure BSS or by a mesh STA to its peer mesh STAs in a mesh BSS. GCR is an extension of DMS. In particular:

a) A GCR agreement applies to a single group address whereas a DMS flow is defined by Traffic Classification (TCLAS) information element(s) and an optional TCLAS Processing information element.

b) DMS offers multicast-to-unicast conversion only, whereas GCR includes several retransmission policies and delivery methods.

4.1.1.2 Stream Classification Service (SCS)

The Stream Classification Service (SCS) is a service that may be provided by an AP to its associated STAs that support the SCS service. The SCS aims to cover two of the targets within the scope of the IEEE 802.11aa amendment: a) The need to differentiate between separate streams within the same access category. In SCS the AP classifies incoming unicast MAC Service Data Units (MSDUs) based upon parameters provided by the non-AP STA. The classification allows User Priority, Drop Eligibility, and EDCA transmit queue to be selected for all MSDUs matching the classification. b) The need to allow for the graceful degradation of the stream in the case of bandwidth shortage [11].

4.1.1.3 Interworking with IEEE 802.1AVB [25]

The IEEE 802.1 Audio/Video Bridging (AVB) Task Group is working on a set of standards that will provide for high quality and low latency streaming of time-sensitive traffic through heterogeneous 802 networks [23]. In particular, the IEEE 802.1Qat amendment specifies the Stream Reservation Protocol (SRP) [24] which is used to reserve network resources over the entire network path between the end STAs, to guarantee the transmission and reception of a data stream across the network with a requested QoS. The source of the stream is called a Talker and the destination is called a Listener.

SRP defines a set of signaling mechanisms that can be used by the Talker to advertise a stream that it has available and define the resources that will be required, or a Listener to request a particular stream it wants to receive. The IEEE 802.11aa Task Group works closely with the AVB Task Group in order to make IEEE 802.11 networks compatible with SRP.

4.1.1.4 Intra-access Category Prioritization

Intra-access category prioritization provides six EDCA transmit queues that map to four EDCAF to enable differentiation between traffic streams that are in the same access category, so that finer grained prioritization can be applied between individual audio video streams or voice streams [11].

4.1.1.5 Overlapping BSS

The IEEE 802.11aa draft evaluates the issue of OBSS thus, in the next section we give a detailed description regarding to the channel selection algorithm, sharing schemes and the main components of these schemes as it is proposed in the draft.

4.1.2 The OBSS Management

The objective of OBSS management is to facilitate co-operative sharing of the medium between BSSs or overlapping APs operating in the same channel that can receive each other‘s frames (i.e. Beacons) [11]. The OBSS Management provides the means to:

- Provide additional information for channel selection
- Extend the admission control mechanism to a distributed environment
- Enable the coordination of scheduled TXOPs between overlapping BSSs

The OBSS Management enables fixed and portable APs to provide to neighboring APs information for the purposes of selecting a channel and for the cooperative sharing of that channel. The OBSS Management use unauthenticated Beacons and Public Action frames (e.g. QLoad Request/Report). Implementations may choose to use additional information, (e.g. a history of collaboration and traffic monitoring) to determine the authenticity of this information.

During the EDCA Admission Control APs overlapping, the main component of the OBSS Management is the QLoad Report element that provides information on the reporting AP's overlap situation, on the reporting AP's QoS traffic load and the total QoS traffic load APs directly overlapping the reporting AP. This information may be used to aid an AP when searching for a channel and also when sharing a channel in an overlap situation.

During the HCCA APs overlapping, the OBSS management uses the HCCA TXOP Advertisement element to coordinate the TXOPs of overlapping HCCA APs and to mitigate the effects of overlapping APs. The OBSS management provides means for the AP to advertise its TXOP allocations thus, another AP can schedule its TXOPs to avoid those already scheduled.

In the following two sections the QLoad Report and HCCA TXOP Advertisement elements, are analyzed in detail.

4.1.2.1 QLoad Report Element

The QLoad Report element contains the set of parameters necessary to support the OBSS management. The format of the QLoad report element is provided in [Annex B]. The QLoad Report element is contained in a public action frame (i.e. QLoad Request or Report) (regarding to the format of public action frame see [Annex B]) that is provided by an AP and optionally, periodically in the Beacon. The QLoad Report element shall not be included in Probe Response frames. The QLoad Report element is transmitted with one of the following ways [11]:

- Upon the receipt of a QLoad Request frame.

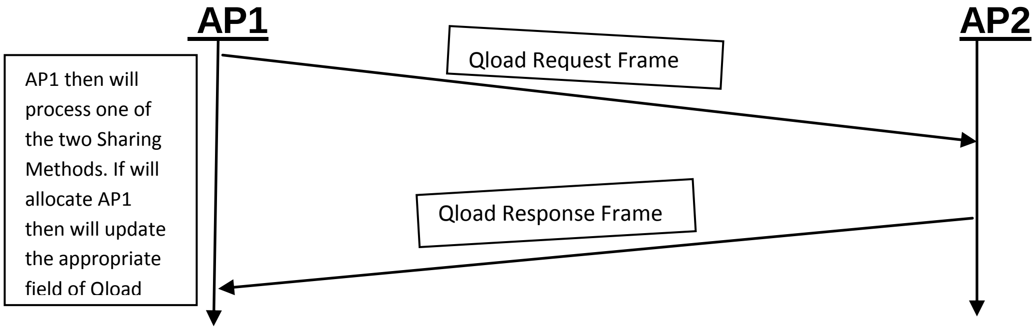

Figure 4.1 Transmission of QLoad Report frame Case 1.

- Whenever there is a change in the contents of the QLoad element, an unsolicited QLoad Report Action frame should be transmitted.

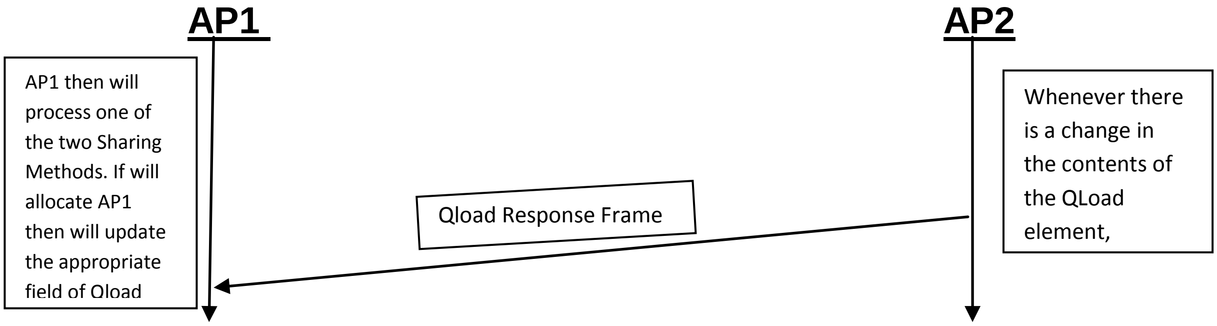

Figure 4.2 Transmission of QLoad Report frame Case 2.

- When dot11QLoadReportActivated is true, the QLoad Report element shall be included in the Beacon frame every dot11QLoadReportIntervalDTIM.

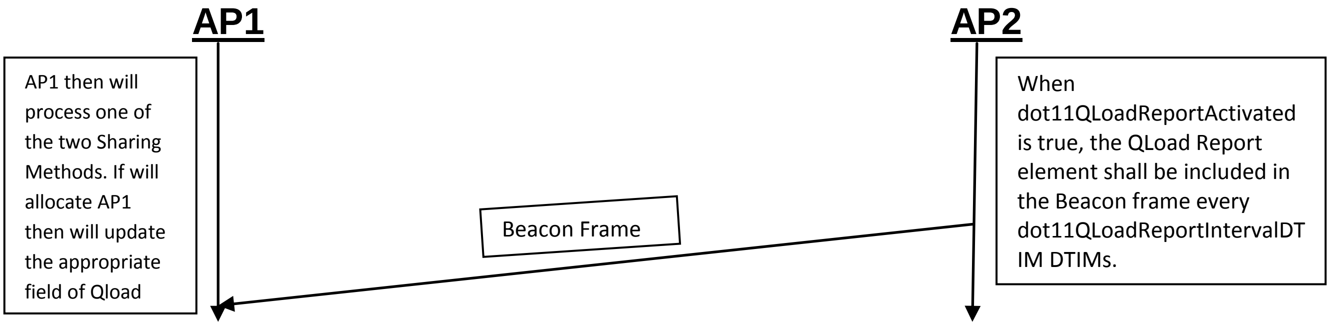

Figure 4.3 Transmission of QLoad Report frame Case 3.

4.1.2.2 HCCA TXOP Advertisement

During the HCCA APs Overlapping, the APs coordinate their TXOP schedules by using HCCA TXOP Advertisement frames. The format of the HCCA TXOP Advertisement frame is provided in [Annex B]. An HCCA AP shall advertise the Duration, Service Interval (SI) and Start Times for each TXOP reservation (the format of the frame it is provided in [Annex B]) in the HCCA TXOP Advertisement element. An HCCA AP overlapping with another HCCA AP shall examine any TXOP Reservation field(s) present in received HCCA TXOP Advertisements before accepting a Traffic Specification (TSPEC) [Annex A] request. The HCCA TXOP Update Count element (see [Annex B] for the format of the frame) which is included in the Beacon frame is used to indicate when an HCCA TXOP schedule has changed.

In [11], when an AP receives a TSPEC request that has the Access Policy subfield of the TSPEC element (see [Annex B] regarding to the format of the element) set to HCCA or HCCA-EDCA Mixed Mode (HEMM) it shall send an HCCA TXOP Advertisement frame to each overlapping HCCA AP that has the QLoad Report bit of the Extended Capabilities information element set to true. These HCCA TXOP Advertisement frames shall have the TXOP Reservation field set to the TXOP that the AP is attempting to schedule. The AP shall not send an Add Traffic Stream (ADDTS) Response frame to the requesting STA until one of the following conditions occurs:

a) The AP has received an HCCA TXOP Response frame (see [Annex B] for the format of the frame) from all the APs to which HCCA TXOP Advertisement frames were sent, with the status field set to 0 (“Successful”).

b) At least two beacon frames have been received from all the APs 1 to which the HCCA TXOP Advertisement frames were sent.

c) A beacon containing the HCCA TXOP Update Count element is received from all the APs to which the HCCA TXOP Advertisement frames were sent

d) A period of three dot11BeaconPeriod TU has elapsed.

Bellow is the sequence diagram represents how the HCCA TXOP Advertisement works.

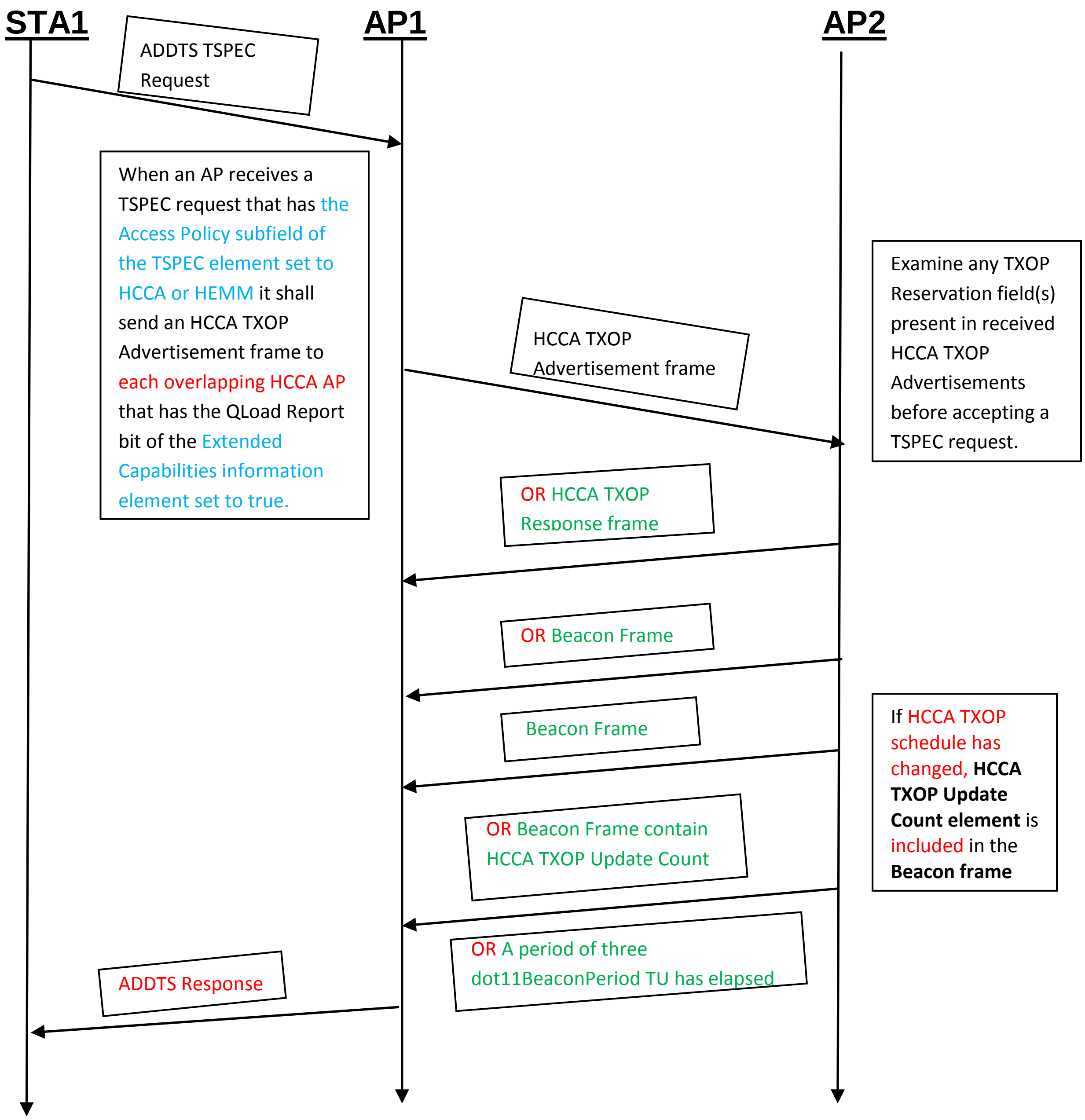

Figure 4.4 Sequence Diagram of HCCA TXOP Advertisement.

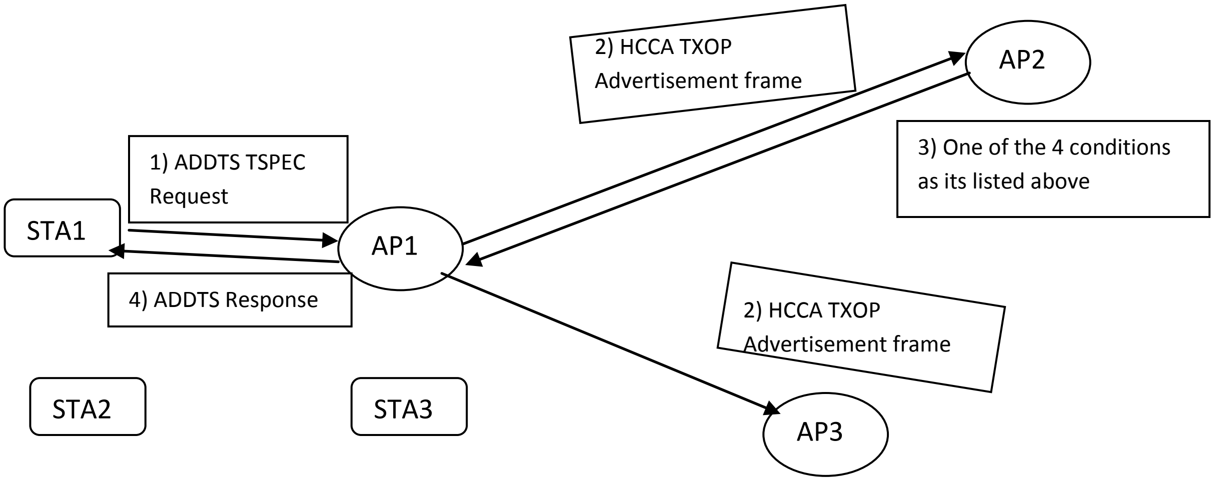

Figure 4.5 HCCA TXOP Advertisement.

If an AP receives another TSPEC request while waiting for one of the above conditions to occur, it shall delay processing this additional TSPEC request until one of the above conditions occurs.

If an AP receives an HCCA TXOP Response frame with the status field set to “The Traffic Stream (TS) schedule conflicts with an existing schedule; an alternate schedule is provided” the AP should create a new schedule for the TSPEC request using the suggestion provided in the HCCA TXOP Response frame. This allows HCCA APs to cooperatively create new HCCA schedules within a beacon period that do not collide. Failure of an AP to use the information in a HCCA TXOP Response frame when scheduling a HCCA TXOP might lead to collisions with an overlapping HCCA AP.

4.1.3 HCCA TXOP Negotiation [11]

An AP for which dot11RobustAVStreamingImplemented is true shall be able to maintain an avoidance TXOP Reservation field for each overlapping HCCA AP. These fields indicate the schedules that the AP should try to avoid using when creating schedules for new TS requests.

Upon reception of an HCCA TXOP Advertisement frame, an AP for which dot11RobustAVStreamingImplemented is true shall discard any records for the AP that sent the HCCA TXOP Advertisement frame and shall prepare a response using the procedures below:

- The AP shall inspect its HCCA schedule to check if the TXOP given in the HCCA TXOP Advertisement frame is in conflict with an existing accepted HCCA TXOP. If there is no conflict, the AP shall send an HCCA TXOP Response frame with the status field set to 0 "Successful" and add the schedule given in the HCCA TXOP Advertisement frame to the list of time periods to avoid when scheduling new HCCA TXOPs.

- If the AP detects that the TXOP given in the HCCA TXOP Advertisement frame is in conflict with an existing accepted HCCA TXOP and this AP is not itself in the process of processing an ADDTS request (see [Annex B] for the frame format), it shall send a HCCA TXOP Response frame with the status field set to "The TS schedule conflicts with an existing schedule; an alternate schedule is provided" and the Alternate Schedule field set to a period of time that does not conflict with any currently accepted HCCA TXOPs and the Avoidance Request field absent. The duration sub-field of the Alternate Schedule field should be greater than or equal to the duration sub-field of the schedule field in the HCCA TXOP Advertisement frame.

- If the AP detects that the TXOP given in the HCCA TXOP Advertisement frame is in conflict with an in-progress ADDTS request for a HCCA TXOP for which TXOP Response frames have not been received, it shall send a HCCA TXOP Response frame with the status field set to "The TS should not be created because the schedule conflicts with an existing schedule…" with the Alternate Schedule and Avoidance Request fields set according to the following rules:

  1. If the MAC address of the AP that received the TXOP Advertisement frame is less than the MAC address of the AP that sent the TXOP Advertisement frame, the Alternate Schedule field is set to a value that does not conflict with any accepted HCCA TXOPs and also does not conflict with the TXOP of the

in-progress ADDTS request. The Avoidance Request field is set to the TXOP of the in-progress ADDTS request.

2. If the MAC address of the AP that received the TXOP Advertisement frame is greater than the MAC address of the AP that sent the TXOP Advertisement frame, then the Alternate Schedule field is set to the value from the TXOP Reservation from the TXOP Advertisement frame. The Avoidance Request field is set to a time period that does not conflict with any accepted HCCA TXOPs nor the TXOP in the Alternate Schedule field and has sufficient duration and service interval to meet the requirements of the in-progress ADDTS request.

The AP shall keep a record of the TXOP proposed in the alternate schedule field in a TXOP avoidance record and avoid scheduling any new HCCA TXOPs in this proposed period until it receives another HCCA TXOP Advertisement frame from the AP to which the HCCA TXOP Response frame was sent.

Case	**Status Code**	**Alternate Schedule Field**	**Avoidance Request Field**
No conflict with existing or in-progress schedules	OK	Not present	Not present
Conflicts with existing schedule, no ADDTS request in progress	The TS schedule conflicts with an existing schedule; an alternate schedule is provided	Period of time that does not conflict with any currently accepted HCCA TXOPs	Not present
Conflict in-progress schedules, RA1 < TA2	—The TS schedule conflicts with an existing schedule; an alternate schedule is provided	Period of time that does not conflict with any currently accepted HCCA TXOPs nor the in progress ADDTS request	Schedule of in-progress ADDTS request
Conflict in-progress schedules, RA < TA	The TS schedule conflicts with an existing schedule; an alternate schedule is provided	Same schedule that was in the TXOP Advertisement	Period of time that does not conflict with any currently accepted HCCA TXOPs nor the period given in the Alternate Schedule field

Table 4.1 HCCA TXOP Negotiation [11].

4.1.4 Channel Selection Using QLoad Report

The most effective mitigation of OBSS is for an AP to choose a channel that is either free, or one that is occupied by another AP that is not fully loaded with QoS traffic. It is recommended that the “Overlap” and “Potential Traffic Self” fields of the QLoad Report element are used by an AP as part of its channel selection procedure and, thus, the AP can make an informed decision as to the best channel to select.

It is recommended that when selecting a channel, the AP should first scan to see if there is a free channel taking account of BSS channel width and channel spacing. If there is a free channel, then an AP should select that one. If a free channel is not available, then it should select channels that have the least number of QoS APs present.

The recommended method for channel selection can be implemented by adoption of the following procedures [11]:

- Create a list of the available channels. Typically this is the list of channels allowed by regulation in the operating regulatory domain, however, this list might be modified by management policy (e.g. removing overlapping channels, avoiding radar detect channels).

- Create an array for each available channel that allows the recording of the QoS AP count, Admission Control Mandatory count, HC count, overlap count and potential load for that channel.

- Step through the list of available channels, listening for beacons for at least dot11OBSSScanPassiveTotalPerChannel TUs per channel.

- Upon completion of the scan of a channel, process the beacons received on that channel, filtered to the set of unique BSSIDs:

  1. Using the capabilities signaled in the beacon, modify the QoS AP count, Admission Control Mandatory count, HC count, overlap count and potential

load of the channel array for the primary channel indicated in the received beacon.

2. If the overlapping AP is using a channel bandwidth that is greater than the channel spacing (e.g. when using the 2.4GHz band or when the overlapping AP allows 40 MHz High Throughput (HT) PLCP Protocol Data Units (PPDUs) 30 in its BSS) also update the channel array for channels that are affected by this overlapping BSS. For example a beacon received on channel 2 indicating a 20MHz BSS also affects channels 1, 3 and 4.

- Upon completion of scanning all of the channels, the AP will have information on the number of APs and the potential load of each channel, including co-channel BSSs.
- If the channel array indicates that there are channels with no other APs, it is recommended to randomly choose one of these “empty” channels.
- Otherwise, create a list of candidate channels by selecting only the channels with the lowest number of QoS APs. For example if the channel scan procedure indicated that there were two QoS APs on channel 3, three QoS APs on channel 6 and two QoS APs on channel 11, the list of candidate channels would contain 3 and 11.
- If this list contains more than one channel, filter the list to the set of channels with QoS APs that indicate support for QLoad reporting (as indicated by the QLoad Report field set to 1 in the Extended Capabilities element).
- If this list contains more than one channel, filter the list to the set of channels with the minimum HC count.
- If this list contains more than one channel and the AP will use Admission Control Mandatory for AC_VI or AC_VO, filter the list to the set of channels with Admission Control Mandatory count greater than zero.

- If this list contains more than one channel and the AP has an HC, 1 filter the list to the set of channels with Admission Control Mandatory count greater than zero.
- If this list contains more than one channel, filter the list to the set of channels with the minimum overlap count.
- If this list contains more than one channel, filter the list to the set of channels with the minimum potential load.
- From the remaining channels in this list, randomly choose one of these channels.

4.1.5 Sharing in an OBSS Situation

In [11], if the Access Factor is greater than one, then there is a potential over-allocation of the wireless medium. APs should avoid this in the Channel selection process but if over-allocation exists, then a sharing scheme is recommended to ensure that each AP has a fair share of the bandwidth. The EDCA Access Factor [Annex B], HCCA Access Factor [Annex B] and Potential Traffic Self fields in the QLoad Report are provided to enable sharing schemes to be used.

The sharing scheme also protects an AP from the neighborhood effect where it has neighbors that are hidden from each other. A major objective of an OBSS sharing scheme is that if a QoS stream is allocated or scheduled, then it will not be compromised by the addition of further streams from any overlapping BSS that would cause the medium to be over-allocated. To achieve this, the overlapping APs must cooperate.

In [11], two sharing schemes are suggested, namely Proportional Sharing and On Demand Sharing, respectively. In each sharing scheme, the purpose is to keep the total allocated traffic to a value such that over-allocation does not occur. The unit that is using in this system is “air-time”, it means second per second (e.g. 0.3s/s or 0.67s/s). The absolute maximum allocation is 1 second per second (100%). In the following descriptions of the two suggested sharing schemes, this value is referred to as "MAV" (Maximum Allocation Value). It is suggested that in order to provide some protection to non-QoS traffic, each AP should select a value for MAV up to a maximum of 0.9

seconds per second. There is no requirement that each overlapping AP must select the same MAV.

4.1.5.1 The Proportional Sharing [11]

The Proportional Sharing scheme is as follows:

a) The AP examines the Access Factor in the QLoad Reports from each overlapping BSS, including its own QLoad, and determines the maximum.

b) If the maximum value from the Access Factor fields is less than or equal to MAV, the AP may allocate up to its advertised Potential Traffic Self traffic.

c) If the maximum value from the Access Factor fields is greater than MAV, then the AP may only allocate up to a value of its Potential Traffic Self divided by the maximum Access Factor, multiplied by MAV.

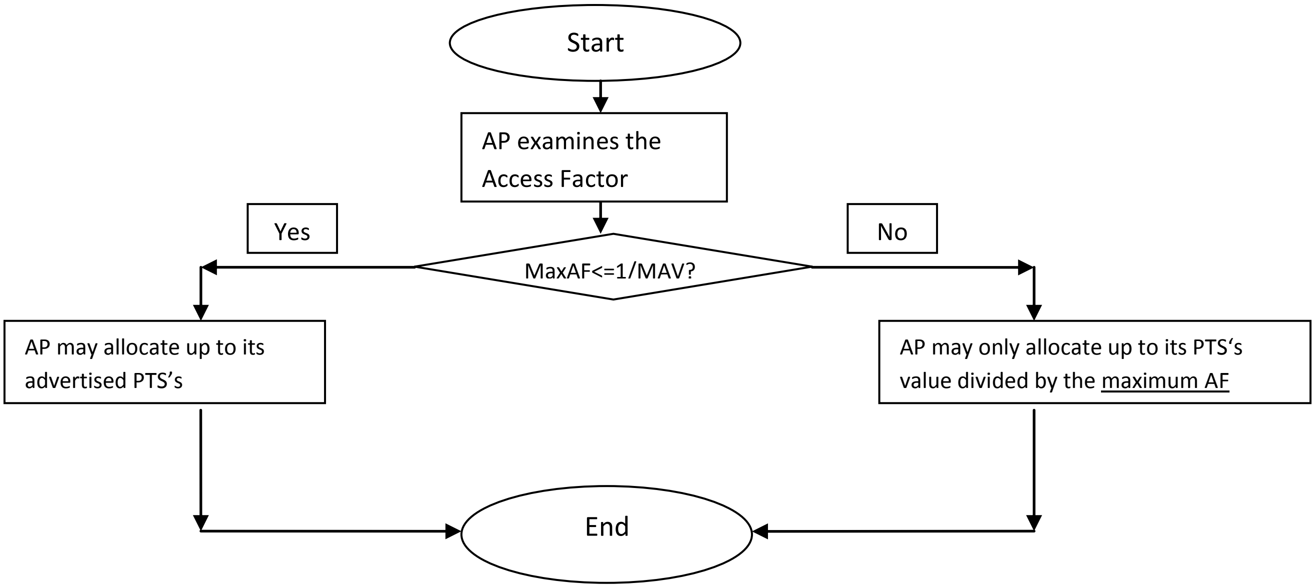

Figure 4.6 The Flowchart of Proportional Sharing scheme.

In the proportional sharing scheme, before an AP allocates a new Medium Time or schedules a new TXOP in response to an ADDTS Request, it shall check that this addition will not exceed its sharing limit, as follows:

- If the Access Factor is less than or greater than MAV, then the AP may allocate up to its advertised Potential Traffic Self (composite stream calculated as MAX traffic = $\mu tot + 2\ \sigma tot$)
- If the Access Factor is greater than MAV, the AP carries out the following:

  1. Calculate the peak traffic value of the Potential Traffic Self, using:

     Peak = *MEAN* + 2 STDEV

  2. Divide this value by the maximum Access Factor. This is termed the maximum allowable Potential Traffic Self traffic.

  3. Calculate the resulting value of the Allocated Traffic Self [Annex B] if the new TSPEC is accepted, as explained in aa.2.3, and then calculate the resulting peak value using: Peak = *MEAN* + 2 *STDEV*.

  4. If the resulting peak value, calculated in step 3 is greater than the maximum allowable Potential Traffic Self traffic, then the TS Request shall be rejected.

  5. If the resulting peak value, calculated in step 3 is less than the maximum allowable Potential Traffic Self traffic, and the TS Request is for EDCA Admission, then it shall be accepted.

  6. If the resulting peak value, calculated in step 3 is less than the maximum allowable Potential Traffic Self traffic and the new allocation is for an HCCA TS, the AP must further check the HCCA Access Factor:

     - If the HCCA Access Factor is less than or equal to MAV, then the AP may allocate up to its advertised HCCA Peak.
     - If the HCCA Access Factor is greater than MAV, an AP may only allocate the new stream if the resulting HCCA Peak is less than or equal to the value of the HCCA Peak divided by the HCCA Access Factor, multiplied by MAV.
     - The AP must then check that it is possible to schedule TXOPs using the HCCA TXOP Advertisement.

If the new stream is allocated, then the AP updates the appropriate fields in its QLoad element. Bellow is the flowchart of how an AP check that this addition (new Medium Time or schedules a new TXOP in response to an ADDTS Request) will not exceed its sharing limit before allocates.

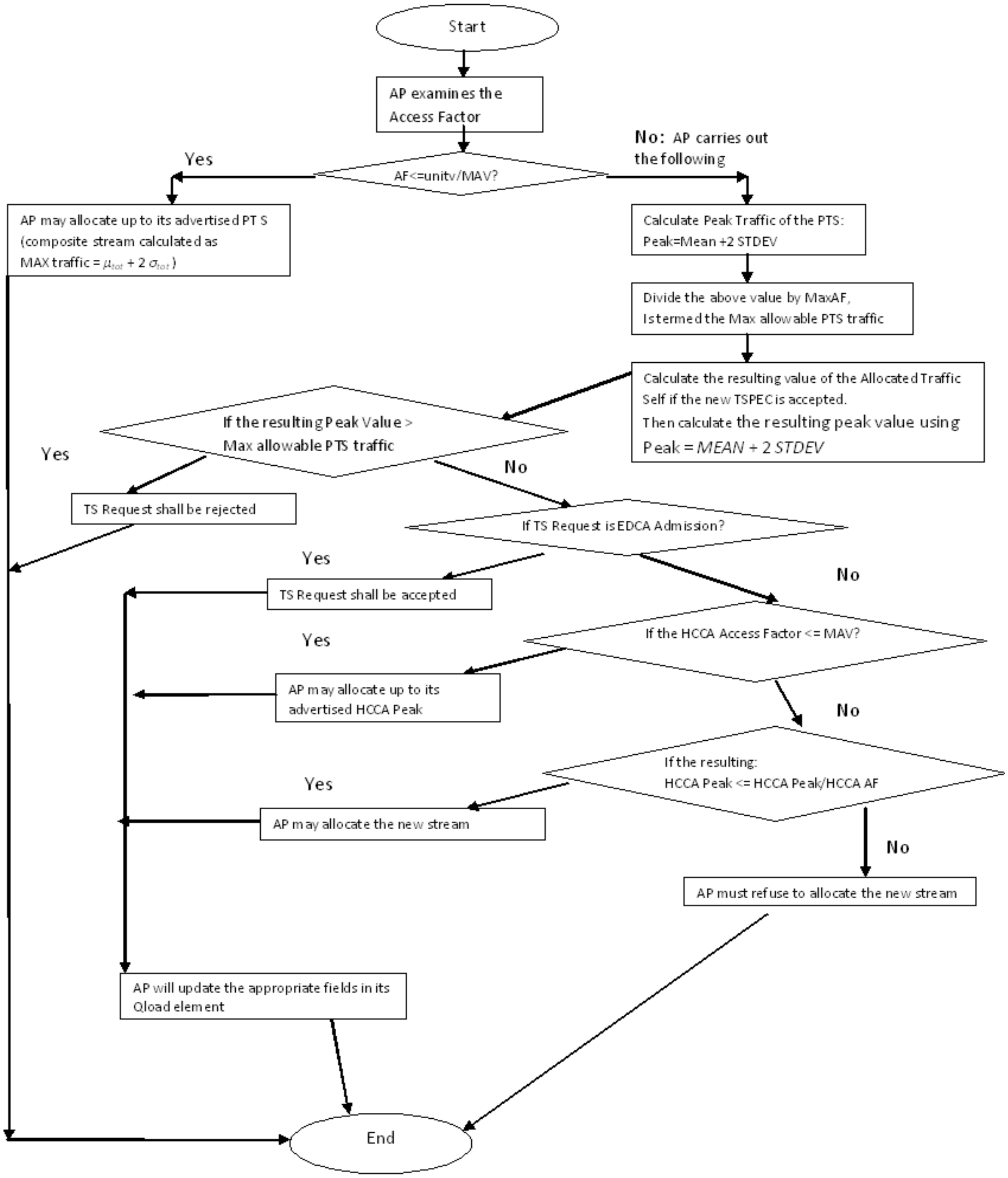

Figure 4.7 The Flowchart of how an AP check for the addition.

4.1.5.2 The On Demand Sharing [11]

The On-Demand sharing scheme, is as follows:

1. Before allocating a new stream, the AP examines the Allocated Traffic Shared [Annex B] values in the QLoad Reports from each overlapping BSS, including its own QLoad, and selects the maximum Allocated Traffic Shared value which has the highest peak value, using:

$$\mathrm{Peak} = \mathrm{MEAN} + 2\ \mathrm{STDEV}$$

The AP also notes the number of AC_VI and AC_VO streams in this maximum Allocated Traffic Shared Field.

2. The AP adds the requested new stream (*new*) to the selected maximum Allocated Traffic Shared 30 value (*max*) determined in step 1, using:

$$MEAN = MEANnew + MEANmax$$

$$STDEV = \mathrm{sqrt}(STDEV2new + STDEV232\ max)$$

3. The AP then calculates the peak value for the new composite stream calculated in step 2, using:

$$\mathrm{Peak} = MEAN + 2\ STDEV$$

4. Using the values of the AC_VI and AC_VO streams noted in step 1, plus the stream represented by the new stream, the AP determines the new EDCA Bandwidth Factor

5. Multiply the peak value calculated in step 3 by the EDCA Bandwidth Factor, determined in step 4. This is the new Peak Traffic requirement

6. If this Peak Traffic requirement value calculated in step 5 is greater than MAV, then the AP must refuse to allocate the new stream

7. If the peak value calculated in step 5 is less than or equal to MAV, and the new allocation is for an EDCA Admission ADDTS, then the AP may allocate that new traffic

8. If the peak value calculated in step 4 is less than or equal to MAV, and the new allocation is for an HCCA ADDTS, the AP must further check the HCCA Access Factor

- If the HCCA Access Factor is less than or equal to MAV, then the AP may allocate up to its advertised HCCA Peak
- If the HCCA Access Factor is greater than MAV, an AP may only allocate the new stream if the resulting HCCA Peak is less than or equal to the value of the HCCA Peak divided by the HCCA Access Factor, multiplied by MAV
- The AP must also check that it is possible to schedule TXOPs using the HCCA TXOP Advertisement.

If the new stream is allocated, then the AP shall update the appropriate fields in its QLoad element. Bellow is the flowchart of On-Demand sharing scheme.

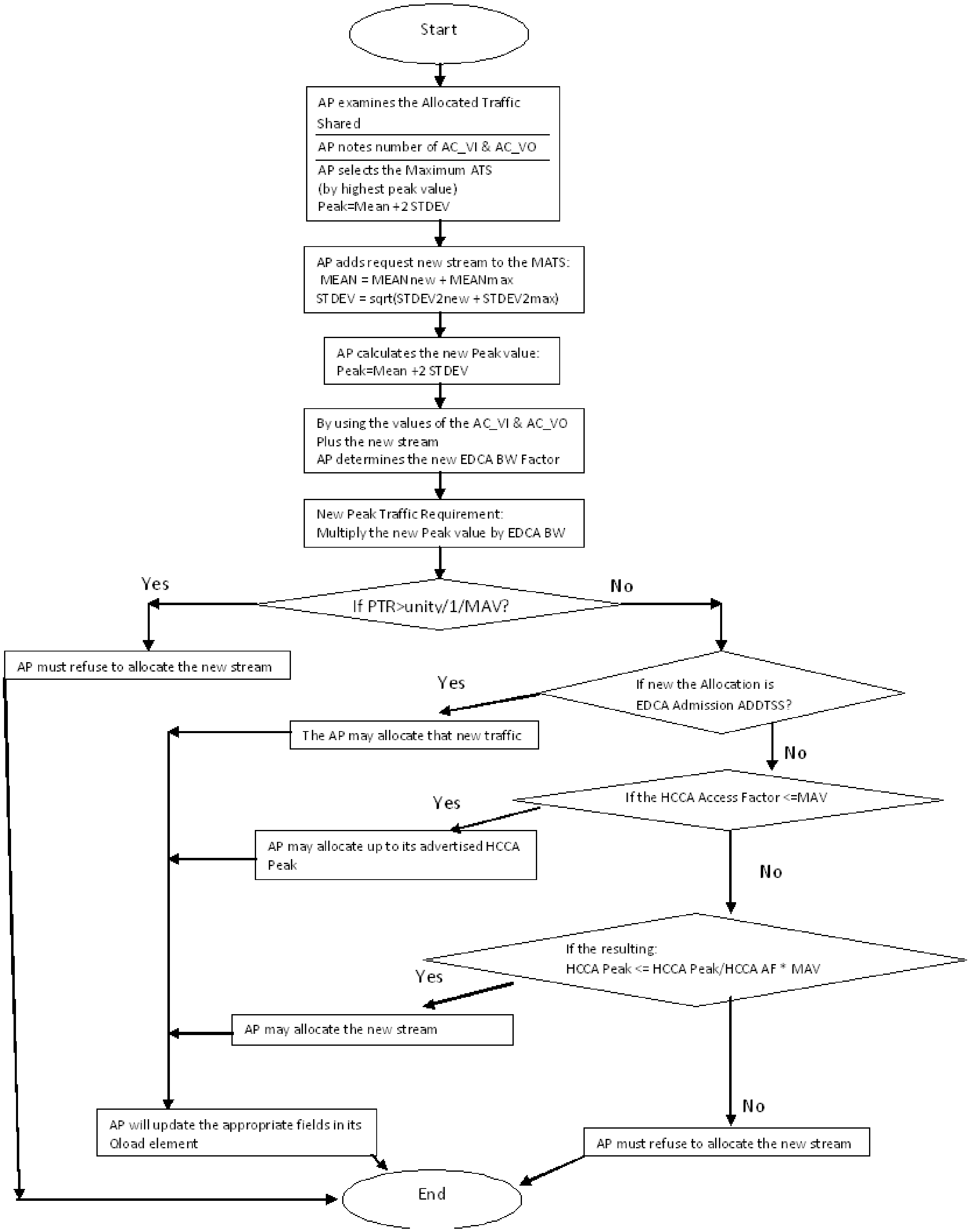

Figure 4.8 The Flowchart of On-Demand Sharing scheme.

4.2 Related Work

A number of mechanisms are proposed to solve or to mitigate the potential interference due to OBSS problem. Bellow we describe in detail the techniques that have been proposed in the past up to today.

4.2.1 Frequency Channel Assignment

In [22], the authors claim that the best way to reduce the probability of overlapping phenomenon is to have a good scanning algorithm for careful channel selection during the initial setup of BSS, to avoid channels that are already in use by other BSSs.

The APs that are located close each other it is recommended to use one of the left non-overlapping channels [see Chapter 3] to minimize the effects of interference. With channel selection algorithm, overlap with zero or just one other is a very common occurrence. In order to analyze what happens when each AP uses a Channel Selection scheme a program has been written, following are the objectives:

1. Determine how many channels are required to ‘guarantee’ zero or one overlaps
2. Investigate the overlap situation and “AP chains”
3. Use results to determine requirements for the OBSS solution

4.2.2 Channel Switching

One of the best ways to avoid the undesirable situation of OBSS is channel switching once OBSS is detected. During the channel switching mechanism, if an AP detects that there is a another BSS (based on the received BSSID0) operates on the same channel then the AP by using the channel switching mechanism switch to another channel thus, it will not being overlap with another BSS since they will operate in different channels.

4.2.3 Falling Back to Narrowband Mode

In [26], the authors propose the falling back to narrowband mode technique (e.g. from 40MHZ to 20MHz mode) and assumes that can be a practical solution. The authors suggest that APs sharing 40MHz would be better served if they dropped back to 20MHz channels. The authors assume that if sharing with an overlap of two BSSs and both

BSSs are suffering severely, then definitely in everyone's benefit to drop back to 20MHz channel.

If sharing with an overlap of one BSS, then could consider that sharing in a channel of 40 MHz is better than an independent 20MHz, however the author believes that in practice, devices will not share equally on 40MHz.

The three previously reported mechanisms have significant disadvantages. Experimental results show the density of OBSS becomes high [27] in apartment scenario, and, thus, both channel selection and channel switching scenarios the effect of frequency channel assignment may be limited due to shortage of available channels, in particular in 2.4 band. In addition, many applications which require broadband traffic with QoS exist in home networks (e.g. live streaming) thus, falling back to narrowband mode may cause shortage of bandwidth [28]. The limited availability of channels implies that they must be re-used, as in cellular communication networks.

4.2.4 Transmission Power Control (TPC)

Transmit Power Control (TPC) is a mechanism that is used within some networking devices in order to prevent too much unwanted interference between different wireless networks.

The network devices supporting this feature are IEEE 802.11.h WLAN devices that operate in the 5 GHz bands compliant with IEEE 802.11a. TPC applies mainly to uplink [Annex A]. The idea of this mechanism is to automatically reduce the used transmission output power when other networks are within the range. Reduced power means mitigated interference problems and increased battery capacity.

TPC works in example of apartments [29], where distance between two OBSSs is limited. However, it is difficult when applied to other scenarios, e.g. houses, where the ranges are more varied there effect of TPC also may be limited.

4.2.5 Beamforming

In [20], beamforming might be also useful because IEEE 802.11ac devices already have beamforming capability to enable multi-user multiple-input and multiple-output MU-MIMO.

Beamforming is a general signal processing technique used to control the directionality of the reception or transmission of a signal on a transducer array. This is achieved by combining elements in the array in such a way that signals at particular angle experience constructive interference and while others experience destructive interference. Beamforming can be used at both transmitter and receiver side to achieve spatial selectivity.

Using beamforming you can direct the majority of signal energy you transmit from a group of transducers (e.g. audio speakers or radio antennas) in a chosen angular direction or you can calibrate your group of transducers when receiving signals such that you predominantly receive from a chosen angular direction.

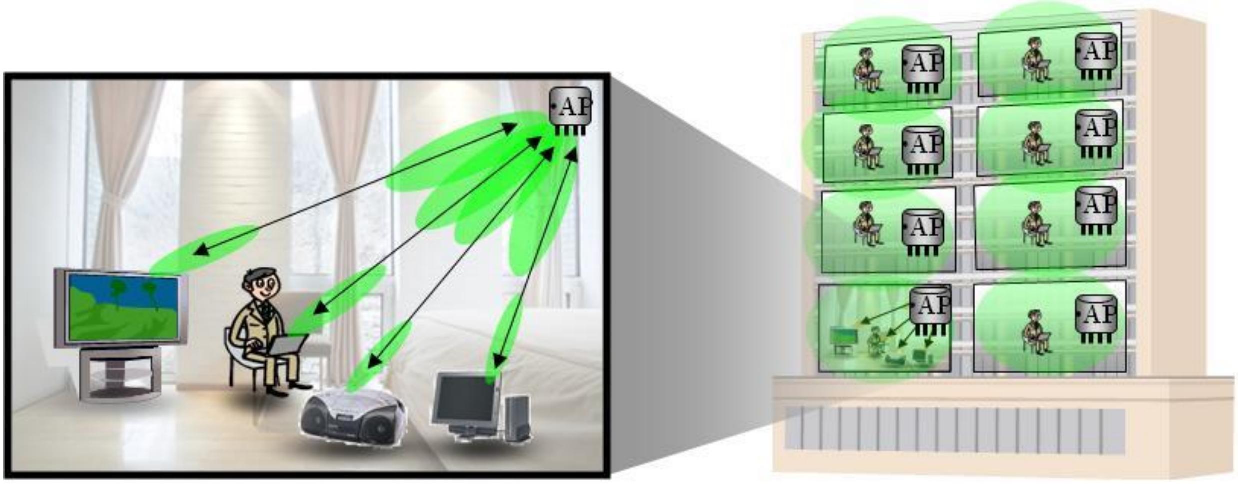

Figure 4.9 Scenario where beamforming is used [20].

The basic concept [20] of interference management using beamforming in OBSS environment is some degrees of freedom on antennas at AP can be used to mitigate interference to the STAs associated on other BSSs to form null to them. When two APs cooperatively work with each other, spatial multiplexing between of two APs is possible.

Hence, the interference management using beamforming enhances throughput performance, see in Figure 4.10.

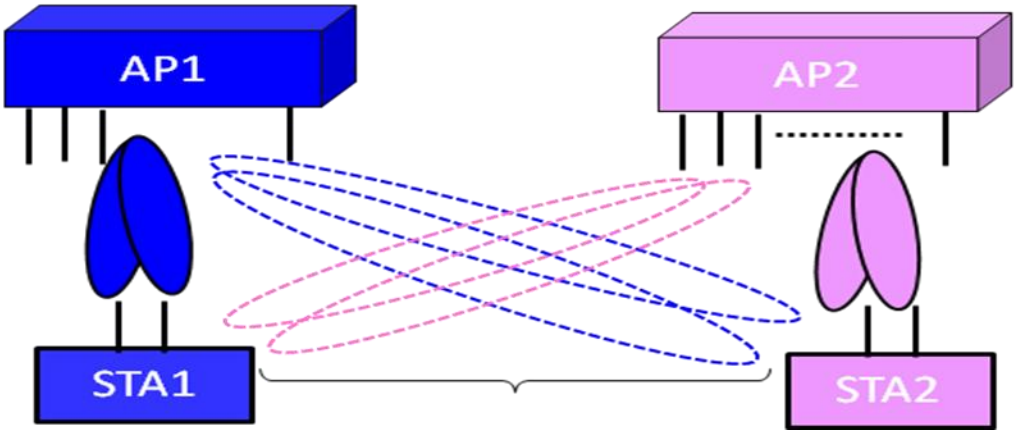

Figure 4.10 Null steering to the STA on the other BSS [20].

Figure 4.11 provides an example of beamforming for interference management in OBSS. It is a case of two APs where both of them obtain complete MIMO channel (see the first slide of figure 4.11). AP1 and AP2 calculate downlink MU-MIMO steering matrices and prepare transmit signals. Null steering to direction of STA2/1 is set by transmission of no signal to the direction (see the second slide of figure 4.11). AP1 and AP2 transmit data frames simultaneously (see the third slide of figure 4.11).

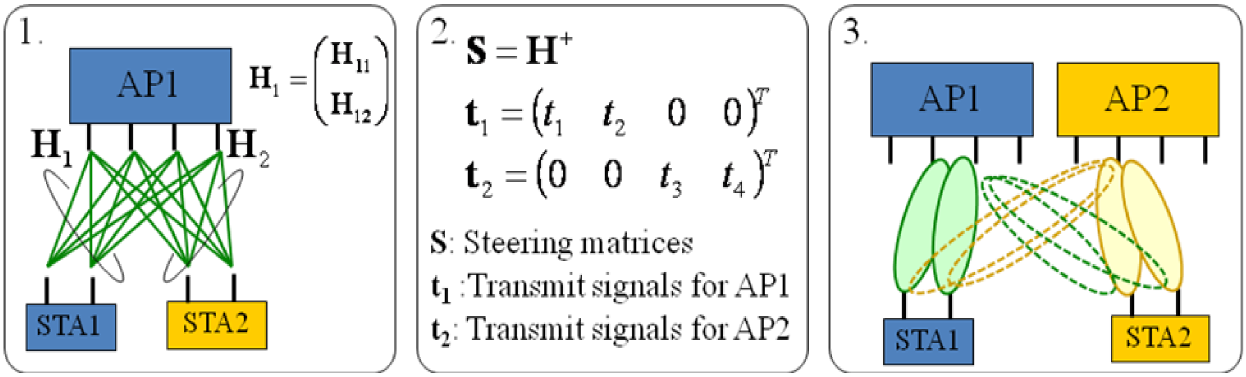

Figure 4.11 Example of use of beamforming [20].

In dense OBSS environment, beamforming technique is attractive. Interference management using beamforming enhances throughput performance due to spatial multiplexing between two APs. When the number of terminals per BSS is 4, there is no degree of freedom for antenna. Actually, there is a problem when there are more STAs in Overlapping area than AP's MIMO antennas can support.

4.3 Other Approaches

4.3.1 On the 20/40 MHz Coexistence of Overlapping BSSs in WLANs

In [30], the authors investigate the impact of 20/40 MHz coexistence on the performance of WLANs. They assume a overlapping scenario where a 802.11n BSS operating in 20/40 MHz mode and a legacy BSS operating in 20 MHz mode, where the overlapping channel is the extension channel of the 20/40 MHz BSS. The scenario where the overlapping channel is the 20 MHz control channel is of little interest, because this scenario is similar to legacy BSSs overlapping. Therefore, in this paper, the authors investigate the scenario where the overlapping channel is the 20 MHz extension channel, and they provide an answer to the fundamental question of whether CCA should be used in the extension channel.

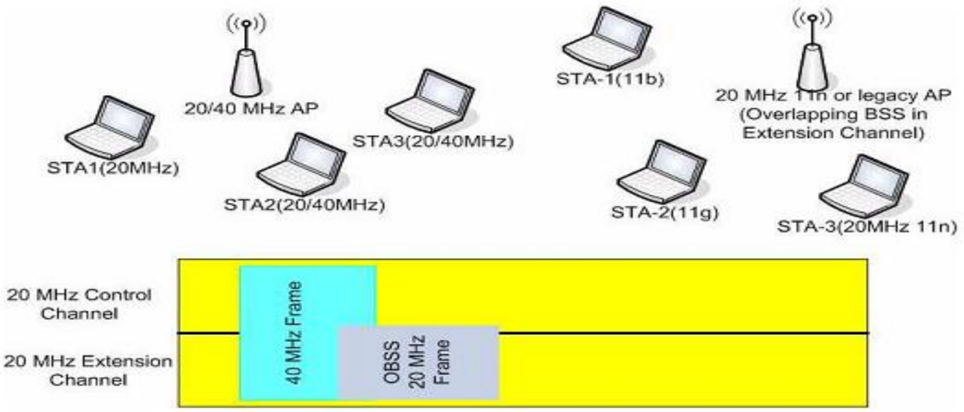

Figure 4.12 The two Overlapping BSSs [30].

Without implement CCA in the extension channel 20/40 MHz capable STAs will start transmitting in 40 MHz mode, causing a collision in the extension channel if the medium is already in use by the STA/AP in the 20 MHz BSS. This collision in the extension channel will result in bad packets reception in both BSSs. As a result, the overall throughput in the network will decrease. Hence, the use of CCA in the extension channel is the first step to avoid collisions in overlapping BSSs.

However, even if CCA is used in the 20 MHz extension channel before a STA/AP transmits a 40 MHz frame, it may not always avoid collisions in the network. The reason is that the transmission in the 20 MHz extension channel is in the SIFS interval when CCA in the extension channel senses the channel idle. To avoid the collision the channel has been idle for at least a PIFS time interval. The reason for using PIFS time interval is that PIFS is greater than SIFS and the STA/AP would have sensed the transmission in the extension channel by this time.

It is important to mention here that collisions could still occur in the aforementioned overlapping BSSs. For example, the presence of hidden nodes could still create collisions in the network.

The results show that if CCA is not used in the extension channel, the throughput of the network and that of individual BSSs will reduce drastically. The reason for this is that the absence of the CCA in the extension channel implies more collisions during 40 MHz transmissions.

The disadvantages of this mechanism are that the collisions could still occur in the aforementioned overlapping BSSs. For example, the presence of hidden nodes could still create collisions in the network. Let us consider the following scenario. A packet is transmitted by a STA in the legacy BSS and it can not be detected (i.e., the received signal strength is below the CCA detection threshold) by a 20/40 MHz STA in the 20/40 MHz BSS that has just gained access to the medium and starts 40 MHz transmission. Collision will occur if the receiving STA of the 40 MHz transmission in the 20/40 MHz BSS or the receiving STA of the 20 MHz legacy transmission in the legacy BSS can hear both transmissions. In addition to the authors, they do not take into account channel width of 80 and 160 MHz.

4.3.2 Channel Access Throttling for Overlapping BSS Management

In [31], the focus is on the strong OBSS scenario, where all APs and member STAs can hear from each other. APs can overhear other AP’s messages (e.g. Beacon) and process them for schedule coordination and synchronization. By controlling how much time each OBSS may be given the prioritized channel access, they can achieve a proportional partitioning of channel capacity among OBSSs.

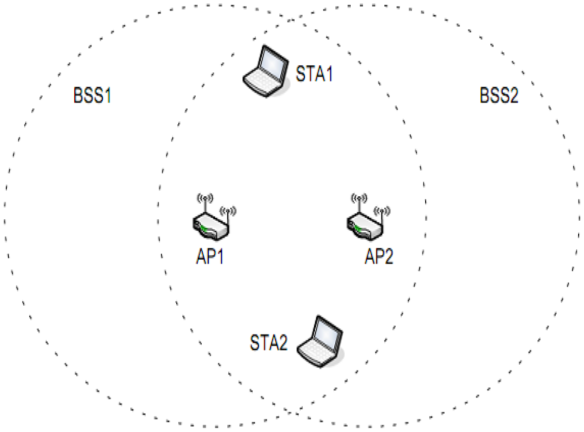

Figure 4.13 Strong OBSS Scenario where the two APs in range of each other [31].

The Channel Access Throttling (CAT) method, the key idea is that compared to EDCA, which differentiates channel access priorities among different access categories (ACs), CAT differentiates access priorities among member STAs. In its simplest form, CAT can employ only two priority groups: a high access priority (or CAT-high) group and a low access priority (or CAT-low) group. CAT achieves the priority differentiation between the two groups using different EDCA channel access parameters, just as EDCA differentiates the four ACs. Again, in its simplest form, CAT may assign only one member STA into the CAT-high group and all the rest to the CAT-low group. In this case, the only CAT-high STA gets "exclusive" channel access, because all the other STAs have low priority and will not win channel access. CAT may rotate which member STA becoming a CAT-high STA according to a schedule to partition channel capacity among the member STAs. To keep the discussion simple yet illustrative, in the rest of this section, we focus on the simplest CAT configuration with only two priority groups, while we can easily generalize CAT to multiple groups.

The two approaches to throttling member STA's channel access are the Periodic and the On-demand.

In the Periodic approach, the AP sets up a schedule relative to a periodic reference time that is available to all member STAs. The Target Beacon Transmission Time (TBTT) can be used as a reference time in practice. A CAT schedule configuration contains two sets of EDCA channel access parameters, one for CAT-high and the other for CAT-low. After receiving the configuration, each member STA needs to periodically adjust its EDCA channel access parameters to the specified values at specified times according to its membership in either CAT-high or CAT-low group.

The On-demand approach specifies that the AP may announce the CAT-low parameters as the default configuration in its Beacon messages just as how a regular EDCA AP announces EDCA parameters to its associated member STAs. Then, at specific times, the AP sends CAT-high channel access parameter configuration to a specific member STA in a similar fashion to polling messages used in scheduled channel access mechanisms.

The disadvantage of this proposal is that it specifies only the case where the all APs and STAs are in overlapping area; it means that they can hear each others frames.

4.3.3 A two-level Carrier Sensing Mechanism for Overlapping BSS Problem in WLAN

In [15], the authors propose a two-level carrier sensing solutions for 20 MHz overlapping BSS. They introduce three scenarios of overlapping BSSs problems namely, scenario A, B and C.

Scenario A, the BSSs are not overlapped. But the transmission range of some STAs in one BSS overlap with transmission range of STAs in the other BSS therefore, this scenario is defined as STA-STA overlap (Figure 4.14).

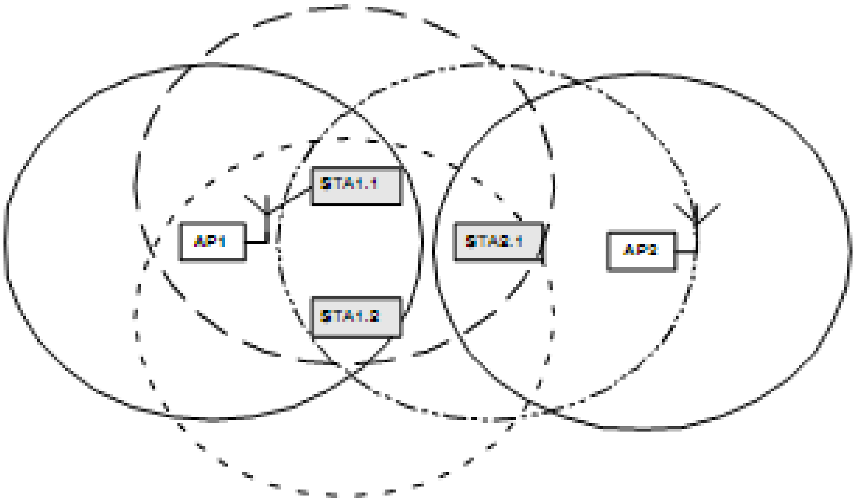

Figure 4.14 STA – STA Overlap [15].

Scenario B, denotes the network configuration that STAs in one BSS are able to hear transmission of AP in other BSS. The coverage areas of the BSSs are indeed overlapped. This scenario is defined as AP-STA-AP overlap (Figure 4.15).

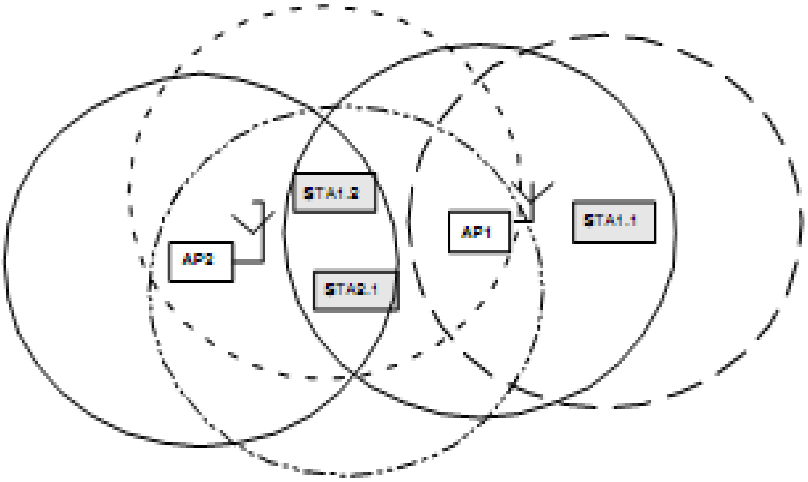

Figure 4.15 AP – STA - AP Overlap [15].

Scenario C shows a situation in which the APs from different BSSs can hear each other and will have the information about other BSS. This scenario is defined as AP-AP overlap (Figure 4.16).

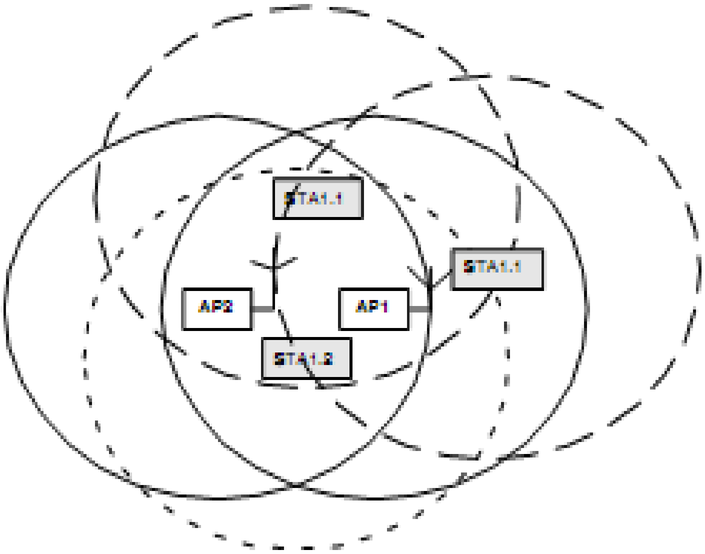

Figure 4.16 AP - AP Overlap [15].

In this approach, two additional network allocation vector (NAV) fields are proposed, one for the self-BSS and the other for overlapping BSS.

- Self BSS Network Allocation Vector (SBNAV)

The proposed SBNAV works in the same way as the legacy NAV. Every time a STA hears a Request to Send / Clear to Send (RTS/CTS) packet, it updates the SBNAV whenever necessary. (As in legacy NAV, SBNAV is only updated when the duration field of the received frame is longer than current SBNAV). Notice that since RTS/CTS frame doesn't contain information about BSS ID, the duration in those frames are always used to set SBNAV, regardless of its originator.

- Overlapping BSS Network Allocation Vector (OBNAV)

Two subtypes of OBNAV are defined, namely, the OBNAV-CP and OBNAV-CFP for the CP and the CFP respectively. While the OBNAV is defined to be one of them whichever has a longer deferral time.

When there is an overlapping BSS operating in CFP, a STA that hears beacon frame from an overlapping BSS sets its OBNAV-CFP to CFPDurRemaining parameter contained in the beacon frame. If a STA is not able to receive the beacon frame, however it can receive DATA frame from the overlapping BSS, it will set OBNAV-CP according to the duration field. OBNAV-CFP may expire or be reset to 0 when the STA hears CF-End from the corresponding BSS. Besides OBNAV-CFP, a STA should also have a counter (named OB counter in this paper) to store the number of overlapping BSSs it has observed, and the OBNAV-CFP can only be reset when it has received the number of CF-Ends that equals the number of overlapping BSSs detected. Figure 4.17 shows an example of OBNAV setting in a multiple overlapping BSSs scenario. Notice that upon the reception of every new beacon the STA will update the OBNAV-CFP.

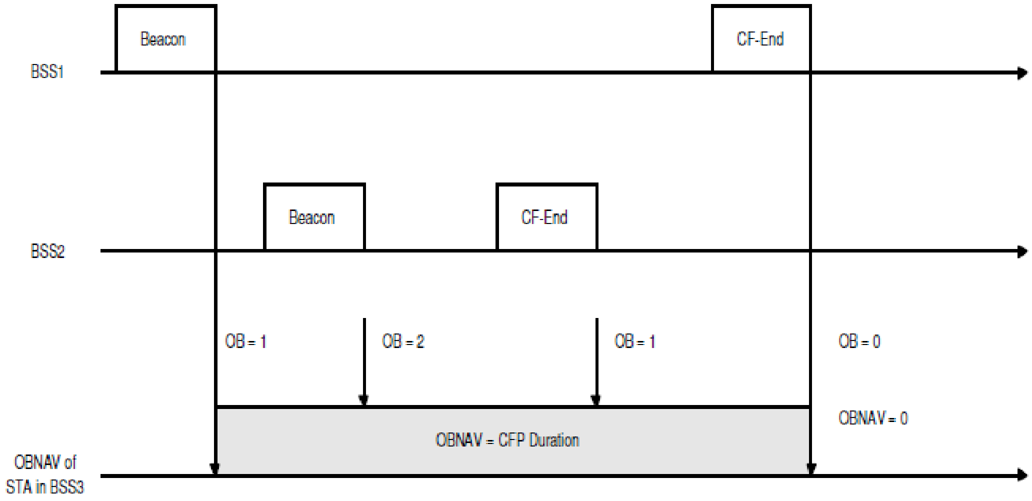

Figure 4.17 Overlapping BSS proposal [15].

When the overlapping BSS is operating in CP, the RTS/CTS from overlapping BSSs are treated as SBNAV, 4 Since DATA frame contains BSS ID information, so STA sets and updates OBNAV-CP according to the duration field of DATA frame generated from overlapping BSSs.

In the proposed overlapping BSSs solution, STAs still follow the rule of NAV STAs won’t access channel unless the NAV is zero in CP, where NAV takes the larger value of OBNAV and SBNAV. The redefinition of NAV maintains good backward compatibility. On the other hand, when polled in CFP, a STA first performs physical carrier sensing and accesses channel only when both of SBNAV and OBNAV indicate a clear channel.

The proposed mechanism can maintain efficient channel usage through implicit scheduling most collisions due to overlapping BSSs are avoided by setting appropriate deferral. But the new network allocation vector is introduced to solve the overlapping BSS problem with minimal hardware requirement it means that it will require changes to IEEE 802.11 standard. In addition to proposal of a two-level carrier sensing solutions are for 20 MHz scenarios overlapping BSS. Moreover, the proposed mechanism introduces very little complexity when there is no overlapping BSS problem exists.

Chapter 5

Performance Analysis and Evaluation

5.1 Introduction

Although current IEEE 802.11 standards family attempts to address the overlapping BSS problem, we have indentified in this thesis that the proposed methods do not work well; therefore, the collisions cannot be avoided during the OBSS. In this chapter, we will first present the simulation results regarding to the legacy scenarios and secondly we will describe in detail our proposed algorithm with simulation results. Finally, we will evaluate our proposed approach in comparison to the legacy one.

5.2 Overlapping and Non - Overlapping Scenarios

The scenarios that we will focus on are the Overlapping and Non – Overlapping respectively. In this subchapter detailed description for each scenario is given about the location of the nodes as well as about the differences between these two scenarios.

During the Overlapping Scenario, there are two BSSs, BSS1 and BSS2, respectively. In each BSS initially there is an AP and four STAs. In every simulation round the number of STAs is getting increased by four STAs up to certain point. The APs and the STAs of both BSSs are operating on the same channel (i.e. channel 1) with Power Transmission (PT) of 0.000202 W. Hence, the nodes are able to cover the range up to 250 meters.

The STAs and the APs of both BSSs are located in the following way:

- The two APs of both BSSs are located in a distance of 100m from each other thus they are in overlapping area and they are able to listen each other physically.
- The two of four STAs from both BSS in the initially simulation round are located in a distance of 180m away from their AP the so-called “edge” STAs. Hence the edge STAs are in a distance of 280m from the AP of the other BSS thus, they are not able to listen each other due the value of PT which covers up to 250m.

- The other two STAs are located close to their AP with direction to the AP of the other BSS they are so-called “overlapping” STAs thus, these STAs of both BSS and APs can listen each other physically thus, they are able to obtain the frames from each other (e.g. Beacon frame).

During the simulation progress, in each simulation round we increase the number of STAs per AP by adding four STAs, two STA to the “edge” group of STAs and the other two to the “overlapping” group. Hence, at the end of simulation process we will have 44 STAs per AP for the overlapping scenario and 60 STAs per AP for the non – overlapping scenario.

During the non - overlapping scenario all previous configurations regarding to the locations of the nodes are the same. However, there are the following two differences:

- The two BSSs are operating in different channels (the BSS1 is operating in channel 1 and the BSS2 is operating in channel 11). Hence, they are not overlapping.
- The increase of the STAs during the simulation progress is ending up to 60 STAs per BSS and the start up is with 8 STAs per BSS. It is because in non – overlapping scenario the interference issue does not occur due the OBSS and, thus, we need to increase the number of STAs more than in overlapping to achieve the same performance.

The goal with “edge’ STAs is to have the strongest overlapping scenario that is possible achieving the more interference during the simulation process due the hidden nodes which are the “edge” STAs. Hence, during the last simulation round in the overlapping scenario we have 44 STAs in the overlapping area (22 from each BSS) and 44 hidden STAs (22 from each BSS in the “edge” group) thus, in total there are 88 STAs that compete to get access to the medium. Regarding to the non - overlapping scenario, since we do not have OBSSs we increased the number of STAs per BSS up to 60 thus, there are 60 STAs which are in contention based mode to get access to the medium in each BSS.

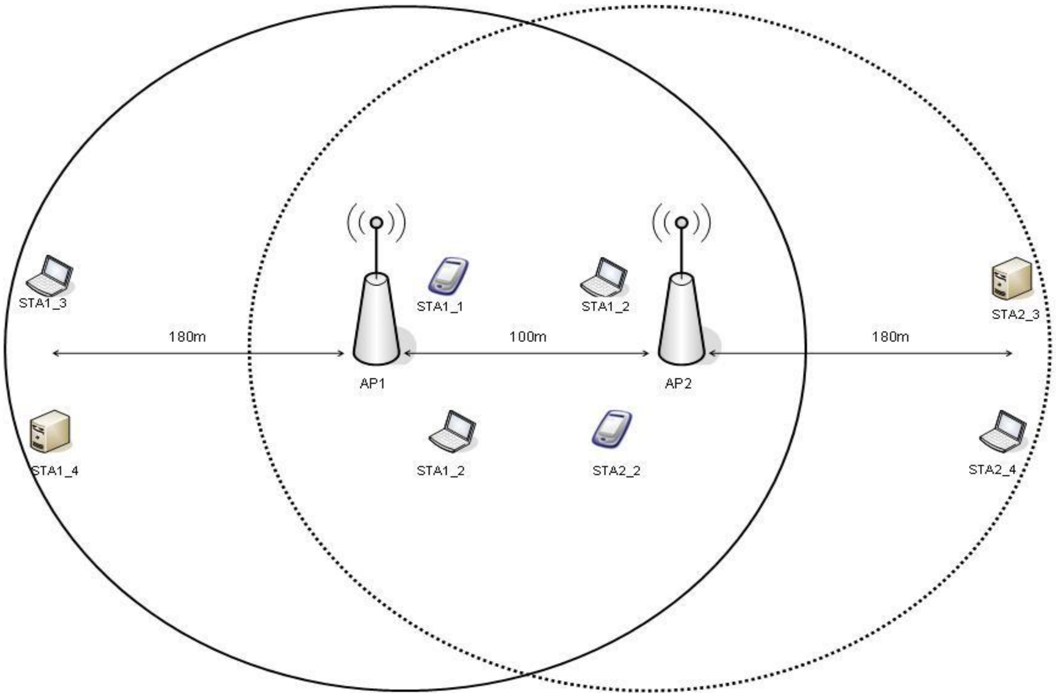

Figure 5.1 The Overlapping and Non - Overlapping Scenarios.

5.3 The Goal

The goal of these simulations is to observe the aggregation throughput and the delay difference between these two legacy scenarios. Hence, we can compare and contrast the legacy with our enhanced proposal scenario.

5.4 Introduction to the Simulation Tool

OPNET Technologies, Inc. is a leading provider of solutions for application and network performance management and network Research and Development (R&D). OPNET's solutions deliver deep data collection and analytics to enable powerful root cause diagnosis. OPNET's solutions have been operationally proven in thousands of customer environments worldwide, including corporate and government enterprises, defense agencies, network service providers, and network equipment manufacturers [32].

5.4.1 OPNET Modeler

OPNET Modeler is a research oriented network simulation tool. It is very powerful software that simulates the real world behavior of wired and wireless networks. Modeler

OPNET Modeler is using to design and study communication networks, devices, protocols and applications and analysis of wireless networks, including the RF environment, interference, transmitter/receiver characteristics, protocol stack, including MAC, routing. It provides a graphical editor interface to build models for various network entities from physical layer modulator to application processes. Users can analyze simulated networks to compare the impact of different technology designs on end-to-end behavior.

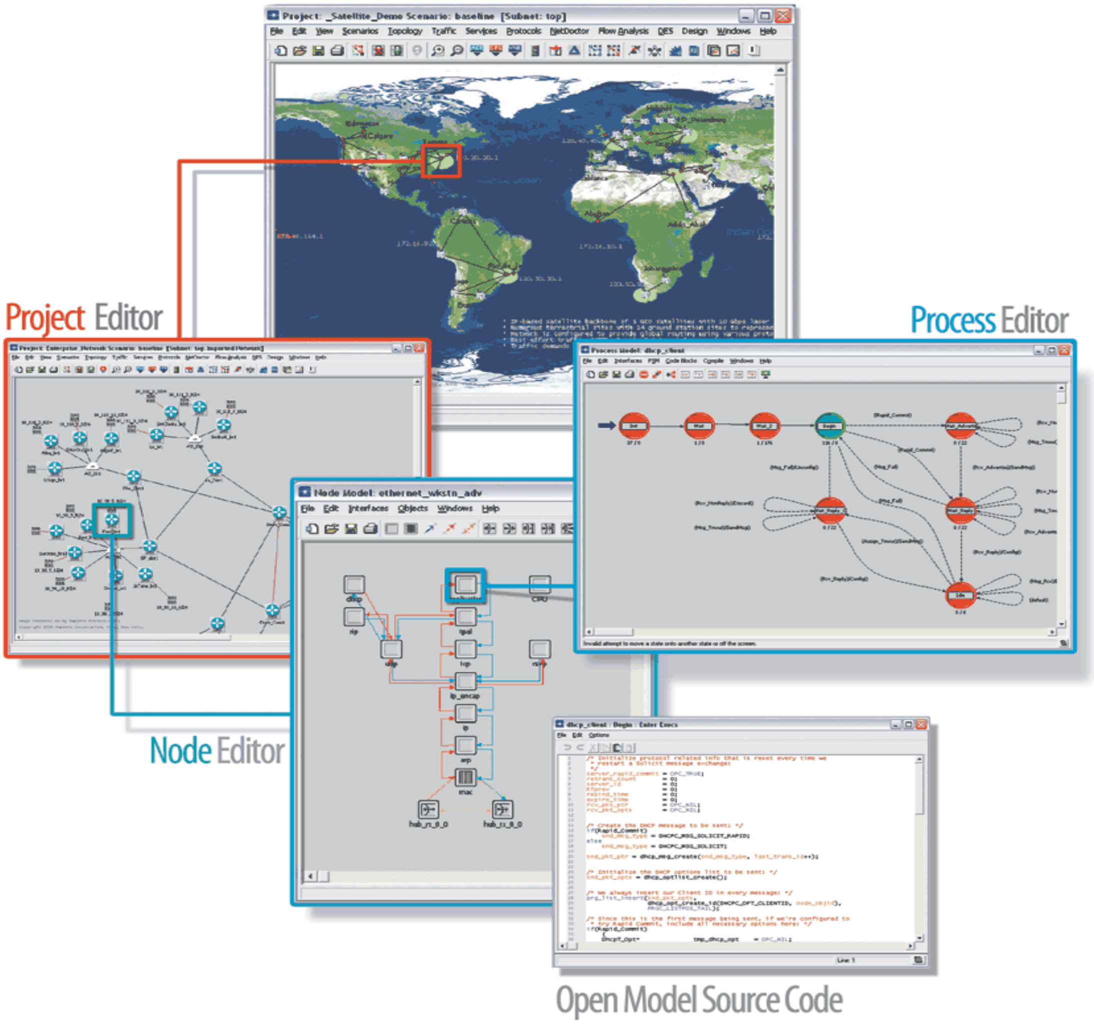

Figure 5.2 OPNET Modeler [32].

5.4.2 Simulation Setup

In this thesis, OPNET Modeler version 12.0 was used for simulating UNIZONE Voice Over IP (VoIP) Application Encoder Scheme (UNIZONE_G.711) over Wi-Fi link for the two scenarios (i.e. Overlapping and Non – Overlapping). The system is based on IEEE 802.11g with data rate of 54 Mbps. The nodes of each BSS operate in the 2.4 GHz band and use the OFDM transmission scheme. In the following tables we describe in detail the simulation parameters of STAs and AP, of the Profile Configuration, of Application Supported Profiles

	CWmin	CWmax	AIFS	TXOPLimit	RetryLimit
AC_VO	31	63	2	1,504	AP 120 STA 7

Table 5.1 EDCA Parameters for IEEE 802.11.

Data rate (bps)	54Mbps
Physical Characteristics	Extended Rate PHY (802.11g)
Power Transmission	0.000202 W
Packet Reception-Power Threshold	-95
Short Retry Limit	7
Long Retry Limit	4
Channel Settings	Overlapping (BSS1&2 – Channel 1) Non Overlapping (BSS1&2 – Channel 1&11 respectively)
Buffer Size (bits)	1200000
Max Receive Lifetime (secs)	0.5

Table 5.2 WLAN MAC Parameters.

Profile Name	Unizone_VoIP
Traffic Type	All Discrete
Application Delay Tracking	
Start Time (seconds)	Start of Simulation
End Time (seconds)	End of Simulation
Sample Every N Applications	All
Maximum Samples	Tracking Disabled

Table 5.3 Applications Supported Profiles.

Profile Name	UNIZONE VoIP Application
Application	
Name	UNIZONE VoIP Application
Start Time Offset (seconds)	uniform (2, 4)
Duration (seconds)	End of Profile
Repeatability	
Inter-repetition Time (seconds)	constant (300)
Number of Repetitions	constant (0)
Repetition Pattern	Serial
Operation Mode	Serial (Ordered)
Start Time (seconds)	uniform (20, 30)
Duration (seconds)	End of Simulation
Repeatability	
Inter-repetition Time (seconds)	constant (300)
Number of Repetitions	constant (0)
Repetition Pattern	Serial

Table 5.4 Profile Configuration Attributes.

Application Name	UNIZONE VoIP Application
Voice	
Voice Table	
Silence Length (seconds)	default
Talk Spurt Length (seconds)	default
Symbolic Destination Name	Voice Destination
Encoder Scheme Table	
Incoming encoder scheme	UNIZONE_G.711
Outgoing encoder scheme	UNIZONE_G.711
Voice Frame per Packet	1
Type of Service	Interactive Voice (6)
RSVP Parameters	None
Traffic Mix (%)	All Discrete
Signaling	None
Compression Delay (seconds)	0.02
Decompression Delay (seconds)	0.02

Table 5.5 Application Configuration Attributes.

5.5 Simulation Results for the Legacy Scenarios

The following are the Simulation Results for both Legacy Scenarios (Overlapping and Non – Overlapping). In these scenarios we examine the two cases during the Uplink (UL) and During the Downlink (DL) regarding to throughput and Delay.

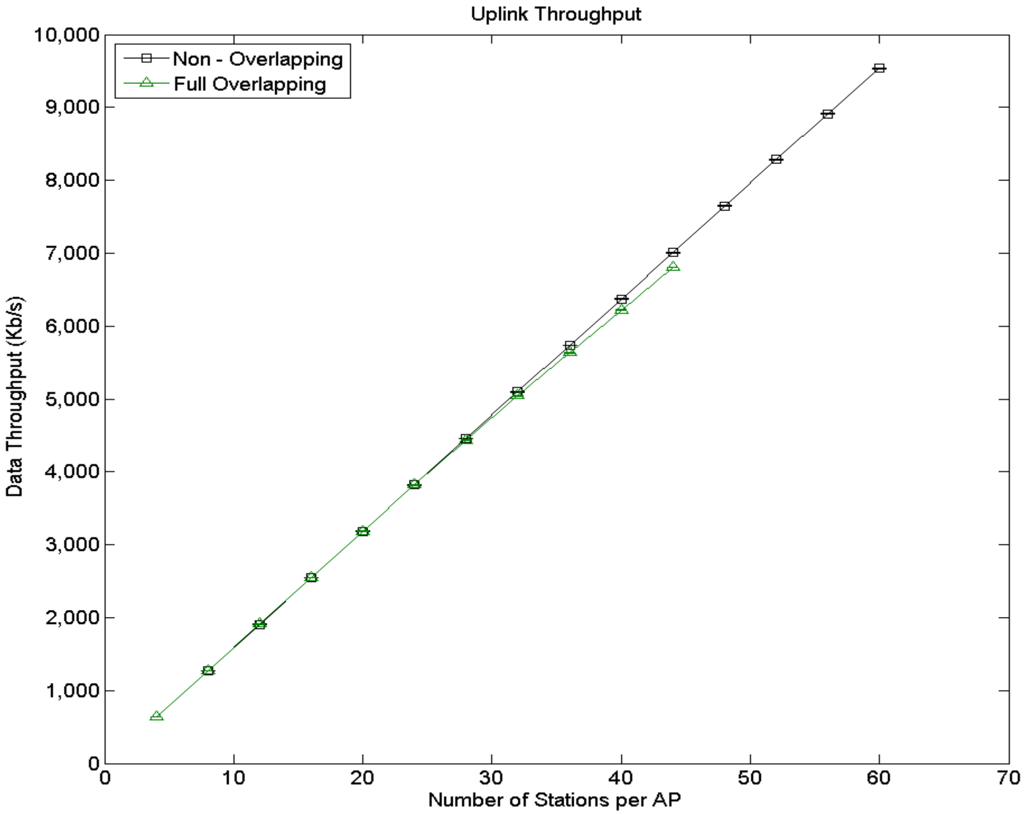

Figure 5.3 UL throughput of Overlapping & Non – Overlapping of Legacy Scenarios.

Figure 5.3 provides the simulation results of UL throughput during the Overlapping and Non – Overlapping legacy scenarios. The UL throughput performances of two graphs are very close and almost there is no decrease. Hence, it seems that during Uplink in Overlapping Scenario with 88 STAs that compete to get access to the medium there is no impact of the collisions that exist due the OBSS problem.

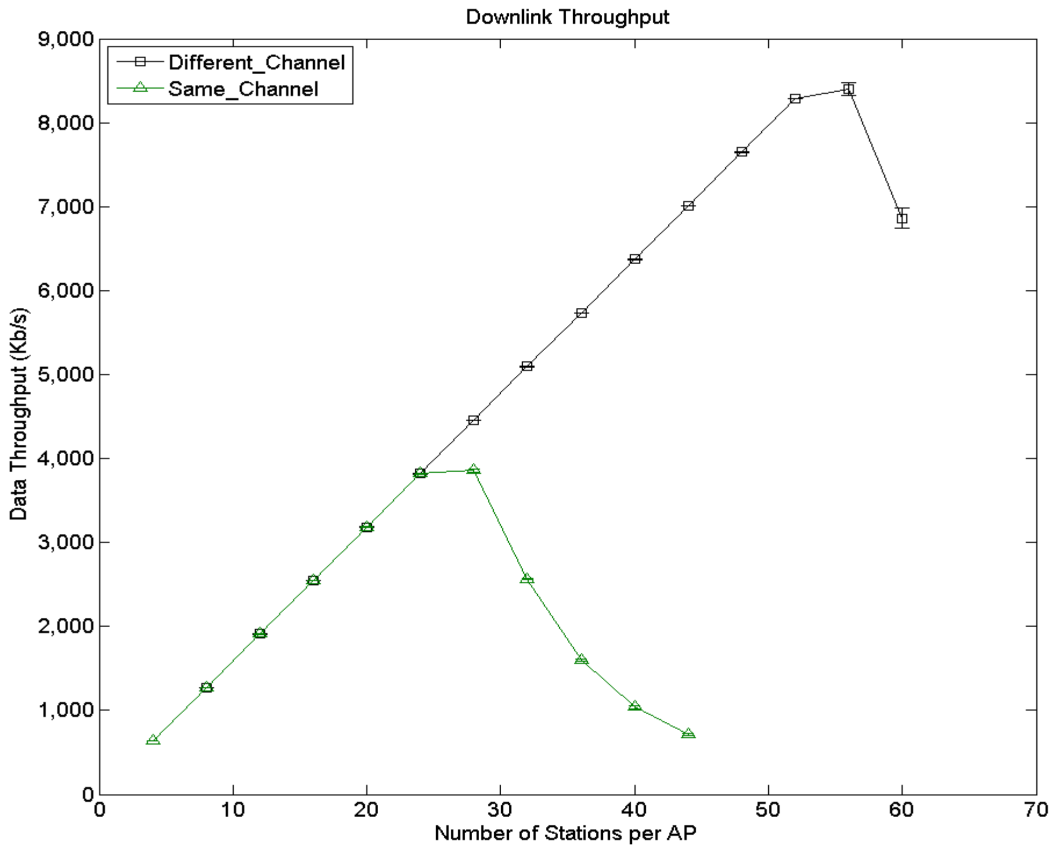

Figure 5.4 DL throughput of Overlapping & Non – Overlapping of Legacy Scenarios.

Figure 5.4 illustrates the simulation results of DL throughput during the Overlapping and Non – Overlapping legacy scenarios. In Non – Overlapping Scenario we observe that at 56 STAs per BSS the decrease starts, on the other hand of Overlapping Scenario the decrease starts at 28 STAs per BSS, it means that 56 STAs in total operate in the same channel and compete for the access of the wireless medium. Hence, in both scenarios the decrease starts at the same number of STAs (i.e. 56).

We observe that there is an impact of Overlapping BSS, cause of, at the point of 48 STAs per BSS in Non – Overlapping scenario and 24 STAs per BSS in Overlapping scenario it means 48 STAs in total that operate in the same channel in the last scenario the value of throughput is around 7.600Kb/s in both cases (i.e. Non – Overlapping: 7.640kb/s, Overlapping 3.820 per BSS thus 3.820 * 2 = 7.640Kb/s since we are calculating the aggregate throughput for the nodes that are operating in the same channel). During the next simulation test when there are 56 STAs per BSS in Non –

Overlapping scenario and 28 STAs per BSS in Overlapping thus in total 56 STAs as well that are competing the aggregate throughput is 8.400Kb/s for the Non – Overlapping scenario and 7.700Kb/s for the Overlapping scenario since it is 3.860Kb/s per BSS thus we need to multiply by 2 to get the aggregate throughput of both BSSs. We observe that there is a deference of 0.700Kb/s between these two scenarios due to the interference by the hidden nodes (i.e. “edge” group of STAs in each BSS) and due to collision that occurred by the OBSS problem.

In this case we do not observe the above impact in the previous simulation tests simply because up to 48 STAs that are operating in the same channel (i.e. 48 STAs in Non – Overlapping scenario and 24 STAs per BSS in Overlapping scenario, in total 48 STAs) the network capacity for the needs of this number of STAs was enough. In all the following simulation rounds the capacity was not enough and this is the decrease of the graphs in both scenarios.

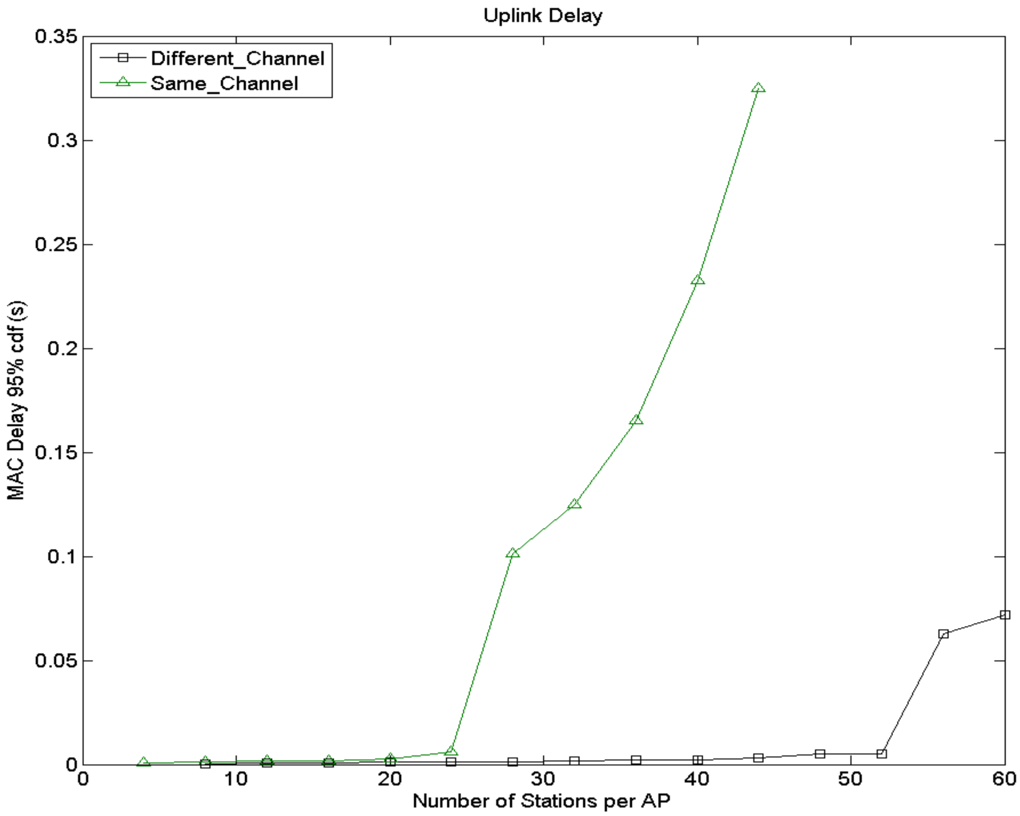

Figure 5.5 UL delay of Overlapping & Non – Overlapping of Legacy Scenarios.

Figure 5.5 shows the simulation results of Uplink (UL) delay during the Overlapping and Non – Overlapping legacy scenarios. Up to 24 STAs per BSS in the Overlapping scenario and up to 48 STAs per BSS in the Non – Overlapping scenario there is no severely deference on the delay performance of both scenarios.

As we can observe the delay starts to increase from the 28 STAs per BSS in total 56 STAs that are operating in the same channel, since there are another 28 STAs from the other BSS that operating on the same channel (i.e. channel 1) when the value of the delay it is increasing to 0.1 sec from 0.005 sec that it was on 24 STAs per BSS. In the other scenario the delay starts to increase from the 56 STAs per BSS up to 0.062 sec from 0.005 sec in case of 48 STAs per BSS. Hence, we observe that there is 40ms deference (0.1 – 0.06=0.04) of delay between of these two scenarios, thus the OBSS problem has apparently impact on the Overlapping scenario.

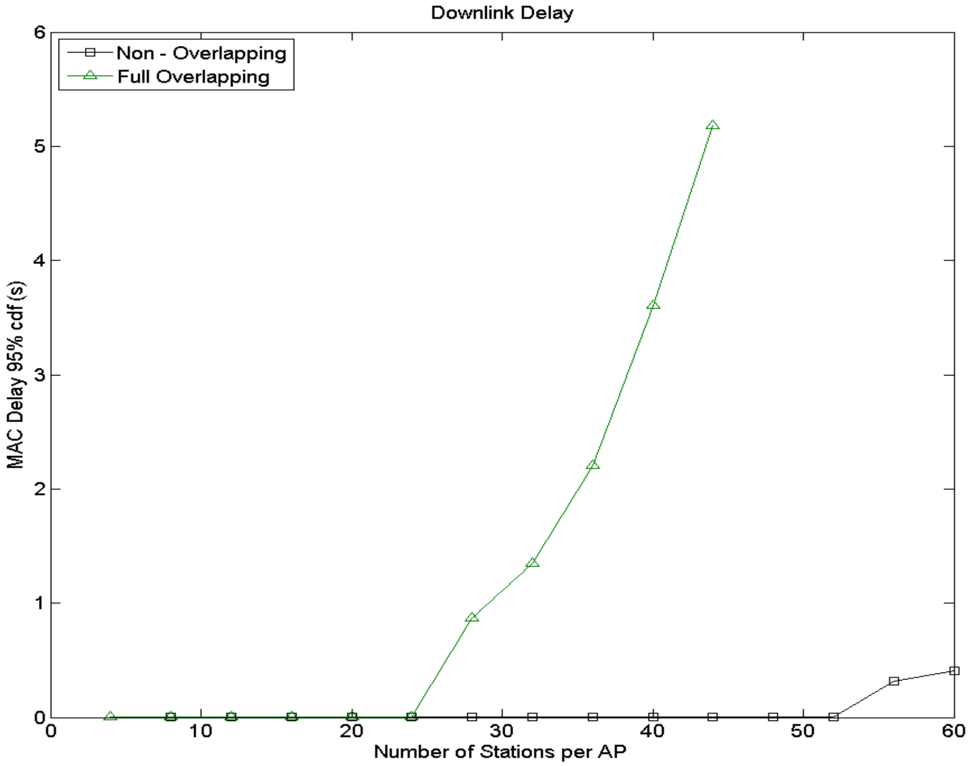

Figure 5.6 DL delay of Overlapping & Non – Overlapping of Legacy Scenarios.

Figure 5.6 provides the simulation results of Downlink (DL) delay during the Overlapping and Non – Overlapping legacy scenarios. Up to 24 STAs per BSS in the Overlapping scenario and up to 48 STAs per BSS in the Non – Overlapping scenario it is easy to observe that there is no impact of interference and collisions due the hidden nodes and the OBSS respectively.

The increase of the delay starts at the point when in Overlapping scenario each BSS has 28 STAs, in other words 56 STAs in total that operate and compete to get the access to the medium. As in the Non – Overlapping scenario, the increase of the delay starts when there are 56 STAs per BSS. It means that in both scenarios the delay increases in the same number of STAs.

The main point is that during the Overlapping scenario the value of the delay at 28 STAs per BSS is 0.865 sec while with the same numbers of STAs in Non – Overlapping (56 STAs per BSS) scenario the values is almost one third (i.e. 0.317 sec) of the Overlapping value. Hence, we are observing that there is impact of the OBSS starting from 28 STAs per BSS on the first scenario and 56 STAs per BSS on the second scenario respectively.

5.6 The Proposed Solution

In the previous chapters, we have highlighted the reasons why overlapping APs sharing capacity is an issue of growing importance and we have summarized different approaches available to address the problem. In this section, we propose a new algorithm that enables the overlapping APs to share capacity in an efficient manner.

In the previous sections, we have presented the two legacy scenarios and the simulation results. Additionally, we have shown the impact of the OBSS problem due to the interference on the APs and STAs performance.

Our proposed solution is based in the well-known fact that avoiding collisions is much more efficient with respect to channel efficiency than resolving them. It is clear that the method currently being adopted by the IEEE 802.11 TGaa and summarized in (Chapter 4 Sharing in an OBSS Situation) will result in a significant capacity loss since collisions between overlapping APs and their corresponding STAs are not avoided but its probability reduced [33]. The solution proposed in this Thesis follows the same philosophy currently being standardized by TGaa of, once no Non - Overlapping channel can be found, split the available resources between the overlapping APs. However, in our case, we exploit the already standardized Quiet Element functionality in order to guarantee that the resources shared are not being used simultaneously by different APs. Thus, we achieve effectively avoiding collisions between APs and STAs of different BSSs and specially, hidden nodes.

The IEEE 802.11-2007 standard [4] defines the Quiet Element as an interval of time during which no transmission shall occur in the current channel. Although the original objective of this functionality was to assist IEEE 802.11 APs in making channel measurements without interference, the same functionality can be exploited for different purposes if desired. An AP in a BSS schedules quiet intervals by transmitting one or more Quiet elements in a public action frame like QLoad Request or Report frame and optionally, periodically in the Beacon frames. STAs receiving a Quiet Element from their

AP set their NAV according to the length of the quiet interval and therefore, neighbouring APs can be sure that no collisions will occur during this period due to transmissions coming from this BSS.

By exploiting the Quiet Element functionality and assuming, as in the TGaa solution case, that overlapping APs can properly process the information contained in the Beacon of the corresponding APs, efficient capacity sharing can be achieved. The main difference with respect to the TGaa approach is that in this case an AP and its associated STAs will not transmit during the advertised Quiet Interval. In this way, during this interval, collisions occur only between AP and STAs within the same BSS. As a result, the larger the load in the overlapping APs, the larger the collision probability reduction and consequently, the capacity sharing efficiency.

5.6.1 How the selection of different Quiet intervals between APs would work

Each AP sends the Beacon frame with 50ms interval from other AP and they keep sending this frame every 100ms. For example, when the first AP will send the beacon frame at time equals to 0.1sec then the second AP will send it 50ms after (0.15 sec) thus, the first AP will send again his second beacon frame at time equals to 0.2 sec.

Normally during this 100ms in an Overlapping situation the nodes of both BSSs are operating as they operate when there is no Overlapping issue. In our case, for a certain time only the first BSS is operating then after this Quiet time period of the second BSS both of the BSS are operating for a certain time as well, then is going the other way around the first BSS is getting into Quiet element period while in this time the second BSS is transmitting and finally after this duration where the first AP is not transmitting both BSS are again in a contention based period trying to get the access to the medium.

The Selection of different Quiet intervals between the APs can be varied up to certain point and it is depend by several parameters (i.e. the load of network, the number of STAs, the number of BSSs that overlap, the applications that are running etc.).

- The maximum Quiet time duration that is possible to be is 50ms since there are two BSSs and each AP sends the Beacon every 100ms according to the above description.

- Hence, during the strong OBSS the Quiet interval should be more than ½ of 50ms that is attributable to each BSS.

- In situation where the OBSS is not strong but still there impact to the performance of the STAs and the AP it is recommended to select Quiet interval less than ½ of 50ms that is attributable to each BSS. The reason that the Quiet time period should be less than ½ of 50ms is because by setting big Quiet interval the delay is getting increased severely. Hence if the small value of Quiet interval it is enough to overcome from the OBSS problem, would be better to select it. In Figure 5.7 the proposed solution is illustrated.

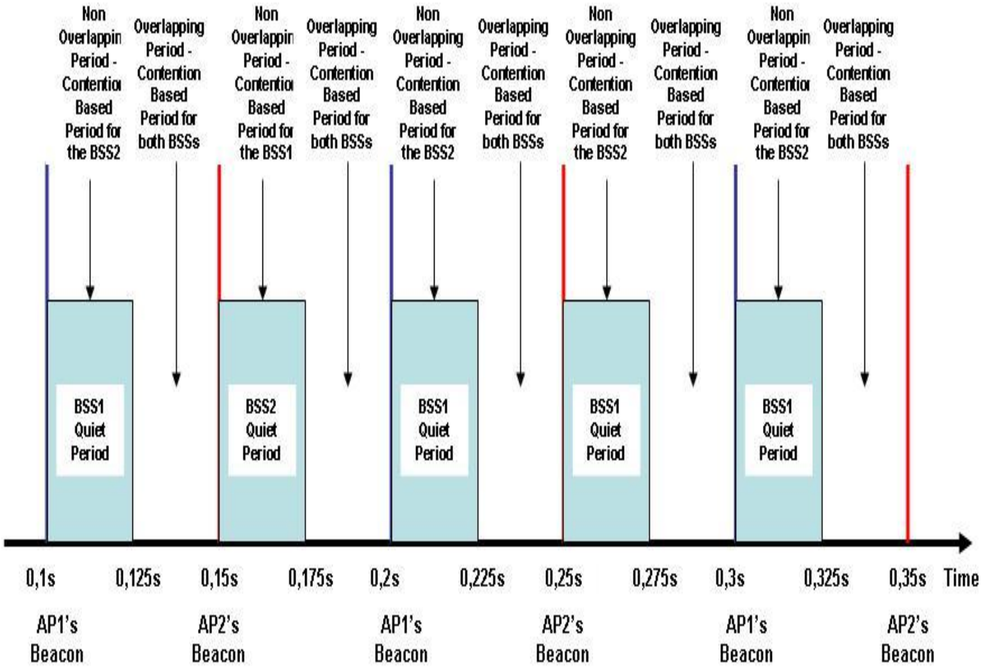

Figure 5.7 The Proposed Algorithm.

5.6.2 Game Theory

In a similar manner (as also defined in TGaa), QLoad indications from overlapping APs can be used autonomously by each AP to decide the amount of capacity that is left free for the use by another overlapping AP. APs providing part of their potential capacity for usage by other APs will expect the same in return. This method provides a good way to ensure capacity sharing fairness since each AP can decide on its own whether the sharing is fair according to its own metrics and needs. In the case of APs mutually benefiting from capacity sharing, win-win situation, capacity sharing will continue and can dynamically adapt to varying needs in time. On the other hand, if an AP assumes that there isn't benefit from deferring its own transmission for capacity sharing, it can decide to reduce the amount of capacity shared or even stop. Since each AP has full control over its capacity sharing, they can leverage this control to ensure fair sharing. In the worst case of users misusing these additional capabilities, AP can simply fall back to default IEEE 802.11 CSMA/CA mechanism.

In other words, our proposed method regarding to the AP capacity sharing it works in a similar way with Game Theory. The Prisoner's Dilemma (PD) see [Annex C] is a fundamental problem in game theory that demonstrates the two strategies the so-called the "Defection Strategy" where the prisoners may confess and testify against the other one and the "Cooperation Strategy" where the prisoners remain silent by do not confessing against the other prisoner [34]. The results of each strategy are shown in Tables 5.6 and 5.7, where it is shown that the two prisoners will gain a greater payoff if they will choose the Cooperation Strategy. Hence, respectively in our proposed algorithm the two BSS will have better results on their throughput and delay performances if APs will cooperate by not transmit during the advertised Quiet Interval.

	Prisoner B - Do not Confess	**Prisoner B - Confess**
Prisoner A - Do not Confess	1year - 1 year	10 years - 0 year
Prisoner A - Confess	0 years - 10 years	5 years - 5 years

Table 5.6 Summary of Classical Prisoner's Dilemma.

	Cooperate	**Defect**
Cooperate	Win - Win	Lose much - Win much
Defect	Win much - Lose much	Lose - Lose

Table 5.7 Classical Prisoner's Dilemma in "Win-Lose" terminology.

5.7 Performance Evaluation of the Proposed Solution

The following are the Simulation Results for both Legacy Scenarios (Overlapping and Non – Overlapping) for the proposed algorithm Quiet element interval of 25ms and 40ms. These scenarios we examined in two cases during the Uplink (UL) and During the Downlink (DL) regarding to the throughput and the delay.

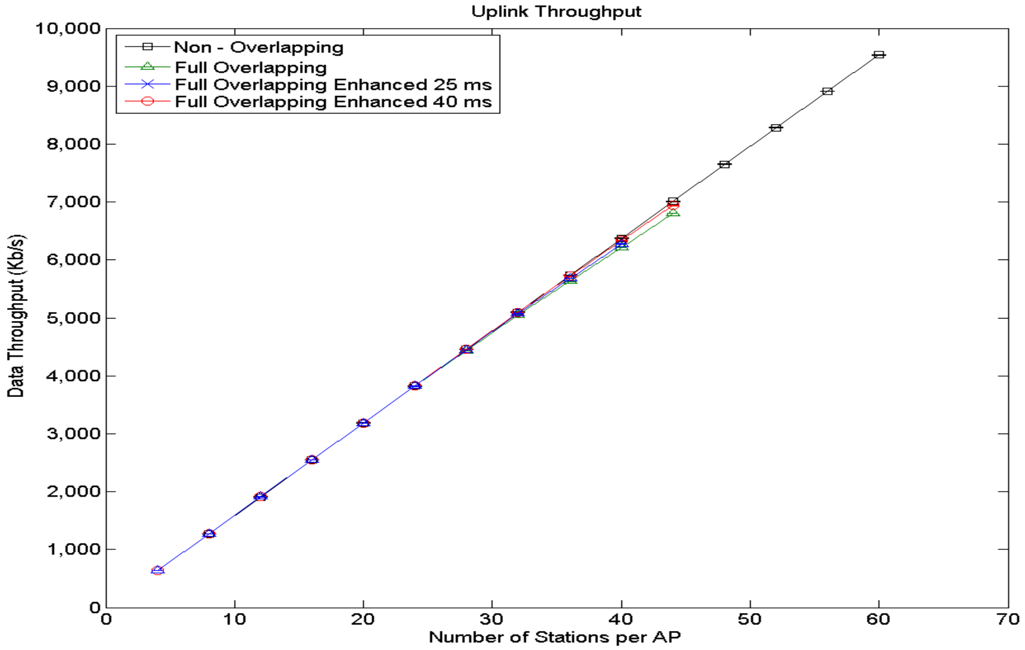

Figure 5.8 UL throughput of Overlapping & Non – Overlapping of All Scenarios.

Figure 5.8 provides the simulation results of DL delay during the overlapping and non – overlapping for legacy and enhanced scenarios with Quiet duration of 25 and 40 ms. During the UL (as we have seen in section 5.5) there is not significant impact of the OBSS problem on the throughput of legacy overlapping and non–overlapping scenarios, since the graphs are very close of each other. Hence, in this case our proposed algorithm didn’t improve the performance severely.

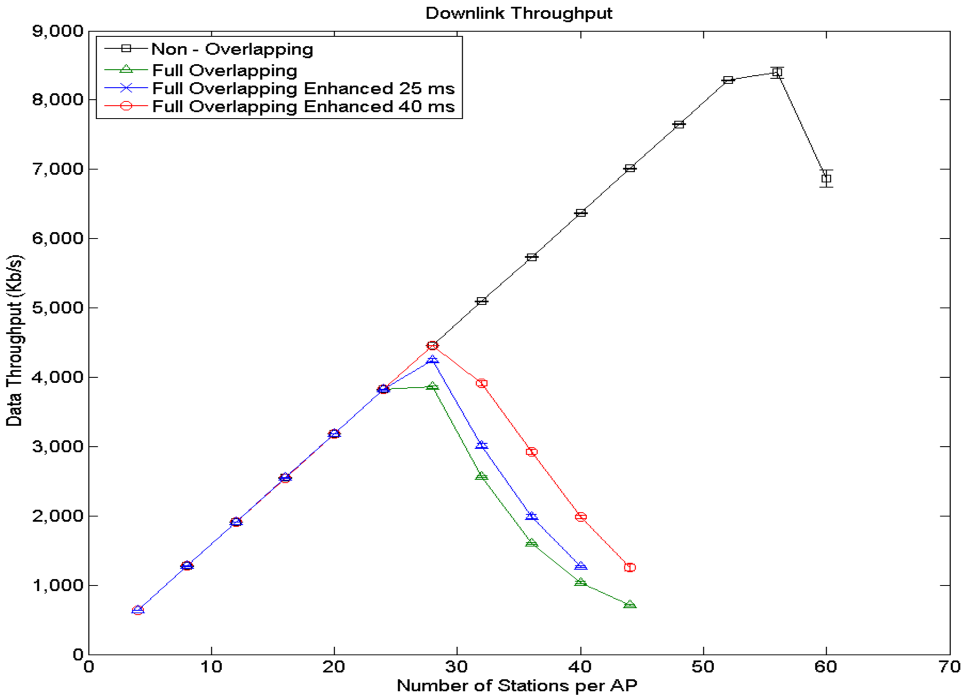

Figure 5.9 DL throughput of Overlapping & Non – Overlapping of All Scenarios.

Figure 5.9 depicts the simulation results of DL delay during the overlapping and non – overlapping for legacy and enhanced scenarios with Quiet duration of 25 and 40 ms. During the DL we observe an enhancement up to 4 STA per BSS, thus, 8 STAs in total since there are two BSSs that are operating in the same channel.

In particular, while the aggregate throughput for the overlapping legacy scenario is 3.860 Kb/s per BSS (7.700 Kb/s for both BSSs) in simulation round of 28 STAs per BSS (56 STAs for both BSSs) and for the non-overlapping is 8.400 Kb/s, in enhanced scenario with Quiet duration of 40 ms the throughput is 4.460 Kb/s per BSS, thus, for both BSSs is 8.920 Kb/s.

Regarding to the enhanced 25 ms scenario there is significant improvement as well. However, not as much as with enhanced scenario of 40 ms.

As we can observe in the next simulation round of 32 STAs per BSS (64 STAs for both BSS), the graph starts to decrease while in non-overlapping scenario starts in simulation round of 56 STAs and 28 STAs per BSS (56 STAs in total) in overlapping legacy scenario respectively.

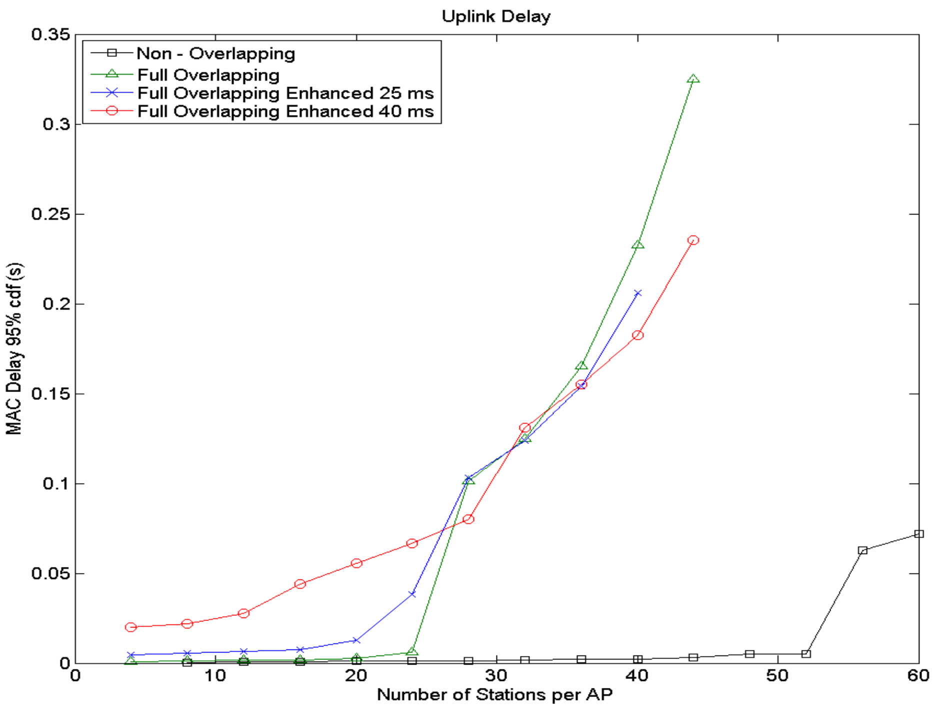

Figure 5.10 UL delay of Overlapping & Non – Overlapping of All Scenarios.

Figure 5.10 provides the simulation results of DL delay during the overlapping and non – overlapping for legacy and enhanced scenarios with Quiet duration of 25 and 40 ms. During the UL delay, we see that the delay on enhanced of 40 ms initially is higher than the enhanced of 25 ms and the other two legacy scenarios, the reason is that in the first simulation rounds there are less STAs thus, the impact of overlapping it is not that significant. Hence, by introducing the quiet period of 40 ms in the beginning, increases the delay performance, since each BSS has to shut for 40 ms in every 100 ms. However, later the value of the enhanced 40 ms is getting less than the rest three scenarios, since the number of STAs per BSS get increased dramatically. Hence, would be good hint if the APs would be enabled to switch to the use of Quiet element only when there is strong OBSS problem.

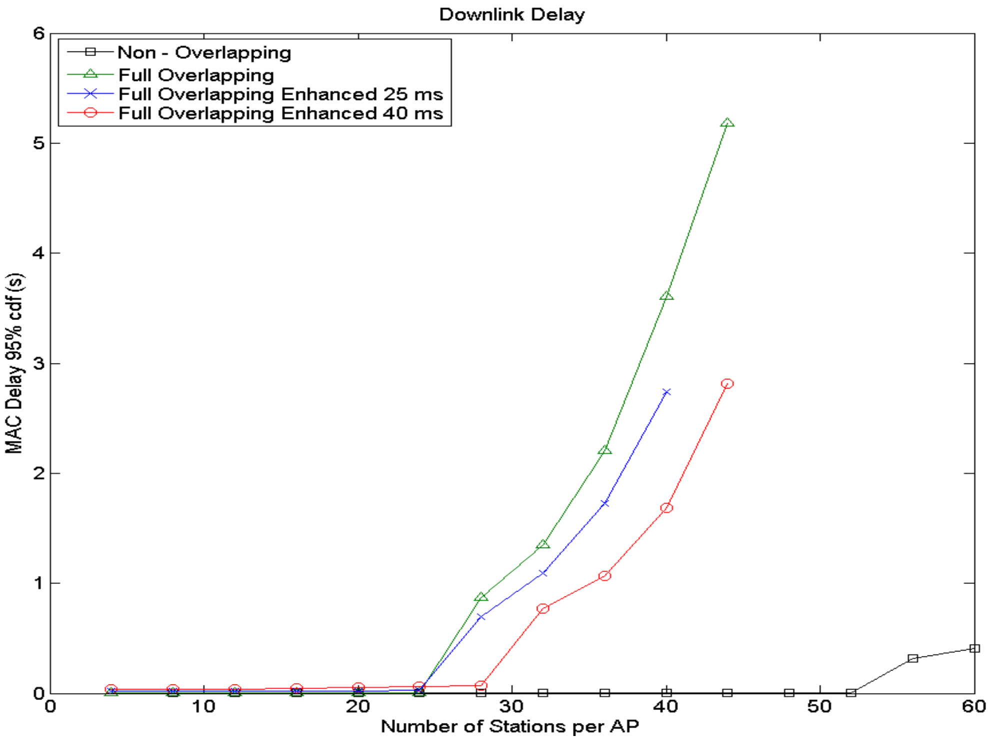

Figure 5.11 DL delay of Overlapping & Non – Overlapping of All Scenarios.

Figure 5.11 illustrates the simulation results of DL delay during the overlapping and non – overlapping for legacy and enhanced scenarios with Quiet duration of 25 and 40ms. Apparently there is significant improvement of the delay performance during the DL, since the value of enhanced scenario of 40ms is close to 3 sec while of overlapping legacy scenario is more than 5 sec.

As we can observe in this case, from the very beginning up to the end the value of the legacy scenario or of the enhanced of 25ms is less than the enhanced of 40ms, it is because during the DL the transmissions happened from the AP to the STA thus, the number of STA has not impact to the DL performance (throughput or delay).

In addition, due to the increase of the STAs in the last simulation rounds the gap between of the two enhanced scenarios is getting increase too. Since there is a need of more bandwidth capacity when there are more STAs per BSS, thus, by introducing the Quiet element interval it is possible to mitigate this problem up to certain point.

5.8 The Case of OBSS between More than Two BSSs

In the previous subchapters, we presented our enhanced algorithm for the case of two BSSs that overlap and we plotted the simulation results demonstrating the enhancement on throughput and delay performance. Respectively, this enhanced algorithm is applicable in case of overlapping between of more than two overlapping BSSs and our proposed method will work utilizing the same principles.

We will examine the case of Figure 3.4 Scenario 3, “Three OBSS, APs within range of each other” (see Chapter 3) where the three AP are listening each other physically and, thus, they are able to receive the Beacon frames of each other. In this case, every time two of three APs will be in Quiet interval while the third will transmit at that time and then in turn each AP will transmit and the other two will get into Quiet interval period.

In particular, in every 100 ms each AP is getting into the Quiet interval twice, since for example the first time, the AP1 and the AP3 are in the Quiet interval due to the AP2 that transmits and then second time, the AP1 and AP2 are in the Quiet interval due the AP3. There is interval time for contention period of for two APs or for all of three APs before the switching to another AP to transmit.

For fair sharing of time, (i.e. 100 ms, since each AP transmits the Beacon frame every 100 ms) the maximum Quiet interval per AP should be up to 33 ms (100/3=33 ms) thus, regarding to the description in subchapter 5.6.1 the algorithm will work for the case of overlapping between of three BSS and more.

Chapter 6

Conclusions and Further Research

6.1 Introduction

This chapter presents the concluding remarks including some potential future research areas. Section 6.2 presents the conclusions drawn from work throughout the thesis and section 6.3 discusses the future research areas and improvements.

6.2 Conclusions

In this thesis, significant focus has been given on the design of a novel approach to enhance the performance of overlapping APs regarding to the capacity sharing in contention-based systems as Wireless LANs.

Initially, a large amount of research work has been carried out, to study a number of technical issues that have been arisen in the past, including distributed coordination of the nodes, management of power and frequencies, network-wise resource and path allocations and so on. Recently, IEEE released the third draft of an upcoming standard, called IEEE 802.11aa, which is an extension to IEEE 802.11 to provide MAC enhancements for robust audio video streaming, we have examined this amendment in detailed, thus, we have taken into account the sharing schemes (i.e. Proportional Sharing and On Demand Sharing). After a thorough research of the state of the art one topic has been selected and an enhancement solution has been designed and evaluated.

The step forward of our work is that we have exploited the already standardized Quiet Element functionality that has been defined in IEEE 802.11-2007 as an interval of time during which no transmission shall occur in the current channel. Thus, we have employed this functionality in our enhanced algorithm in order to introduce QoS support in IEEE 802.11 networks.

Finally, we have used OPNET Modeler simulation to evaluate our proposed mechanism, and we have studied an overlapping and non-overlapping scenario for the simulation to estimate the throughput and delay performance of the STAs and APs of each BSS. We have performed simulations for these scenarios with and without utilizing our enhanced algorithm in order to check its effectiveness. The results showed that by enabling our proposed algorithm into the ACs, the performance will improve significantly.

6.3 Further Research

As for future work, it would be interesting to study and obtain more Overlapping BSSs enhanced scenarios measurements. Additionally, would be more than interesting to run other QoS applications such as Video, live streaming, IPTV and mixed traffic in order to evaluate the performance of our proposed solution under various traffic conditions.

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List of Abbreviations and Acronyms

AC	Access Category
ACK	Acknowledgement
ADDTS	Add Traffic Stream
AIFS	Arbitration Interframe Space
AP	Access Point
A/V	Audio Video
AVB	Audio Video Bridging
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
BWA	Broadband Wireless Access
CA	Collision Avoidance
CAP	Controlled Access Phase
CAT	Channel Access Throttling
CCA	Clear Channel Assessment
CCK	Complementary Code Keying
CEPT	European Conference of Postal and Telecommunications Administrations
CFP	Contention Free Period
CP	Contention Period
CS	Carrier Sense

CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space
DL	Downlink
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum
DMS	Directed Multicast Service
DTIM	Delivery Traffic Indication Message
EC	Executive Committee
EDCA	Enhanced Distributed Channel Access
EDCAF	Enhanced Distributed Channel Access Function
EIFS	Extended Interframe Space
EIRP	Equivalent Isotropically Radiated Power
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FCA	Frequency Channel Assignment
FCC	Federal Communications Commission
FHSS	Frequency Hopping Spread Spectrum
GATS	Group Addressed Transmission Service

GCR	Groupcast with Retries
GPS	Global Positioning Systems
HC	Hybrid Coordinator
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
HEMM	HCCA-EDCA Mixed Mode
HT	High Throughput
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IFS	Interframe Space
IR	Infrared
IrDA	Infrared Data Association
ISM	Industrial, Scientific and Medical
ITU-R	International Telecommunication Union Radiocommunication Sector
LMSC	Local Area Network / Metropolitan Area Network standardization committee
LOS	Line of Sight
MAC	Media Access Control
MAV	Maximum Allocation Value
MAN	Metropolitan Area Network
MIMO	Multiple-Input Multiple-Output

MPDU	MAC Protocol Data Unit
MU-MIMO	Multi-User Multiple-Input and Multiple-Output
MSDU	MAC Service Data Unit
NAV	Network Allocation Vector
OBNAV	Overlapping BSS Network Allocation Vector
OBSS	Overlapping Basic Service Set
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
PC	Point Coordinator
PCF	Point Coordination Function
PD	Prisoner's Dilemma
PIFS	Point Coordination Function Interframe Space
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependent
PPDU	PLCP Protocol Data Unit
PPM	Pulse Position Modulation
PSK	Phase Shift Keying
PT	Power Transmission
QoS	Quality of Service

QAP	QoS enhanced Access Point
QSTA	QoS enhanced Stations
R&D	Research and Development
RIFS	Reduced Interframe Space
RF	Radio frequency
RLAN	Radio Local Area Network
RTS	Request to Send
SBNAV	Self BSS Network Allocation Vector
SCS	Stream Classification Service
SDM	Spatial Division Multiplexing
SDMA	Space-Division Multiple Access
SI	Service Interval
SIFS	Short Interframe Spacing
SRP	Stream Reservation Protocol
STA	Station
STBC	Space Time Block Coding
TAG	Technical Advisory Groups
TBTT	Target Beacon Transmission Time
TCLAS	Traffic Classification
TGaa	Task Group AA
TGac	Task Group AC

TGAVB	Task Group AVB
TGe	Task Group E
TGn	Task Group N
TPC	Transmit Power Control
TS	Traffic Streams
TSF	Timing Synchronization Function
TSPEC	Traffic Specification
TU	Time Unit
TV	Television
TXOP	Transmission Opportunity
UL	Uplink
U-NII	Unlicensed National Information Infrastructure
UP	User Priority
U.S.	United States
VHT	Very High Throughput
WG	Working Groups
Wi-Fi	Wireless Fidelity
WiMAX	Wireless Metropolitan Area Network
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

Bibliography

[1] ”About IEEE”, *IEEE*, [Online]. Available: http://www.ieee.org/about/index.html (Last accessed: August 2011).

[2] “Overview and Guide to the IEEE 802 LMSC”, *IEEE-802*, [Online]. Available: http://www.ieee802.org/IEEE-802-LMSC-Overview-and-Guide-01.pdf (Last accessed: August 2011).

[3] A. R. Prasad and N. R. Prasad, “802.11 WLANs and IP Networking Security QoS and Mobility”, Artech House, 2005, Chapter 3.

[4] IEEE Standard 802.11-2007, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, June 2007.

[5] P. Roshan and J. Leary, “802.11 Wireless LAN Fundamentals”, Cisco Systems, 2004, Chapter 2.

[6] E. Perahia and R. Stacey, “Next Generation Wireless LANs Throughput, Robustness, and Reliability in 802.11n”, Cambridge University Press, 2008, Chapter 7.

[7] S. Mangold, S. Choi, G.R. Hiertz, O. Klein, B. Walke, “Analysis of IEEE 802.11e for QoS support in wireless LANs”, IEEE Wireless Communications Magazine, December 2003.

[8] D. Gao and J Cai, “Admission Control in IEEE 802.11e Wireless LANs”, IEEE Network, vol. 19, July-August 2005.

[9] A. J. C. Moreira, “Performance Evaluation of the IEEE 802.11 Infrared Physical Layer”, First International Symposium on Communication Systems and Digital Signal Processing, pp. 10-15, April 1998.

[10] V. Vermeer, “Wireless LAN; Why IEEE 802.11 DSSS?”, IEEE, April 1997.

[11] IEEE P802.11aa/D3.01, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 3: MAC Enhancements for Robust Audio Video Streaming, March 2011.

[12] E. Perahia "VHT below 6GHz PAR plus 5C's", Doc.: IEEE 802.11-08/0807r4, Sept. 2008.

[13] "ISM Band Computer Definition", *YourDictionary,* [Online]. Available: http://computer.yourdictionary.com/ism-band (Last accessed: August 2011).

[14] "Wi-Fi / WLAN channels, frequencies and bandwidths" *Radio-Electronics.com,* [Online]. Available: http://www.radio-electronics.com/info/wireless/wi-fi/80211-channels-number-frequencies-bandwidth.php (Last accessed: August 2011).

[15] Y. Fangy, D. Gu, A. B. McDonaldy, J. Zhang, "A two-level carrier sensing mechanism for overlapping BSS problem in WLAN", IEEE Workshop on Local and Metropolitan Area Networks (LANMAN), pp. 1-6, Sept. 2005.

[16] K. Heck, "Wireless LAN Performance in Overlapping Cells", Vehicular Technology Conference, VTC 2003-Fall. 2003 IEEE 58th, vol. 5, Oct. 2003.

[17] G. Wu, S. Singh and T. Chiueh "Implementation of dynamic channel switching on IEEE 802.11-based wireless mesh networks", WICON '08 Proceedings of the 4th Annual International Conference on Wireless Internet, Nov. 2008.

[18] T. TANDAI, "Interferential packet detection scheme for a solution to overlapping BSS issues in IEEE 802.11 WLANS", Personal, Indoor and Mobile Radio Communications, IEEE 17th International Symposium, Sept. 2006.

[19] A. Ashley, B. Hart and G. Smith, "OBSS Requirements", Doc.: IEEE 802.11-08/0944r5, July 2008.

[20] Y. Asai, T. Ichikawa, "Interference Management Using Beamforming Technique in OBSS Environment", Doc. IEEE802.11-10/0585r2, May 2010.

[21] J. Kneckt, M. Kasslin and J. Marin, “Reserving STA”, Doc.: IEEE 802.11-11/0127r1, Jan. 2011.

[22] G. Smith, “Overlapping BSS Analysis of Channel Requirements”, Doc.: IEEE 802.11-08/1470-04-00aa, May 2009.

[23] G.M. Garner, F. Feifei, K. den Hollander, J. Hongkyu, K. Byungsuk, L. Byoung-Joon, J. Tae-Chul, J. Jinoo Joung, "IEEE 802.1 AVB and its application in carrier-grade Ethernet," IEEE Communications Magazine, vol.45, no.12, pp.126-134, December 2007.

[24] IEEE Standard for Local and metropolitan area networks-Virtual Bridged Local Area Networks Amendment 14: Stream Reservation Protocol (SRP), IEEE Std. 802.1Qat, 2010.

[25] K. Maraslis, P. Chatzimisios and A.C. Boucouvalas, “An overview of the IEEE 802.11aa Draft Standard”, technical report, Department of Informatics, Alexander TEI of Thessaloniki, May 2011.

[26] G. Smith, “20/40MHz Channel Selection”, Doc. IEEE802.11-09/0740/r0, June 2009.

[27] K. Nishimori, "Measurement results for OBSS in home network scenarios", Doc. IEEE 802.11-09/1031r0, Sept. 2009.

[28] P. Loc and M. Cheong, “TGac Functional Requirements and Evaluation Methodology”, Doc. IEEE802.11-09/0451/r12, Apr. 2009.

[29] M. Kasslin and A. Lappeteläinen, “Transmitter Power Control (TPC) for 802.11 WLAN - Rev.1”, Doc. IEEE802.11-00/190, July 2000.

[30] A. E. Xhafa, A. Batra and A. Zaks, “On the 20/40 MHz Coexistence of Overlapping BSSs in WLANs”, Journal of Networks, vol. 3, July 2008.

[31] B. Han, L. Ji, S. Lee, R. R. Miller, B. Bhattacharjee, “Channel Access Throttling for Overlapping BSS Management”, Communications, 2009. ICC ‘09.IEEE International Conference, June 2009.

[32] “About OPNET”, *OPNET*, [Online]. Available: http://www.opnet.com (Last accessed: August 2011).

[33] G. Smith “Proposed Edits to Clause aa.4.1 – CID 254 LB164”, Doc.: IEEE 802.11-10/1324r2, Nov. 2010.

[34] Y. Xiao, X. Shan and Y. Ren, “Game Theory Models for IEEE 802.11 DCF in Wireless Ad Hoc Networks”, Communications Magazine, IEEE, vol. 43, March 2005.

Appendix A - IEEE Standard 802.11 2007

Access Point (AP): Any entity that has station (STA) functionality and provides access to the distribution services, via the wireless medium (WM) for associated STAs.

Channel: An instance of communications medium use for the purpose of passing protocol data units (PDUs) between two or more stations (STAs).

Contention-free Period (CFP): The time period during operation of a point coordination function (PCF) when the right to transmit is assigned to stations (STAs) solely by a point coordinator (PC), allowing frame exchanges to occur between members of the basic service set (BSS) without contention for the WM.

Contention Period (CP): The time period outside of the contention-free period (CFP) in a point coordinated basic service set (BSS). In a BSS where there is no point coordinator (PC), this corresponds to the entire time of operation of the BSS.

Downlink: A unidirectional link from an access point (AP) to one or more non-AP stations (STAs).

Distribution System (DS): A system used to interconnect a set of basic service sets (BSSs) and integrated local area networks (LANs) to create an extended service set (ESS).

Hidden Station: A STA whose transmissions cannot be detected using carrier sense (CS) by a second STA, but whose transmissions interfere with transmissions from the second STA to a third STA hybrid coordination function (HCF): A coordination function that combines and enhances aspects of the contention-based and contention-free access methods to provide QoS stations (STAs) with prioritized and parameterized QoS access to the WM, while continuing to support non-QoS STAs for best-effort transfer. The HCF includes the functionality provided by both enhanced distributed channel access (EDCA) and HCF controlled channel access (HCCA). The HCF is compatible with the distributed coordination function (DCF) and the point coordination function

(PCF). It supports a uniform set of frame formats and exchange sequences that STAs may use during both the contention period (CP) and the contention-free period (CFP).

Hybrid Coordinator (HC): A type of coordinator, defined as part of the QoS facility, that implements the frame exchange sequences and medium access control (MAC) service data unit (MSDU) handling rules defined by the hybrid coordination function (HCF). The HC operates during both the contention period (CP) and contention-free period (CFP). The HC performs bandwidth management including the allocation of transmission opportunities (TXOPs) to QoS stations (STAs). The HC is collocated with a QoS access point (AP).

Point coordinator (PC): The entity within the STA in an AP that performs the point coordination function.

Quality of Service (QoS): The ability to provide different priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow.

Traffic Specification (TSPEC): The QoS characteristics of a data flow to and from a non-access point (non-AP) QoS station (STA).

Uplink: A unidirectional link from a non-access point (non-AP) station (STA) to an access point (AP).

Wireless Medium (WM): The medium used to implement the transfer of protocol data units (PDUs) between peer physical layer (PHY) entities of a wireless local area network (LAN).

Appendix B - IEEE 802.11aa Draft

QLoad Request frame format

The QLoad Request Action frame is transmitted by an AP to request information from another AP.

Order	Information
1	Category
2	Public Action
3	Dialog Token
4	QLoad Report element

Table Annex B 1 QLoad Request frame Action field format.

The Category field is set to the value indicating a Public Action frame

The Public Action field is set to the value for a QLoad Request Action frame.

The Dialog Token field is set by the requesting STA to a non-zero value that is used for matching action responses with action requests.

The QLoad Report element contains the QLoad report corresponding to the AP sending the request.

QLoad Report frame format

The QLoad Report Action frame is transmitted by an AP responding to a QLoad Request frame.

Order	Information
1	Category
2	Public Action
3	Dialog Token
4	QLoad Report element

Table Annex B 2 QLoad Request frame Action field format.

The Category field is set to the value indicating a Public Action frame

The Public Action field is set to the value for a QLoad Request Action frame.

The Dialog Token field is set by the requesting STA to a non-zero value that is used for matching action responses with action requests. The Dialog Token field is set to 0 when an unsolicited QLoad Report frame is sent by the AP.

The QLoad Report element contains the QLoad report corresponding to the AP sending the request.

QLoad Report element

The QLoad Report element contains the set of parameters necessary to support OBSS management.

Element ID	Length	Potential Traffic Self	Allocated Traffic Self	Allocated Traffic Shared	EDCA Access Factor	HCCA Peak	HCCA Access Factor	Overlap

Table Annex B 3 QLoad Report element format.

Element ID Field is set to the value for QLoad Report element.

Length Field is a one octet field whose value is set to 20.

The Potential Traffic Self field represents the peak composite QoS traffic for this BSS if all the potential TSPECs from the non-AP STAs are active.

Allocated Traffic Self field represents the composite QoS traffic for this BSS based upon TSPECs admitted within the same BSS.

Allocated Traffic Shared field represents the sum of the Allocated Traffic Self values that have been received from overlapping APs, plus the Allocated Traffic Self value of the AP itself.

EDCA Access Factor is the sum of the Potential Traffic Self fields that have been(Ed) received or obtained from overlapping APs, plus the Potential Traffic Self of the AP itself. The EDCA Access Factor is expressed as a fraction rounded down to a multiple of 1/64. When the EDCA Access Factor is greater than 254/64 the field is set to a value of 255.

HCCA Peak field is the total peak HCCA TXOP requirement, over a period of one second, for the AP and BSS, for all the HCCA TSPECs that are included in the QLoad. HCCA Peak is expressed in multiples of 32µs over a period of one second. The HCCA Peak field is reserved if HCCA is not supported.

HCCA Access Factor field is the sum of the HCCA Peak fields in the QLoad Report elements from the APs of overlapping BSSs, plus the HCCA Peak field of the AP itself. It is expressed as a fraction rounded down to a multiple of 1/64. When the HCCA Access Factor is greater than 254/64 the field is set to a value of 255.

Overlap field indicates the number of other APs that are sharing the same channel and whose beacons have been(Ed) detected or obtained by the AP issuing this beacon. A value of 0 indicates that this AP has not received one or more beacons on the same channel from any other AP within the last 100 beacon periods of this AP.

HCCA TXOP Advertisement frame

Category	Public Action	Dialog Token	Number of Reported TXOP Reservations	Number of Pending TXOP Reservations	Active TXOP Reservations	Pending TXOP Reservations

Table Annex B 4 HCCA TXOP Advertisement frame Action field format.

The Category field is set to the value indicating a Public Action frame.

The Public Action field is set to the value for an HCCA TXOP Advertisement Public Action frame.

The Dialog Token field is set by the AP to a non-zero value that is used for matching action responses with action requests.

The Number of Reported TXOP Reservations is a field of one octet that contains a positive integer that specifies the number of Active TXOP Reservations reported in this frame. A value of 0 indicates that no TXOP Reservations are active.

The Number of Pending Reported TXOP Reservations is a field of one octet that contains a positive integer that specifies the number of Pending TXOP Reservations reported in this frame. A value of 0 indicates that no TXOP Reservations are in the process of being activated.

The Active TXOP Reservation field contains zero or more TXOP Reservation fields. These fields indicate HCCA TXOPs that the AP has scheduled and are active. The start time field of the TXOP Reservation field is relative to the Timing Synchronization Function (TSF) of the sending AP.

The Pending TXOP Reservation field contains zero or more TXOP Reservation fields. These fields indicate new HCCA TXOPs that the AP is scheduling. The start time field of the TXOP Reservation field is relative to the TSF of the sending AP.

HCCA TXOP Response frame

Category	Public Action	Dialog Token	Status Code	Schedule Conflict	Altemate Schedule	Avoidance Request

Table Annex B 5 HCCA TXOP Response frame format.

The Category field is set to the value indicating a Public Action frame.

The Public Action field is set to the value for a HCCA TXOP Response Public Action frame.

The Dialog Token field is set to the value of the Dialog Token field from the corresponding HCCA TXOP Advertisement public action frame.

The Status Code field is set to either the value 0 (meaning “Successful”) or <ANA> (meaning “The TS schedule conflicts with an existing schedule; an alternative schedule is provided”).

The Schedule Conflict field is only present when the Status Code field is non-zero. The Schedule Conflict field indicates the TXOP Reservation from the HCCA TXOP Advertisement frame that conflicts with an existing or in-progress schedule. Its value is between 1 and the value from the Number of Reported TXOP Reservations field of the HCCA TXOP Advertisement frame. A value of 1 indicates the first TXOP Reservation in the HCCA TXOP Advertisement frame, a value of 2 indicates the second TXOP Reservation in the HCCA TXOP Advertisement frame, and so on. The value of zero is reserved.

The optional Alternate Schedule field is only present when the Status Code field is non-zero. When the Alternate Schedule field is present, it contains an alternate to the TXOP reservation given in the corresponding HCCA TXOP Advertisement public action frame. The start time subfield of the Alternate Schedule field is relative to the TSF of the destination AP.

The optional Avoidance Request field may be present when the Status Code field is non-zero. When the Avoidance Request field is present, it indicates a TXOP schedule that the AP sending the TXOP Response frame is requesting to be avoided by the AP that is the destination of the TXOP Response frame. The start time subfield of the Avoidance Request field is relative to the TSF of the destination AP.

TXOP Reservation

The TXOP Reservation field is of length 6 octets.

Duration	Service Interval	Start time

Table Annex B 6 TXOP Reservation field format.

The Duration Field specifies the duration of the TXOP in the units of 32µs.

The Service Interval is an eight bit unsigned integer that specifies the SI of the reservation in the units of microseconds.

The Start time field is the offset from the next TBTT to the start of the first SP and indicates the anticipated start time, expressed in microseconds, of the first TXOP after the TBTT.

HCCA TXOP Update Count element

The HCCA TXOP Update Count element is used by an AP to advertise its change in TXOP state to its overlapping APs.

Element ID	Length	Update Count

Table Annex B 7 HCCA TXOP Update Count element format.

The element ID is set to the value for this information element.

The length is set to one.

The Update Count field is used to indicate that a change has occurred in the number of active HCCA or HEMM TSs.

TSPEC element

The TSPEC element contains the set of parameters that define the characteristics and QoS expectations of a traffic flow, in the context of a particular STA, for use by the HC and non-AP STA(s) or a mesh STA 4 and its peer mesh STAs in support of QoS traffic transfer using the. The element information format comprises the items as defined in this subclause.

ADDTS Request frame format

Order	Information	Notes
1	Category	
2	QoS Action	
3	Dialog token	
4	TSPEC	
5 – n	TCLAS	Optional
n + 1	TCLAS processing	Optional
n + 2	U-APSD Coexistence	Optional
n + 3	Expedited bandwidth request element	Optional
n + 4	Intra-access Category Priority element	Optional
n + 5	Higher Layer Stream ID	Only in AP Initiated TS Setup

Table Annex B 8 ADDTS Request frame Action field format.

Calculating Medium Time

This annex uses the following formula for calculating and estimating medium times in both ACM and non- ACM QoS modes:

mediumTime(s,d,m,p) = s ×pps × MAC Protocol Data Unit (MPDU)ExchangeTime

Where:

pps = ceiling((d / 8) / m)

MPDUExchangeTime = duration(m,p) + SIFS + duration(14,p)

duration() is the PLME-TXTIME primitive that returns the duration of a frame based on its payload size and the PHY data rate employed.

Calculation of Allocated Traffic Self

Allocated Traffic Self represents the total BSS load of all streams that the AP has allocated at any one time and the number of AC_VI and AC_VO streams that make up that total. It is recommended that the AP should calculate the mean and standard deviation using the Minimum Data Rate, Mean Data Rate and Peak Data Rate fields of admitted TSPECs and to re-calculate Allocated Traffic Self as each TS is added or deleted. It is recommended that the values of the Mean and Standard Deviation subfields placed in the Allocated Traffic Self field, for allocated streams is calculated using:

MINi = mediumTime(Surplus Bandwidth Allowance, Nominal MSDU Size, Minimum Data Rate, Minimum PHY Rate)

MEANi = mediumTime(Surplus Bandwidth Allowance, Nominal MSDU Size, Mean Data Rate, Minimum PHY Rate)

MAXi = mediumTime(Surplus Bandwidth Allowance, Nominal MSDU Size, Peak Data Rate, Minimum PHY Rate)

If TSPECi has the Minimum Data Rate and Peak Data Rate fields populated:

$\sigma i = sqrt(MAXi-MINi)^2$

else if TSPECi has the Mean Data Rate and Peak Data Rate fields populated:

$\sigma i=(MAXi-MEANi)/2$

Otherwise

$\sigma i=0$

Mean = $\Sigma \mu i$

Standard Deviation = $sqrt \Sigma \sigma_I^2$

Calculation of Allocated Traffic Shared

Allocated Traffic Shared is the sum of the values expressed in the Allocated Traffic Self fields of all overlapping APs, including its own Allocated Traffic Self. It is recommended that the values of the mean μ, and standard deviation σ, placed in the Allocated Traffic Shared field, for *n* overlapping APs is calculated using:

$\mu= \Sigma\mu_n$

$\sigma= \surd(\sigma_n^2)$

Calculation of EDCA Access Factor

The Access Factor is the total traffic requirement for all the overlapping APs that may be greater than 1. It is recommended that the Access Factor be calculated from the addition of all the Potential Traffic Self fields of the APs that are overlapping as follows: First calculate the Overlap Traffic for all the overlapping APs. Each AP should note the reported Potential Traffic Self fields for every overlapping AP, including the AP‘s own Potential Traffic Self, and calculate the maximum traffic of the composite stream, using the formula:

Overlap Traffic = $\mu_{tot} + 2\ \sigma_{tot}$

Where, for *i* Potential Traffic Self fields:

$\mu_{tot} = \Sigma \mu i$

$\sigma_{tot} = \sqrt{} \Sigma \sigma_i^2$

This Overlap Load value will be in multiples of 32µs per second.

The following procedure is then recommended to calculate the EDCA Access Factor:

b) Sum the AC_VI and AC_VO priority streams reported in the Potential Traffic Self fields of its own QLoad Report and all the QLoad Reports of overlapping APs, and determine the EDCA Bandwidth overhead Factor.

c) Multiply the Overlap Traffic and the resulting EDCA Overhead Factor together. This value represents the total overlap peak traffic requirement for the overlapping APs in multiples of 32µs per second.

d) Convert the total overlap peak traffic to a fraction (seconds per second) by multiplying by 32×10^{-6}

e) Round the resulting fraction value rounded down to a multiple of 1/64.

For example, if the total overlap peak traffic is 74268 (32µs per second), this is 2.376576 (seconds/second). Now 2.376576 x 64 = 152.1 rounded to 152. Hence, the EDCA Access Factor octet, in this case, would be 1001100 (152 in binary, representing the fraction 152/64)

EDCA Overhead Factor

The Potential Traffic Self field also includes the number of AC_VI and AC_VO streams that make up the composite stream. The recommended calculation for Medium Time for an admitted EDCA is given in L.2.2. This value includes the duration of the packet plus SIFS and ACK times. The Medium Time therefore does not include the access time. For example, for a single stream, between each transmitted packet there is a time period due to SIFS, AIFSN and contention window, and for two or more streams, there is also the time when each packet is delayed while another packet is being transmitted. Hence, in order to calculate the total time or bandwidth required to service multiple EDCA streams, an overhead is present that must applied.

It is recommended that a fixed value of 1.34 is used for EDCA Overhead Factor. The value of the EDCA Overhead Factor is dependent upon many factors, including:

- Number and mix of streams, voice and video
- Mixture of PHY Rates and PHYs
- Mixture of streams‘ data rates
- Use and mix of aggregated MSDUs
- Choice of EDCA parameters including different settings in overlapping BSSs

Based on a range of simulations the value of EDCA Overhead Factor is normally in the range 1.26 to 1.43. These simulations, however, were not exhaustive and did not include the effects of hidden nodes and non-802.11 interference.

Calculation of HCCA Access Factor

It is recommended that the HCCA Access Factor is calculated as follows:

a) Sum the HCCA Peak values in all the QLoad Reports of all the overlapping APs, including its own.

b) Convert the total peak traffic to a fraction (seconds per second) by multiplying by 32 x 10^-6.

c) Round the resulting fraction value to the nearest 1/64 and enter the result into the Access Factor Field.

For example, if the total overlap peak traffic is 74268 (32μs per second), this is 2.376576 (seconds/second). 1 Now 2.376576 x 64 = 152.1 rounded to 152. Hence, the

HCCA Access Factor octet, in this case, would be 152 2 (representing the fraction 152/64)

Appendix C - Definitions

Interference: In communications and electronics, interference is the phenomenon that occurs when two waves meet while travelling along the same medium. Interference cause as a results alternation, modification, or disruption of a signal as it travels along a channel between a source and a receiver. The term typically refers to the addition of unwanted signals to a useful signal.

Interframe Spacing (IFS):

After each frame transmission, IEEE 802.11 Stds require an idle period on the medium, the time interval between frames is called the IFS. Five different IFSs are defined to provide a buffer between frames to avoid interference and priority levels for access to the wireless media. The use and the length of each IFS is dependent from the previous frame type, the following frame type, the coordination function in use and the PHY type. Figure Annex C 1, shows the IFSs.

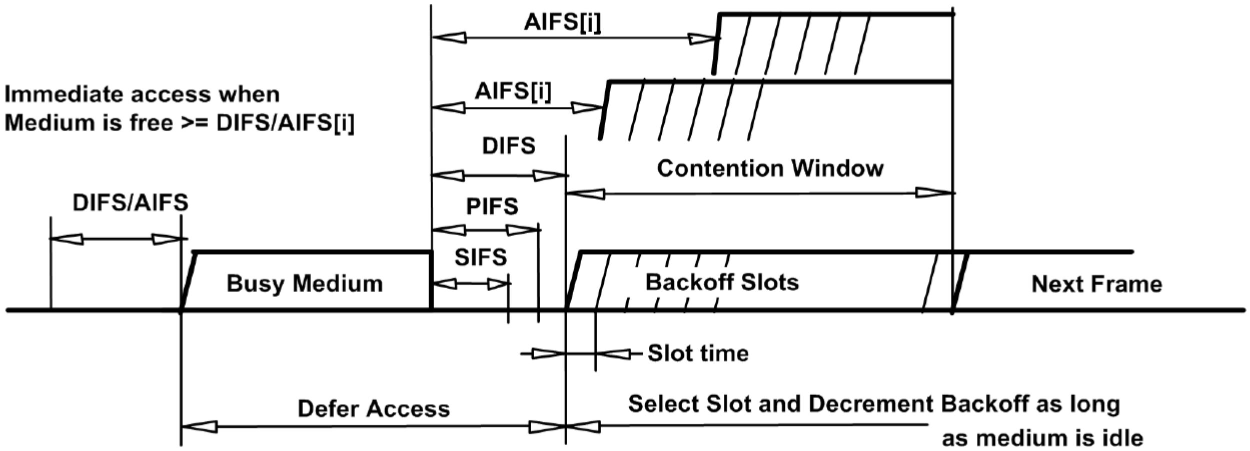

Figure Annex C 1 The IFS [4].

Short Interframe Space (SIFS)

For 802.11-2007, SIFS is the shortest of the IFSs. However, with IEEE 802.11n a shorter IFS Reduced Interframe Space (RIFS) was introduced. SIFS are used within all of the different coordination functions. The SIFS is used prior to transmission of an ACK frame, a CTS frame, the second or subsequent MPDU of a fragment burst, and by a STA responding to any polling by the PCF. SIFS is used to separate a response frame from the frame that solicited the response, for example between a data frame and the ACK response, SIFS is also used to separate individual frames in a back-to-back data burst. The SIFS duration for a particular PHY is defined by the aSIFSTime parameter. For the IEEE 802.11a, 802.11g, and 802.11n PHYs the value is 16 µs.

PCF interframe space (PIFS)

The PCF Interframe Space (PIFS) defer provides the next highest access priority following SIFS and are used by STAs during the contention-free period (CFP) in PCF mode to gain priority access to the medium at the start of the CFP. Because PCF has not been implemented in 802.11 devices, you will not see PIFS used for this purpose. However, PIFS may be used by a STA to transmit a Channel Switch Announcement frame. In order to gain priority over other STAs during contention, the AP can transmit a Channel Switch Announcement frame after observing a PIFS.

PIFS duration can be calculated as follows: PIFS = aSIFSTime + aSlotTime

Where the aSIFSTime and aSlotTime are calculated as follows:

aSIFSTime = aRxRFDelay + aRxPLCPDelay + aMACProcessingDelay + aRxTxTurnaroundTime

aSlotTime = aCCATime + aRxTxTurnaroundTime + aAirPropagationTime + aMACProcessingDelay.

DCF interframe space (DIFS)

The DCF Interframe Space (DIFS) is used by STAs operating under the DCF mode to transmit data frames and management frames. The duration of a DIFS is longer than both the SIFS and PIFS. A STA has to sense the status of the medium before transmitting. A STA is allowed to transmit if the medium is continuously idle for DIFS duration or if it determines that the medium is idle for the duration of the DIFS plus the remaining backoff time following the reception of a correctly received frame. If the channel is found busy during the DIFS interval, the STA should defer its transmission.

DIFS duration can be calculated as follows: DIFS = aSIFSTime + 2 * aSlotTime

Arbitration Interframe Space (AIFS)

The Arbitration Interframe Space (AIFS) is used by STAs operating under the EDCA mode to transmit all data frames (MPDUs), all management frames and the following control frames: PS-Poll, RTS, CTS (when not transmitted as a response to the RTS), BlockAckReq, and BlockAck (when not transmitted as a response to the BlockAckReq) [4]. The size of the AIFS varies based on AC. This process gives higher-priority STAs a shorter AIFS and lower-priority STAs a longer AIFS. The shorter the AIFS, the higher the chances of accessing the channel first. A STA using the EDCA mode shall not transmit within an EIFS-DIFS+AIFS[AC] plus any backoff time

The basic contention logic of EDCA is the same as with DCF, but in order to facilitate QoS, there are some notable differences. While DCF can designate a single DIFS value for each PHY, EDCA establishes unique AIFS durations for access categories (AC). For this reason, an AIFS is typically notated as an AIFS[AC].

AIFS duration can be calculated as follows:

AIFS[AC] = aSIFSTime + AIFSN[AC] X aSlotTime

Extended Interframe Space (EIFS)

The Extended Interframe Space (EIFS) value is used by STAs that have received a frame that contained errors. After an erroneous frame is detected (due to collisions or transmission errors), a STA must remain idle for at least an EIFS interval before it reactivates the backoff algorithm. By using this longer IFS, the transmitting STA will have enough time to recognize that the frame was not received properly before the receiving STA commences transmission. If, during the EIFS duration, the STA receives a frame correctly (regardless of intended recipient), it will resume using DIFS or AIFS, as appropriate.

EIFS duration can be calculated as follows:

EIFS (DCF) = aSIFSTime + DIFS + ACKTxTime

EIFS (EDCA) = aSIFSTime + AIFS[AC] + ACKTxTime

Prisoner's Dilemma (PD)

Two suspects are arrested by the police. The police have insufficient evidence for a conviction, and, having separated the prisoners, visit each of them to offer the same deal. If one testifies for the prosecution against the other (defects) and the other remains silent (cooperates), the defector goes free and the silent accomplice receives the full 10-year sentence. If both remain silent, both prisoners are sentenced to only one year in jail for a minor charge. If each betrays the other, each receives a five year sentence. Each prisoner must choose to betray the other or to remain silent. Each one is assured that the other would not know about the betrayal before the end of the investigation.