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THESIS

Study and Analysis of wireless networking 802.11n protocol

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PREFACE

In 1999 the first standard was published after many years from the first wireless packet transmitted in Hawaii. Laptops contributed to the adoption of IEEE 802.11 as the wireless standards. Since then many amendments were published, each time feeding the need for higher throughput. 802.11a/b/g amendments are the most known wireless protocols, with b and g being the most deployed. IEEE 802.11g with the increased throughput was massively considered the standard of IEEE 802.11 family. But the continuous need for higher throughput directed to the implementation of IEEE 802.11n. The amendment boosted the throughput and range with the technologies introduced in both PHY and MAC layer. Key features are PHY MIMO and MAC frame aggregation with block ACK. With the enhancements the throughput achieved in PHY is up to 600 Mbps and MAC above 100 Mbps. Along with QoS, the IEEE 802.11n amendment will be deployed everywhere.

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INTRODUCTION

The purpose of this dissertation is to present an overview of IEEE 802.11n focusing on the MAC layer. The dissertation is organized in 6 chapters:

1. Introduction to WLANS: This chapter is the introductory part of the dissertation. Contact is made with most known wireless protocols and the PHY and MAC layers of OSI. Moreover basic legacy access channel mechanism DCF and the enhanced distributed EDCA is promptly analyzed. This chapter concludes with introduction to IEEE 802.11n.
2. IEEE 802.11n PHY: This chapter refers to and analyzes the technologies used for IEEE 802.11n PHY such as MIMO.
3. IEEE 802.11n MAC: Key features of MAC are analyzed
4. IEEE 802.11n Literature review: Papers that study performance of 802.11n in overall and its MAC key features in different scenarios.
5. IEEE 802.11n other issues: Interworking, QoS and Security are the topics discussed here. Papers for QoS and Security assist to have an overview of the protocol, the MAC mechanisms and issues that are significant for a secure and less delay performance.
6. Future research and conclusions: IEEE 802.11n paved the way to even more HT. Very High Throughput Study Group was formed to find ways to achieve at least 1 Gbps throughput. IEEE 802.11ad/ac are the early first VHT protocols to be developed.

CHAPTER 1

INTRODUCTION

INTRODUCTION

In this chapter the basics of WLAN are discussed, such as history, known WLAN protocols, the Physical and the MAC layer and IEEE 802.11 DCF and IEEE 802.11e EDCA mechanisms. Furthermore there is an introduction of IEEE 802.11n protocol with its key features, which will be further discussed in later chapters.

1. INTRODUCTION TO WLANS

Wireless Local Area Networks (WLAN) the last years experience a massive growth with the arrival of IEEE 802.11 devices. This is due to the fact that gives users the mobility to move around within a local area and still be connected to the network, the ease of installation and the use of laptops.

So what is a WLAN? It's a network that usually extends an existing wired local area network and provides wireless network communication over short distances using radio or infrared signals.

Its beginnings date back in 1971 where the first packet-based wireless network was created at the University of Hawaii. They named the network ALOHANET and the system included seven computers over four islands communicating with a central computer, without using phone lines, in a bi-directional star topology. WLAN devices were developed for commercial use after several years but these initial systems were expensive and because of this reason the deployment was only feasible when running cable was difficult. Finally increased commercial interest was observed as a result of the advances in technology and the standardization of WLAN with IEEE 802.11, which led to cost reduction, resulting in a more convenient and feasible deployment of a wireless network. Then Wi-Fi Alliance (WFA) was formed in 1999 to certify interoperability between IEEE 802.11 devices, because of the mass production of different manufacturers. Therefore WLANs are deployed in homes, businesses, small areas(hot-spots) and know great growth.

The initial version of IEEE 802.11 standard was influenced by Ethernet (802.3) for wired LANs in 1997, adopting the distributed access protocol, carrier sense multiple access(CSMA) in MAC layer. For a quick review; all network architectures are based on a layered model called OSI (Open Systems Interconnection) model, designed by the International Organization for Standardization (ISO), as seen in Figure 1. The OSI model provides an extensive list of functions and services that can occur at each layer. It also describes the relation of each layer with the layers directly above and below it.

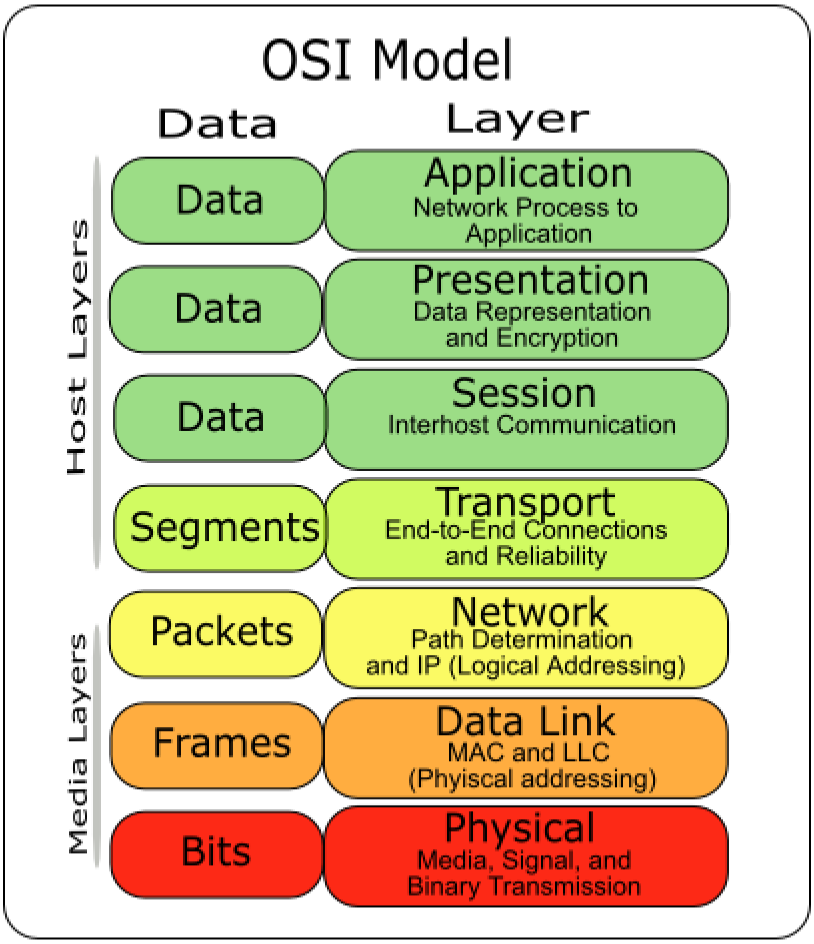

Figure 1. OSI Model [11]

The OSI Layers Physical and Data Link provide the necessary procedures to access the media and the physical means to send data over a network. Therefore these two layers are also responsible for data rates, a connection or network accomplish and are also the case study of the researchers for improving data rates.

The Data Link layer exchanges the data over a common medium and :

- Encapsulates the data units from the upper layers to frames and permits the access to the media
- Using media access control and error detection, it controls how data is placed/received onto/from the media

To be further analyzed, the Data Link layer consists of two sub-layers: the upper sub-layer called Logical Link Control (LLC) layer which encapsulates into frames the Network layer packets and identifies the Network layer Protocol (for example IP) and the lower one called Media Access Control (MAC) which physically addresses the frame (MAC address) and completes the creation of the frame as shown in Figure 2.

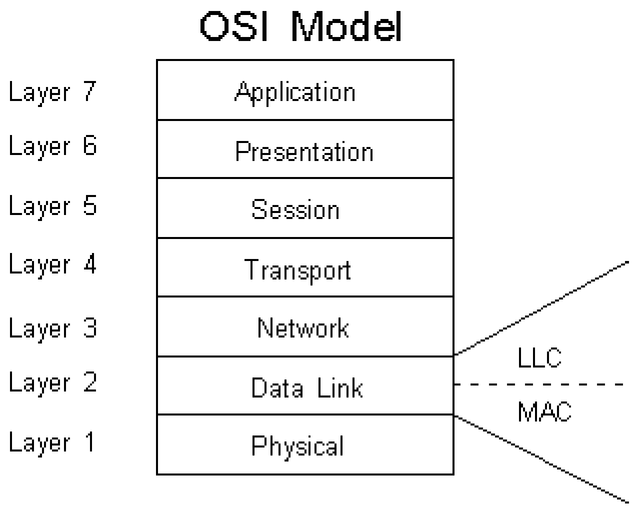

Figure 2. Data Link Sub-layers: LLC, MAC [12]

So getting back on how IEEE 802.11 works, CSMA is a MAC mechanism for medium access. Ethernet (802.3) is based on CSMA/CD (collision Detection), whereas IEEE 802.11-based WLANs use a similar mechanism known as carrier sense multiple access with collision avoidance (CSMA/CA). CSMA/CA is a listen before talk (LBT) mechanism. A station ready to transmit data senses the medium if it is idle, if not, it waits until the channel is available before transmitting. If two or more stations transmit at the same time then collision occurs. Ethernet is able to sense a collision on the medium because when transmitting at the same time the signal level on the wire increases, the computers transmitting detect the signal change assuming that a collision has occurred and defer their transmission. IEEE 802.11 wireless stations do not have this capability because air is the medium. In order to communicate, IEEE 802.11 access mechanism must avoid collisions. CSMA/CA is more ordered than CSMA/CD. To understand how the mechanism works a simple telephone conference call analogy example will be more helpful [4]:

- Before a participant speaks, she must indicate how long she plans to speak. This indication gives to the potential speakers an idea of how long to wait before they have an opportunity to speak.
- Participants cannot speak until the announced duration of a previous speaker has elapsed.
- Participants are unaware of whether their voices are heard while they are speaking, unless they receive confirmation of their speeches when they are done.
- If two participants happen to start speaking at the same time, they are unaware of the fact that they are speaking over each other. The speakers determine they are speaking over each other because they do not receive confirmation that their voices were heard.
- The participants wait a random amount of time and attempt to speak again, should they not receive confirmation of their speeches.

The above rules help prevent collisions. In order to function, preventing collisions is very important to wireless networks, because there is no collision detection mechanism. The CSMA/CA detects a collision when a station transmitting data does not receive an expected acknowledgment. This ways WLAN's are more robust since the performance drop of the network due to a collision is much higher on a wireless LAN than on a wired LAN. CSMA/CA access mechanism and the alikeness to Ethernet protocol, contributed to the establish of IEEE 802.11 as the wireless standard, against other WLAN technologies, such as HyperLAN.

2. WLAN PROTOCOLS

The original IEEE 802.11 standard specified three Physical Layers (PHYs) in 1997: infrared at 1 Mbps, 2.4 GHz frequency hopped spread spectrum (FHSS) at

1 or 2 Mbit/s and 2.4 GHz direct sequence spread spectrum (DSSS) at 1 or 2 Mbps. In 1999 two standards follow up: IEEE 802.11a and IEEE 802.11b, then in 2003 IEEE 802.11g and introducing Quality of Service (QoS) in 2005 with IEEE 802.11e.

IEEE 802.11a

The IEEE 802.11a is a standard that uses the same features of data link layer of IEEE 802.11 standard but differs in the Physical layer with the use of OFDM technology. This standard operates at a frequency of 5 GHz, 20 MHz channel bandwidth and provides data rates up to 54 Mbps, with achievable throughput of 24 Mbps. The thinking behind the use of 5 GHz band was the fact that the 2.4 GHz band was heavily used and using the relatively unused 5 GHz band will give IEEE 802.11a an advantage. On the other hand the use of such a high frequency brings a disadvantage, which is the deduction of operation range due to the fact that IEEE 802.11a signals are absorbed more easily by obstacles, like walls, because of the smaller wavelength. This results to the deduction of the range because it cannot penetrate as far as other standards like IEEE 802.11b. However, IEEE 802.11a working at 5 GHz, has the same or greater range due to less interference.

IEEE 802.11b

IEEE 802.11b was released the same time as IEEE 802.11a and uses the same features as the original standard such as DSSS in Physical and same media access. It operates at a frequency of 2.4 GHz, 20 MHz channel bandwidth and provides data up to 11 Mbps. Because of the increased throughput in compare to the original standard, it led to the acceptance of IEEE 802.11b as the protocol to use in wireless LANs. A major disadvantage of the IEEE 802.11b is the interference of the transmissions from other devices operating in the 2.4 GHz band such as Bluetooth and cordless telephones.

IEEE 802.11g

IEEE 802.11g released in 2003, applies the same access features as the original standard but uses the same OFDM technology as IEEE 802.11a. It operates at a frequency of 2.4 GHz, 20 MHz channel bandwidth with maximum data rates up to 54 Mbps and an average throughput of 22 Mbps. IEEE 802.11g is fully backwards compatible with IEEE 802.11b, so both can coexist and interoperate. IEEE 802.11g standard was rapidly adopted, due to the increase in data rates as well as to reductions in manufacturing costs. Most wireless devices now operate in a dual band IEEE 802.11b/g mode. In a network, however, the existence of multiple protocols will lead in reduce of the data rate of the overall network, because the data rate that will be used will be the one of the protocols with the lower rate. Like IEEE 802.11b, a major disadvantage for IEEE 802.11g is also the interference in transmissions from other devices operating in the 2.4 GHz band.

IEEE 802.11e

To understand the reason behind this amendment, Quality of Service (QoS) must be referred. With the increase in data rates, the demand for networked real time services grew (like VoIP, HDTV, Streaming Video, Online games), so did the need for networks to provide assistance for these delivery services. To ensure the delivery of such services, there is a demand that both the application of the service and the network infrastructure are capable to organize and set the delivery of the data. QoS is a control mechanism that can provide different priority to different users or data flows, or guarantee a certain level of performance to a data flow in accordance with requests from the application program.

Why is QoS important? Each type of traffic has its unique requirements in terms of bandwidth, delay, loss, availability. With the increase in real time services networks have to support many different types of applications. Many of these applications require low latency, otherwise the quality may be significantly affected resulting in a deduction of the performance or not functioning at all. For example in VoIP if there is a significant delay or packet loss then the experience significantly falls resulting in a bad communication or not communication at all. So QoS can be applied to support these services for best use. It can do that by prioritizing the network traffic. This means that packets are categorized based on the application and get different priority based on their category. For example a voice packet has a higher priority than a video packet.

IEEE 802.11e is an amendment to the IEEE 802.11 family standards that defines Quality of Service for use in wireless LAN applications through enhancements to the MAC layer. IEEE 802.11e defines 8 user priorities which are grouped into 4 Access Categories (AC) defined as Voice, Video, Best Effort, and Background. Each access category contains 2 different user priorities, as shown in Figure 3. Because the DCF supports only best effort services and doesn't guarantee in bandwidth and delay the design of this priority scheme is based on three major changes which now the MAC works and it's called Enhanced Distributed Coordination Access (EDCA). The three major changes are:

- 4 priority queues (Access Categories) are created for traffic
- Each of the 4 priority queues has an Arbitration Inter-Frame Space (AIFS) value which replaces the Distributed Inter-Frame Space (DIFS) value previously used in DCF for all data and management frames
- In addition to unique time values to each queue, Random Back off timers defining the Contention Window minimum (CWmin) and maximum (CWmax) values, exist for each of the 4 priority queues

Table 9-1—UP-to-AC mappings

Priority	UP (Same 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
Highest	5	VI	AC_VI	Video
	6	VO	AC_VO	Voice
	7	NC	AC_VO	Voice

Figure 3. Access Categories (AC) for QoS [13]

The DCF and EDCA mechanisms are analyzed further in this chapter and in order for the future protocols and how these mechanisms work to be discussed, it is important to clarify how MAC and PHY are implemented and function.

2.1. PHY

As already shown above in the OSI model the PHY is the first layer. The Physical Layer protocols describe the means, in other words how to activate, maintain and deactivate physical connections for bit transmission to and from a network device. In simple words this means that the role of the OSI Physical layer is to convert the binary digits of Data Link layer's frames into signals and to transmit or/and receive these signals to/from the medium which can be copper wires or optical fiber or wireless, that connect network devices. The PHY works in the following way: At the stage of a communication process when PHY is ready to send, the user data has been segmented by the Transport layer, placed into packets by the Network layer, and further encapsulated as frames by the Data Link layer. The Physical layer takes the frame from the upper layer (Data Link) and creates signals that represent the bits in each frame. When signals are created are then sent on the medium one at a time. As already mentioned the physical, beside sending signals also receives from the medium. Signals from the media are restored to bits and are passed to the Data Link layer as a complete frame. Sending along with receiving and how these two work depend on the device and the protocol that is being used at the Physical layer. Technologies for physical transmission for all these protocols are: Narrowband Transmission, Spread Spectrum Transmission, Frequency Hoping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM).

The radio frequency spectrum consists of sections known as bands. Radio signals transmit on only one frequency known as *narrowband transmission*. Radio stations take advantage of narrowband transmissions by transmitting on only one frequency, such as 102.6 or 93.1 FM. A disadvantage of narrowband transmissions is the interference from another radio signal that is being transmitted at or near the same frequency. *Spread spectrum transmission* is an alternative to narrowband transmission and as its name says, it takes a narrow weaker signal and spreads it over a broader portion of the radio frequency band. This way of transmission reduces the effect of and leads to lower power consumption.

Moreover radio receivers will ignore the signal spread considering it as noise, allowing for greater security and creating less interference with other systems. *Frequency Hopping Spread Spectrum (FHSS)* invented in 60's, used 84 frequencies. During the transmission the frequency continually changes. The first short burst is transmitted at one frequency, the second at another frequency, and so on. The amount of time spent on a specific frequency is known as the *dwell time*, and the sequence of changing frequencies is known as the *hopping code*. Bluetooth make use of FHSS in the 2.4 GHz frequency, changing the frequency 1600 times a second. *Direct Sequence Spread Spectrum (DSSS)* is a spread-spectrum modulation technique with data rates of 1,2 Mbps at 2.4 GHz, in which the transmitted signal takes up more bandwidth than the information signal that is being modulated. DSSS multiplies the data being transmitted by a "noise" signal, a pseudorandom sequence of 1 and -1 values, creating a much higher transmission frequency and spreading the original signal into a much wider band, resulting in an effect similar to "white noise" or static. A receiver can extract meaningful data from the transmission by multiplying it by the same pseudorandom sequence (1 and -1 values). This process is known as "de-spreading." The DSSS is effective against jamming, can share a single channel among multiple users and reduces the chance that a transmission will be intercepted. Providing additional data rates, DSSS was used with complementary-code keying(CCK). This coding allows a receiver to correctly read them. DSSS/CCK provided 5.5 or 11 Mbps at 2.4 GHz. *Orthogonal frequency-division multiplexing (OFDM)* is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method. OFDM splits a communication signal in several different channels, each operating at a different frequency. This process makes it possible for multiple channels to operate within close frequency levels without interfering one another in any other data transmission in any one channel. OFDM was introduced with the development of IEEE 802.11a and provided data rates up to 54 Mbps at 5 GHz, but because of this band the adoption was low. OFDM was used again with IEEE 802.11g but this time at 2.4 GHz and data rates up to 54 Mbps and experienced large market success.

2.2. MAC

The medium access control (MAC) layer provides addressing and channel access control that makes it possible for multiple stations on a network to communicate with each other. The basic IEEE 802.11 MAC layer uses the distributed coordination function (DCF) to share the medium between multiple stations. DCF relies on CSMA/CA and optional IEEE 802.11 RTS/CTS (Ready to Send/Clear to Send) to share the medium between stations. To ensure fairness each station sends one packet but the drawback lies in the fact that if a station with a large packet and low bit rate sends the packet then it will take a long time to send its packet and transmission from all other stations will be held off. The original IEEE 802.11 MAC defines another coordination function called the point coordination function (PCF). This is available only in "infrastructure" mode, where stations are connected to the network through an Access Point (AP). PCF mode is optional and is not widely implemented by the APs or Wi-Fi. APs use the PIFs interval to send *beacon* frames, in which between these *beacon* frames, the PCF defines two periods: the Contention Period (CP) and the Contention Free Period (CFP). In the CP, DCF is used and in the CFP, the AP sends Contention-Free-Poll (CF-Poll) packets to each station “asking” them if they have packets to send. In this period the AP is the coordinator of the communication between the stations and all the packets of the communication go through the AP. Although this allows a better management of real time services, PCF does not define classes of traffic as it is done in QoS. With the need of QoS to improve the function and efficiency of real time services, the IEEE 802.11e brought a major enhancement to IEEE 802.11 legacy MAC. The IEEE 802.11e enhances the DCF and the PCF, through a new coordination function, called the hybrid coordination function (HCF). HCF, defines two methods of channel access: HCF Controlled Channel Access (HCCA) and Enhanced Distributed Channel Access (EDCA), both defining Traffic Categories (TC) for QoS traffic.

3. IEEE 802.11 DCF and IEEE 802.11e EDCA

The widely used distributed coordination function (DCF) is a distributed channel access mechanism based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). A successful packet transmission in DCF is illustrated in Figure 4.

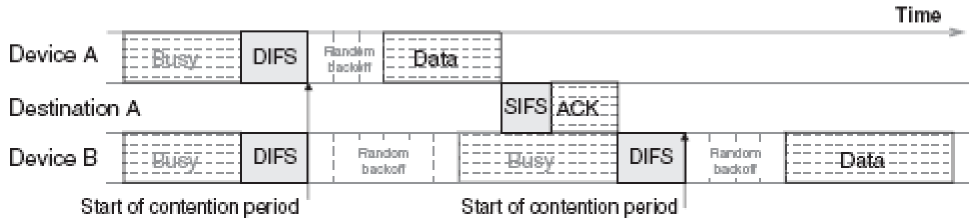

Figure 4. A successful data transmission [www.cisco.com]

Optional RTS/CTS (Request To Send/Clear To Send) mechanism could be along with the CSMA/CA channel contention mechanism as shown in figure 5. In wireless devices the default setting for RTS/CTS operation is off.

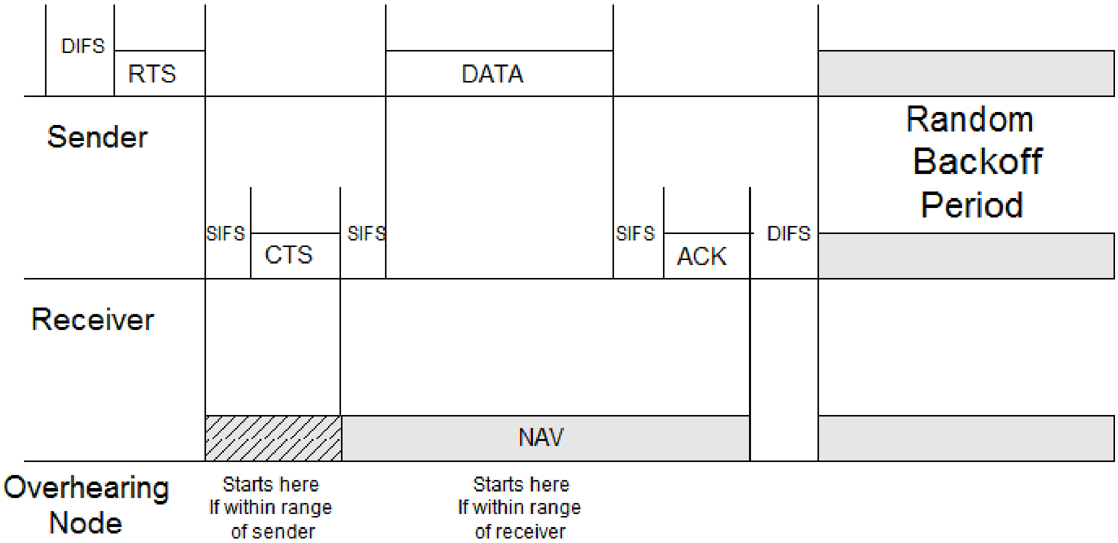

Figure 5. Data transmission with RTS/CTS [www.cisco.com]

When a station has a data frame to transmit, MAC headers are added. The station waits a fixed time interval called Distributed Interframe Space (DIFS) before transmission. After the DIFS MAC “listens” to the channel to see if is idle. If the channel is idle MAC enters in a backoff procedure with a backoff timer, which is determined randomly by the contention window (CW). MAC continues to “listen” If the channel is still idle during and after the backoff procedure and if it is the station immediately accesses the channel, else “freezes” the backoff timer for as long as it is busy and continues the countdown when channel is sensed idle again. The transmitting station sends the data and waits an acknowledgement (ACK) from the station that received the data. A short interframe space (SIFS) time is applied between the response and the reason that created the response, e.g. data and ACK. This interval is used before replying the ACK message. The whole transmission procedure ends when the sending station successfully receives the ACK frame (Figure 6).

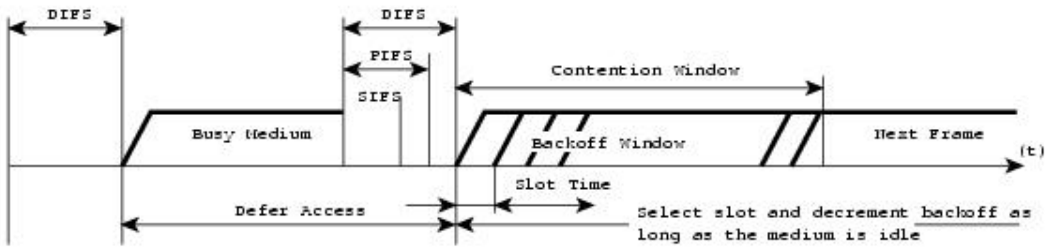

Figure 6. Transmission Procedure [www.ieee.org]

Enhanced distributed channel access (EDCA) is a contention-based channel access mechanism, extension of the basic DCF and introduced in IEEE 802.11e providing QoS. Support of QoS is provided with four access categories (ACs), each with independent and different backoff and contention parameters. The parameters of ACs are set to provide differentiated QoS priorities for ACs (Figure 3). Under EDCA, traffic leaving the system is sorted logically into four queues, one for each AC (Figure 7). An instance of the EDCA media access “runs” for each logical queue, contending for access with its own AC’s parameters when the queues are not empty. The EDCA access functions like DCF to compete for access to the medium. A station that has data to transmit defers for a fixed period, the arbitration inter-frame space (AIFS) instead of DIFS. If the medium is idle then it defers for a random backoff period. The parameters for EDCA access are similar to the parameters that are used for the DCF, but defined per AC. That means that there is an AIFS interval for each AC and is referenced as AIFS[AC]. The same way the backoff procedure is defined based on the AC and the contention window from which the random backoff count is selected is referenced as CW[AC]. In case two or more instances of ACs competing for access, gain access at the same time, a collision occurs. The highest priority AC gains the access and the other one doubles its contention window and re-tries for another access attempt.

IEEE 802.11e MAC besides providing QoS it also introduced a key concept called Transmission Opportunity(TXOP).

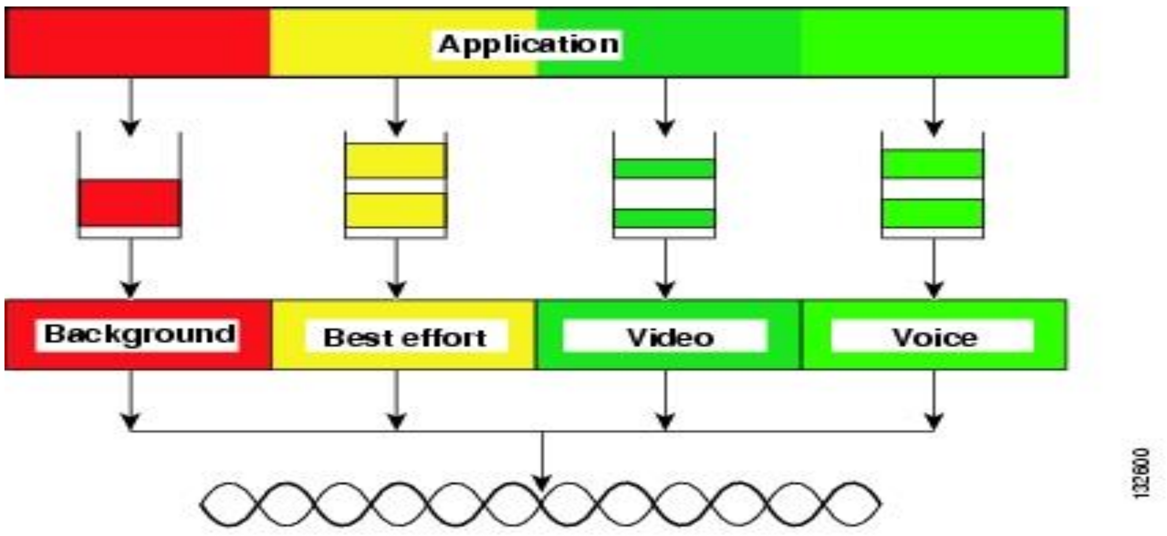

Figure 7. Logical Queues for each AC [www.cisco.com]

TXOP mechanism defines a period of time during which a station accessing the channel may transfer multiple data frames of a particular traffic class without entering backoff procedure, which reduces the overhead and enhances the efficiency of channel utilization. Along with TXOP the block Acknowledgment (block ACK) mechanism was introduced to further enhance the channel utilization efficiency. A single Block ACK can acknowledge a block of data frames instead of an ACK frame for each individual data frames resulting in the reduce of the overhead, because SIFSs and multiple ACKs are saved.

DCF's inefficient channel utilization because of the overhead resulting in limiting achievable throughput and the need for HT(High Throughput) led the researchers to find ways to improve MAC efficiency so that the overhead can be reduced to achieve higher throughput. Although IEEE 802.11e adds support of QoS, TXOP and block ACK the inefficiency in channel utilization is not fully resolved. To satisfy the need of HT and further improve the efficiency, research in MAC and PHY layer led to IEEE 802.11n.

4. IEEE 802.11n

With the need of higher data rates beyond 25 Mbps of IEEE 802.11a/g, proposals for developing an amendment capable of at least 100 Mbps in MAC throughput led to IEEE 802.11n. In January 2002 major interest was expressed at Wireless Next Generation Standing Committee (WNG SC) for higher data rates extending that of IEEE 802.11a/g. The new High Throughput (HT) Study Group (SG) was formed in September 2002 to formulate the purpose and scope of the amendment. HT SG's work continued in TGn. IEEE 802.11n Task Group (TGn) was created in September 2003 to develop an amendment to the IEEE 802.11 standard and decided to proceed with a call for proposals in May 2004. With a call of proposals, companies or group of people form proposal teams and create a proposal that on acceptance would become the initial draft of the amendment. All the proposals were based on same features and technologies, such as MIMO, 40 MHz bandwidth, frame aggregation techniques and block Acknowledgment and in January 2006 a joint proposal was adopted and submitted in TGn. Therefore drafts were issued with proposals, comments, Letter Ballots and Sponsor Ballots until June of 2009 when draft 11.0 passes sponsor ballot. One month later this year there was approval to send Final WG draft to Standards Board. Finally the final draft was approved on September and published on October of 2009.

IEEE 802.11n advantage is the significant increase in both throughput and range in the 2.4 and 5 GHz bands. The PHY data rate starts from 270 Mbps and increases up to 600 Mbps with four spatial streams and 40 MHz bandwidth, whereas range from 70 meters indoors to 250 meters outdoors. Based on the foundation of IEEE 802.11a/b/g/e, numerous new features in PHY and MAC layers are introduced to enhance the throughput of IEEE 802.11 WLAN. The major features are: MIMO-OFDM, 40MHz channel operation, Beam Forming, Space Time Block Coding (STBC), Green Field mode, Short guard interval (GI), low density parity check (LDPC) introduced in physical layer and Frame Aggregation, enhanced Block ACK, Reduced Interframe Space (RIFS), Reverse direction introduced in MAC. All these features will be further analyzed in later chapters, specifically in chapter 2 the PHY and in chapter 3 the MAC ones. In order for devices working under IEEE 802.11n to coexist and be compatible, the IEEE

802.11n PHY operates in one of three modes: Non HT, Mixed and Green Field mode. Non HT, or else Legacy Mode, makes it possible for legacy standards (IEEE 802.11a/b/g) to communicate with IEEE 802.11n devices in both 2.4 and 5 GHz bands with maximum speed of the legacy standard being used. Mixed Mode ,or also known as L-SIG TXOP Protection, packets are transmitted on multiple frequencies and bands to support multiple standards with legacy header. The Greenfield mode is an optional high-throughput mode, which is not backward compatible with legacy (IEEE 802.11a/b/g) protocols and is expected to provide maximum performance benefits of IEEE 802.11n.

5. Conclusions

Technology advances, demand and interest for HT will lead to the research and develop of new WLAN standards in the future. Currently IEEE 802.11n with its PHY and MAC features, paved the way for research of higher data rates and ranges. An introduction of IEEE 802.11 family standards was made here along with the new WLAN protocol of IEEE 802.11n and its key features. Chapter 2 covers the PHY layer of IEEE 802.11n and chapter 3 the MAC layer providing a more comprehensive review, further investigating it. Chapter 4 accumulates papers and proposals about the MAC, Chapter 5 covers Interworking, QoS and Security of IEEE 802.11n and Chapter 6 concludes and discusses future protocols.

CHAPTER 2

IEEE 802.11n Physical Layer

INTRODUCTION

In this chapter the Physical layer of IEEE 802.11n is discussed. Physical layer's data rates go up to 600 Mbps, achieved by MIMO (Multiple Input Multiple Output) technology through the use of multiple transmit and receive antennas and by channel bonding which is a 40 MHz bandwidth mode. Further enhanced with the use of techniques, such as Spatial Division Multiplexing (SDM), Transmit Beam forming, Low Density Parity Check (LDPC) and Space Time Block Coding (STBC), throughput is increased, by two to four times, as well as the range of the transmission.

1. IEEE 802.11n Physical Layer

In order to remember, the OSI Physical layer converts the binary digits of Data Link layer's frames into signals and transmits or/and receives these signals to/from the medium which can be copper wires or optical fiber or wireless. For more details about the Physical layer go back to Chapter 1 at 2.2 PHY. To achieve higher throughput and range, IEEE 802.11n describes technologies and techniques that modify the IEEE 802.11 standard. IEEE 802.11n PHY uses Orthogonal Frequency Division Multiplexing OFDM (see Chapter 1 for details) modulation to transmit and operates at 2.4 GHz and 5 GHz frequency bands.

MIMO

The major key feature introduced to increase the PHY data rate is MIMO (Multiple Input Multiple Output), which is the use of multiple antennas for transmission and reception of data. From traditional Single Input Single Output (SISO) systems, by using multiple antennas, there is an increment from one antenna and a single spatial stream to four antennas and four spatial streams. This increases the data rate by a factor of four, so MIMO alone provides higher data rates. Spatial stream is one of several bit streams that are transmitted over multiple spatial dimensions created by the use of multiple antennas at both ends of a communication link, as defined in IEEE 802.11n standard. Benefits of MIMO besides the increment in throughput and range is the decrease of bit error rate because of the increased spectral efficiency.

40 MHz

Another key feature of IEEE 802.11n is the increase of the 20 MHz channel bandwidth to 40 MHz. This is an optional feature that allows the combination of two adjacent 20 MHz channels into a 40 MHz, transmitting in a wider channel bandwidth improving the amount of data by a factor of two. The trade-off is the reduce in number of the total available channels and at the same time the interference it causes especially in the 2.4 GHz band, where more devices operate and available channels are less than the 5 GHz.

Techniques to boost the benefits of using multiple antennas are spatial division multiplexing (SDM), space time block coding (STBC) and transmission beam forming.

Spatial Division Multiplexing (SDM)

To achieve higher throughputs using multiple antennas (MIMO), SDM is used. Multiplexing is a method of combining many signals into a single transmission channel. Spatial multiplexing is the transmission of several different data bits via several spatial channels. SDM is a technique that involves the combination of multiple data streams across spatial dimensions in a single transmission. Multiple antennas are used to transmit independent data streams which are individually received by the receiver.

Space Time Block Coding (STBC)

STBC is an optional PHY feature of IEEE 802.11n. In difficult environments the transmitting signals, due to phenomena like reflection (signal changes direction and returns to the medium from which it originated) and/or scattering (signal deviates from straight trajectory) and/or refraction (change in signal's direction because of its speed change) are weakened and/or may be corrupted. STBC is a technique that on the transmitting side transmits multiple copies of data stream across multiple antennas and on the receiving side it combines all the copies received in an optimal way. This leads to the increase of the data copies that are correctly decoded resulting in more information being extracted.

Transmit Beam forming (TxBF)

Transmit Beam forming is an optional PHY technique in which the goal is the improvement of the receive signal strength to further enhance the reception in the receiver. Before transmission a session exchange of PHY protocol data units occurs to calibrate the radio channel. Channel estimates are used to generate a spatial mapping matrix. Based on the information gathered from this process, beam forming is used to aid the signal quality and higher quality means that data rates are available at longer range. There are two types of beam forming: implicit and explicit beam forming.

- Implicit beam forming is based on the fact that a channel between two stations A and B is the transpose of the channel between stations B and A. So a transmitting station will use the transpose of its own channel estimates to estimate the ones of the remote side.
- In Explicit beam forming the transmitting station requires from the remote one to send the channel estimates or mapping matrices back to the transmit station for beam forming.

Although TxBF is considered a PHY technique, it requires also MAC control for channel calibration and exchange of information for channel estimates or mapping matrices.

There are also other optional PHY features that help achieve increase in throughput and range.

Low Density Parity Check (LDPC) codes

LDPC codes are optional PHY features of IEEE 802.11n developed by Robert G. Gallager in 1963 but found use in 2009 for the amendment. LDPC code is an error correcting code and is used to ensure an efficient and reliable transmission over a noisy channel providing a better coding performance. The codes are constructed from sparse parity check matrices that are randomly generated.

Guard Interval (GI)

GI is another optional feature which is used to assure that individual transmissions will not interfere with one another. The transmissions may come from different users or the same user. The purpose of the guard interval is to offer protection to propagation delays, reflections etc, to which transmission signals are sensitive. In IEEE 802.11 family the GI used is 800 ns between each OFDM symbol. To increase data rates the GI in IEEE 802.11n is reduced to 400 ns between each OFDM symbol providing 11% data increase. The drawback in the use of the shorter GI is the higher packet error rate when delay exceeds GI.

Greenfield mode

The Greenfield mode is an optional HT mode in which there is no backward compatibility. In Greenfield mode the non HT preamble of the Mixed mode is omitted for higher efficiency. It is used when the environment is free of any legacy devices so backward compatibility is not required. IEEE 802.11n Mixed mode preamble has a length of 36 μs for one spatial stream and up to 48 μs for four. With the elimination of the preamble that supports backward compatibility Greenfield's preamble is 12 μs shorter, increasing efficiency which is essential for real time services such as VoIP.

Other minor modifications were also made to increase the data rate. The highest coding rate in IEEE 802.11 is 3/4. In IEEE 802.11 PHY this is increased to 5/6 for an additional data rate increase of 11%. Moreover with the advance in technology it was justified the use of two extra frequency subcarriers into the guard band on each side of the waveform, increasing the data rate by 8%.

With the introduction of all these new features another functional requirement generated for IEEE 802.11n, the interoperability with the other wireless protocols of IEEE 802.11 family. This requirement was met in the PHY by defining a Mixed format waveform that begins with legacy preamble. The legacy preamble allows the legacy devices to detect the IEEE 802.11n Mixed format packet, decode it and defer their transmission. To ensure the backward compatibility between 20 MHz and 40 MHz devices, the preamble of the 40 MHz is identical to the 20 MHz and is repeated in two adjacent 20 MHz band channels that form the 40 MHz. Mixed format which enables backward compatibility increases the overhead which results in efficiency deduction.

2. Conclusions

In this chapter technologies and techniques used to achieve higher data rates and range proposed by IEEE 802.11n PHY were discussed. Some of these improvements are optional because problems occur when legacy devices are in the same WLAN. To ensure backward compatibility with the legacy devices, Mixed format mode is used by IEEE 802.11n PHY. On the contrary when no legacy devices are present in the WLAN Greenfield format mode is used instead to take advantage of the HT devices. If these optional mechanisms are employed in a WLAN consisting only of HT devices the PHY rate can achieve data rates up to 600 Mbps (four spatial streams and 40 MHz band). Mandatory and optional features of IEEE 802.11n PHY are shown in Figure 8.

Mandatory	Optional
1, 2 spatial streams	3,4 spatial streams
20 MHz	40 MHz
Mixed Format	Greenfield Format
MIMO/SDM	Transmission Beam forming
	STBC
Convolution Code	LDPC code

Figure 8. Mandatory and Optional IEEE 802.11n Features

CHAPTER 3

IEEE 802.11n MAC Layer

INTRODUCTION

In this chapter the MAC layer of IEEE 802.11n is discussed. To satisfy the need of high speed WLANs, mechanisms introduced in IEEE 802.11n increase the MAC efficiency, boosting the MAC throughput over 100 Mbps. Frame Aggregation, Block ACK, Reverse Direction, TXOP, RIFS are the key features of this throughput enhancement. IEEE 802.11n adds QoS support and uses TXOP and Block ACK of IEEE 802.11e and further enhances them.

1. Medium Access Control

Medium Access Control is the lower sub layer of the OSI Data Link Layer and provides addressing and channel access control that makes it possible for multiple stations on a network to communicate with each other. For access mechanisms and types of medium access you can go back to Chapter 1 at 2.2 MAC and 3. IEEE 802.11 DCF and IEEE 802.11e EDCA sub chapters. Channel access mechanisms, DCF, EDCA, HCCA are further analyzed.

DCF

In DCF a station that wants to transmit data senses the medium for a duration of distributed inter frame space (DIFS). If the medium remains idle during and after DIFS the station transmits, else it remains to go idle, defers for DIFS and then waits for a random backoff period. If medium remains idle during the DIFS and backoff period then station transmits, else it “freezes” the backoff timer and resumes countdown when medium is again idle. For stations to determine the state of the medium DCF uses both PHY and MAC functions. The station uses energy detection to sense the PHY and MAC uses a virtual carrier sense mechanism called network allocation vector (NAV). So a station determines the medium idle when only both PHY and MAC mechanisms indicate it. Furthermore an optional feature of DCF called RTS/CTS is used to minimize the chance of collisions especially for hidden node scenarios. In DCF there is no coordinator to organize and control channel access, so stations compete for channel access.

In order to understand more how channel access works, a reference is made to channel access timings. Channel access timings are shown in Figure 9.

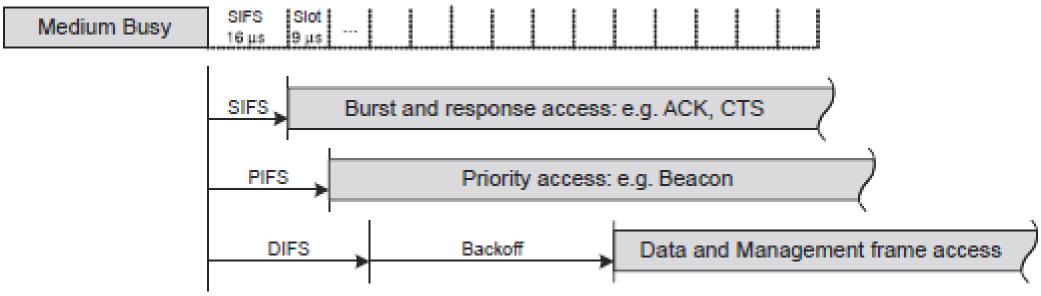

Figure 9. Basic Channel Access timings [1]

- Short Inter frame Space (SIFS) is a short timer used for the change of antennas state, from transmitting to receiving and vice versa. It is also used to separate data frames in data burst. The SIFS duration for IEEE 802.11n is 16 μs and it is defined by a parameter called aSIFSTime.
- PCF Inter Frame Space (PIFS) is a timer that AP uses to coordinate the channel access in a network, gaining access to send a Beacon or start a contention free period. PIFS timer is given by the adding of aSIFSTime and aSlotTime.
- DIFS is a timer used to transmit data and management frames and is given by the equation: DIFS = aSIFSTime + 2 x aSlotTime.
- Slot time is a timer that provides time for transmitting station's preamble to be detected by other stations. IEEE 802.11n slot time is 9 μs.
- Random Back off time is a random number generated by multiplying a random integer number drawn from contention window with Slot times. The contention window starts with CWmin and doubles each time there is an unsuccessful transmission until it reaches CWmax. When CWmax is reached it remains at that value until a successful delivery which resets the CW.

DCF promotes fairness by allowing each station to send the same number of data frames when it transmits. This results to stations achieving same throughput beside individual PHY data rates. The drawback in this is that if a station with a large packet and low bit rate sends the packet then it will take a long time to send its packet and transmission from all other stations will be held off.

EDCA

Enhanced distributed channel access (EDCA) is a contention-based channel access mechanism, extension of the basic DCF and introduced in IEEE 802.11e providing QoS. Support of QoS is provided with four access categories (ACs), each with independent and different backoff and contention parameters. The parameters of ACs are set to provide differentiated QoS priorities for ACs (Figure 3). EDCA access functions work like the ones of DCF, they compete for the access after an Arbitration Inter Frame Space (AIFS) timer. The changes for EDCA is the AIFS instead of DIFS, which has a value for each AC (AIFS[AC]) and the CW from which backoff timer depends from the AC (CW[AC]).

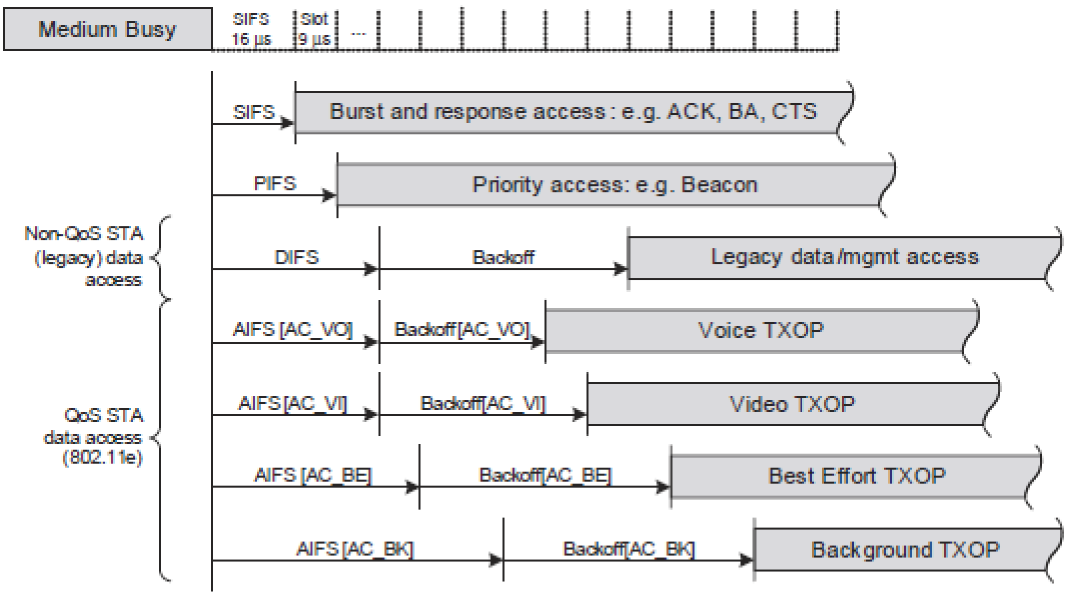

Figure 10. Channel Access priorities for DCF and EDCA [1]

Channel access timings for EDCA are shown in Figure 10. AIFS for an AC is given by the equation:

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

Furthermore prioritize access in EDCA is given through the use of AIFSN and the CW[AC] in order to provide stronger differentiation between the access parameters.

DCF's inefficient channel utilization because of the overhead resulted in limiting achievable throughput. Improving MAC efficiency was crucial to achieve higher throughput. Although IEEE 802.11e adds TXOP and block ACK the inefficiency in channel utilization is not fully resolved. This can also be shown from the theoretical throughput upper limit (TUL). TUL simply means that increasing the raw data rate even to infinity without reducing the overhead , the throughput achieved is bounded to a maximum value. TUL shows how important is to reduce the overhead to achieve HT data rates.

Researches upon TUL and MAC inefficiency presented the problem and at the same time the solution, improvement of the MAC efficiency. IEEE 802.11n MAC features boost the efficiency of the MAC achieving throughput of at least 100 Mbps. The key features are:

- Frame Aggregation
- Block ACK
- Reverse Direction
- RIFS

2. MAC Mechanisms

Frame Aggregation

FA is the key feature for increasing efficiency because the MAC efficiency improves as the frame size increases as shown in Figure 11.

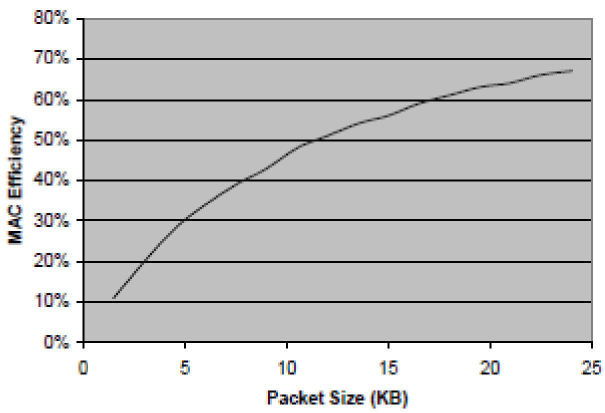

Figure 11. MAC efficiency versus packet size [3]

The time of the data on air decreases when the rates increase but at the same time the overhead remains the same decreasing efficiency. FA aggregates multiple data packets into one larger data frame. In this way the data length increases (more packets in one large frame) increasing the efficiency by reducing the overhead (header and SIFS are saved for each packet). There are two forms of aggregation: Aggregate MAC Service Data Unit (A-MSDU) and Aggregate MAC Protocol Data Unit (A-MPDU). For FA the mechanisms can be used individually or by combining them in a two level aggregation.

A-MSDU obtains MSDUs from the LLC that have the same destination address and same traffic id (TID) and aggregates them into a single MPDU. The encapsulation is shown in Figure 12.

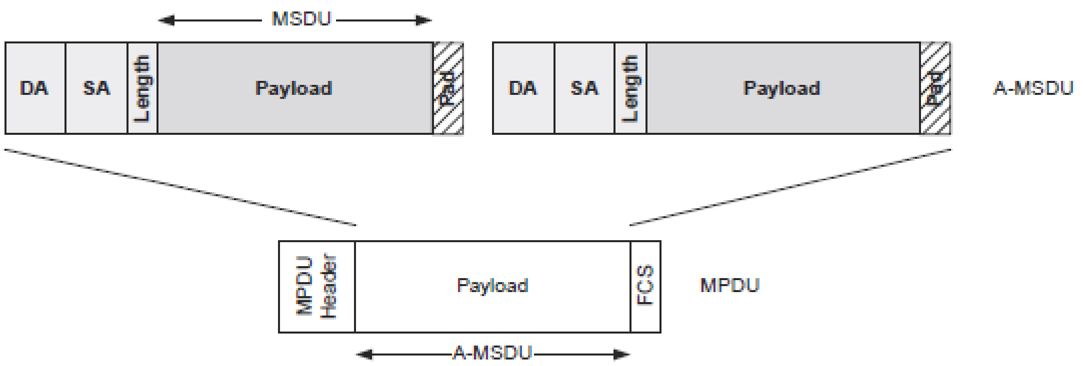

Figure 12. A-MSDU encapsulation [1]

Each MSDU sub frame header together with SDU is padded with 0 to 3 bytes to round it, to be multiple of 4 bytes for ease in the de-aggregation process. Maximum length of an A-MSDU is either 3839 or 7935 bytes and there is also a maximum waiting time before creating an A-MSDU parameter.

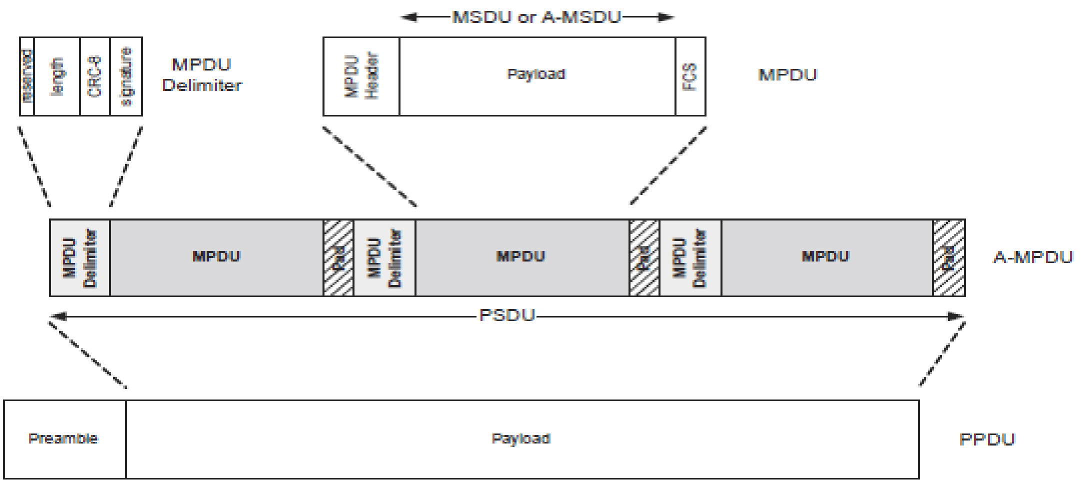

Figure 13. A-MPDU encapsulation [1]

If an error occurs in an A-MSDU or MSDU the whole A-MSDU has to be retransmitted.

A-MPDU aggregates MPDUs at the bottom of the MAC. Figure 13 shows the A-MPDU encapsulation. Unlike A-MSDUs, MPDUs ready for transmission are aggregated in an A-MPDU without waiting for more. All MPDUs have same destination address and same TID. Like MSDUs, MPDUs have an MPDU delimiter at the beginning (separates MPDUs) and padding at the end ensuring that each one is a multiple of 4 bytes. In deaggregation process first CRC integrity is checked then if the value is right starts the deaggregation progress. Maximum aggregation size is 65535 which is multiple times of that of A-MSDU. The advantage of A-MPDU in BER environments consists in the fact that if an error occurs, then the MPDU with the error is only retransmitted decreasing delay and overhead.

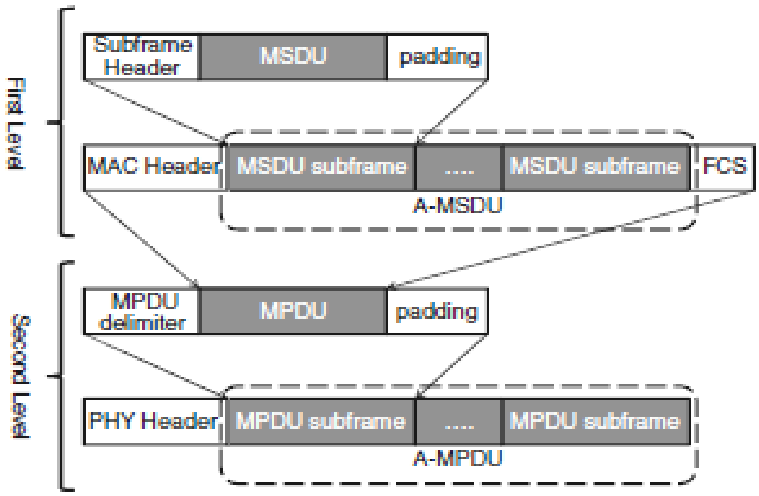

Figure 14. Two level aggregation [5]

In two level aggregation the MSDUs received by the upper layer are in hold for a short time until MSDUs with same destination address and TID form the maximum size of A-MSDU. Then the A-MSDU with MSDUs with same destination address and TID which couldn't be aggregated in the A-MSDU are concatenated to form an A-MPDU. The FA doesn't support fragmentation, therefore only complete MSDUs can be aggregated to A-MPDU. The two level FA is shown in Figure 14.

Block ACK

Block ACK was first introduced with IEEE 802.11e to further enhance the MAC efficiency and increase throughput. IEEE 802.11n uses this feature and enhances it even further with the use of FA. Block ACK acknowledges multiple data frames with one block ACK reducing the overhead. There are two forms of Block ACK the original of IEEE 802.11e and the enhanced introduced in IEEE 802.11n to improve efficiency with combination of aggregation and higher data rates. The enhanced two forms are called HT-immediate Block ACK and HT-delayed Block ACK.

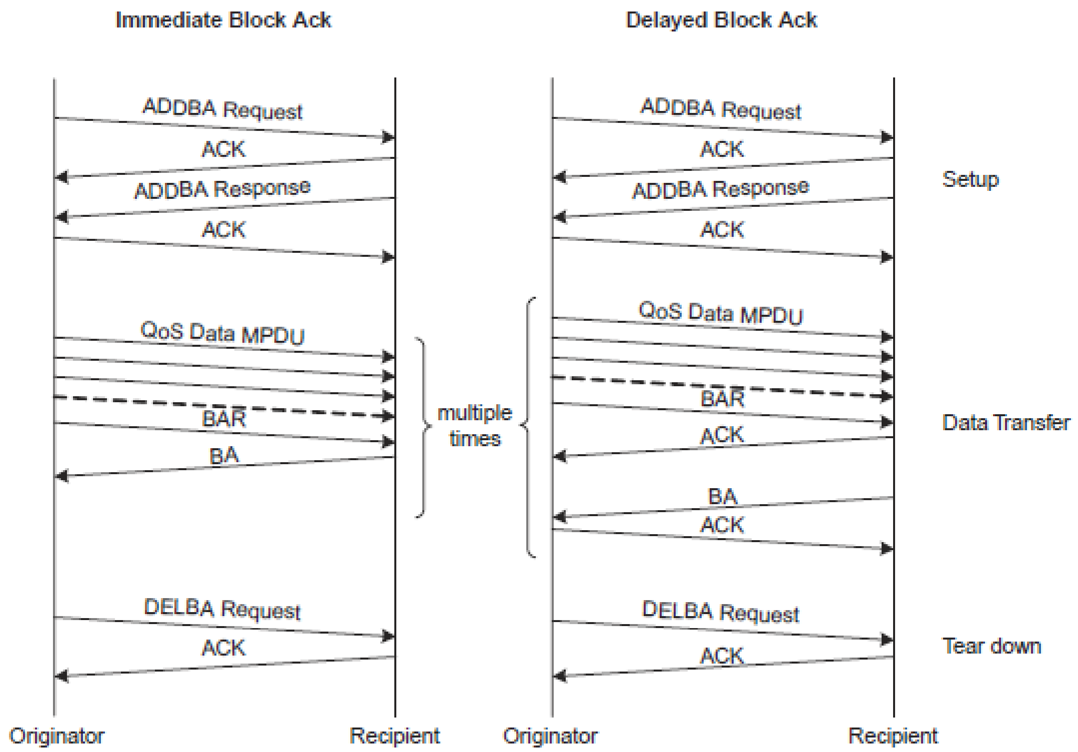

Figure 15. Immediate and delayed Block ACK [1]

The IEEE 802.11e immediate and delayed block ACK mechanisms are shown in Figure 15. The difference between these two mechanisms is found in the handling of the BAR and BA frames. With Immediate Block ACK the BAR causes the immediate BA response, whereas with delayed Block ACK the BAR solicits an ACK from the recipient to the originator followed by BA, which is then acknowledged by the recipient. For IEEE 802.11n the above process is changed to support multiple MPDUs in an A-MPDU. As frame size increases from FA also error rate increases in BER environments. By supporting A-MPDUs this drawback is overcomed because only MPDUs with errors are retransmitted (Block ACK acknowledges the correct MPDUs). Block ACK mechanism is implemented only for A-MPDU with 64 as the maximum number of MPDUs in an A-MPDU. Block ACK bitmap can acknowledge 64 because the original Block ACK of IEEE 802.11e contained a bitmap with 64 x 2 bytes. The 2 bytes were used to support fragmentation which is not allowed in IEEE 802.11n. So they were reduced to 1 byte and Block ACK is known also as compressed Block ACK.

Reverse Direction

In TXOP operation, the transmission is uni-directional, decreasing performance of network services that are delay sensitive like VoIP and on-line gaming. Performance of real time services is improved in bi-directional traffic. The TXOP operation only facilitates the forward direction, transmitting station to receiving station, but not the reverse direction transmission, receiving station to transmitting station. Reverse direction mechanism allows the owner of TXOP to share possible free TXOP time to its peer as shown in Figure 16. This way TXOP is fully utilized showing network throughput improvement .

In RD, there are two types: RD initiator and the RD responder. RD initiator is the station that owns the TXOP and has the right to grant the remainder of TXOP by sending Reverse Direction Grant (RDG) to the RD responder. RD responder is the station receiving the transmission. RDG is set from the RD initiator in a QoS data or BAR MPDU. How much time is left in TXOP is carried in the Duration/ID field of the MPDU. When the RD responder receives the MPDU with RDG set, it responds with an ACK or BA. If the ACK or BA is set with the More bit, the RD initiator will wait for the transmission from the RD responder. Last MPDUs have their More bit set to zero. Once RD initiator gains control of TXOP, may grant to same or different station the remaining TXOP or use it for its own transmission (Figure 17). RD enhances the performance of TXOP and benefits delay sensitive services like VoIP.

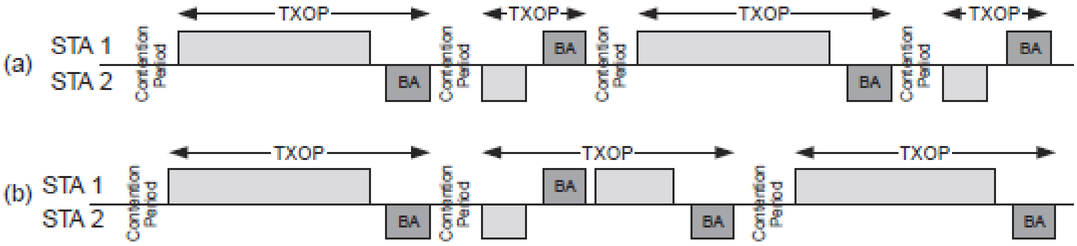

Figure 16. TXOP utilization without (a) and with (b) RD [1]

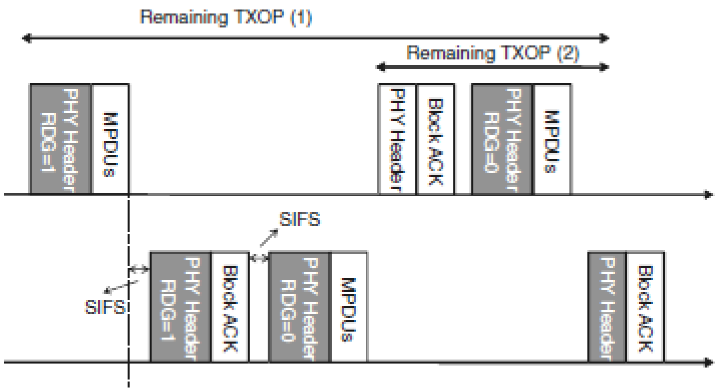

Figure 17. Reverse Direction Exchange [5]

RIFS

Prior to IEEE 802.11n SIFS was used as the minimum time for the antenna to change from transmitting to receiving and vice versa. So it was used usually between a Data and an ACK frame. IEEE 802.11n defines a smaller inter-frame spacing, Reduced Inter Frame Space (RIFS) a MAC mechanism used to replace SIFS in some scenarios. RIFS is used to separate multiple data in a data burst from a single transmitting station and when no SIFS-separated response transmission is expected. RIFS cannot be used between frames transmitted by different stations, and it can only be used when the network is HT network (only HT stations are connected and no legacy network is near) using the Greenfield mode to achieve HT. It accomplishes similar goals to the MAC aggregation functions explained earlier, with less implementation complexity. IEEE 802.11n defines a RIFS interval of 2 μs, whereas SIFS is 16 μs. RIFS is a means of reducing overhead and thereby increasing network efficiency.

3. Conclusions

MAC key features of IEEE 802.11n were presented in this chapter. All the mechanisms contribute to the overall performance. AF increases efficiency and throughput in most scenarios (in high BER environments FA without BA decreases throughput) and with the use of BA the performance of the network. Enhanced IEEE 802.11n BA or else compressed BA enhanced the function of old BA by reducing the overhead because of the BA bitmap decrease. BA is essential to high BER environments because with FA it improves performance. RD with the bi-directional enhances TXOP efficiency and benefits delay sensitive services. Finally RIFS when in HT network replaces SIFS aiding the network in achieving HT reducing the overhead (from 16 μs to 2 μs) and increasing efficiency. For every scenario combining properly these mechanisms will result in great performance. Figure 18 shows the throughput enhancements done in MAC from IEEE 802.11e to IEEE 802.11n.

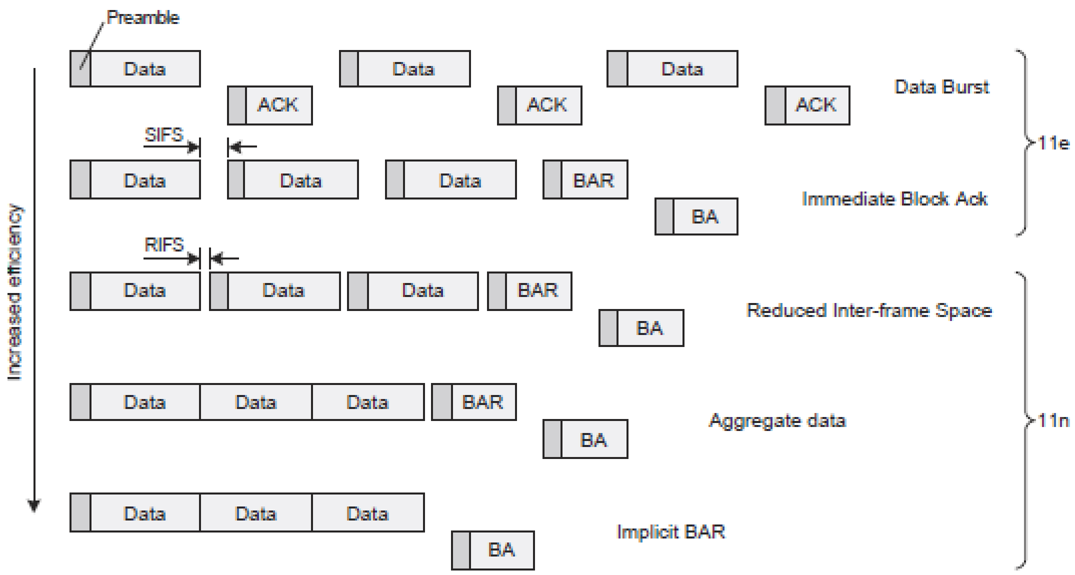

Figure 18. Throughput enhancements [1]

CHAPTER 4

IEEE 802.11n MAC literature review

INTRODUCTION

Before the publication of IEEE 802.11n, studies were conducted to research the amendment's features, evaluate performances, propose new mechanisms. The development of the amendment was based on studies and proposals. Features implemented in works were discoursed and some of them were adopted by the amendment. Nowadays studies research multiple scenarios to export conclusions in advantages and disadvantages of the protocol. Consequently this chapter focuses on literature review of IEEE 802.11n.

1. MAC literature review

Overall Protocol Performance

In [7] they present an overview of the MAC and PHY enhancements for IEEE 802.11n. A set of PHY layer and MAC layer enhancements are presented, that allow an IEEE 802.11 network to achieve throughput more than 100Mbps. A simulation is implemented for a home scenario that consists of several types of applications for two types of modes: ACF and SCAP and EDCA. Results (Figure 19) demonstrate that the proposed enhancements significantly improve the application layer throughput with EDCA. Through simulation, they have shown that the enhancements enable the support of several flows with high throughput and low latency requirements. The enhancements also improve the performance for EDCA operation, where an application layer throughput higher than 50Mb/s was achieved with several users contending for the media.

[5] begins with an overview of the legacy MAC and IEEE 802.11e mechanisms. Moreover the MAC and PHY features of IEEE 802.11n are presented. Wang and Wei examine the network performance enhancement by the proposed IEEE 802.11n MAC layer features: aggregation, block acknowledgement, and reverse direction mechanism. A simulation is run in NS-2 platform for VoIP service. The simulation results demonstrated the effectiveness of IEEE 802.11n MAC layer enhancement improving the VoIP performance. IEEE 802.11n indeed improves

the channel efficiency and provides high quality WLAN networking support for VoIP service. Results and figures of this paper are shown later on in chapter 5, QoS section.

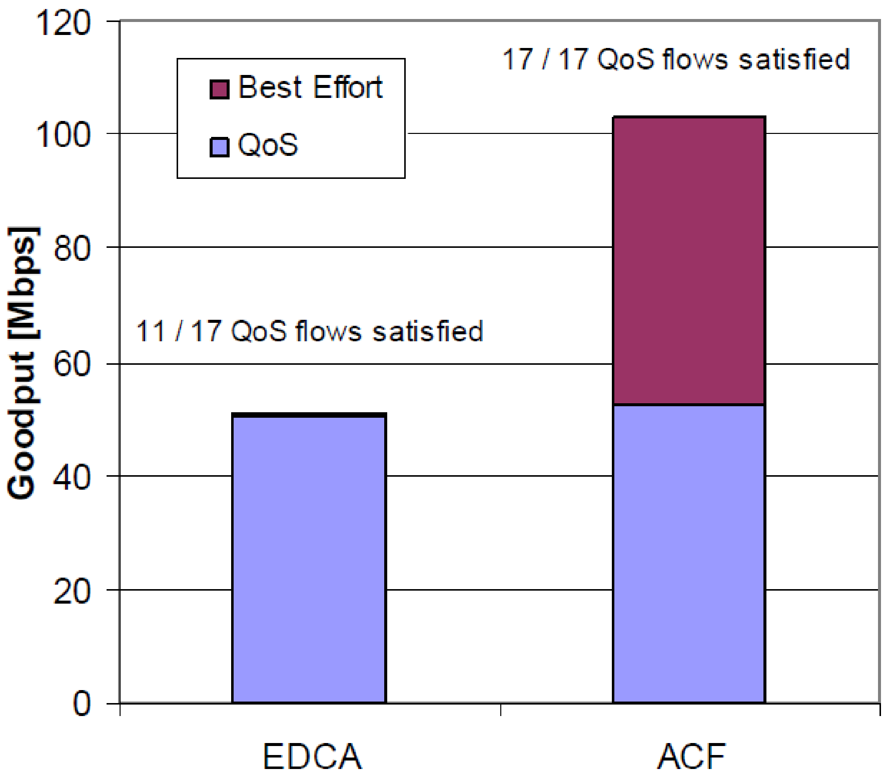

Figure 19. QoS and best effort throughput with EDCA and ACF mode of operation [7]

In [34] they use IEEE 802.11n in a scenario for cars. Results show that the indoor average throughput was over 250 Mbps at near distances. The maximum coverage range from car to car was 850 m with 15 Mbps. The coverage range is suitable enough to communicate in a vehicular network scenario. 2 streams can provide high speed data transmission at near distances, whereas 1 stream is useful to provide a large coverage area at low speed data transmission.

Frame Aggregation Performance

B. S. Kim et al. [15] investigate the two aggregation mechanisms (A-MSDU and A-MPDU) and their performance in an error free environment. They propose an analytical model based on Discrete Time Markov Chain (DTMC) and then verify it based on simulations. Figure 20 shows the throughput both aggregation mechanisms achieve for varying aggregation sizes when there are 24 stations in the network. As aggregation size increases, A-MSDU achieves higher throughput because the overhead is smaller than of the one of A-MPDU. When aggregation size is small the difference in throughput is negligible because the overhead difference is also small.

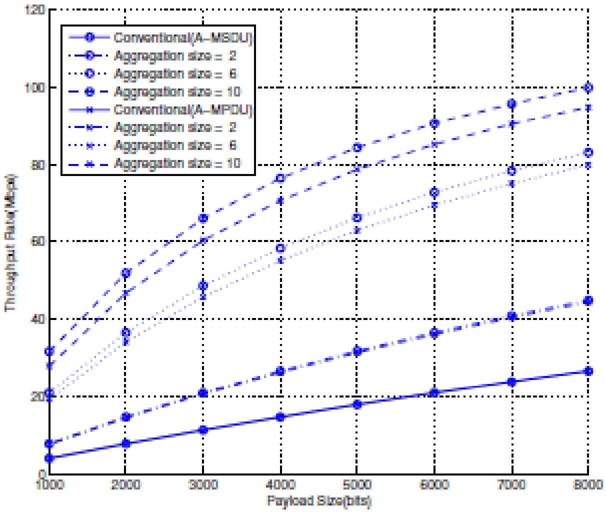

Figure 20. Throughput of A-MSDU and A-MPDU vs. Payload size for varying aggregation sizes (24 stations in network) [15]

As a result under error free environment the A-MSDU aggregation mechanism outperforms the A-MPDU mechanism. As the frame aggregation size increases the overall throughput performance is improved.

D. Skordoulis and Q. Ni et al.[33] analyze the performance of each aggregation scheme based on a point to point simulation. Both are HT stations and there is no interference or channel fading and there are no errors so no retransmission is required.

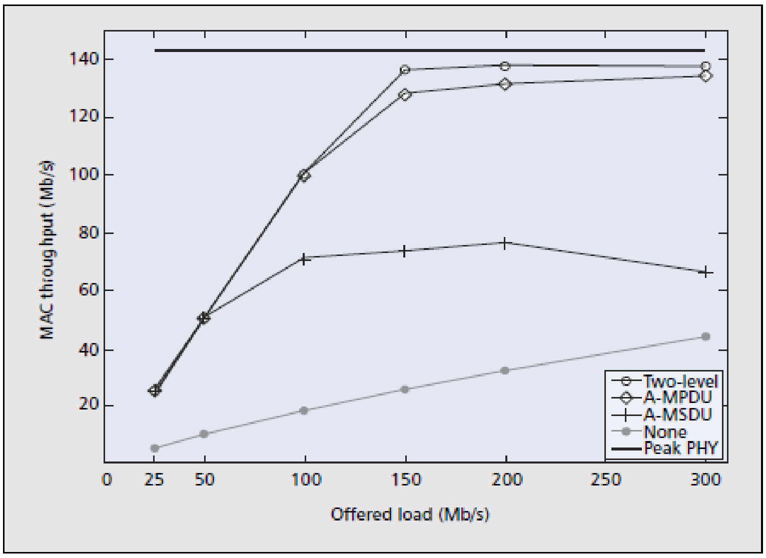

Figure 21. Throughput vs. Increased offered load for varying packet sizes [33]

Simulation results (Figure 21) show that any type of aggregation mechanism achieves higher throughput that the legacy 802.11 standards. Moreover for small packet sizes all aggregation mechanisms have the same throughput. When packet size increases A-MPDU and two level aggregation mechanisms achieve throughput that reaches the PHY peak.

B. Ginzburg and A. Kesselman [33] investigate the performance of A-MSDU and A-MPDU in ideal and error prone environments with both UDP and TCP traffic. In the ideal environment with PHY rate of 130 Mbps and 20 MHz channel width, A-MPDU channel utilization reaches 95% for UDP and 85% for TCP traffic in regards to A-MSDU which reaches 70% and 50% respectively. Correspondingly with PHY rate of 300 Mbps and 40 MHz channel width, A-MPDU channel utilization reaches 90% for UDP and 78% for TCP traffic in regards to A-MSDU which reaches 52% and 33% respectively (Figures 22-23). In error prone environments A-MPDU channel utilization for both PHY rate of 130 Mbps and 20 MHz channel width and 300 Mbps and 40 MHz channel width for both UDP and TCP traffic is higher than of A-MSDU (Figures 24-25). A-MPDU along with Block ACK mechanism needs to retransmit only the MPDUs with errors in regards to A-MSDU which it whole must be sent again.

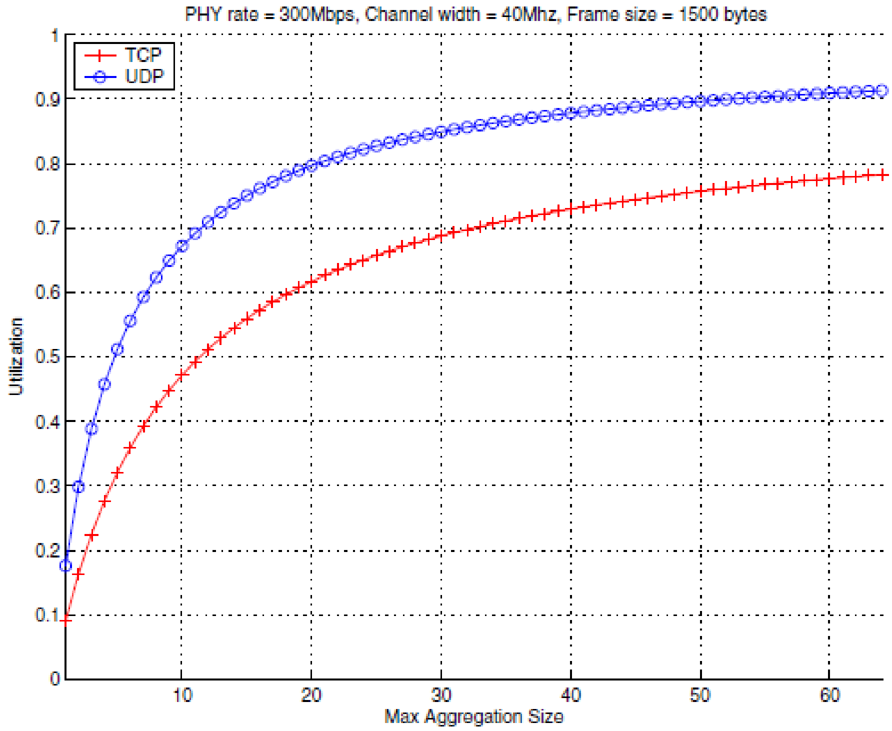

Figure 22. A-MPDU ideal channel utilization [37]

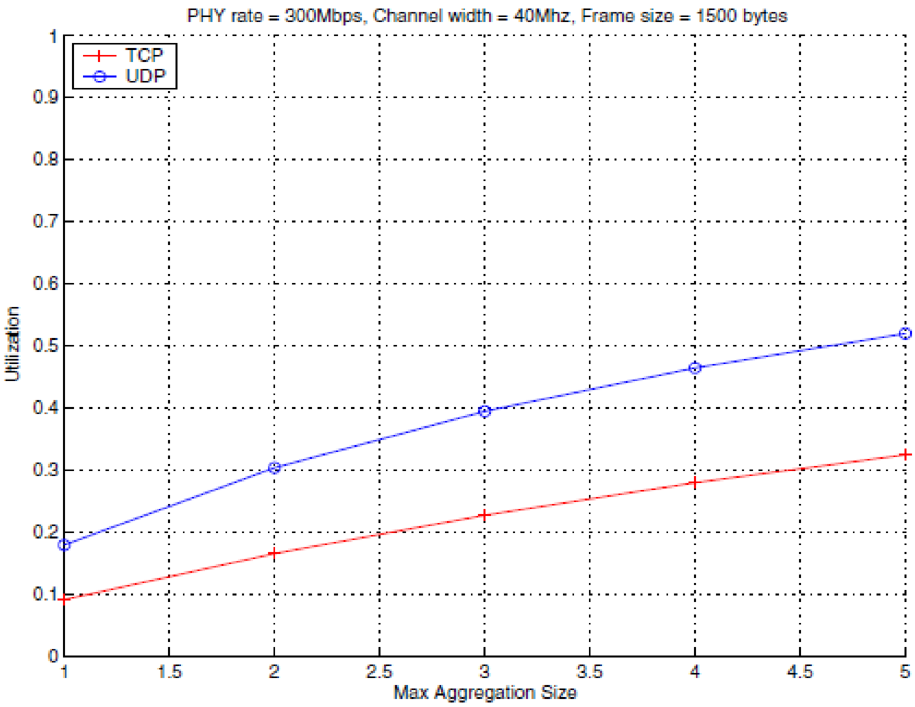

Figure 23. A-MSDU ideal channel utilization [37]

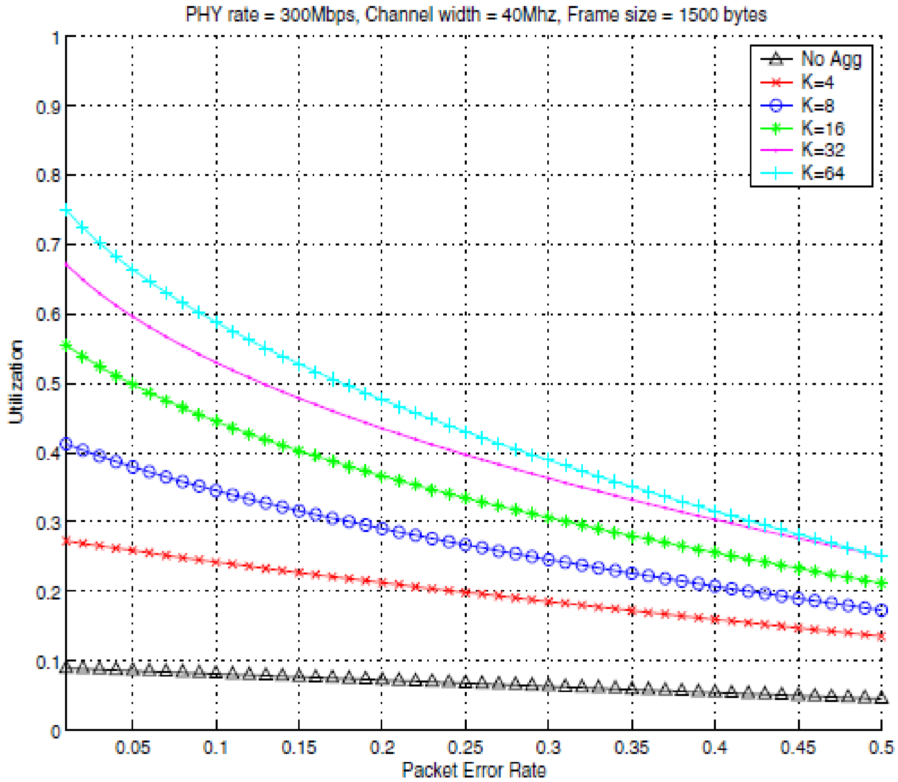

Figure 24. A-MPDU noisy channel utilization for TCP [37]

To conclude the aggregation mechanism used for our network depends from many variables (errors, noise, jitter etc.). A-MPDU is the best aggregation mechanism for real time and busy networks, because in these networks noise and errors occur and A-MPDU with BA can reduce the retransmissions and increase the same time the efficiency.

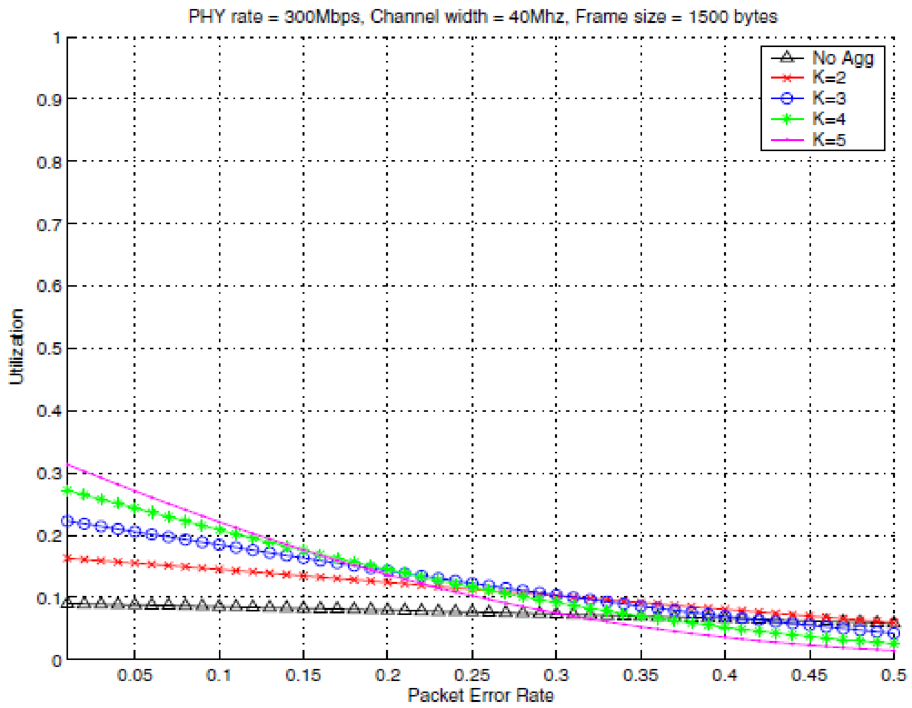

Figure 25. A-MSDU noisy channel utilization for TCP [37]

Aggregation Schedulers

A subject of study is the optimal frame size of the aggregation mechanism for maximum throughput. The fact is that in different environments different sizes help boost throughput.

T. Selvam and S. Srikanth [24] present a simple frame aggregation scheduler for IEEE 802.11n which dynamically chooses the size and aggregation technique on many variables. The algorithm is shown in Figure 26. Simulation results compared to fixed size aggregation schemes indicate that the proposed method is superior in lightly loaded conditions as compared to the fixed size A-MPDU methods.

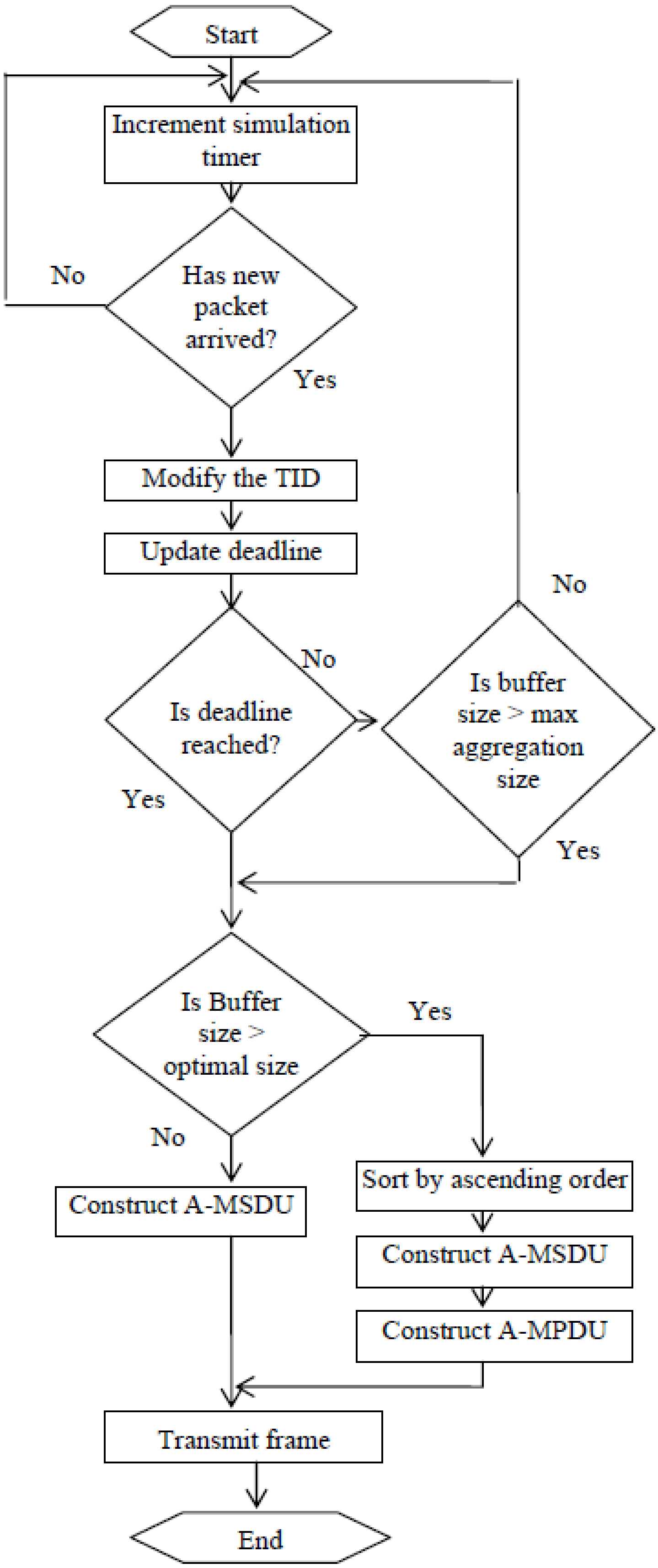

Figure 26. Algorithm of proposed frame aggregation scheduler [24]

K. T. Feng and P. T. Lin [36] propose a frame-aggregated link adaptation (FALA) algorithm to dynamically adjust system parameters in order to improve the network goodput under varying channel conditions. For the purpose of maximizing the network goodput, both the optimal frame payload size and the modulation and coding schemes are jointly acquired according to the signal-to-noise ratio under specific channel condition. Results illustrate that the proposed FALA protocol can effectively increase the goodput performance comparing with other existing link adaptation schemes, especially under dynamically changing environments.

In [35] X. He et al, propose a frame size adaptation algorithm for A-MPDU in 802.11n networks, aiming at achieving maximum throughput by choosing an optimal frame size under poor channel conditions. The optimized frame length is selected from a look-up table stored locally which is established based on analytical and simulation results. Moreover a data rate is selected based on Signal to Noise Ratio (SNR) for transmitting the frame with optimal length. Results are shown in Figure 27.

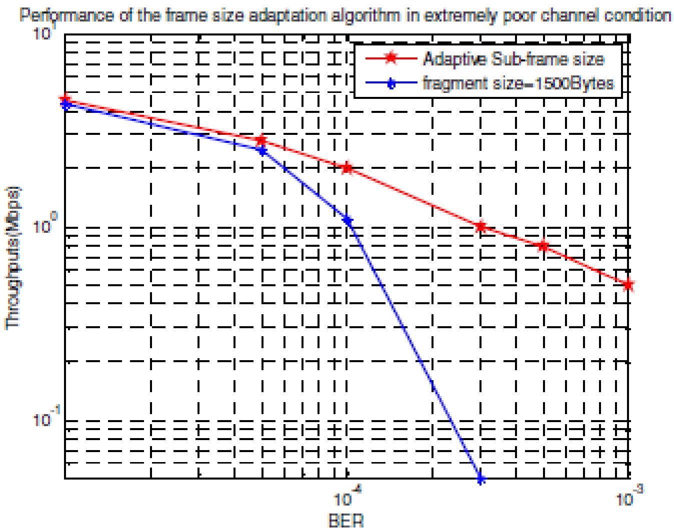

Figure 27. Performance of the proposed adaptation algorithm in poor channel condition [35]

Aggregation Mechanisms

T. Li et al [18] develop a novel scheme called aggregation with fragment retransmission (AFR). In the AFR scheme, multiple packets are aggregated into and transmitted in a single large frame. If errors happen during the transmission, only the corrupted fragments of the large frame are retransmitted. An analytic model is developed to evaluate the throughput and delay performance of AFR over noisy channels and to compare AFR with similar schemes in the literature. Optimal frame and fragment sizes are calculated using this model. Transmission delays are minimized by using a zero-waiting mechanism where frames are transmitted immediately once the MAC wins a transmission opportunity. AFR is used for simulations implementing real time services and the results show performance improvement further optimizing CSMA/CA.

2. Conclusions

Studies for IEEE 802.11n begun before first draft and continue after the publication of it. The first studies investigated the mechanisms to be used by the draft and their performance. After the publication studies investigate the performance of IEEE 802.11n in various environments and in different scenarios, but moreover analyze the weaknesses and propose new schemes. As the amendment gains more popularity more research work will be appear and more proposals to enhance the protocol will be done.

CHAPTER 5

IEEE 802.11n other issues

INTRODUCTION

Apart from the improvements in MAC and PHY layers there are also other issues to be considered. These new features offered in throughput and range increase, but issues like Interworking, QoS and Security are equally significant. Networks expanding with IEEE 802.11n, networks running delay sensitive services and networks requiring security profit more with the use of IEEE 802.11n. Performance evaluations are given in each issue's section by related works.

1. Interworking

Nowadays many types of wireless networks exist, each for different use and each used for different coverage: Wireless Local Area Networks (WLAN), Wireless Metropolitan Area Networks (WMAN) and cellular networks. IEEE 802.11n, WiMax and 2.5G GPRS are examples of networks belonging to WLAN, WMAN and cellular networks respectively. Each of these networks offer different services, data rates and range. To support mobility of a service from one environment to another (either spatially or network transition) the mobile device should be able to connect automatically to a network with the best signal without the loss of service during the transition. The transition from one network to another with different transmission rates is called Vertical Handoff. So different networks interacting with each other is called Interworking and some of them are 3GPP/WLAN, IEEE 802.11u with external networks etc.

3GPP/WLAN Interworking is implemented through six scenarios based on simple to more complex interworking mechanisms. 3GPP refers to third generation partnership project supporting a 3G UMTS (Universal Mobile Telecommunications System) and WLAN to IEEE 802.11a/b/g/n. Cellular networks and WLANs are very common and widely deployed to provide seamless service continuity through smooth Vertical Handoff. Seamless service continuity means transition parameters, data loss and connectivity break, are minimized.

IEEE 802.11u is a standard that will aid in the improvement of the interworking with external networks through MAC enhancements. IEEE 802.11u contains requirements in the areas of enrollment, network selection, emergency call support, emergency alert notification, user traffic segmentation, and service advertisement.

802.21 standard enables seamless handoff between dissimilar networks including 802 and non 802 networks. 802 consists of 802.3 (Ethernet), IEEE 802.11 family (WiFi) and 802.16 (WiMax). Non 802 consist of cellular 3GPP (3G UMTS) and 3GPP2 (3G CDMA 2000). The seamless handoff is accomplished by a conceptual layer 2.5 specified my media independent handoff (MIH). This layer is between the OSI Data Link Layer and the Network Layer. The standard provides information to allow handing over to and from cellular, IEEE 802.11, 802.15, 802.16 and 3GPP networks through different handover mechanisms.

Aside the advantages of interworking, challenges also emerge such as QoS issues, different data rates, handoff mechanisms, security, AAA etc. However once the challenges are altered users with mobile devices will enjoy the new mobility experience.

2. QoS

As already explained in Chapter 1, QoS is a control mechanism that can provide different priority to different users or data flows, or guarantee a certain level of performance to a data flow in accordance with requests from the application program. First appeared in 2005 with the IEEE 802.11e amendment to ensure better performance for real time services and is also implemented in IEEE 802.11n. Each application requires different needs for throughput, delay or error so traffic is prioritized in logical queues resulting in better performance for delay sensitive services. IEEE 802.11n increased throughput and range in addition with QoS further enhances, compared to legacy protocols, the performance of these services. Nowadays applications like VoIP, online video streaming, online gaming, IPTV are very popular and due to mobility and growth of the wireless services, more users access the internet. In this section we refer to papers that have studied and evaluated the performance of real time services, such as the ones referred above, with the use of IEEE 802.11n.

Online Gaming

In [19] they investigate the IEEE 802.11n MAC layer performance for a real time online game through a simulation where clients simultaneously connect to a game server and play. In this simulation the MAC layer mechanisms the IEEE 802.11n introduces (Frame Aggregation, TXOP, Reverse direction, Block ACK) are investigated under heavy background traffic. Results show how the network performance and MOS (Mean Opinion Score) are improved by IEEE 802.11n MAC mechanisms.

MOS is a numeric scale from 1 to 5, where 1 is the lowest and 5 the highest, indicating the quality of the online game experience for this case. Because of the heavy background traffic, delay, jitter increases and packets are even dropped, making online experience less enjoyable.

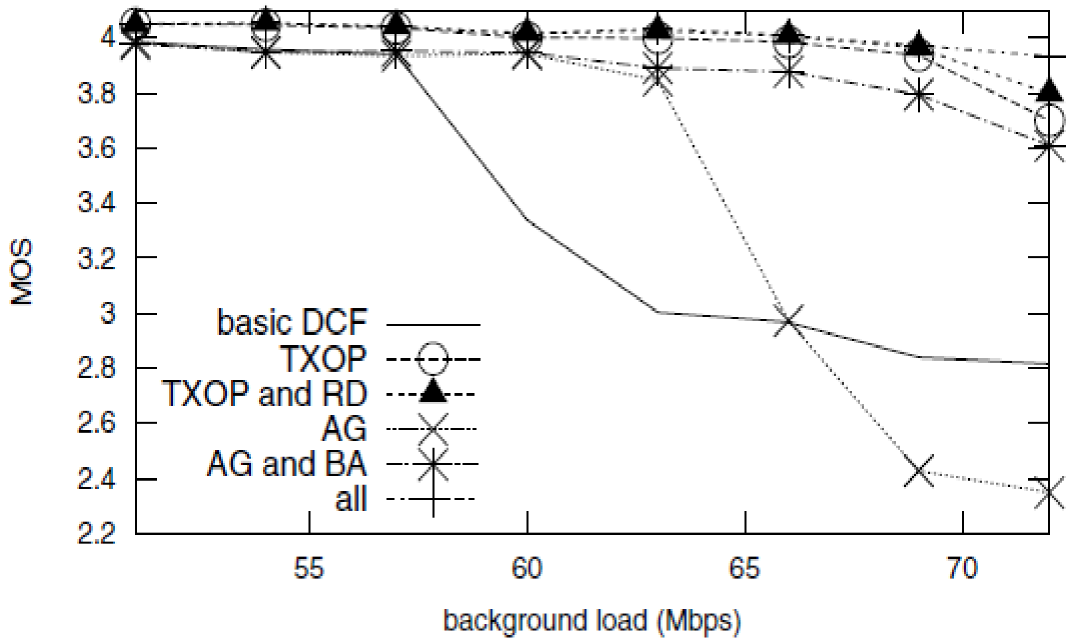

Figure 28. MOS scores vs. Background Traffic load [19]

In the simulation, the different scenarios are implemented for different use of the MAC mechanisms. These are: DCF, Frame Aggregation, Frame Aggregation with Block ACK, TXOP and TXOP with Reverse Direction. Figure 28 shows the MOS score for each mechanism implementation as background load increases. TXOP with RD outperforms the AG with BA because in a TXOP packets are transmitted sequentially reducing the overhead and improving downlink delay and RD allowing receiving stations to send data to transmitting station improving uplink delay. Figure 29 shows the relative delay (the difference between a user's delay and that of the other players) with a 78 Mbps background traffic load. To conclude as shown in the figure TXOP has the lowest value in relative delay which means that delay among players is almost the same improving the fairness of the network.

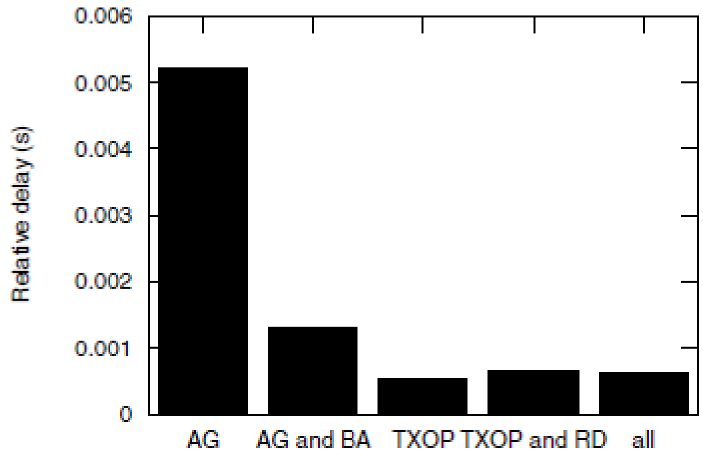

Figure 29. Relative downlink delay with 78 Mbps background load [19]

IPTV (Internet Protocol Television)

Internet Protocol television (IPTV) is a system through which Internet television services are delivered over the Internet and broadband Internet access networks, instead of being delivered through traditional radio frequency broadcast, satellite signal, and cable television formats. The work done in [23] evaluates the IPTV performance of IEEE 802.11n, when no background traffic is present in the wireless network, for the first time so it can be used by the IPTV service providers to evaluate the performance of IPTV in wireless networks and in the customer's home wireless network. Subjects of this research are the delay, packet loss, jitter and bandwidth in the application layer. Two types of wireless environments with several users were implemented: the indoor and the outdoor. For these two environments three scenarios are used and analyzed where the number of IPTV clients can vary randomly over time. One scenario for the indoor environment and two scenarios for the outdoor one. The difference in the outdoor scenarios is the different implementation of the network and because the first was used to measure the performance for a single user and the other one to measure the mean values for multiple users. For this study the interference coming from the AP was not considered. Furthermore one multicast video channel was used for all scenarios because the use of two or more multicast video channels led to poor wireless network performance. Figures 30 to 32 show the results from the measure of the network indoors whereas Figures 33 to 35 the results from outdoors with multiple users.

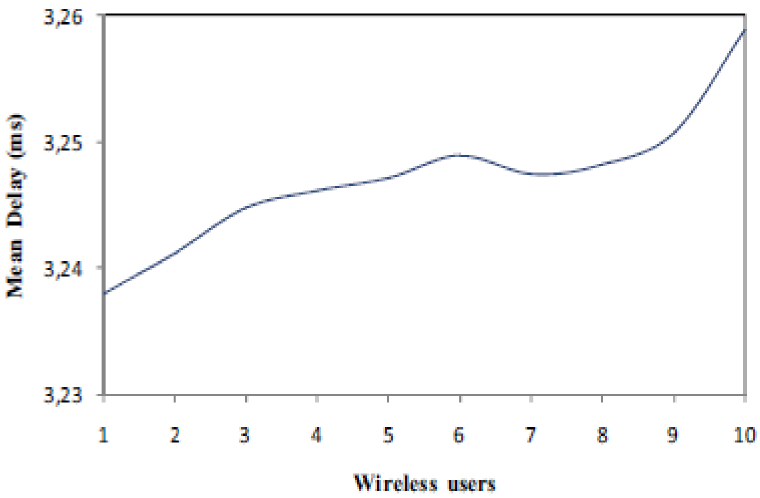

Figure 30. (Indoors) Mean delay for 1 multicast channel [23]

As Figure 30 shows that the delay increases as more people are added to the network.

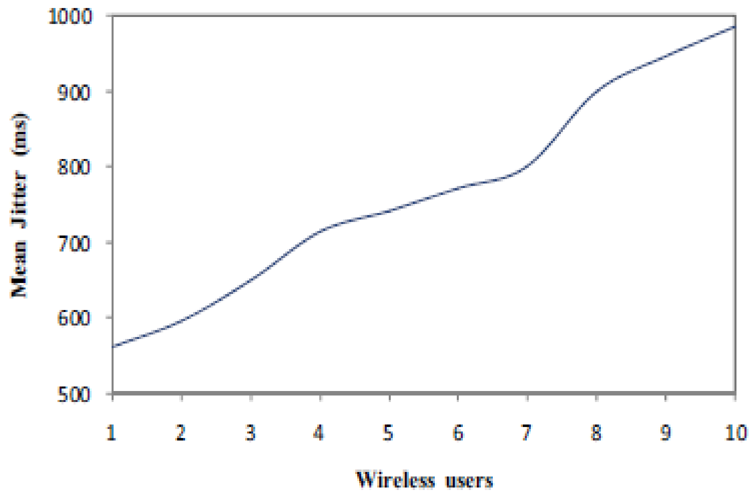

Figure 31. (Indoors) Mean Jitter for 1 multicast channel [23]

In Figure 31 and also Figure 33 Jitter increases fast when clients join the network but besides this fact no significant video or audio problems were observed. Figure 13 shows how the packet loss increases with added users.

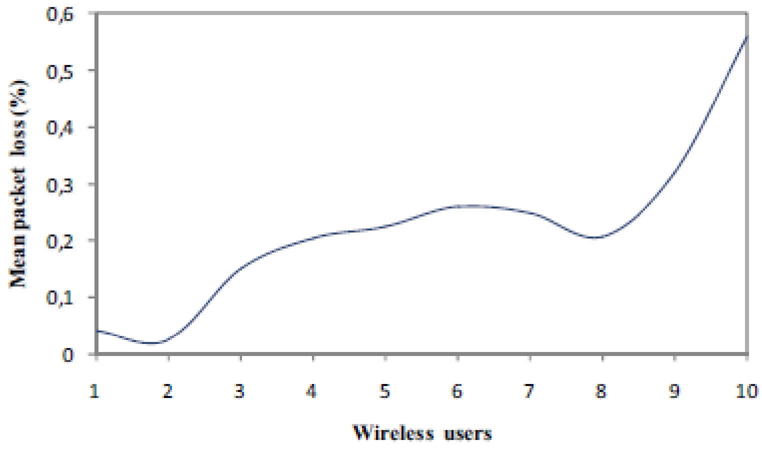

Figure 32. (Indoors) Mean packet loss for 1 multicast channel [23]

Figure 34 shows the delay according to the number of the users. From one to seven users the delay increases but then it remains constant. In Figure 35 maximum percentage of lost packets occurs when one user is in the network. When more users join the percentage falls and remains stable.

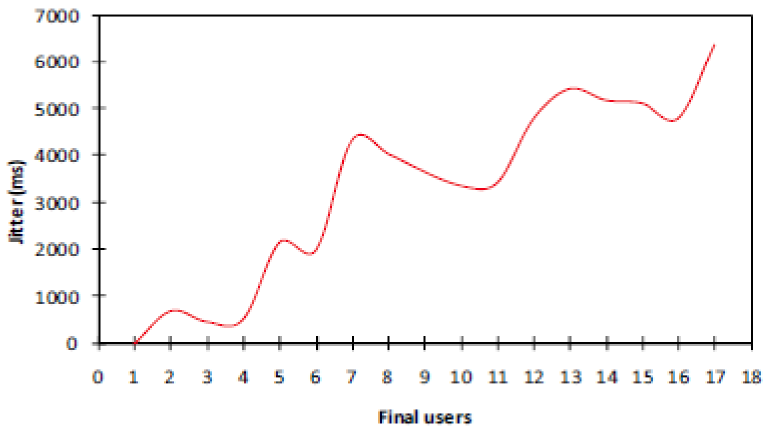

Figure 33. (Outdoors) Mean Jitter for 1 multicast channel [23]

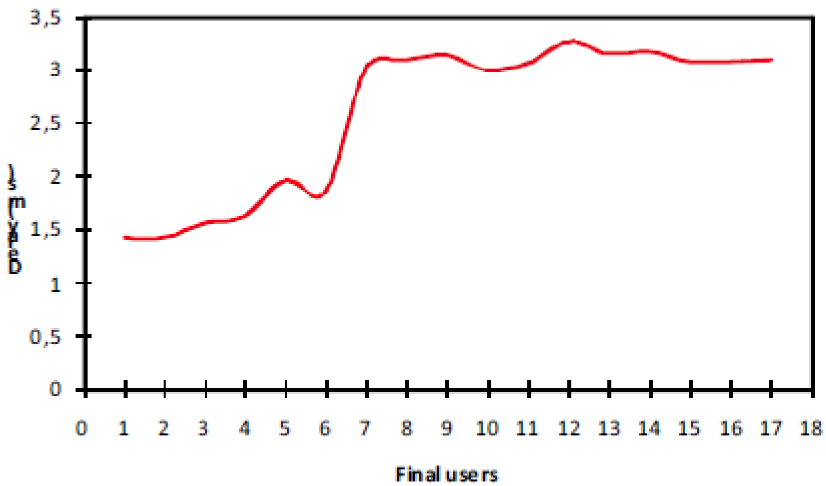

Figure 34. (Outdoors) Mean delay for 1 multicast channel [23]

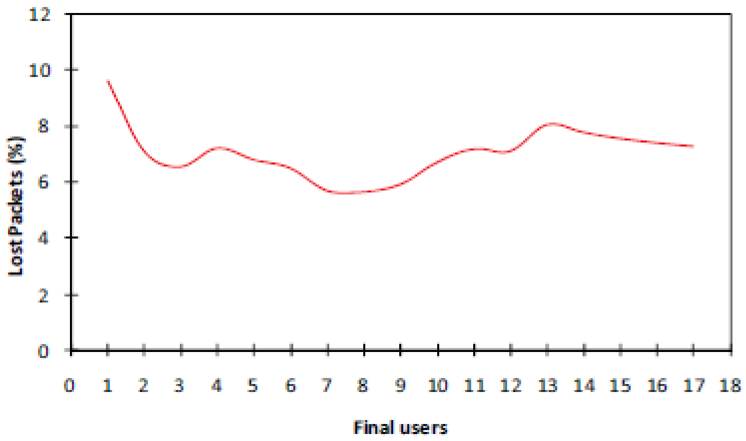

Figure 35. (Outdoors) Mean packet loss for 1 multicast channel [23]

In general delay, jitter and packet loss do not increase linearly with the number of users. Indoors delay increases as the number of users increase whereas delay remains stable outdoors after a number of users. Jitter increases in both scenarios but no video or audio problems occurred. Packet loss increases according to the number of the clients indoors but outdoors remains constant. Concluding results are affected by the hardware, software and network implementation and modifying them will change the results.

Besides the performance evaluation of IPTV over IEEE 802.11n this paper doesn't explain the MAC mechanisms that were used for the scenarios. Future works should consider more than one multicast channel, interference and moreover evaluate their results depending on the use of different combinations of the MAC mechanisms the IEEE 802.11n offers.

In-flight Video Streaming

Airlines plan to deploy wireless networks inside the planes to be used by the passengers when in-flight. This way airlines want to offer entertainment with the ease of the wireless installation and the low cost. IEEE 802.11n offers high throughput and increased range so [28] evaluates the performance of video streaming over IEEE 802.11n with the use of NS-2. Two scenarios are implemented in relation to the MAC aggregation mechanisms, A-MSDU and A-MPDU. In first simulation, a CBR (Constant Bit Rate) UDP traffic is transmitted from an access point to a client under ideal channel. The packet interarrival time depends on the packet size and CBR traffic has a rate equal to the physical transmission rate. The packet size is varied from 600 bytes to 1400 bytes. Results are shown in Figures 36 and 37 with physical transmission rate *R* equal to 150 and 300 Mbps respectively.

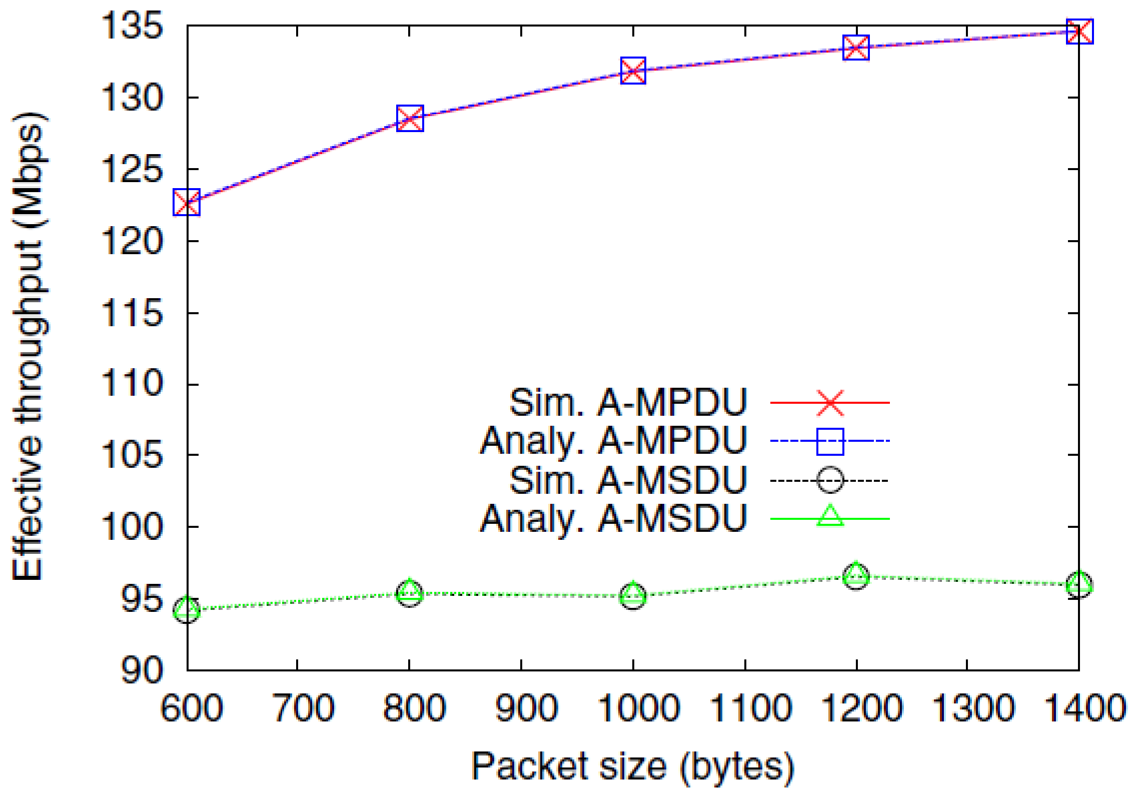

Figure 36. Average effective bit rate at R = 150 Mbps under ideal channel [28]

The graphs show that A-MPDU outperforms A-MSDU in effective throughput under ideal channel conditions. Where A-MSDU remains almost stable for all packet sizes and in both physical rates, A-MSDU effective throughput increases with the packet size. The second simulation had similar settings but this time under channel error conditions, at a physical rate of 300 Mbps and maximum retransmission limit of 7. Results are shown in Figures 38 and 39. As the error rate increases, effective throughput for both aggregation mechanisms decreases with A-MSDU affected the most and A-MPDU the least.

The results show clearly that under error free and channel error conditions, the A-MPDU aggregation mechanism outperforms the A-MSDU one. The maximum effective throughput was achieved by A-MPDU at 300 Mbps physical Although

IEEE 802.11n PHY can achieve rates up to 600 Mbps with four spatial streams, the use of more than two streams is optional. Concluding an AP under

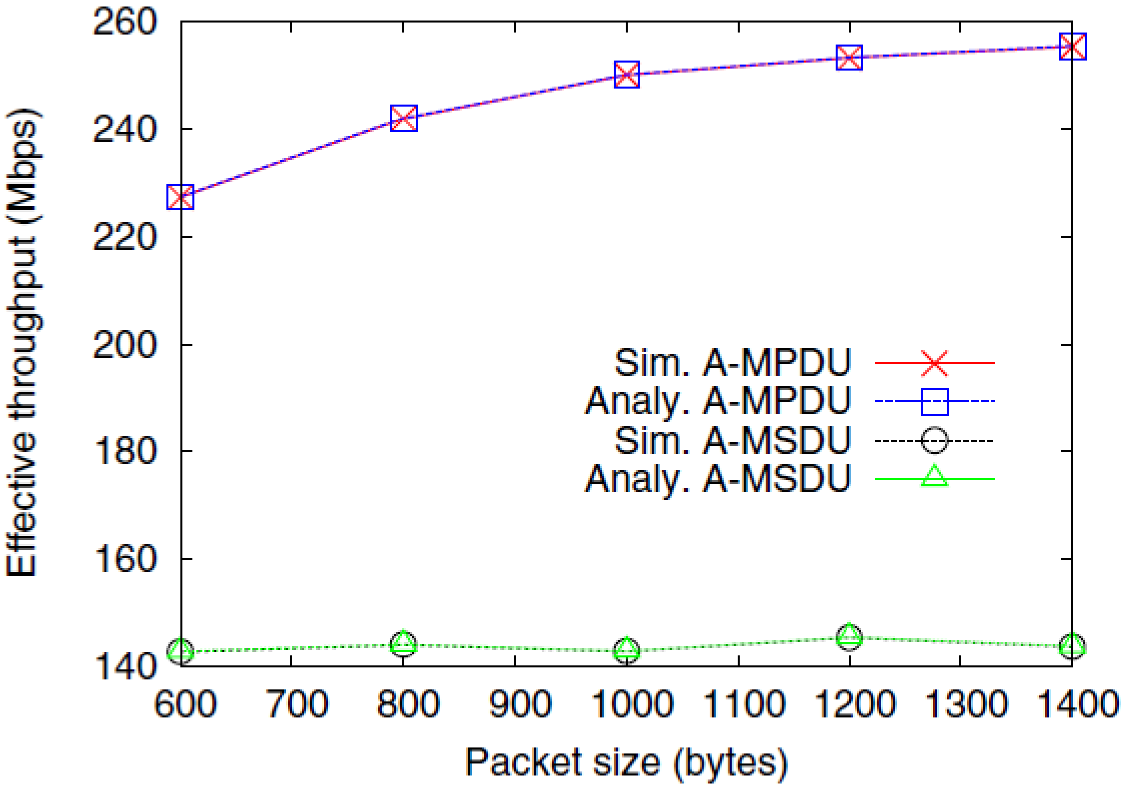

Figure 37. Average effective bit rate at R = 300 Mbps under ideal channel [28]

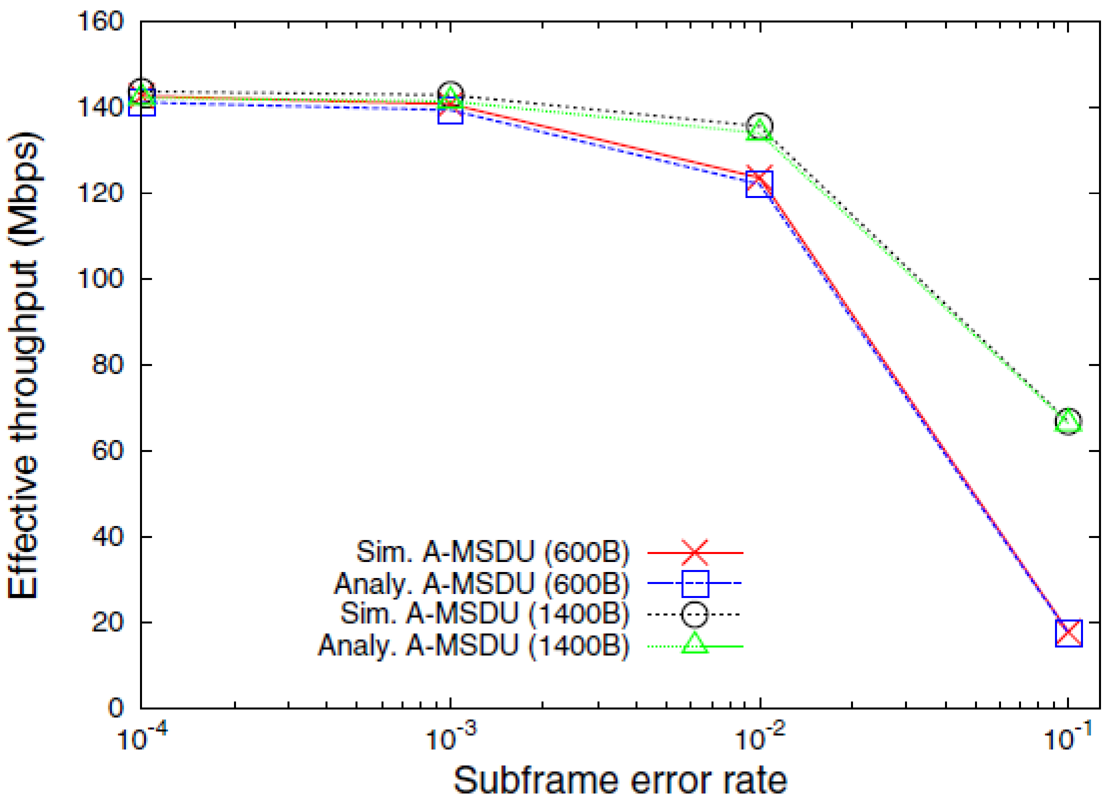

Figure 38. Average effective bit rate of A-MSDU at R = 300 Mbps under channel errors [28]

IEEE 802.11n video streaming with constant bit rate of 6.5 Mbps per client and A-MPDU frame aggregation can support up to 39-40 passengers, so a plane carrying 100 passengers will need three APs in no overlapping channels to support video streaming.

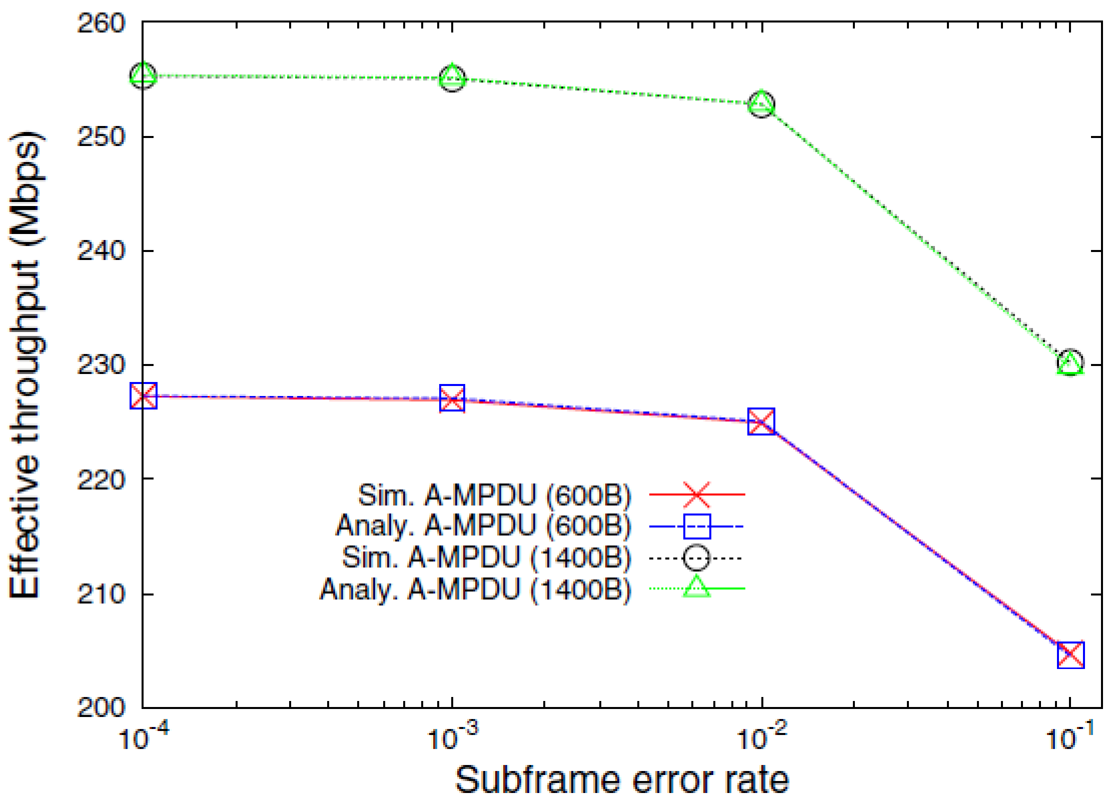

Figure 39. Average effective bit rate of A-MPDU at R = 300 Mbps under channel errors [28]

Video Transmission

[20] inspects the performance of video transmission over IEEE 802.11n with A-MPDU aggregation mechanism. Performance evaluation is analyzed through the performances of throughput, delay, sub frame size and retry limit with the use of NS-2. For the simulation a video sequence of 30 fps (frames per second) along with H.264/SVC coding and JSVM9.15 video codec were used. Results of the simulation show that increasing the number of the sub-frames increases the throughput (Figure 40). The drawback is the increase in delay because the aggregation frame waits for a certain number of sub frames. Moreover the optimal sub frame size depends entirely on channel conditions and contributes to the improvement of the throughput, which means more video users. Figure 41 shows

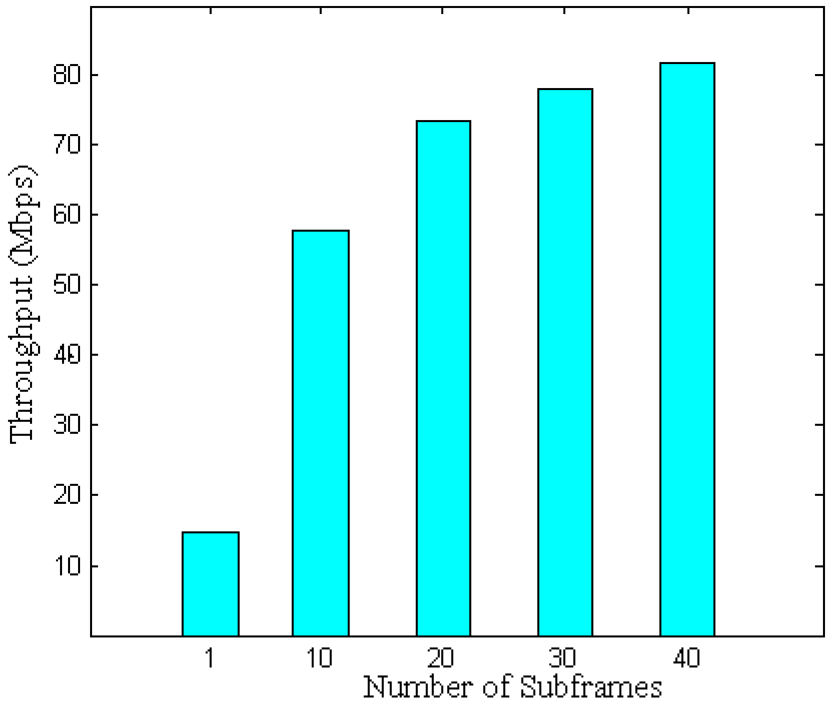

Figure 40. Throughput for A-MPDU under different number of sub frames [20]

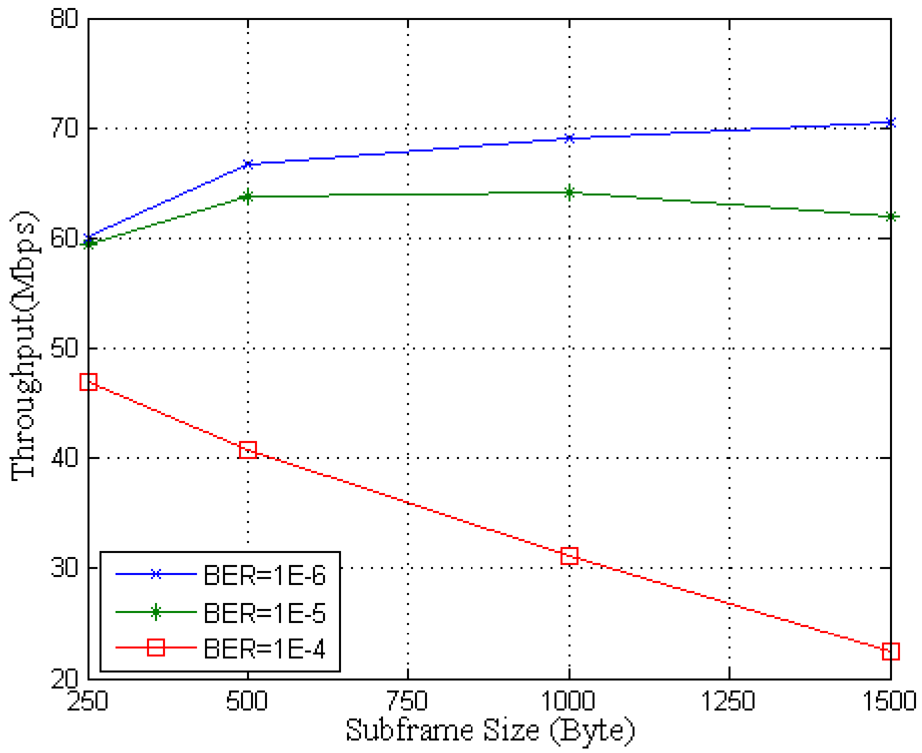

Figure 41. Throughput for A-MPDU under different sizes of sub frame [20]

the throughput variation depending on sub frame size in error prone environment. When BER is high throughput decreases with the increase of the sub frame size, with 250 Bytes having the highest throughput. Finally the retransmission policy improves video quality with the increase of the retry limit but also depends on channel conditions because it adds to the percentage of packet delay.

VoIP

An investigation of the service quality of VoIP over IEEE 802.11n with the use of the three IEEE 802.11n MAC mechanisms is discussed in [5]. A simulation with several different scenarios is designed to evaluate the performance of the MAC mechanisms. NS-2 platform is used to run the simulation, measuring the frame aggregation (A-MPDU was used for aggregation), Block ACK and reverse direction (RD). As shown in Figure 42 the R-score (it is a VoIP quality measurement tool, with values from 0(Worst) to 100(Best) calculated by delay, coding efficiency and data loss) decreases when the background traffic increases with no AG mechanism whereas R-score with AG remains stable.

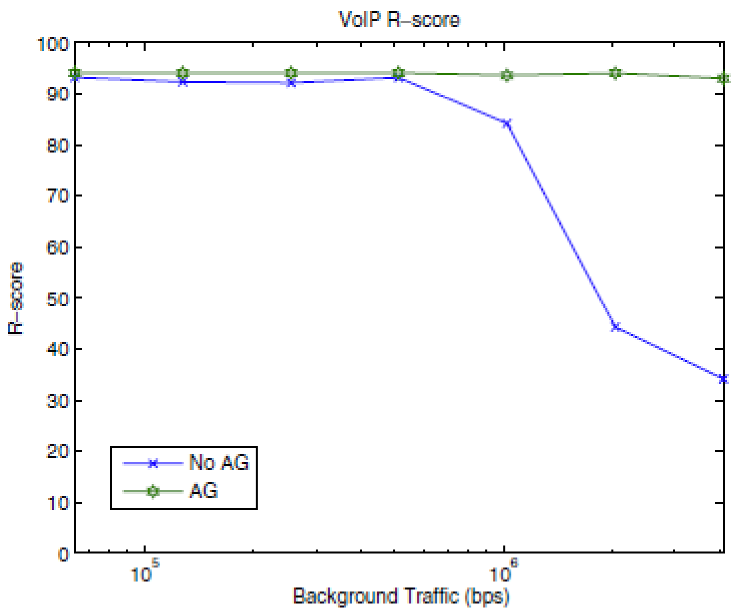

Figure 42. VoIP R-Score for no AG and with AG [5]

Furthermore Figures 43 and 44 show the throughput achieved in low and high BER (Bit Error Rate) environments as the packet size increases with the use of Block ACK. In low BER environments less errors occur so the Block ACK size adds to the overhead that is why it achieves more throughput. Instead in high BER errors occur more frequently so with Block ACK only the sub frames with errors are retransmitted. Although Block ACK size adds in overhead it remains a necessary mechanism to be applied with AG.

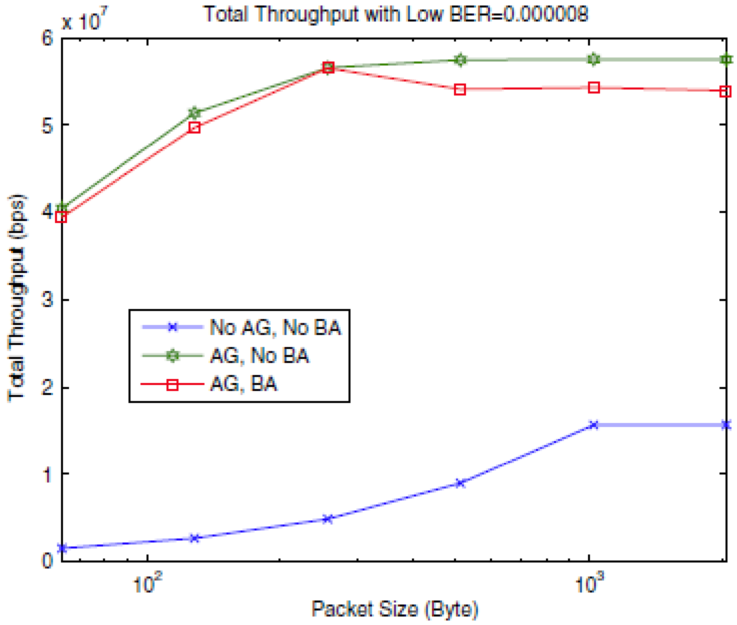

Figure 43. Block ACK performance in Low BER environment [5]

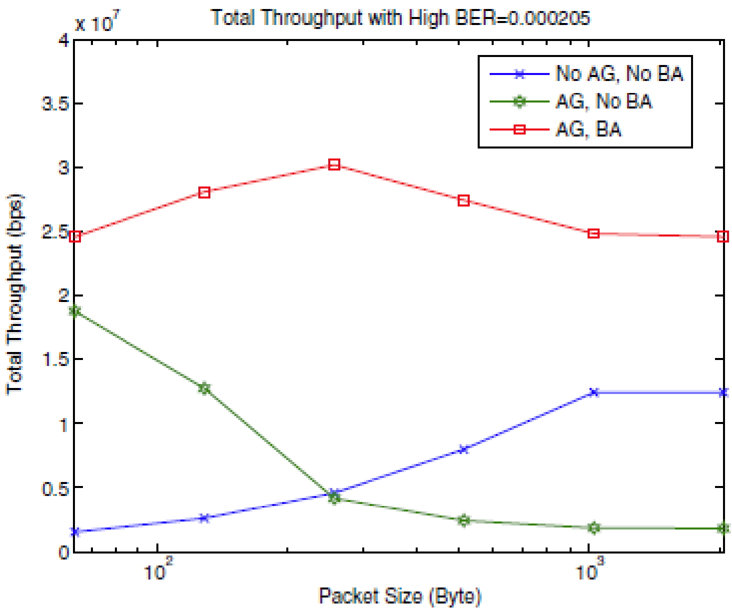

Figure 44. Block ACK performance in High BER environment [5]

Two scenarios to evaluate the delay in both low and high BER are shown in Figures 45 and 46. In low BER aggregation and RD further reduce the delay but Block ACK because of the extra size adds to the overhead resulting in a slightly increase in delay, whereas in high BER Block ACK helps reducing the delay time.

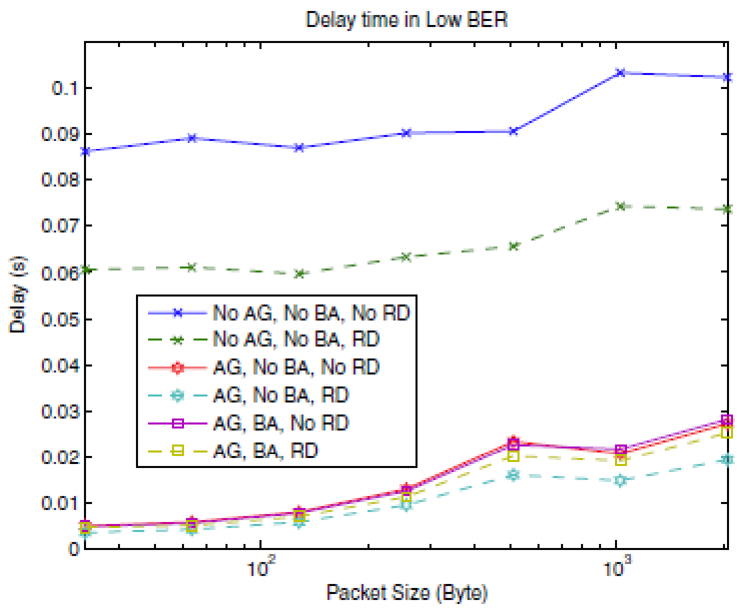

Figure 45. Delay Time in low BER [5]

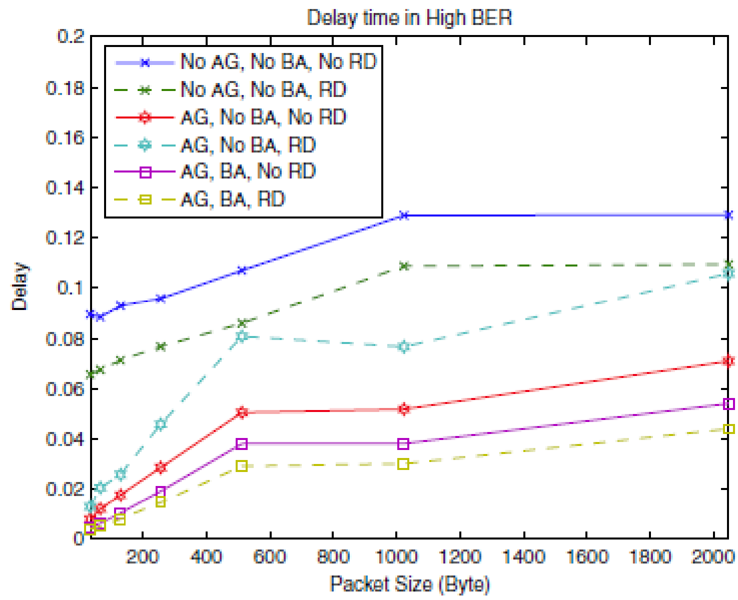

Figure 46. Delay Time in high BER [5]

Overall results for VoIP R-score in low and high BER environments are shown respectively in Figures 47 and 48. In low BER the R-score slightly decreases when the number of users increases but remains high when AG is used. In high BER with the increase of the number of the users the R-score decreases fast with scenarios running AG, BA (RD and no RD) having the highest score. The results show that the enhancements of the MAC layer of IEEE 802.11n significantly improve the network performance in general and specifically the quality of VoIP.

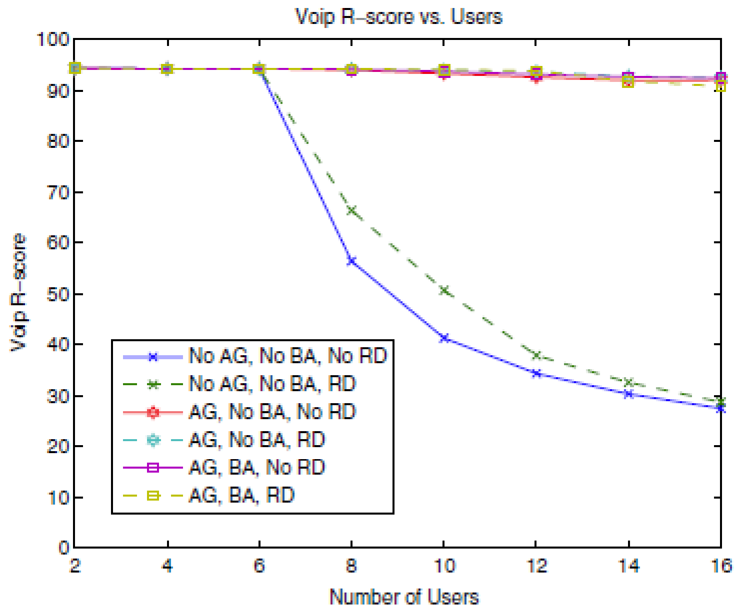

Figure 47. VoIP R-score in low BER [5]

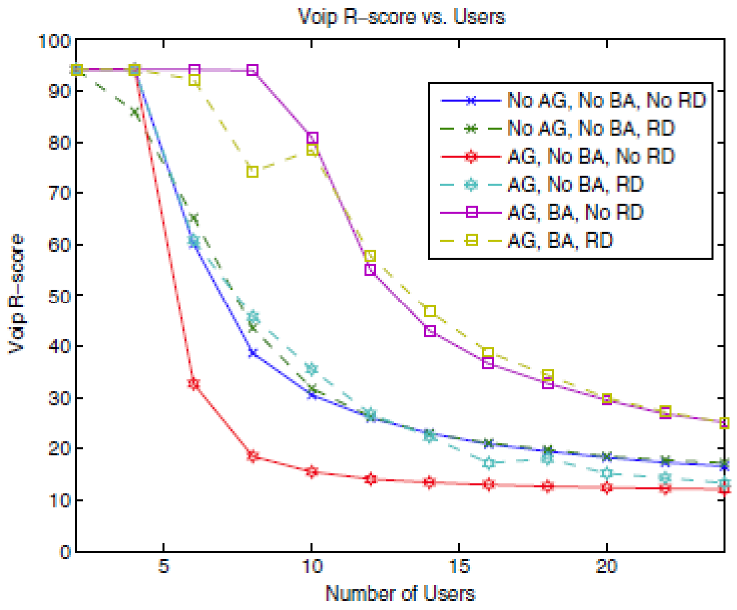

Figure 48. VoIP R-score in high BER [5]

3. Security

Security is mandatory for any communication to be considered safe and private from others. In wired networks security can be achieved by securing the physical access, installing firewalls to routers and clients etc. In contrast security in WLANs is harder to achieve because the medium is air and anyone in range can eavesdrop the communication. So wireless networks need more effort to maintain security. This can be achieved by following the three concepts of secure communication: Authentication, Confidentiality, Integrity. Authentication ensures that stations joining the network are the ones claiming to be by asking username and password. Confidentiality ensures that no one can “hear” and read the network traffic by encrypting the messages. Only the stations that know how to decrypt the encrypted message can receive it. Integrity ensures that the messages received are not altered by any means and that it the same with the original sent by the transmitting station. Encryption methods used in IEEE 802.11 WLANs from oldest to newest are: WEP, WAP and WAP2. WEP uses an open or shared key for authentication and RC4 encryption algorithm. WPA uses TKIP (Temporal Key Integrity Protocol) which uses a message integrity check and like WEP RC4 algorithm. Finally WPA2 encrypts with CCMP (CTR (Counter mode) with CBC-MAC (Cipher Block Chaining Message Authentication Code) Protocol) which uses AES (Advanced Encryption Standard) algorithm.

Devices under IEEE 802.11n are required to support WPA2, encrypting data with AES. In order to allow backwards compatibility TKIP (RC4 algorithm) has to be supported to make it possible for legacy devices to connect securely to the network. The drawback to this, is that high throughput data rates cannot be achieved when using TKIP. Security is associated to network performance because of the extra overhead.

The impact on the performance is shown in [9] and [10]. Both papers evaluate the performance of IPv4 and IPv6 using IEEE 802.11n with and without WPA2. [9] investigates the performance in two scenarios where there is one server running Windows Server 2008 wired to one AP under IEEE 802.11n which is in wireless communication with one client running XP in the first scenario and Vista in the second for TCP traffic. [10] follows the same settings with difference in client running Windows 7 and traffic consists of UDP packets. Figures 49-50 show that in both networks, IPv4 throughput is higher than of IPv6. Enabling WPA2 results in the deduction of the throughput for both IPv4 and IPv6. The highest bandwidth was achieved with XP and IPv4 at around 120 Mbps rate. In Figure 51 the impact of WPA2 was also compared for the windows 7-Windows Server 2008 scenario. Again WPA2 results in the decrease of the throughput when it is applied.

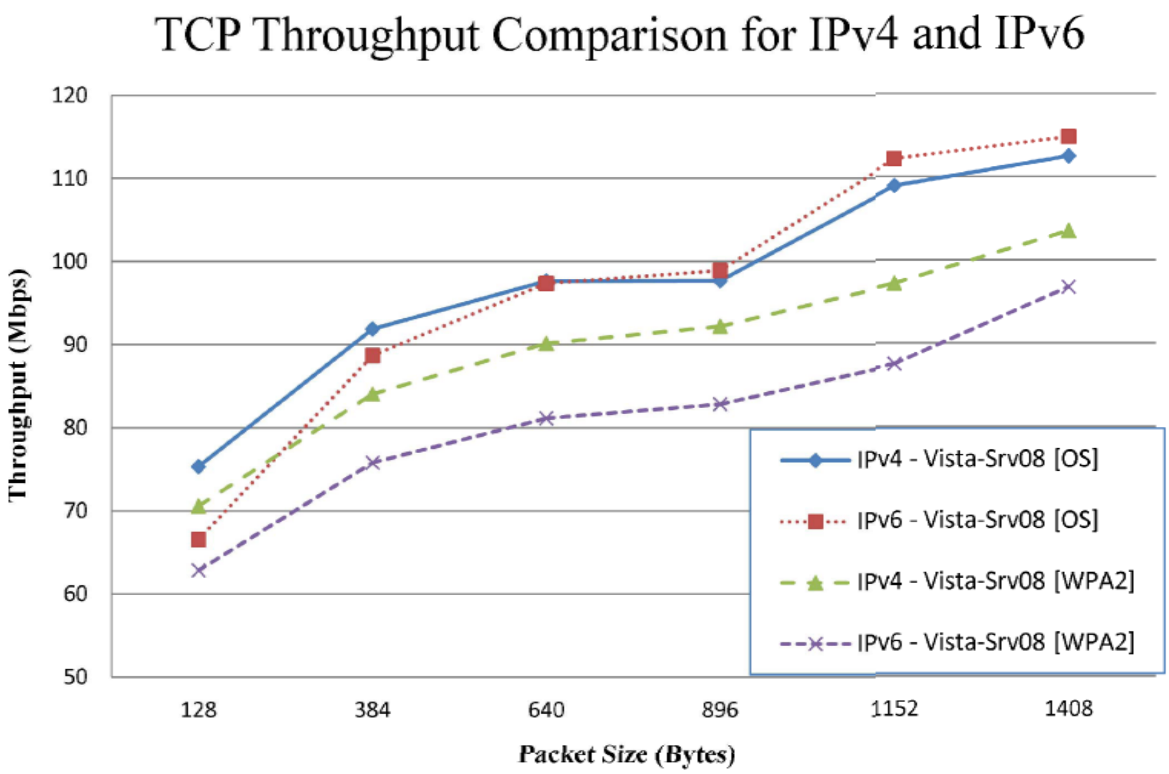

Figure 49. TCP Throughput comparison for IPv4 and IPv6 on Vista-Windows server 2008 on Open System vs. WPA2 [9]

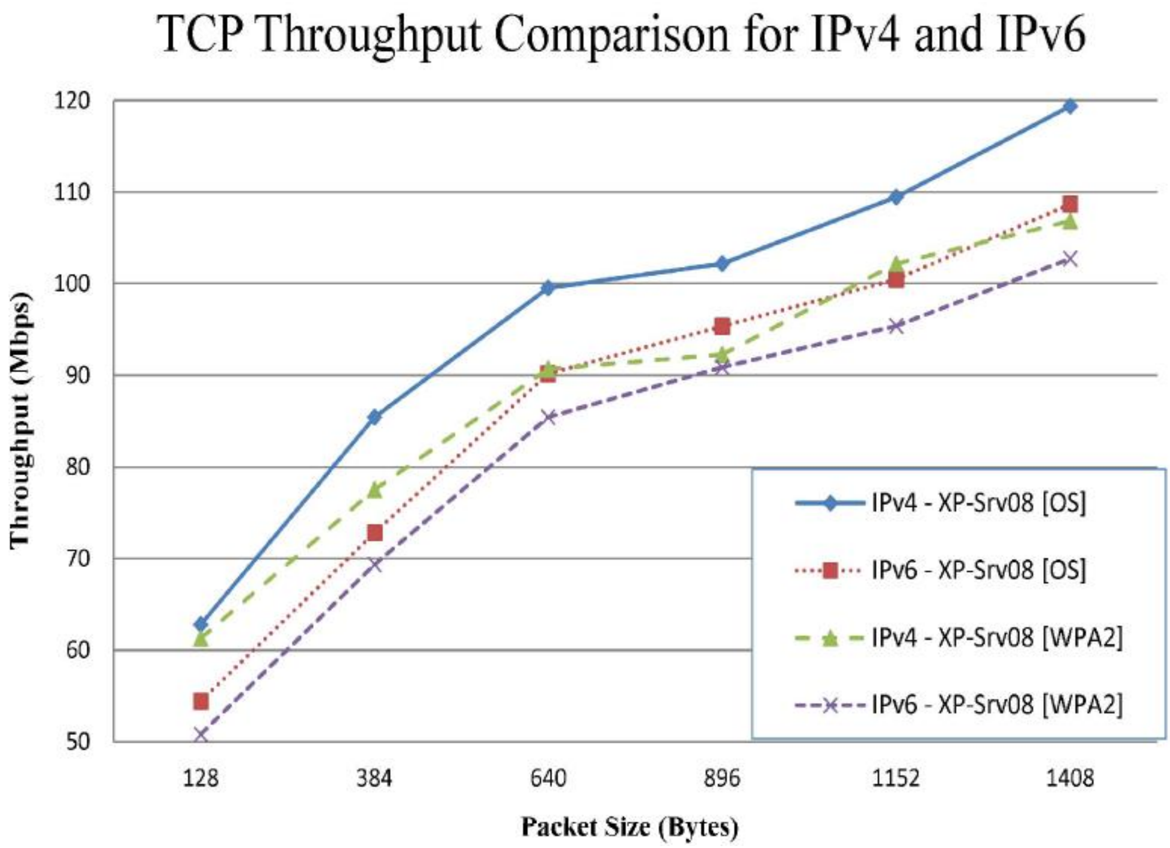

Figure 50. TCP Throughput comparison for IPv4 and IPv6 on XP-Windows server 2008 on Open System vs. WPA2 [9]

IPv4 without WPA2 achieves the highest UDP throughput at around 175 Mbps. In both [9] and [10] simulations IPv4 performs better with or without WPA2 and when WPA2 is applied the network throughput drops.

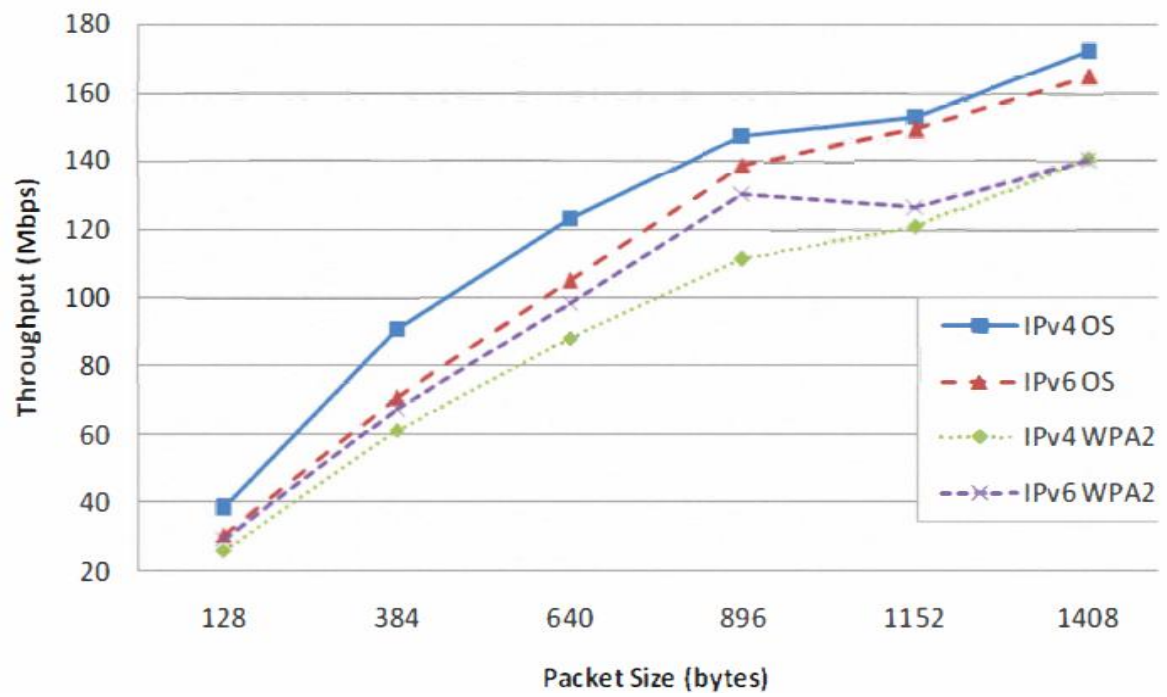

Figure 51. UDP Throughput comparison for IPv4 and IPv6 on Windows 7-Windows server 2008 on Open System vs. WPA2 [10]

There is a deduction in throughput but having a secure network is more important. On the other hand, IEEE 802.11n offers very high throughput in contrast to the legacy devices so a deduction on network's performance is negligible compared to the impact on the performance of the legacy devices.

4. Conclusions

Issues like QoS and security which are directly associated with the operation of IEEE 802.11n and interworking were discussed in this chapter. QoS is important for real time services to function properly and MAC mechanisms of IEEE 802.11n enhance the performance of the services as shown in above works. Security is important for a secure network despite the fact that the overhead decreases throughput. Finally interworking offers many advantages in mobility but challenges must be altered in order to increase mobility experience.

CHAPTER 6

Future research and Conclusions

INTRODUCTION

IEEE 802.11n is the amendment of IEEE 802.11 family that increases both throughput and range significantly in contrast to the legacy amendments. Although high throughput and range have been achieved, research to boost throughput data rates even more won't stop. Bandwidth demands continue to increase. So Very High Throughput Study Group was formed in 2007 to find ways for throughput of at least 1 Gbps. Several standards are currently developed to help WLAN meet the need for throughput.

1. Future Research

Very High Throughput (VHT) Study Group was formed to research the means of achieving throughput of at least 1 Gbps over MAC. This means that MAC efficiency must improve more, besides the improvement in PHY. Basic requirement for VHT Study Group is the backwards compatibility, maintaining the network architecture of the IEEE 802.11 system. Another requirement is the seamless fallback from 60 GHz to 2.4/5 GHz IEEE 802.11n networks when needed. At 60 GHz frequency band various other systems exist such as 802.15.3c, standard ECMA 387 so it is also required that mechanisms will be developed to help coexistence with the other systems.

Parallel with the research of this next generation technology, discussions started for the type of applications that would run over this technology. Some of the models proposed were: HDTV in home network, rapid upload and download of large files to/from a server, campuses etc. Moreover discussions to identify which model will run in <6 GHz or 60 GHz were conducted. These conversations led to the decision of associating 60 GHz band with short distance, single link applications requiring high data rates like uncompressed video and desktop storage and display. Whereas, applications like lightly compressed video streaming around a home were associated to <6 GHz. VHT Study Group currently develops two Very High Throughput WLAN amendments: IEEE 802.11ac and IEEE 802.11ad.

IEEE 802.11ac

IEEE 802.11ac task is an amendment trying to achieve aggregate throughputs beyond 1 Gbps in the 5 GHz band [27]. This is the first time that a IEEE 802.11 amendment is targeting to improve the total network throughput rather than only improving the throughput of a single link. The increased throughput can be achieved by the following mechanisms:

• Multi-user multiple-input multiple-output (MU-MIMO)

• Channel bandwidths of 80 and 160 MHz

• 256-quadrature amplitude modulation (QAM)

With MU-MIMO multiple packets are transmitted at the same time to multiple clients. MU-MIMO defines up to eight spatial streams divided up to four clients. Assuming that the clients can receive two spatial streams and with 80 MHz channel bandwidth, data rate per client reaches 866 Mbps which means that total data rate (3.46 Gbps) is four times more the one without MU-MIMO. Challenges for future MU-MIMO devices are the link adaptation in an environment where the number of clients changes and time variation in the channel because MU-MIMO requires accurate channel knowledge in order to minimize inter user interference.

The channel bandwidth improvement introduces 80 MHz and 160 MHz bands. Like IEEE 802.11n, 80 MHz band uses two adjacent 40 MHz and 160 MHz two 80 MHz bands that is not need to be adjacent. In 160 MHz data rate of 866 Mbps is achieved from one spatial stream. Increasing the spatial streams up to eight the total data rate reaches 6.93 Gbps.

Quadrature amplitude modulation is the combination of amplitude modulation and phase shift keying. With the changes in radio frequency technology a 256 QAM is possible for IEEE 802.11ac. QAM further boosts the data rates keeping the same coding scheme as IEEE 802.11n, 5/6. The amendment is still in an initial form and further changes may apply to the final form.

IEEE 802.11ad

In January 2009, Task Group AD (TGad) began the process of developing a 60 GHz amendment to IEEE 802.11 [28]. TGad is in the process of the functional requirements of IEEE 802.11ad, firstly the functional requirements are identified. The primary requirement is the throughput achievement of at least 1 Gbps. IEEE 802.11ad operates at 60 GHz like other network systems so coexistence needs to be considered. Requirements include the backward compatibility with IEEE 802.11, the seamless fallback from 60 GHz to 2.4/5 GHz bands and vice versa, at least of 1 Gbps PHY throughput, 1 Gbps throughput of at least 10 meters and support of uncompressed video such as data rate, packet loss ratio and delay. Transmit Beam forming is included to achieve the above. As any new developing amendment in order to reach the final form challenges must be altered, like beam forming, MAC channel access, spatial reuse and more. Currently TGad develops the Functional Requirements, Evaluation Methodology, and Channel Model documents. When these are complete, the next step in the process will be to issue a call for proposals that will include new technological advancements for 60 GHz.

2. Overall Conclusions

WLANs are deployed massively all over the world because of their ease of installation, low cost, mobility and because they reach where wires can’t. This massive adaptation is based also in technological market with the production of laptops, PDAs and more. IEEE 802.11 family consists of amendments with different area coverage and data rates [26]. The need for higher throughput leads to the research of new amendments since the appearance of IEEE 802.11a/b in 1999. Then IEEE 802.11g offering higher throughput was published and adopted as the WLAN amendment. IEEE 802.11e was published to aid in performance of delay sensitive services like VoIP, online gaming and more. The need for even more throughput in PHY and MAC layer led to IEEE 802.11n. Having many new and enhanced features of IEEE 802.11e, like TXOP or block ACK, IEEE 802.11n improves network efficiency and throughput. Several simulations and scenarios are run to evaluate the amendment’s performance in different environments, with dissimilar combination of its MAC mechanisms on various services. Moreover proposals are made to further enhance or add functions to IEEE 802.11n operation. Functions like multicast or algorithms to control aggregation size depending on BER for improving performance are considered research challenges. In addition improving PHY and MAC layer to achieve even more higher throughput is a challenge.

To conclude, IEEE 802.11n, with the increase in range and throughput due to PHY technologies and MAC mechanisms and enhancements, boosts the network performance for any traffic class as shown in previous chapters and MIMO and Frame Aggregation with Block ACK are considered the most significant features at the PHY and MAC layer respectively.

3. Conclusions

The need for throughput of at least 1 Gbps led to the formation of the Very High Throughput Study Group. Two amendments are developed but both are in early stage, the IEEE 802.11ac and IEEE 802.11ad. Both amendments will achieve, as functional requirements identify, at least 1 Gbps operating in <6 GHz and 60 GHz band respectively, but first some challenges have to be altered.

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