Experimental Performance Evaluation and Frame Aggregation Enhancement in IEEE 802.11n WLANs

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***Abstract*:** The IEEE 802.11n standard promises to extend today's most popular WLAN standard by significantly increasing reachability, reliability, and throughput. Ratified on September 2009, this standard defines many new physical and medium access control (MAC) layer enhancements. These enhancements aim to provide a data transmission rate of up to 600 Mbps. Since June 2007, 802.11n products are available on the enterprise market based on the draft 2.0. In this paper we investigate the effect of most of the proposed 802.11n MAC and physical layer features on the adhoc networks performance. We have performed several experiments in real conditions. The experimental results demonstrated the effectiveness of 802.11n enhancement. We have also examined the interoperability and fairness of 802.11n. The frame aggregation mechanism of 802.11n MAC layer can improve the efficiency of channel utilization by reducing the protocol overheads. We focused on the effect of frame aggregation on the support of voice and video applications in wireless networks. We also propose a new frame aggregation scheduler that considers specific QoS requirements for multimedia applications. We dynamically adjust the aggregated frame size based on frame's access category defined in 802.11e standard.

***Keywords*:** IEEE802.11n, Quality of Service, Performance Evaluation, Frame Aggregation.

1. Introduction

The IEEE 802.11 wireless local area networks (WLANs) are being deployed widely and rapidly in many different environments. However, the demand of multimedia applications, that require more bandwidth like audio and video stream transfers, is increasing over WLANs. With the inefficiency of IEEE 802.11a/b/g [1] standards in term of throughput, need to further improvement of these propositions have been raised. Therefore, significant research efforts have been made in this direction. The IEEE 802.11n [2] stands out as a solution and promises both higher data rates up to 600 Mbit/s and further range. The 802.11n Task Group (TGn) has come up with many amendments to address the various issues related to physical (PHY) layer, medium access control (MAC) layer and enhance the functionalities of WLAN. The first draft 802.11n was approved in 2006. Draft 2.0 which is widely considered to provide a stable foundation for commercial products was approved in 2007. The standard was ratified on September 2009 [2].

In the physical layer, 802.11n uses a MIMO technology where multiple antenna elements can be combined to achieve either higher PHY data rates (in Spatial Division Multiplexing (SDM) mode) or higher range (in Space Time Block Coding (STBC) mode). It uses channel bonding, where two 20 MHz channels of legacy 802.11 can be combined to a single 40 MHz channel, thus increasing the PHY data rate. In the MAC layer, 802.11n introduces three key enhancements: frame aggregation that consists of combining multiple data frames into an aggregate one, block acknowledgment mechanism where a single-block acknowledgment (ACK) frame is used to acknowledge several received frames and reverse direction mechanism which allows transmission in both directions. These features make IEEE 802.11n a promising technology for building WLANs [3].

Today, several 802.11n draft 2.0 based products are available in the market. But, we do not know much about their performance due to the lack of experimentation investigation by the research community. In this paper we provide a detailed performance study of 802.11n by experimentally evaluating the potential impact of new MAC mechanisms and their combination on throughput under diverse scenarios in adhoc networks. We have also examined the interoperability and coexistence of 802.11n with legacy devices. We looked up the fairness of 802.11n in indoor environments. The results of the experimentation showed that the 802.11n protocol is not completely fair, the effect of frame aggregation depends greatly on the network conditions, and the IEEE 802.11n offers a good backward compatibility with the flexibility of selection of the operating mode.

In addition, we propose a new frame aggregation scheduler that takes into account specific QoS requirements (delay, jitter, bandwidth...) for real time applications such as VOIP and video streaming. Based on IEEE 802.11e service differentiation, four access categories are defined. Frames of the same access category and which are sent to the same destination are aggregated.

We dynamically adjust the aggregated frame size based on QoS requirements. Results show that maximizing the size of aggregated frame for high rate applications can greatly enhance the QoS. However, for low rate applications such as VOIP, aggregation technique can leads to large delay so affecting the QoS. We have then defined various aggregated frame size depending on access category.

The rest of the paper is structured as follows. In Section 2, we give a short overview of 802.11n MAC and PHY enhancements. Section 3 presents related works. In Section 4, measurement environments and the equipments used are described; the obtained results are presented and discussed. In

Section 5, we analyze the effect of frame aggregation on the support of multimedia applications. In section 6 we explain the proposed frame aggregation scheduler. Simulation results are then presented. Finally, conclusions are given in Section 7.

2. Overview of 802.11n enhancements

802.11n introduces several enhancements to the 802.11 PHY and MAC layers that significantly improve the throughput and reliability of wireless communication. In the following, we provide a brief description of these features [3,4].

2.1. PHY layer enhancements

2.1.1. Multiple Input Multiple Output (MIMO)

The IEEE 802.11n standard is the first IEEE 802.11 standard to introduce a MIMO-based physical layer, providing higher data rates up to 600 Mbit/s and higher range. MIMO technology provides the ability to receive and/or transmit simultaneously through multiple antennas. 802.11n defines many MxN antenna configurations, ranging from 1x1 to 4x4. This refers to the number of transmit M and receive N antennas. In general, the more antennas an 802.11n device uses simultaneously, the higher its maximum data rate. However, multiple antennas do not by themselves increase data rate or range. Those improvements come from how the MIMO device actually uses its multiple antennas [5]. MIMO links can operate in two different modes described in what follows:

- Spatial Division Multiplexing (SDM)

SDM subdivides an outgoing signal stream into multiple streams. These streams are being spatially multiplexed and transmitted simultaneously from the multiple antenna elements, within one frequency channel. Arriving with different strengths and delays at the receiver, the multiple streams are separated and recovered using signal processing techniques. MIMO SDM can significantly increase data throughput as the number of resolved spatial data streams is increased.

- Space Time Block Coding (STBC)

In STBC technique, multiple copies of the same data stream are transmitted across a number of antennas. By comparing arriving spatial streams, the receiver has a better chance of accurately determining the original signal stream in the presence of RF interference and distortion. Thus, STBC improves reliability by reducing the error rate experienced at a given Signal to Noise Ratio (SNR).

2.1.2. *Channel bonding*

The increase in the PHY transmission rate in IEEE 802.11n technology is also due to the use of wider channel bandwidth. Legacy 802.11 devices operate on 20 MHz channels. In contrast, 802.11n based products support both 20 MHz and 40 MHz channels. The 20 MHz channels are to be used where the spectrum availability is limited. However, the 40 MHz channels are the combination of two adjacent 802.11g channels, called also channel bonding. If properly implemented, the 40 MHz channels can be more desirable than two times the usable channel bandwidth of two 802.11 legacy channels [4]. Channel bonding provides higher PHY data rates, and in particular doubles the peak rate. This allows direct doubling of the PHY data rate from a single 20 MHz channel.

2.2. MAC layer enhancements

802.11n introduces three key enhancements which address the inefficiencies of the traditional 802.11 MAC layer. These are explained in the following.

2.2.1. Frame Aggregation

In order to reduce MAC layer overhead caused by inter-frame spacing and preamble and avoid the wasted time due to backoff and collisions of the 802.11 MAC protocol, new 802.11n devices have the option of bundling frames together for transmission. This mechanism is called frame aggregation. 802.11n supports two different forms of aggregation, known as A-MSDU and A-MPDU.

- MAC Service Data Unit Aggregation (A-MSDU)

The term MSDU refers to the payload that is carried by the 802.11 MAC layer frame. It consists of an LLC header, IP header and the IP packet payload. The A-MSDU aggregation technique combines multiple MSDUs with the same 802.11e quality of service into a single MAC frame (MPDU). The maximum A-MSDU size allowed by 802.11n is 8192 bytes. 802.11n receivers can acknowledge an A-MSDU frame by sending a single ACK frame, thus reducing the acknowledgement overhead. The disadvantage of A-MSDU technique is that an error in receiving an A-MSDU transmission incurs the overhead of having to retransmit the entire A-MSDU again. Fig. 1 shows the structure of an A-MSDU frame.

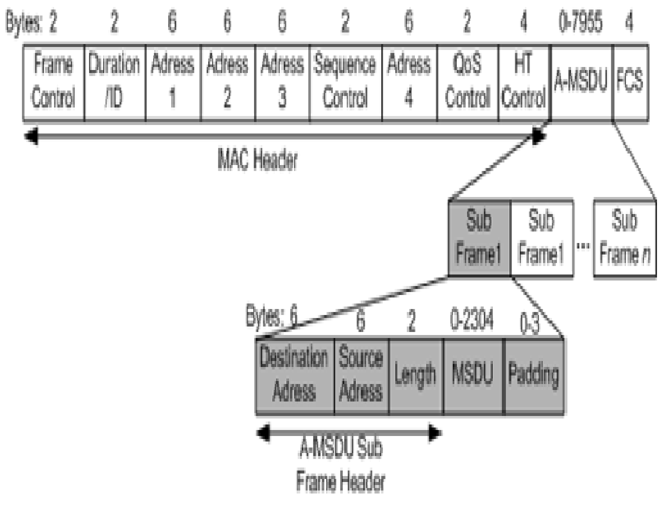

Figure 1. A-MSDU frame format

- MAC Protocol Data Unit Aggregation (A-MPDU)

A-MPDU occurs later, after MAC headers are added to each MSDU. It groups multiple MPDUs frames as a single frame. The maximum A-MPDU size allowed by 802.11n is 65535 bytes. A-MPDU does not have the limitation that all MSDUs must be destined to the same MAC address as A-MSDU technique.

The Block ACK must be used in this case in order to distinguish between lost and successful MPDUs, thus allowing the selective retransmission. This can be very useful in environments which have a high number of collision or transmission errors. Fig. 2 shows the structure of an A-MPDU frame.

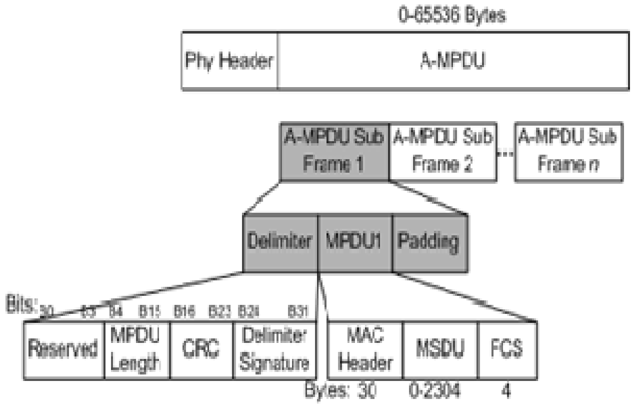

Figure 2. A-MPDU frame format

2.2.2. Block Acknowledgment

In legacy 802.11 MAC protocol, each of the frames transmitted to an individual address (not multicast or broadcast frames) is immediately acknowledged by the recipient. In order to reduce the overhead, 802.11n introduced the Block Acknowledgment (BACK) scheme. This is achieved by collecting many individual ACKs into a single BACK frame to acknowledge the receipt of multiple MPDUs. When using A-MPDU, block acknowledgment allows a selective retransmission of only those constituent frames that are not acknowledged. In environments with high error rates, this selective retransmission mechanism can provide some improvement in the effective throughput of a WLAN using MPDU aggregation over that of one using MSDU aggregation [6].

2.2.3. Reverse Direction

Reverse direction is an optional mechanism used to reduce the time and increase the efficiency for network traffics that have a bi-directional nature, for example VoIP or TCP traffic because of backward TCPAck flow. It allows transmission in both directions from different application streams. During a transmission opportunity (TXOP), the sender may grant permission to the receiver to send data frames with the response frame in a reverse direction.

3. Related works

There are several studies that have evaluated the performance of 802.11n by simulation, for example in [7] Wang et al. examined most of the new features of 802.11n using network simulator. But, there are only a few works that have performed experimental evaluation. In the following we will discuss some measurement works on the performance of 802.11n. In most of these studies, the experimental devices are based on draft 2.0.

Shrivastava et al. [8] presented an experimental study on the performance of IEEE 802.11n standard using a real testbed. They specially studied the impact of channel bonding and interference of 802.11g on 802.11n-links. Khattab et al. [9] experimentally showed that 802.11n medium access worsens flow starvation as compared to 802.11a/b/g and designed an asynchronous MIMO MAC protocol that resolves the problem. In [10], Pelechrinis et al. focus on the impact of the different 802.11n specific features on the peak performance. Recently, Verma et al. [11] evaluated the 802.11n draft 2.0 based products using the channel emulator. They presented the results of measurement campaign using Ralink RT2870 chipset. Pelechrinis and al. [12] evaluated the packet delivery ratio performance of 802.11n links when operating at the highest supported PHY data transmission rates. Pefkianakis et al. [13] studied MIMO based rate adaptation in 802.11n wireless networks in a real testbed in infrastructure mode and proposed a novel MIMO rate adaptation scheme that zigzags between intra- and inter-mode rate options.

Relation to these works, we rather study the effect of most proposed MAC 802.11n enhancements on the throughput in adhoc networks; we focus on the impact of channel bonding, aggregation, guard interval... In addition, we investigate the interoperability and coexistence of 802.11n with legacy devices. We consider the impact of different 802.11n operating modes on the network performance. Finally, we study the fairness of 802.11n by analyzing the bandwidth sharing feature. Among the novelties of this paper, no other work (using the same devices) has explored all the 802.11n MAC and physical features together.

In addition, there are many works that have examined the aggregation mechanism of 802.11n MAC layer. In [4], a detailed description of frame aggregation mechanisms is given. In [14] Lin et al. proposed an optimal frame size adaptation algorithm with A-MSDU under error-prone channels. Sidelnikov et al presented in [15] a simple fragmentation-aggregation scheme which combines the MSDU fragmentation and A-MPDU aggregation. In [16], Feng et al. evaluated an aggregated selective repeat ARQ (ASR-ARQ) algorithm which incorporates the conventional selective repeat ARQ scheme with the consideration of frame aggregation. Chan and al proposed an error-sensitive adaptive frame aggregation (ESAFA) scheme [17] which can dynamically set the size of AMSDU frame based on the maximum frame-error-rate (FER) tolerable by a particular multimedia traffic. In [18], Kim et al. investigated the effect of frame aggregation on the throughput. They proposed an analytical model based on an enhanced discrete time markov chain (DTMC) model in order to describe the postbackoff behaviour due to frame aggregation. Saif et al proposed an aggregation scheme (mA-MSDU) [19] that reduces the aggregation headers and implements a retransmission control over the individual sub frames at the MSDU level. In [20], Selvam et al. presented a frame aggregation scheduler that dynamically chooses the aggregated frame size and aggregation technique based on various parameters.

Opposed to these works, we focus on the impact of frame aggregation technique on the support of multimedia applications. We present a detailed simulation study of the influence of aggregation feature on transmitting voice and video applications over 802.11n networks. In addition, we propose a new frame aggregation scheduler for QoS-sensitive applications such as VoIP and VoD. We take the advantage of IEEE 802.11e service differentiation and we implement the aggregation mechanism correspondingly for each access category. We dynamically adjust the aggregated frame size based on QoS requirements. In fact, aggregation can degrade the QoS when it is used with low rate applications such as VOIP by increasing the delay and the jitter. This will be discussed in the next section.

4. Experimental performance evaluation of 802.11n protocol

In order to evaluate the performance of IEEE 802.11n protocol, we have performed several experiments. We have designed different scenarios to examine the performance of each enhanced MAC feature in 802.11n discussed in previous sections.

All experiments were performed using the D-Link DWA-160 Xtreme N Dual Band Draft 802.11n USB Adapters (revision B) [21] with RAlink RT2870STA driver. These devices support signals in either the 2.4 or 5 GHz frequency range and permit a maximum theorically throughput of 300 Mbps. They are configured and managed through many parameters. Most important ones are shown in Table 1. We also used netperf 2.4.5 [22] throughput measures.

Table 1. DWA-160 PHY and MAC parameters

NetworkType	NetworkType: Infra or Adhoc
WirelessMode	Mode: 11ABGN or legacy 11g only.
TxBurst	Transmission Burst: Enable or Disable
TxPre	Transmission Preamble: Long or short
TxPower	Transmission Power
Channel	depends on CountryRegion
RTSThreshold	RTS Threshold [1..2347]
HtBw	High throughput BandWidth 20 or 40 MHz
HtMcs	Ht Modulation and Coding Schemes: [1..15]
HtGi	Ht Guard Interval: 800ns or 400ns
HtOpMode	Ht Operation Mode: mixed or greenfield format
HtBaWinSize	Ht Backoff Window Size: [1..64]
PktAggregate	Packet Aggregate: disable or enable

4.1. Overall 802.11n enhancements

We first start looking at the global effect of different new 802.11n features on the throughput. We create an indoor adhoc network the topology shown in Fig. 3. Then we changed the following parameters:

- HtBw: To analyze the effect of channel bonding on the throughput, this parameter is set to 20MHz or 40 MHz.
- HtGi: An option to reduce the guard interval between transmissions (800ns or400ns, which boosts the throughput.
- HtOpMode: This parameter is changed to discuss the backward compatibility of 802.11n devices with legacy ones. The standard defines three operating modes: HT or Green field, Non-HT and HT Mixed. These are detailed later.
- TxPre: The preamble is used to synchronize transmissions. The 802.11n amendment defines three different preambles corresponding to the different operating modes. The device that we have used offers only the possibility to change it from short to long.
- PktAggregate: This parameter is set to true to activate aggregation.

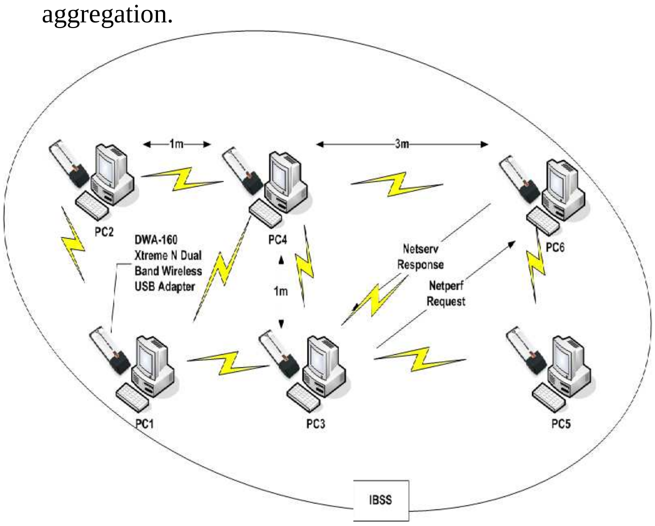

Figure 3. Adhoc network topology

Many schemes are evaluated combining different experimental parameters (Table 2).

Table 2. Experimented schemes

	HtBw(MHz)	HtGi(MHz)	HtOpMode	TxPre	Agg
1	20	800	Mixed(MM)	Long	No
2	40	800	Mixed	Long	No
3	40	400	Mixed	Long	No
4	40	400	Greenfield(GF)	Long	No
5	40	400	Greenfield	Short	No
6	40	400	Greenfield	Short	Agg

Fig. 4 and Fig. 5 show the throughput versus the packet sizes for various parameters combinations using UDP and TCP protocol respectively. Obviously, using UDP, the throughput is greater than using TCP. The reason is that TCP is connection oriented protocol. The maximum throughput value obtained, using UDP with bandwidth of 40MHz, is 170Mbps and only 95Mbps with 20MHz. In parallel using TCP, the throughput reaches 140Mbps and 85Mbps as maximum respectively with bandwidth of 40 MHz and 20 MHz. Furthermore, with TCP the values of throughput do not vary too much, they are almost constant. However, the fluctuations are more important in UDP schemes (e.g. the throughput varies from 110Mbps to 170Mbps with 40MHz).

In addition, we observe that HtBw feature has a significant impact on the throughput. This one is increased to almost double when using a channel bandwidth of 40 MHz. By comparing scheme 2 and scheme 3, we can also notice that reducing the guard interval to 400ns improves lightly the throughput. In fact, the short guard interval can reduce the overhead of the protocol. The TxPreamble feature has not significant impact. The aggregation and the operating mode features will be discussed with more details in the next sections.

We can conclude that, under normal conditions of tests, except HtBw, the other parameters haven't a real impact on the throughput.

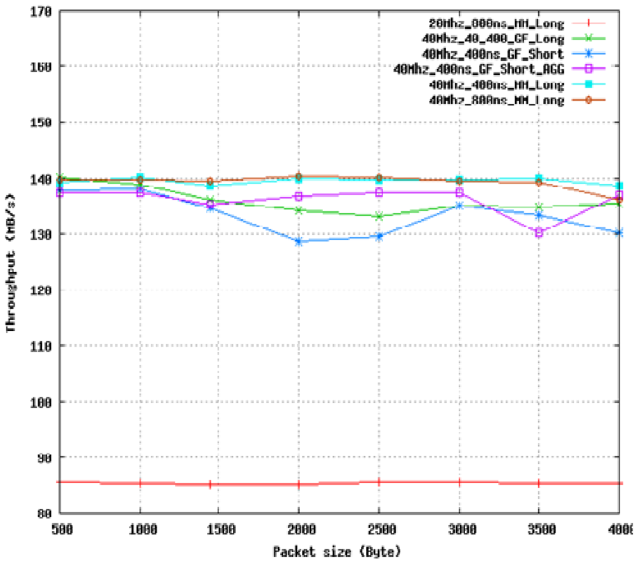

Figure 4. Throughput versus the packet sizes for varying parameters combinations using UDP protocol

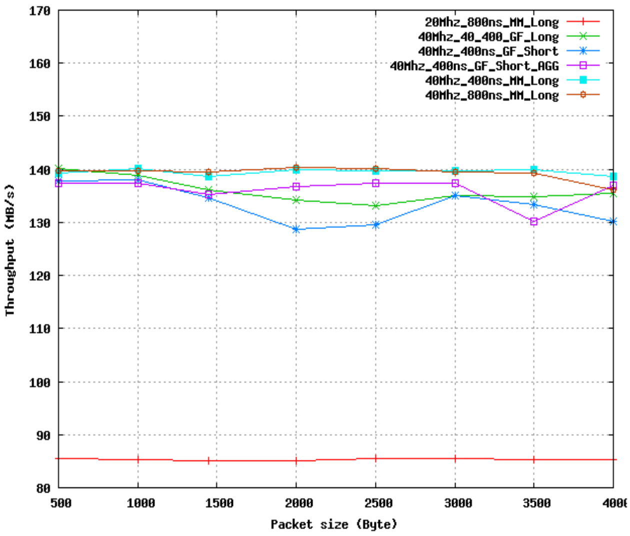

Figure 5. Throughput versus the packet sizes for varying parameters combinations using TCP protocol

4.2. Interoperability and coexistence

There are three 802.11n operating modes:

- High Throughput (HT) mode: A 802.11n device using HT mode, also known as Greenfield mode, assumes that there are no nearby legacy stations using the same frequency band.
- Non-HT (legacy) mode: A 802.11n device using non-HT mode sends all frames in the old 802.11a/g format so that legacy stations can understand them. That device must use 20 MHz channels and none of the new HT features.
- HT Mixed: In this mode, HT enhancements can be used simultaneously with HT protection mechanisms that permit communication with legacy stations. HT mixed mode provides backwards compatibility.

We create different scenarios to examine the performance and interoperability of these three operating modes of 802.11n. We used two stations from our topology of tests shown in Fig. 3. Then, each time we changed the parameter HtOpMode at the transmitter and the receiver nodes. The tests were performed with UDP protocol. The results are shown in Fig. 6. We observe that when the transmitter node is operating in HT mixed mode (11ABGN), the throughput depends on the receiver mode. It becomes greater if the receiver operates in Greenfield mode (11N) than the mixed one (the difference is about 60Mbps). As in the first case, if the transmitter mode is Greenfield, the average throughput decreases significantly when the receiver mode changes from 11N to 11ABGN. The reason that, when we use the mixed mode, the overhead is more important and especially we have to use a bandwidth of 20MHz to provide compatibility.
Finally, we can find that, using legacy mode (11ABG), the devices deliver no better performance than 802.11a/g. The average throughput is about 18Mbps.

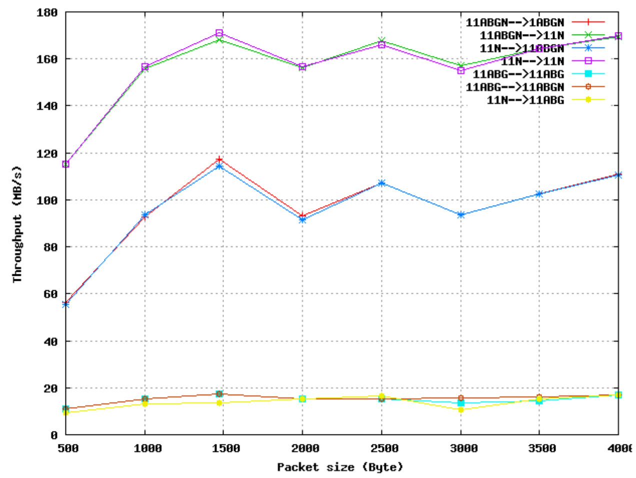

Figure 6. 802.11n interoperability and coexistence for various operating mode

4.3. Fairness

To evaluate 802.11n fairness, we examine the bandwidth sharing feature. We create three pairs of 802.11n stations as shown in Fig. 3 (PC1→PC6), in the same independent basic service set (IBSS), operating in Greenfield mode (802.11n only) with the same configuration. Each UDP traffic is started at different instants: the traffic 1→2, 3→5 and 4→6 are started respectively at 0s, 60s and 120s and they are stopped respectively at 300s, 180s and 240s. We measure the throughput every 10s for each traffic. The results are shown in Fig. 7.

We observed that the throughput decreases as the number of traffic increases. In addition, we remark that the total throughput rises when we have more traffic flow in the network e.g. at t=150s we have three different traffics and the total throughput is almost 250Mbps but at t=50s we have only 160Mbps. Furthermore, the flow which is started in first doesn't keep the large part of the bandwidth, for example at t = 130s the traffic 4→6 (which is started the latest) gets about half of the total band while the two other flows share the other half. Finally, we can conclude that the distribution of bandwidth between different flows is not completely fair. Notice that in this case a differentiation of service is required to transmit multiple traffic with different priorities.

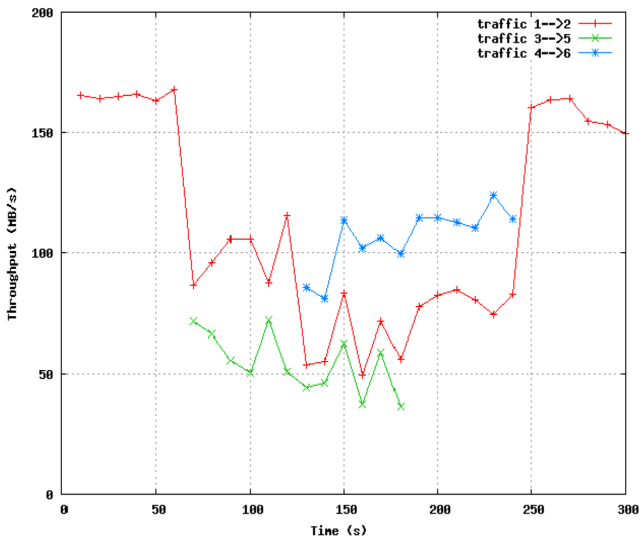

Figure 7. 802.11n fairness for sharing bandwidth

5. Effect of 802.11n frame aggregation on the support of multimedia application

The driver used in experimentation does not permit sufficiently to parameterize the aggregation if it is enabled. That's why we have investigated the aggregation mechanism using simulation. In order to study its effect on the performance of voice and video applications, we have performed several simulations in Network Simulator 2 (NS-2) platform [23]. We used IEEE 802.11n MAC and PHY module implemented in [7] which is based on TKN 802.11e EDCA module [24]. This module contains the implementation of A-MPDU aggregation, block ACK and reverse direction mechanisms in MAC layer. MIMO technique is also implemented in physical layer. To this implemented module, we added the A-MSDU scheme. To examine the effect of aggregation features, we perform several different scenarios. Used simulation parameters of MAC and PHY layers are shown in Table 3 [7], [25].

Table 3. Default parameter settings in simulation

Parameter	Value
Slot time	20 µs
SIFS	10 µs
DIFS	34 µs
TXOP limit	3.264 ms
PHY layer data rate	216 Mbps
Bit error rate	0.000008

5.1. The impact of aggregation on voice applications

Generally, in a voice/video over IP (VoIP) system, analogue signals are first digitized, compressed and encoded into digital voice/video streams by the codec. The output streams are then packetized for efficient and network friendly transmissions over an IP-based network [25, 26]. In general, multimedia streams are encapsulated with RTP/UDP/IP headers. Voice quality depends on selected coding scheme. The mostly used voice codecs are listed in Table 4. Every codec use different compression algorithms to conserve bandwidth and to reduce the effects of delay jitter and loss resulting in different bit rates. G.711 is the international standard for encoding telephone audio, which has a fixed bit rate of 64Kbps. With a 10 ms sample period, corresponding to a rate of 100 packets per second, the payload size is 80 bytes. When the sample period is increased to 20 ms, corresponding to 50 packets per second, the payload size is increased to 160 bytes accordingly. Compared to G.711, G.723 and G.729 have lower bit rates at a cost of higher codec complexity.

Table 4. Voice codecs

Voice codec		G.711	G.723a	G.729
Codec bit rate (Kbps)		64	5.3/6.3	8
Sample period (ms)	rate (fps)	Payload (B)	Payload (B)	Payload (B)
10	100	80	-	10
20	50	160	-	20
30	33.33	240	20/24	30
40	25	320	-	40
50	20	400	-	50

To investigate the effect of frame aggregation on the quality of voice applications, we modify the implementation of A-MPDU module. We set statically the size of aggregated frame. When it is set to 1, the aggregation feature is off. Otherwise MAC layer sends only aggregated frame with the corresponding size. When the queue is empty, the MAC layer has to wait for other packets to construct A-MPDU frames. We simulate three voice traffics using different CBR applications. Each one has the specific features of G.7xx codec. The network is not saturated. Fig. 8 and Fig. 9 show respectively the average throughput and the average delay versus the aggregation size (number of sub frames) for these traffics. Obviously, the average rate for each traffic is slightly greater than the source rate. This is thanks to the high physical link rate (216Mbps) hence the propagation delay is negligible compared to the sample period. For example the throughput of G.711 traffic is increased from 64kbps to 70kbps. Furthermore, when we boost the size of aggregated frame, the average rate is increased lightly. It is improved of 5kbps when the size of aggregated frame is set to 60 sub frames. However, varying the aggregation size has a significant impact on the packet delay. It is highly increased when we raise the size of aggregated frame. This is due to the time added when waiting for other packets in the queue to construct the A-MPDU frame. Thus, it will be unfavorable because voice applications are delay sensitive. Consequently, we can conclude that the use of aggregation for low rate applications degrade the end-to-end delay although the network is not saturated.

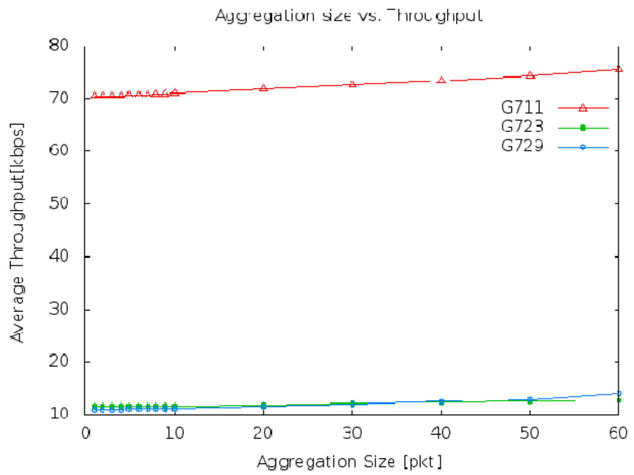

Figure 8. Average throughput versus the aggregation size for voice applications

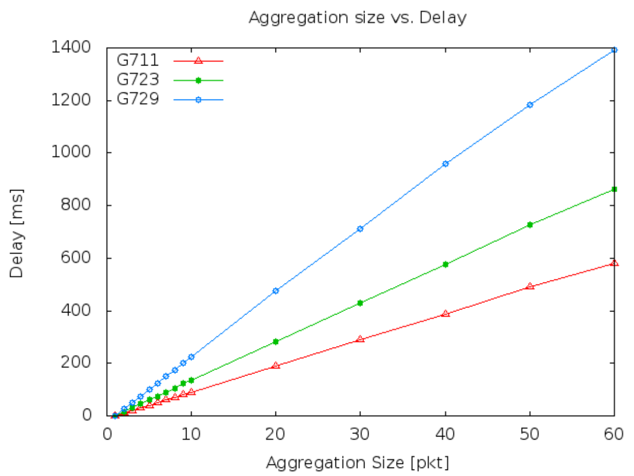

Figure 9. Average delay versus the aggregation size for voice applications

5.2. The impact of aggregation on video applications

Usually, video streaming services are high rate applications such as IPTV, video conferencing, etc. The ITU-T H.26x video compression standards are the most commonly used formats. H.264/MPEG-4 AVC (Advanced Video Coding) is one of the latest international video coding standards that support very high data compression. The H.264 codec has a broad range of applications that covers all forms of digital video from low rate Internet streaming applications (e.g., 64 Kbps) to broadband high definition video (HDV) applications (e.g., 240+ Mbps). Table 5 shows some levels of video coding. Each scheme coding uses different frame rate, resolution and maximum compressed video rate. At a particular level, higher resolution provides better image quality and higher frame rate results. For example, the level 3.2 supports up to 20Mbps video rate, with the frame resolution 1280x720 pixels at the frame rate of 60 frames per second. Level 4.2 supports up to 50Mbps video rate with the resolution of 1920x1080 pixels at the frame rate of 60fps

Table 5. Levels on H.264/MPEG-4 AVC

Level	Video bit rate (bps)	Resolution@ frame rate (fps)
1	64 k	QCIF @ 15
1.3	768 k	CIF @ 30
2	2 M	CIF @ 30
2.2	4 M	SD @ 15
3	10 M	SD @ 30
3.2	20 M	1280x720 @ 60
4	20 M	HD 1080 @ 30
4.2	50 M	1920x1080 @ 60
5	135 M	2048x1024 @ 72
5.1	240 M	4096x2048 @ 30

Similarly to voice evaluation, we simulate video traffics using different H.264 codecs. Fig. 10 and Fig. 11 show respectively the average throughput and the average delay versus the aggregation size for different H.264 traffics. We note that for high rates, maximizing the aggregation size increases the average throughput. For H.264 level 5, it rises from about 22Mbps to 130Mbps when we boost the aggregation size from 1 to 20 sub frames.

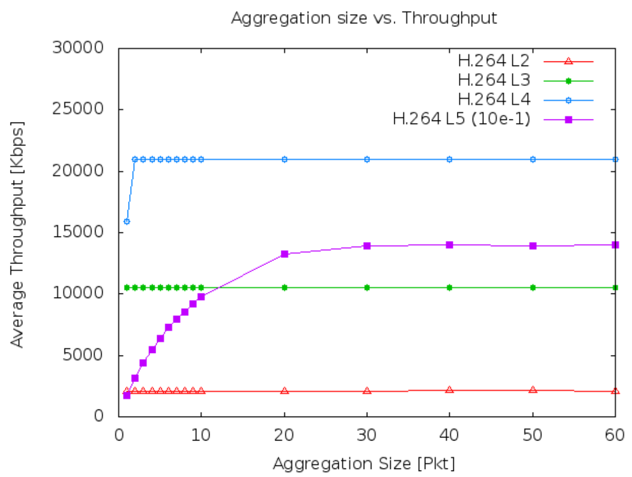

Figure 10. Average delay versus the aggregation size for video applications

Furthermore, the aggregation impact on delay depends greatly on the codec rate. For all codec levels, delays are reduced when increasing the frame aggregation size. But, when the sub frames are forced to wait in queue to construct the whole aggregated frame, average delays become higher. For H.264 L2, average delay decreases until an aggregation size of 10 sub frames. Beyond this threshold, it bounds to 20 ms and starts to increase proportionally to frame aggregation size.

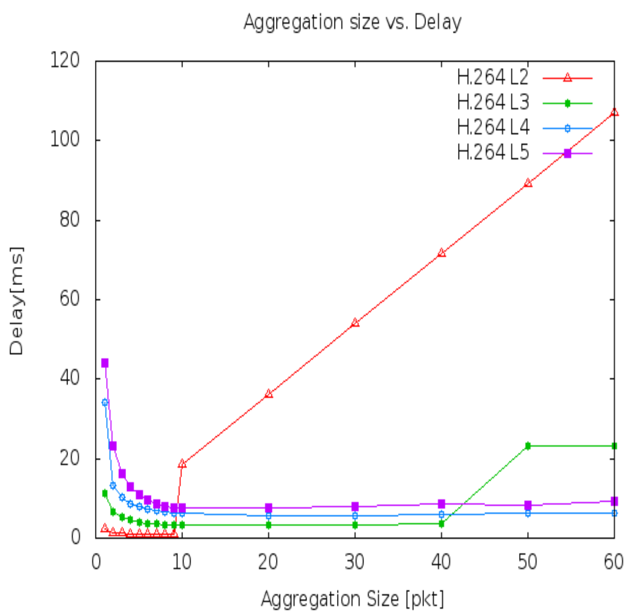

Figure 11. Average delay versus the aggregation size for video applications

6. Proposed frame aggregation scheduler

The IEEE 802.11n standard does not define a specific implementation of aggregation mechanism in MAC layer. In this section we propose a new frame aggregation scheduler that takes into account the QoS applications requirements. We combine 802.11e service differentiation and frame aggregation. In fact, the 802.11e introduces two new access modes EDCA and HCCA enhancing the QoS. These enhancements are based on the introduction of the concept of Access Categories (AC) to provide service differentiation. The standard defines four ACs as shown in Table 6 [27], [28]. Each AC has a specific handling in the access mode depending on the QoS requirements. Prioritization is ensured by assigning different values of contention parameters such as arbitration interframe space (AIFS), contention window (CW), and transmission opportunity duration (TXOP).

Table 6. Priority to access category mappings

802.1D Priority	Access Category (AC)	Designation
1	0	Best Effort
2	0	Best Effort
0	0	Best Effort
3	1	Video Probe
4	2	Video
5	2	Video
6	3	Voice

The goal of the proposed scheduler is to improve the effectiveness of aggregation mechanism. Fig. 12 illustrates the activity diagram and a pseudocode implementation of the proposed scheduler.

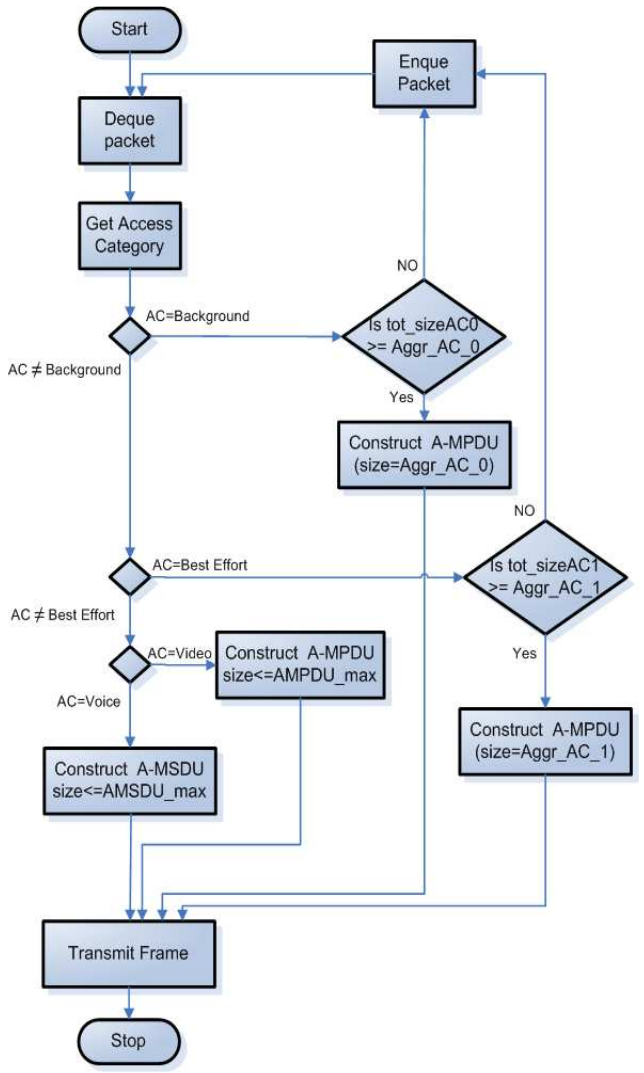

Figure 12 (a) The proposed scheduler activity diagram

```
Algorithm 1 Algorithm of the proposed scheduler
Input: p := deque_packet()
Output: packet to transmit
  var :
  agg_ac_x := aggregation size of the access category x
  tot_size_ac_x := total size of frames having the same
  access category in queue
  AMPDU_max := maximum size of AMPDU aggregation

  AMSDU_max := maximum size of AMSDU aggregation

  switch (access_category)
  case background:
    if agg_ac_0 <= tot_size_ac_0 then
      construct AMPDU frame with size = agg_ac_0
      transmit_frame()
    else
      enque_packet()
    end if
  case best effort:
    if agg_ac_1 <= tot_size_ac_1 then
      construct AMPDU frame with size = agg_ac_1
      transmit_frame()
    else
      enque_packet()
    end if
  case video:
    construct AMPDU frame with size <=
    AMPDU_max
    transmit_frame()
  case voice:
    construct AMSDU frame with size <=
    AMSDU_max
    transmit_frame()
  end switch
```

Figure 12 (b). The proposed scheduler Pseudocode implementation

Steps involved in our algorithm are:

- Define the minimum and maximum aggregation sizes for each AC priority
- Check frame access category
- Compute the total size (tot_size_AC_x) of frames having the same AC in queue
- Select the corresponding aggregation scheme according to the AC value

Frame aggregation is very effective in the case of high rate traffics and in saturated network. Otherwise, waiting for other packets in queue increases highly the delay especially those that arrive earlier. But, it can boost the throughput and reduce the network load. That's why; we forced packets, which are insensitive to delay such as Background and Best effort ACs, to wait for other packets. Once the aggregation size corresponding to each AC (Aggr_AC_x) is reached, frames are transmitted using A-MPDU aggregation. On the other hand, we have to not violate the maximum tolerable delay for delay-sensitive applications such as voice and video ACs. Then, when the MAC layer receives a packet of AC 2 or AC 3 from the upper layer, all packets in queue having the same AC are directly transmitted with or without aggregation.

A-MSDU scheme is used for voice being more adequate for applications that have small frame size [19].

We simulated a simple saturated network model to evaluate how the proposed scheduler influences the performance of voice, video and data traffics over WLAN. The simulation scenario consists of one wireless station connected to three others. Three different traffics are transmitted simultaneously. Each traffic has a different access category. Voice, ftp and video traffics are transmitted respectively at 64kbps, 1Mbps and 20Mbps. Traffics are started at different instants, 0s, 50s and 100s respectively for ftp, video and voice. The simulation stops at 150s. Average throughput and average delay variation are computed every 10s.

Fig. 13 and Fig. 14 show the scheduler impact on the delay and throughput of each traffic. The results demonstrate the effectiveness of our proposed scheduler in case of saturated conditions. In fact, when aggregation mechanism is enabled, the average delay is highly decreased for each traffic and the throughput is greatly enhanced. We also note that the throughput is more stable even during the period when all traffics are present (100s-- 150s).

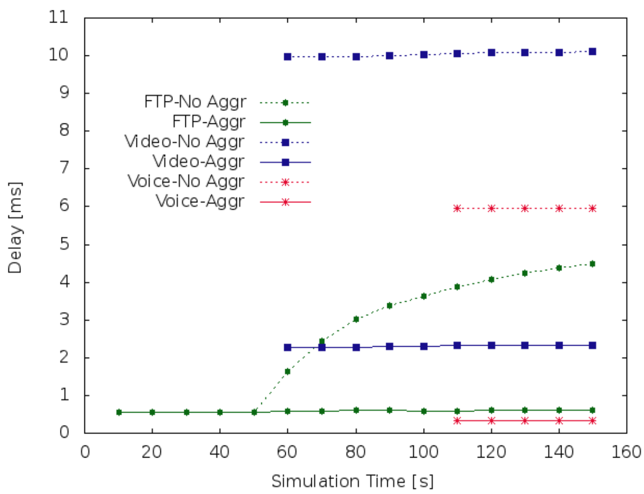

Figure 13. The impact of the proposed scheduler on delay

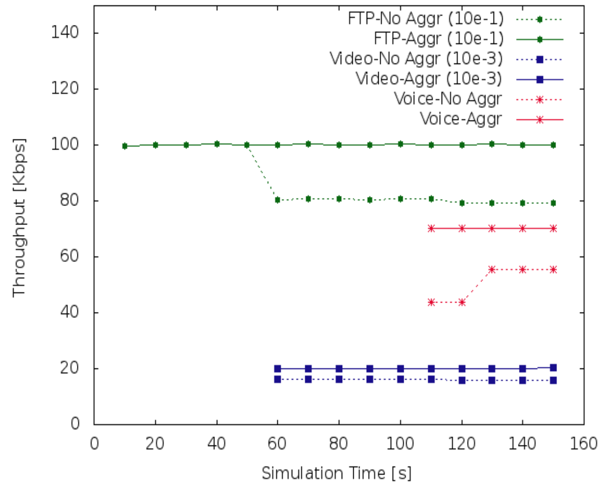

Figure 14. The impact of the proposed scheduler on throughput

7. Conclusions

In this paper, we presented a measurement study of the new IEEE 802.11n features in a real indoor adhoc networks. We performed several experiments scenarios using UDP and TCP traffic types with Ralink RT2870 chipset. Our results can be summarized as follows.

- The channel bonding feature has a significant impact on the throughput. Using a bandwidth of 40 MHz can considerably increase the throughput. Other features such as the short guard interval (400ns) can increase lightly the throughput in some situations.
- IEEE 802.11n offers a good backward compatibility with the flexibility of selection of the operating mode.
- Aggregation can enhance the throughput. But, if the packet loss rate is high, it can degrade the network performance.
- The distribution of 802.11n bandwidth among much traffic is not completely fair.

We have also shown the impact of the aggregation mechanism on the transmission of voice and video applications over 802.11n WLANs. Simulation results showed different effects depending on the rate application. Aggregation scheme is very effective in case of high rate traffics. But, it can degrade the QoS by increasing the frame delay when it is used with low rate application such as VOIP. In order to improve the efficiency of the aggregation implementation, we have presented a simple scheduler which combine 802.11e service differentiation and 802.11n frame aggregation. Each access category has a corresponding aggregation scheme with the appropriate parameters. Results have indicated that the proposed scheduler can enhance the QoS in lightly loaded conditions. Continuity of this work, we are currently trying to improve the use of aggregation under lossy environments.

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