IEEE 802.11a, 802.11e and HiperLAN/2
Goodput Performance Comparison in Real Radio Conditions

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Abstract-- **A MAC performance comparison between IEEE 802.11a, 802.11e and HiperLAN/2 WLAN standards is presented integrating both physical layer rate adaptation and retransmission mechanisms. Some simulations of the different MAC and error control layers have been conducted using a binary error pattern captured from an actual OFDM modem instead of an error model. The performance is evaluated by assessing the maximum total goodput provided by the systems in typical radio environments. Finally, an analysis of the results establishes the conditions in which the mechanisms specific to each protocol become profitable.**

Index terms— **WLAN, MAC, Error Control, Link Adaptation**

I. INTRODUCTION

Although they share a similar 5GHz Orthogonal Frequency Division Multiplexed (OFDM) physical layer, the Wireless LANs (WLANs) standards IEEE 802.11a/e and HiperLAN/2 (H/2) implement very different medium access mechanisms. So far, many performance studies about these WLANs have focused on Medium Access Control (MAC) performance evaluation based on simulation of the physical (PHY) layer [1] or packet error models [8]. However, the performance of the MAC and Error Control (EC) layers greatly depends on the radio channel evolution and the OFDM modem capabilities that are not completely reflected by these simulations. For this reason, we have considered here MAC/EC simulations based on PHY measurements captured by an actual OFDM modem.

To adapt to the fluctuating radio channel conditions, the OFDM PHY layer provides several PHY modes that can be selected via a Link Adaptation (LA) mechanism. The impact of LA on throughput and error rate is major, and the performance of further mechanisms provided by the different MAC/EC layers greatly depends on it.

Among performance parameters, the total offered goodput has been chosen to compare MAC/EC protocols defined by 802.11a/e and H/2 standards. Goodput is defined as the throughput offered to the upper layer while guarantying no data loss. Goodput measurements can be easily obtained from a simple point-to-point configuration. We also show the impact on goodput of system parameters such as queues length in an error-prone environment.

The contribution of this paper is the following: in the next section, the basic operation of the protocols is revisited. In section III, the PHY measurements and the simulation procedures are described. Section IV shows how the MAC/EC layers are influenced by the 5GHz radio channel behaviour and which assumptions can be made for all simulated protocols. Some protocol-specific parameters are fixed from simulation results in section V. In section VI, the goodputs provided by the different MAC/EC layers are compared and their performance is analysed to highlight their respective benefits. Finally, the conclusions are drawn in section VII.

II. STANDARD PROTOCOL OVERVIEW

Both standards use the same PHY layer based on OFDM that allows high bit rate transmission on frequency selective channels with a relatively low complexity. It provides several PHY modes that combine different coding rates and modulations. PHY modes can be dynamically selected through LA to achieve a compromise between throughput and error rate [8]. Basically, transmission is organised in so called PHY bursts constituted of a PHY preamble, used for synchronisation and channel estimation, followed by the MAC payload encoded with the PHY mode selected by LA.

Although some differences distinguish PHY layers of both standards, e.g. scrambler, preamble, PHY mode set [1][6], their intrinsic performance remains similar.

The legacy IEEE 802.11 [2] proposes two MAC operating modes: the Distributed Coordination Function (DCF) based on a Carrier Sense Multiple Access with Collision Avoidance scheme (CSMA/CA) and the Point Coordination Function (PCF) allowing contention free access. Basically, in DCF mode, prior to emitting a frame, a station shall listen to the radio medium for a given period to check if the channel is free. If the channel is busy, the station waits for an exponential backoff period before sensing the channel again. The receiver systematically acknowledges each packet and an unacknowledged packet is immediately retransmitted. MAC packets have a variable length and are directly encapsulated into PHY bursts. An optional frame fragmentation mechanism is also provided to improve error robustness. In this article, we consider the 5GHz OFDM PHY layer defined by the 802.11a supplement associated with the DCF mode (shortly called 802.11a in the following).

IEEE 802.11e extends the PCF mode in order to improve QoS capabilities, throughput performance and real-time application support [7]. For that purpose, a Hybrid Coordination Function (HCF) introduces resource allocation in a centralised Access Point (AP). A super frame is also defined that contains two parts: a Contention Free Period (CFP) where resources are scheduled by the AP and a Contention Period (CP) operating in DCF mode used notably for terminal association. In the CFP, the HCF grants variable time slots to terminals according to their needs. Overhead is reduced thanks to a shorter inter-frame period and an improved acknowledgement scheme. A transmitter can send successive frames or fragments acknowledged by the receiver in a single "BlockAck" frame previously requested by the transmitter.

In HiperLAN/2 [3], MAC implements a centralised Time Division Multiple Access (TDMA) / Time Division Duplex (TDD) scheme based on a 2ms frame. This frame contains up to 4 phases: broadcast, downlink (from the AP), uplink (to the AP) and direct link (between two stations). MAC Packet Data Units (PDUs) have a fixed length payload of 48 octets and are grouped per terminal into a PHY burst. Resource allocation is connection oriented, centralised in the AP and performed dynamically according to the need of connections and radio channel conditions. The EC sub-layer provides an Automatic Repeat reQuest (ARQ) mechanism providing fast retransmission of corrupted PDUs.

III. SIMULATION PROCEDURE DESCRIPTION

A. *PHY Layer Measurements*

Our laboratory has developed a full OFDM hardware experimental platform. For the measurements, two OFDM modems are connected via a hardware channel emulator operating at the Intermediate Frequency (IF) stage at 140MHz. An additional noise generator is inserted to adjust the average level of the channel signal-to-noise ratio (C/N).

At PHY level, a Pseudo Random Binary Sequence (PRBS) is transmitted over this emulated point-to-point radio link. The receiver decodes and compares it with the reference sequence and the resulting bit error pattern is processed offline. Due to implementation constraints, the bit error sequence only represents 90% of the whole acquisition time. The remaining 10% contains the PHY preambles, guard times and overhead induced by our hardware implementation. However, the channel behaviour during these missing parts can be extrapolated by running long time sequence captures. For this reason, all the measurements have been performed over a 300 second time period.

Two typical channel models have been used for measurements: the BRAN channel C [5] that reproduces large open space environment in non-line-of-sight radio conditions, and the BRAIN home channel that is representative of a domestic environment [4]. The following PHY modes have been considered for different C/N mean values: 64QAM¾, 16QAM¾, 16QAM9/16, QPSK¾, QPSK½. Table 1 summarises the features of both channels.

Table 1: Channel profiles used in hardware emulator (Delay/Average relative power)

Tap number	BRAN Channel C	BRAIN Home channel
1	0ms/-3.3dB	0ms/0dB
2	50ms/0dB	6.5ms/-1.3dB
3	80ms/-0.9dB	19ms/-1.3dB
4	180ms/-1.5dB	31ms/-7.9dB
5	230ms/-3dB	44ms/-11.8dB
6	600ms/-9.4dB	75ms/19.3dB

B. *MAC/EC Simulations*

IEEE 802.11a/e and HiperLAN/2 MAC/EC sub-layers have been simulated using the measurements performed at PHY level. The bit error patterns captured at PHY level are used as an input error model to determine when errors occur on transmitted packets.

The MAC/EC simulators have been stimulated with a single Constant Bit Rate (CBR) source that generates 1500-octet fixed size packets. An input data queue stores the received packets before their processing by the MAC and their emission on the radio link. Incoming packets causing a queue overflow are discarded. The maximum goodput is then defined as the highest throughput offered to the CBR source by the MAC/EC layer without any loss.

IV. RADIO CHANNEL IMPLICATIONS

A. *Radio Channel Behaviour*

An analysis of the PHY captures shows that a large number of errors is concentrated in long bursts whatever the radio channel is. Their duration can be longer than 10 ms with Bit Error Rates (BER) greater than 10^{-2}. These long error bursts are mainly the result of localised effects such as destructive interference or strong fading on every radio path due to Doppler spread. Their occurrence and duration depend on the environment. For both considered indoor channels, the maximum velocity is about 6km/h which induces a maximum Doppler frequency of 10Hz. This explains the duration of observed effects that are particularly amplified for low average C/N.

B. *Long Error Bursts Filtering*

These long error bursts have a strong impact on MAC protocol performance. During these, radio conditions become so difficult that every transmitted MAC packet is corrupted whatever its size is, causing numerous packet retransmissions, long delay and packet loss experienced by the upper layer. These intervals where the MAC becomes completely jammed can be avoided by the use of a more robust PHY mode that provides a better BER compatible with MAC requirements. The LA criterion used to determine when to change PHY mode may be any PHY layer characteristic that reflects the quality of the radio link, such as instantaneous C/N. As both standards include LA, impact of such a mechanism must be taken into account. The acquired sequence shall therefore be corrected to reflect the effect of LA before being provided to the MAC and EC simulations.

We have chosen to define an ideal LA mechanism common to both standards and independent from implementation constraints. For a given PHY mode, long error bursts are first detected, removed and replaced by an equivalent sequence obtained with the next more robust PHY mode. The same filtering process is applied in a recursive manner to the remaining long error bursts until the most robust PHY mode is reached. Resulting from that filtering, a PHY mode usage ratio can be calculated for each sequence. This ratio conveys the proportion of time that a physical mode has been used in a sequence for a particular C/N mean value.

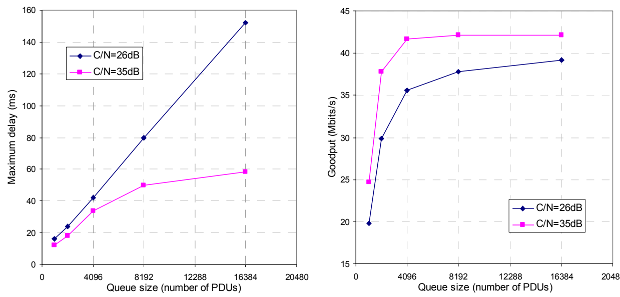
Long error bursts are defined by the following characteristics: (1) a mean BER over the burst duration greater than 10^{-3} ; (2) a burst duration longer than 5ms ; (3) a BER (200µs moving average) peak within the burst greater than 10^{-2}.

C. *MAC Input Queue Size*

The input queue absorbs the delay introduced by retransmissions due to the error bursts. With an infinite queue and assuming the retransmission window never stalls, the user goodput is equal to $R(1-PER)$ where R is the mean link throughput and PER is the mean Packet Error Rate. It is to be noted that the delay cannot be bounded in such a system. A finite queue results in a maximum delay that may be approximated by $Size_{Queue}*8/(R*(1-PER))$ where $Size_{Queue}$ is the queue length in bytes. As input packets are implicitly discarded beyond this maximum delay, the maximum reachable goodput decreases when the queue becomes smaller. However, measurements show that PER is subject to important variations over long periods, which limits the application field of the previous formula. For this reason, some simulations have been performed in order to determine the most adequate queue size.

Figure 1 illustrates the impact of queue size on delay and throughput for the H/2 protocol environment when C/N varies, using the most efficient PHY mode (64QAM¾) in BRAN channel C. In that stringent configuration, the value optimising both delay and goodput is close to 4096 PDUs (around 200 KBytes). Such a queue size allows to reach the maximum goodput for a high C/N whereas the goodput loss does not exceed 10% for a higher level of noise.

In order to fairly compare the performance of the different MAC/EC protocols, the input queue length is set identical for all of them.



(a) Queue effects on maximum delay **(b) Queue effects on goodput**

Figure 1. Queue effects on H/2 performance with 48-octet PDUs

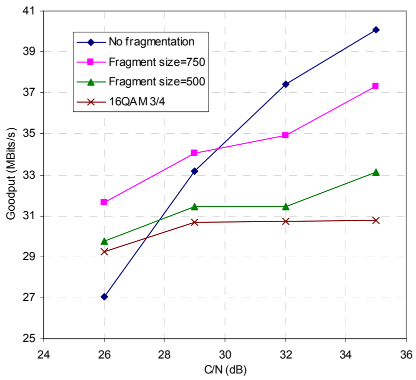


Figure 2. Effect of fragmentation on 802.11e MAC protocol (64QAM¾ on filtered BRAN channel C)

V. MAC/EC PARAMETERS SETUP

A. *Effect of Fragmentation (IEEE only)*

IEEE 802.11 protocols provide fragmentation capabilities in order to reduce the PER and to increase the resulting goodput. Reference [8] has shown that this mechanism is not interesting for 802.11a in DCF mode, mainly because of its intrinsic PHY/MAC overhead. Nevertheless, this overhead is significantly decreased in 802.11e when using contention free access and grouped acknowledgements.

Figure 2 shows the impact of fragmentation on the maximum goodput for 64QAM¾ PHY mode over a BRAN channel C with 1500-octet packets. It appears that fragmentation becomes efficient for a C/N lower than 29dB and a fragment size of 750 octets. However, 16QAM¾ PHY mode can be used without fragmentation in this C/N range to limit the goodput drop. Indeed, fragmentation is counterproductive for better C/N values. Consequently, next simulations of 802.11 MAC protocol have been performed without fragmentation.

B. *Acknowledgement Policies*

Unlike legacy 802.11 where acknowledgements are returned frame per frame, 802.11e allows to group acknowledgements in a so called BlockAck frame. In order to bound the retransmission delay, a maximum interval between successive acknowledgements has to be introduced. An acknowledgement is also requested by the transmitter when its input queue becomes empty or when the retransmission window is full. Upon acknowledgement reception, corrupted frames are retransmitted first. Different simulations have been conducted to determine an optimal maximum interval between two acknowledgements in order to maximise the goodput. These simulations show that an acknowledgement request every 16 frames is a good compromise. Beyond this limit, retransmission window stalls too frequently.

In HiperLAN/2, acknowledgements are returned on a per frame basis. Corrupted PDUs are retransmitted first in the frame following their previous emission. We assume that resource is always allocated for ARQ acknowledgements transmission so that PDUs to be retransmitted are known from the transmitter at any time (see Table 2).

For the sake of simplification, we suppose that acknowledgements do not experience errors.

C. *MAC/EC Parameters Summary*

It is to be noted that for all simulations, number of retransmission may be infinite. For 802.11e, the super frame does not include a contention period. Otherwise, Table 2 summarises the MAC/EC parameters used in simulations.

Table 2: MAC/EC parameters

Common parameters	
Traffic source	CBR with user data packets of 1500 octets.
Input queue size	200 Kbytes
Number of retransmissions per data frame	∞
Error on acknowledgements	No
IEEE 802.11e parameters	
Fragment size	No fragmentation
Maximum period between acknowledgements	16 data frames
Retransmission window size (fixed by the standard)	64 data frames (96kB)
Super frame duration	100ms
Contention Period	None
HiperLAN/2 parameters	
Maximum period between acknowledgements	One H/2 frame (2ms)
Retransmission window size	512 PDUs (26kB)
Number of allocated ARQ acknowledgements per frame	4 for 64QAM¾, 3 for 16QAM ¾, 2 for other PHY modes

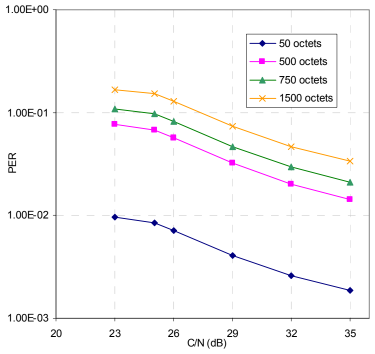
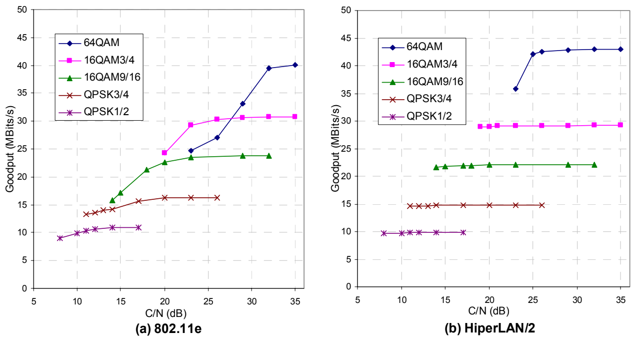


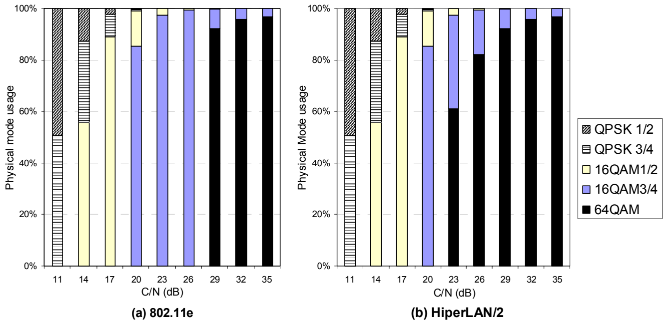
Figure 3: Packet size effect on PER
(64 QAM, filtered BRAN Channel C)



(a) 802.11e

(b) HiperLAN/2

Figure 4: Maximum goodput per PHY mode
on BRAN channel C after long error bursts removing



(a) 802.11e

(b) HiperLAN/2

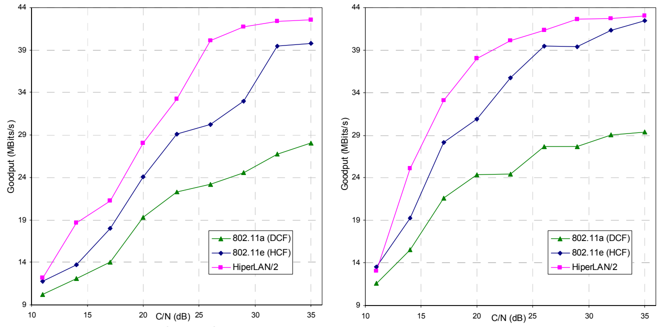
Figure 5: PHY mode usage on BRAN channel C

VI. SIMULATION RESULTS

For each modulation, Figure 4 compares the maximum goodput reached by 802.11e and HiperLAN/2 on a BRAN channel C excluding long error burst periods. From the PHY mode usage ratio given by LA (see section IV.B), we have evaluated the usage of the different PHY modes for both standards presented in Figure 5.

Figure 4b shows that H/2 sustains a high constant goodput over a wide C/N range for each PHY mode. Indeed, on this channel, H/2 mean PER remains relatively low (less than 10^{-2}) over the whole operating range of each PHY mode, as shown in Figure 3 for the particular case of 64QAM¾. Residual error bursts not filtered by LA are not frequent enough to degrade the performance. On the contrary, 802.11e is suffering from higher PER (up to 10^{-1}), due to large frame size (1500 octets). The operating range of the more efficient PHY modes is thus reduced.

Although not detailed here, 802.11a has a similar behaviour to 802.11e with an overall lower performance. An identical analysis has been performed for the BRAIN Home channel. The results are close to those obtained for channel C. The LA correction is amplified and the resulting PER after filtering is sensibly lower. The operating range of the more efficient PHY modes is then wider, particularly for 802.11e.



(a) BRAN Channel C

(b) BRAIN Home channel

Figure 6: maximum goodput comparison**.**

Goodput after LA filtering against average C/N is illustrated by Figure 6 for H/2 and IEEE 802.11 standards. These goodput charts reflect, for BRAN channel C and BRAIN Home channel, the effects of the link adaptation and their specific medium access and retransmission mechanisms. This figure highlights the benefits of 802.11e over 802.11a. It can be noted that the contention free access and the improved retransmission scheme allow to increase the performance mainly when the radio link is reliable. Indeed, as inter frame and backoff periods are defined as fixed time intervals in 802.11a, the degradation due to contention access is strengthened for higher C/N and for efficient PHY modes. After all, large packets remain a weakness, not resolved by 802.11e, that causes a drastic degradation of each PHY mode performance when radio conditions become difficult. High induced PERs prevent the retransmission mechanism from offering an effective service. As fragmentation cannot be used due to its inherent overhead, a more robust modulation shall be selected by LA that also leads to a rapid degradation of goodput.

Unlike in 802.11e, the H/2 ARQ mechanism allows to sustain a better goodput for high C/N values thanks to the short size of H/2 packets and its fast retransmission abilities. In Figure 6, a comparison of the curve slopes of 802.11e and H/2 for C/N values ranging from 23 to 32dB highlights this effect. In addition, as the operating range of each PHY mode is wider, we can assume that the system would be less sensitive and more tolerant to the flaws inherent to an imperfect LA scheme.

The goodput performance also depends on the actual channel behaviour as shown in Figure 6. As mentioned above, 802.11e achieves relatively better performance over the BRAIN Home channel. Indeed, on this channel, long error bursts filtered by LA are more frequent but fewer errors occur outside these periods. This underlines the critical function of the LA since the effects of long error bursts cannot be corrected by retransmission mechanisms as efficiently as by LA.

VII. CONCLUSIONS

The quality of the radio channel at 5GHz is very unstable and fluctuating with time. The method presented in this paper, based on measurements performed with an actual OFDM modem, allows to simulate medium access and error correction schemes with more realistic channel behaviours than those provided by PHY simulations or usual error models. Performance of IEEE 802.11a/e and HiperLAN/2 protocols can be fairly compared in an environment close to reality. For that purpose, the maximum reachable goodput versus the signal to noise ratio is a good indicator for performance estimation.

We have then highlighted some profitable mechanisms provided by the different standards. Firstly, whatever the channel is, an efficient link adaptation is required to avoid long error bursts due to location dependant errors. Goodput performance achieved by 802.11e and H/2 shows that a contention free access is required to optimise the usage of the more efficient PHY modes. A fast retransmission scheme based on short packets proves to be more effective and tolerant to correct residual distributed errors left by LA. At last, the input queue size shall be chosen carefully since it has a strong impact on the maximum delay and help improving resilience to error.

However, the performance of a MAC protocol cannot completely be characterised by the global offered goodput in a point-to-point configuration. To obtain a comprehensive comparison, parameters such as multiplexing efficiency and maximum delay in a multi-user environment should also be taken into account. Alternatives to LA as a mean to maximise goodput in a multi-user environment will have to be also considered. Among these, redistribution of transmission resource lost by terminal experiencing location dependant errors will be the subject of a future work.

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