Beyond WiFi 5: How to reach higher throughputs?

Technological obstacles and solutions

Sebastien Simoens, Pietro Pellati, Karine Gosse, Jeremy Gosteau, Marc de Courville

{ simoens, pellati, gosteau, gosse, courville}@motorola.com

Centre de Recherche de Motorola, Gif-sur-Yvette, France

Abstract

The IEEE 802.11 High Throughput Study Group has started to define requirements for the next generation of 802.11 Wireless LANs operating in the 5 GHz band. The 802.11a standard, commercially known as WiFi 5, defines a physical layer which reaches 54 Mbit/s. However, the throughput offered to upper layers by WiFi 5 products based on the plain 802.11 MAC layer cannot exceed 30 Mbit/s for long (1500 bytes) packets and 10 Mbit/s for shorter (250 bytes) ones. This article investigates the technological deadlocks and solutions when trying to achieve a significant throughput increase from the current WiFi 5 limits. When increasing the PHY bit rate to hundreds of Mbit/s, the MAC overhead becomes the main limitation to a throughput increase. In this paper we compare the theoretical throughput limits of 802.11, 802.11e and the TDD/TDMA MAC of HIPERLAN/2 and conclude that current 802.11 MAC cannot be adopted as is in a future High Throughput standard, whereas TDD/TDMA and to a lesser extent 802.11e are better candidates We then present physical layer techniques which enable to reach 100 Mbit/s throughput and extended range.

1. Introduction

The widespread adoption of Wireless Local and Personal Area Networks (WLAN/WPAN) in the home, enterprise, and public access environments is taking place today. The leading standard so far remains IEEE802.11, thanks to the success of the products certified by the WiFi Alliance. Most WiFi devices commercialized today operate in the 2.4 GHz ISM band and comply with the 802.11b physical layer standard, which specifies a peak bit rate of 11 Mbit/s. This specification can be seen as a wireless equivalent to the well known 10-base-T wired Ethernet access. The WiFi 5 products, operating between 5.2 GHz and 5.8 GHz in unlicensed bands and based on the 802.11a physical layer standard, will progressively replace or complement the already deployed 802.11b WLANs. They offer 54 Mbit/s maximum bit rate at the physical layer, but as shown below in this paper the actual throughput available for the upper layers (e.g. the TCP/IP stack) cannot exceed 30 Mbit/s.

Clearly, there exists a demand for even higher throughputs up to say a hundred of Mbit/s. In the enterprise environment, a 100-Base-T connection is common and Gigabit Ethernet already exists, therefore future High Speed WLANs will have to offer peak throughputs approaching a hundred Mbit/s in order to keep up the pace. Hot Spot operators would be interested in offering high throughput links over longer range which would allow them to reduce the number of Access Points, thus lowering the deployment costs for the same or even better coverage. In the home environment, the simultaneous distribution of high definition video streams inside the house is the most bandwidth hungry application, requiring tens of Mbit/s.

Based on these observations, the 802.11 Working Group has created the High Throughput Study Group (HTSG) which is in charge of defining the scope and requirements of a future High Throughput WLAN operating at 5 GHz. This step is the first one in a process which will possibly lead to the creation of a Task Group in charge of the technical specification of a future standard. This paper takes the creation of the HTSG as an opportunity to study not only evolutionary paths beyond WiFi 5, but also to assess the potential impact of more fundamental changes at both the PHY and MAC levels.

Before investigating the evolution of 802.11, it is necessary to examine the WLAN and WPAN standardization efforts ongoing worldwide. This is the purpose of the second section, with an emphasis on the 5 GHz OFDM physical layer shared by IEEE802.11a[1] , ETSI BRAN HIPERLAN/2[2] and ARIB MMAC HiSWANa. Section 3 performs a comparison of relative throughput performance analysis of 802.11a, 802.11e, and HIPERLAN/2 (H/2), and studies the limiting impact of the MAC overhead on the throughput gain that can be expected when increasing the raw physical bit rate. It turns out that H/2 and to a lesser extent 802.11e have a much better MAC efficiency than plain 802.11 at such high bit rates. Therefore, in section 4, we investigate the throughput performance obtained by combining these two MAC layer specifications with various physical layer techniques such as Multiple Antennae and Channel Bundling. Since this paper is more network-oriented, we do not detail the signal processing aspects of the physical layer strategies, but rather assess them from the strict point of view of throughput and range increase. Finally, we draw conclusions in section 5.

2. Overview of WLAN / WPAN standards

Although the dominant product on the marketplace today is IEEE802.11b, several standards have been developed that are able to support high rate applications, while many others are currently under development in various standardization committees and industrial groups. The aim of this section is to give an overview of their relevant technical characteristics.

WPAN Technologies: Bluetooth and IEEE802.15

The Bluetooth radio system was one of the first technologies designed for WPAN applications, providing a physical layer bit rate of 1 Mbit/s. Bluetooth technology establishes a short-range, low-power radio link between two or more devices operating in the 2.4 GHz ISM band. Bluetooth employs Gaussian Frequency-Shift Keying (GFSK) modulation with pseudo-random frequency hopping over the entire ISM band to improve data integrity. The target applications are low data rate peripherals networking and synchronization of devices (e.g. a mobile phone and a PDA). Bluetooth is able to support up to three voice channels, along with general data traffic. Bluetooth is promoted by an industry led Special Interest Group (SIG), and served as the basis for the IEEE 802.15.1 standard.

Another technology, currently under standardization, is the IEEE 802.15.3 high rate WPAN. The salient characteristics of this standard include:

- Ad hoc connections with QoS support
- Power management to save battery life
- Low-cost and low-complexity MAC and PHY layer implementations
- Support for high speed data rates (up to 55 Mbit/s)

Channel access is based on a MAC super-frame, divided into a Contention Access Period (CAP), where a CSMA/CA mechanism is used and reserved for non-QoS data frames, and a Contention Free Period (CFP) reserved to carry data with QoS constraints, as it is shown in Figure 1. This division is dynamically adjustable.

Beacon	CAP		CFP							
	Command	Data	MTS 1	MTS 2	GTS 1	GTS2	...	GTS N-1	GTS N	MTS N

Figure 1: Structure of the 802.15.3 MAC frame

At the physical layer, 802.15.3 employs a symbol rate of 11 Mbaud, with one of five distinct modulation schemes: uncoded QPSK at 22 Mbit/s; 16/32/64-quadrature amplitude modulation (QAM) at 33, 44, and 55 Mbit/s and finally a more robust 11 Mbit/s QPSK trellis coded modulation. The final version of the IEEE 802.15.3 high rate WPAN standard is expected to be approved in late 2002. This technology is especially suited for short-range multimedia applications such as transfer of image files from a digital camera to a PC, or as a cable replacement technology for home entertainment systems.

In addition to the features mentioned above, a new physical layer is also currently being standardized by 802.15.3. The newly formed 802.15.3a Study Group is currently investigating Ultra Wideband (UWB) technologies for a new physical layer capable of greater than 100 Mbit/s over short distances (typically 10 meters). Conventional radios like all those described in this paper transmit their power in a bandwidth that is small in comparison to their carrier frequency, whereas the UWB signal bandwidth is of the same order of magnitude as its center frequency (several GHz). This technology could potentially be used for bandwidth hungry applications (e.g. several video streams in parallel).

WLAN standards: IEEE802.11 a,b,e,g and Hiperlan 2

WLANs are designed with a greater coverage area in mind than a WPAN. The most common WLAN standard today is IEEE 802.11. Originally released in 1997, many task groups have since been created to enhance alternately the MAC layer or the PHY layer in order to achieve better performance in the unlicensed 5 GHz UNII band as well as in the original 2.4 GHz ISM band.

The original standard released in 1997 defined a CSMA/CA based MAC, two PHY layers in the 2.4 GHz band, and a third PHY based on Infrared (IR). The 2.4 GHz PHY employs Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) respectively to achieve between 1 and 2 Mbit/s. Two years later the task group 802.11b ratified a new standard for the PHY layer operating at 2.4 GHz. This specification introduces Complementary Code Keying (CCK) capable of data rates of 5.5 and 11 Mbit/s. This standard is clearly the most successful WLAN standard to date.

Following 802.11b was 802.11a [1][3], a new PHY for the 5GHz UNII band. The transmission technique employed is Orthogonal Frequency Division Multiplexing (OFDM), which when combined with convolutional coding and bit interleaving is very robust against multi-path propagation, especially in Non Line Of Sight (NLOS) conditions. An interesting feature of 802.11a is Adaptive Modulation and Coding (AMC) also known as Link Adaptation. By selecting a constellation from BPSK to 64QAM and a convolutional coding rate (1/2 to 3/4), the data rate on top of the physical layer can be varied from 6 to 54 Mbit/s, and adapted to the link quality, as shown on Figure 2.

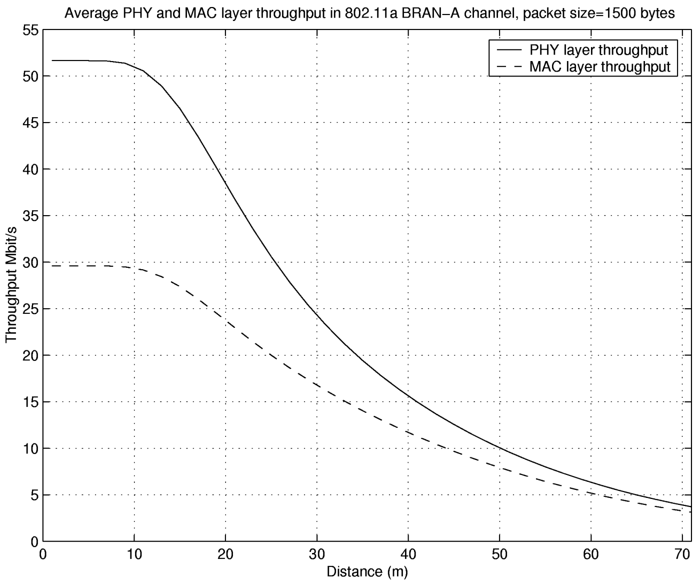

Figure 2: Throughput vs. distance of an 802.11a link with/without MAC overhead

Figure 2 illustrates the throughput of a single 802.11a connection as a function of the distance from the access point. The transmitted power is 200mW, which is the maximum level tolerated for indoor use. The indoor propagation environment is modeled by assuming a log-distance path loss model of exponent 3.6, with a shadowing variance equal to 5 dB, and a typical Non Line Of Sight channel with 50 ns r.m.s. delay spread. The link adaptation is based on the knowledge of the signal to noise ratio, which we assume is perfectly known. The packet size is 1500 bytes. It can be observed that the throughput on top of the MAC layer never exceeds 30 Mbit/s, although the terminals transmit with the 54 Mbit/s rate when they are close to the Access Point. This limitation is due to the MAC overhead, and will be further investigated in the next section.

IEEE 802.11a operates between 5.2GHz and 5.8 GHz in channels spaced by 20 MHz. The largest amount of unlicensed spectrum available at 5GHz is in Europe, where 19 channels are available, whereas Japan has only 4 channels available. Regulatory issues concerning the deployment of these networks are not completely solved, especially their coexistence with other systems such as military, aeronautical, and naval RADARs and satellite systems sharing the same spectrum. Task Group H within the 802.11 WG has been charged with solving these issues using Dynamic Frequency Selection and Power Control. Another 2.4 GHz physical layer specification is also under development by Task Group G. 802.11g products will be required to coexist with the various products already operating in this band (Bluetooth, 802.11b,...). The 802.11g physical layer includes a mandatory OFDM mode in order to achieve 802.11a data rates. Optional 8PSK and CCK-OFDM modes are also included.

This paper will not address security or the inter-access point protocol developed by Task Groups I and F respectively. However, the work performed by Task Group E should be taken into account when considering technical solutions for a next generation 802.11 standard. 802.11e, still under standardization though nearing completion [3], adds several mechanisms to the existing legacy 802.11 MAC in order to improve the Quality of Service support. In addition to the well-known Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) access technique of the Distributed Coordination Function (DCF), a Hybrid Coordination Function (HCF) is introduced where a hybrid coordinator (typically located in the Access Point) schedules the transmission opportunities of the terminals, based on individual requests. Additionally, the Enhanced DCF (EDCF) mechanism introduces priority to the contention based channel access mechanism to support soft QoS. Another feature of interest in 802.11e is the so-called Group Acknowledgement. After contending for a transmission opportunity, the terminal gaining access to the channel is able to transmit several packets with a single acknowledgement at the conclusion of the data burst. In the following section, additional performance gain as a result of this mechanism is investigated.

The approach of IEEE so far has been to enhance PHY and MAC layers separately. In Europe, the new HIPERLAN specification, called HIPERLAN type 2 (H/2) [2][4] has defined both a PHY and a MAC. Several comparisons have been performed between H/2 and 802.11a [5]. The PHY layer of H/2 is very similar to 802.11a, though the MAC layer is significantly different from 802.11, employing a centralized network architecture based on TDD/TDMA. Each MAC frame is divided into four phases (broadcast, up-link, down-link, random access) the length of which is determined by the AP. The target applications are the same as 802.11, though H/2 may be better adapted to time critical services, and has a highly efficient MAC protocol. MAC efficiency is of particular interest for future generation 802.11 standards, as will be illustrated in the following section.

In this section, we have given an overview of the existing access techniques in WPAN and WLAN networks. The focus of the next section is the 802.11a Physical layer, and on specific problems occurring when attempting to increase the data rate.

3. Can the 802.11 MAC support higher rates?

In the previous section, it was observed through simulation that the throughput on top of an 802.11a network is limited to a point significantly below the 54 Mbit/s theoretically achievable by the physical layer. Xiao and Rosdahl [14] have derived formulas for theoretical maximum throughput for the existing CSMA/CA 802.11 MAC. This result implies that a straightforward increase in physical bit rate will not necessarily lead to a corresponding increase in throughput.

In [6], the same authors compare the throughput performance of 802.11 and 802.11e group acknowledgement mode as a function of new physical layer bit rates. It is shown that the MAC overhead of 802.11e can be reduced by transmitting a group of packets in a single transmit opportunity, resulting in a much higher throughput than plain 802.11 at high physical bit rates. In this section, we extend this work and show that compared to the HIPERLAN/2 protocol, the MAC efficiency of 802.11e remains limited at high physical bit rates by the Inter Frame Spaces, which reduce the effect of increasing the group size.

The 802.11 DCF mentioned before in this paper describes two techniques for obtaining channel access. The default scheme, or basic access mode, employs a two-way handshake. This mechanism is characterized by the immediate transmission of a positive acknowledgement (ACK) by the destination upon successful reception of an MPDU.

In addition to the basic access method, a four-way handshaking technique known as *request-to-send / clear-to-send* (RTS/CTS) has been standardized for dealing with the hidden station problem.

As the DCF is based on CSMA/CA, inter-frame spaces (IFS) are employed for controlling medium access. Prior to sensing the channel to determine whether it is free, a station has to wait for the specified IFS. Four different IFSs are specified in 802.11, representing four different priority levels for the channel access. The shorter the IFS, the higher is the priority.

In order to evaluate limit performance some assumptions have been made:

1. Basic Access Mode (there is no RTS/CTS, which would lead to an even higher overhead).
2. There are only two nodes in the Basic Service Set (BSS): one is the sender and the other is the receiver.

Therefore, the transmitter never has to contend with any other station to access the medium. It gets a transmission opportunity at the end of the minimum contention phase which is defined in the standard. Moreover there is no collision. Under these assumptions, the throughput is maximized and can be shown equal to:

$$MaxThroughput = \frac{8L_{data}}{\frac{CW_{\min}T_{slot}}{2} + T_{difs} + T_{d\_data} + \tau + T_{sifs} + T_{d\_ack} + \tau} \quad (1)$$

where:

$$T_{d\_data} = T_{preamble} + T_{h\_phy} + T_{sym} * \left\lceil \frac{16 + 6 + 8 * 28 + 8L_{data}}{N_{dbps}} \right\rceil \quad (2)$$

$$T_{d\_ack} = T_{preamble} + T_{h\_phy} + T_{sym} * \left\lceil \frac{16 + 6 + 8 * 14}{N_{dbps}} \right\rceil \quad (3)$$

with:

N_{dbps} : number *of* data bits per OFDM symbol

T_{sym}: transmission time of an OFDM symbol

T_{h_phy}: transmission time of PHY header

τ: propagation delay

and: $T_{slot} = 9\mu s$, $T_{sifs} = 16\mu s$, $T_{difs} = 34\mu s$, $CW_{\min} = 15$, $T_{preamble} = 16\mu s$, $T_{h\_phy} = 4\mu s$, $T_{sym} = 4\mu s$, $\tau = 1\mu s$. We refer the reader to [6] and [14] for a detailed explanation of each term in the equation.

Data Rate (Mbps)	**Modulation**	N_{dbps}
6	BPSK	24
9	BPSK	36
12	QPSK	48
18	QPSK	72
24	16-QAM	96
36	16-QAM	144
48	64-QAM	192
54	64-QAM	216

Table 1: Parameters for the various modes of 802.11a

When PHY layer bit rate goes to infinity, N_{dbps} goes to infinity as well but still at least OFDM symbol is required to transmit the data and one for the acknowledgement, so that we find a throughput limit slightly different from [14]:

$$LIMIT = \frac{8L_{data}}{\frac{CW_{\min}T_{slot}}{2} + T_{difs} + 2T_{preamble} + 2T_{h\_phy} + 2\tau + T_{sifs} + 2T_{sym}} \tag{4}$$

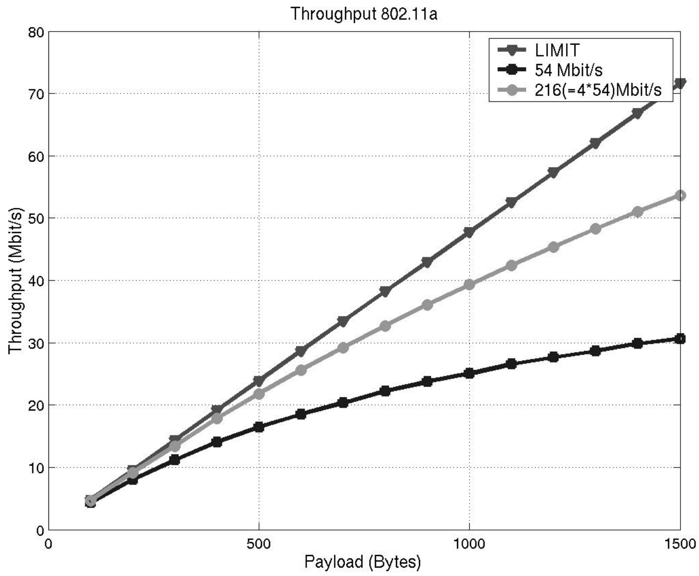

Figure 3: Maximum throughput vs payload size of an 802.11a link for various packet sizes

Based on the parameters of Table 1, MaxThroughput is plotted on Figure 3 for PHY layer bit rates 54 Mbit/s and 216 Mbit/s. The theoretical throughput limit when raw bit rate approaches infinity is plotted as well. The maximum throughput of 802.11a is about 30 Mbit/s for packets of 1500 bytes and only 10 Mbit/s for 250 bytes ones. This can severely restrict the performance of applications which generate small packets. For instance, a VoIP source transmitting a packet every 20 ms and using a 32 kbit/s vocoder will generate 120 byte packets including the RTP,UDP and IP headers. Apart from this dependence on the payload size, the 802.11 protocol also suffers from a heavy MAC overhead: at a physical bit rate of 216 Mbit/s, the throughput saturates below 80 Mbit/s. The reason is that at such a bit rate, the total duration to transmit a data packet is mainly consumed by the carrier sensing, the acknowledgements and the signalling, and not by the transmission itself. Actually, the MAC overhead at 216 Mbit/s amounts to more than 70% of the total medium occupation. Although the 802.11 parameters have been modified from 802.11b to 802.11a, the CSMA/CA imposes an overhead which cannot be scaled down proportionally to the physical bit rate increase.

Improvement of the 802.11 MAC protocol are being studied within the 802.11 Task Group e. The access technique is called Hybrid Coordination Function (HCF) and includes both contention and polling. Once the sender is granted a transmission opportunity (TxOP) by the HCF scheduler, it is allowed to transmit a sequence of packets. Moreover, a single group-acknowledgement packet can acknowledge the MPDUs obtained by the fragmentation of up to 64 higher layer data packets (MSDU). In the following, fragmentation is not considered because we are only interested in the maximum achievable throughput on an error-free channel, whereas fragmentation reduces the maximum theoretical throughput (SIFS are introduced between fragments) but improves the throughput on error-prone channels. The Group Acknowledgement mechanism is illustrated by Figure 4.

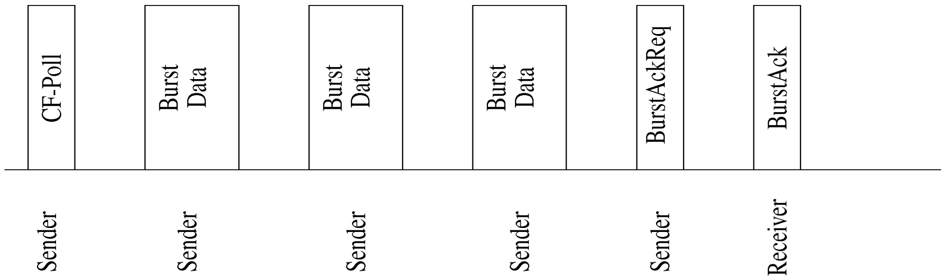

Figure 4: Illustration of the Group Acknowledgement feature of 802.11e

Neglecting the overhead required to obtain the TXOP, the formula for maximum throughput is given in [6] as:

$$MaxTroughput = \frac{8L_{data}N_{burst}}{T_{cf\_poll} + N_{burst}T_{d\_data} + T_{b\_a\_r} + T_{b\_a} + T_{sifs}(N_{burst}+2)} \quad (5)$$

where

$$T_{cf\_poll} = T_{preamble} + T_{h\_phy} + T_{sym} * \left\lceil \frac{16+6+8*L_{data}}{N_{dbps}} \right\rceil \quad (6)$$

$$T_{b\_a\_r} = T_{preamble} + T_{h\_phy} + T_{sym} * \left\lceil \frac{16+6+8L_{b\_a\_r}}{N_{dbps}} \right\rceil \quad (7)$$

$$T_{b\_a} = T_{preamble} + T_{h\_phy} + T_{sym} * \left\lceil \frac{16+6+8L_{b\_a\_r}}{N_{dbps}} \right\rceil \quad (8)$$

$$T_{d\_data} = T_{preamble} + T_{phy} + T_{sym} * \left\lceil \frac{16+6+8L_{h\_data} + 8L_{data}}{N_{dbpa}} \right\rceil \quad (9)$$

$T_{b\_a\_r}$: transmission time of a burst acknowledgement request T_{b_a}:transmission time of a burst acknowledgement

T_{sym}: transmission time of a symbol N_{burst}: the number of packets in a burst transmission

When PHY layer bit rate goes to infinity, once again we find a slightly different formula for the throughput limit:

$$LIMIT = \frac{8 * L_{data} * N_{burst}}{(N_{burst}+3)(T_{preamble} + T_{h\_phy} + T_{sym}) + T_{sifs}(N_{burst}+2)} \quad (10)$$

In addition to the previously defined 802.11a parameters, values L_{h_data}=36; $L_{b\_a\_r}$=22;L_{b_a}=56 are used for numerical computation. Besides, in [6] the authors assumed that a maximum of N_{BURST} =16 MSDUs were transmitted per TxOP. In order to evaluate the limits of 802.11e, we plot on Figure 5 the maximum achievable throughput for both N_{BURST} =16 and N_{BURST} =64.

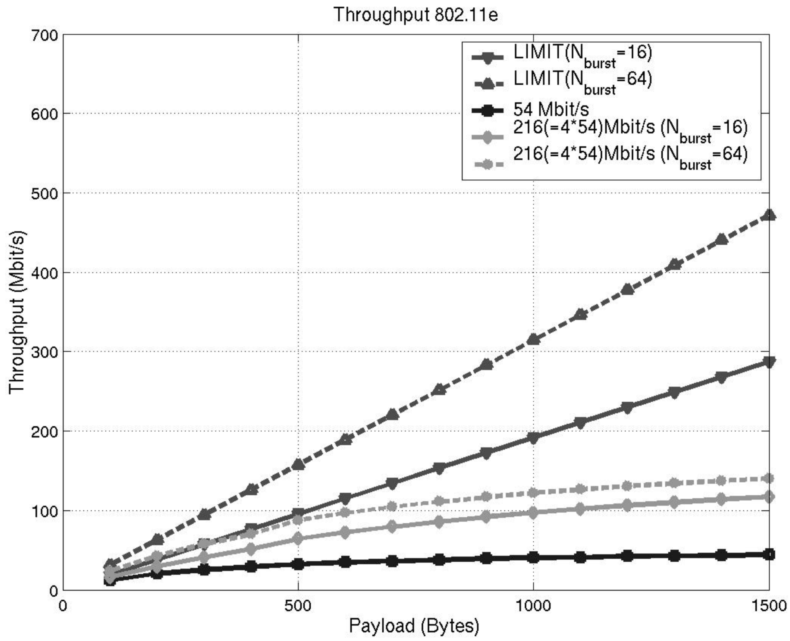

Figure 5: Maximum throughput vs payload size of an 802.11e link for various packet sizes

IEEE802.11e offers much higher throughput than 802.11 when PHY bit rate increases. However, the overhead is still very significant (almost 50 % at 216 Mbit/s raw bit rate). Increasing the number of MSDUs transmitted per TXOP from 16 to 64 does not bring significant improvement of the MAC efficiency. This limitation comes from the fact that a SIFS of 16 µs is inserted between each MSDU.

As mentioned before, the PHY layer of HIPERLAN/2 (H/2) is very similar to IEEE 802.11a, so the main difference between the two standards is that H/2 features a centralized architecture and a TDD/TDMA frame structure. A good description of the H/2 MAC is given in [7]. The Access Point (AP) allocates the radio resource to the uplink, downlink and direct link connections, as described on the example of Figure 6.

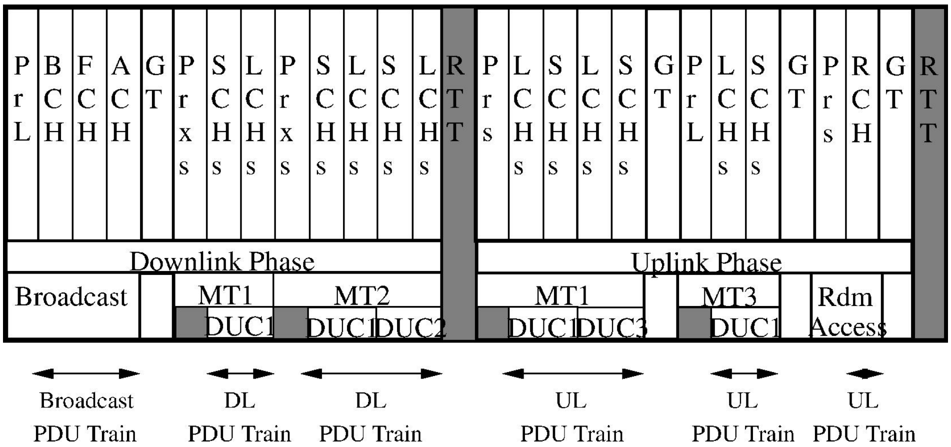

Figure 6: Structure of the HIPERLAN/2 MAC frame

The Mobile Terminals (MT) can access using a form of slotted Aloha to the Random Access Channel (RCH), located at the end of the MAC frame, in order to associate to the AP and request resource. The total duration of the MAC frame is $t_{frame} = 2ms$.

A PDU train groups two types of DLC PDUs: Long Channel PDUS carry mainly the payload of connections. The size of this PDU is 54 bytes, whereby 48 bytes are allocated for the payload, the rest is used for CRC and Convergence Layer signaling (for Segmentation and Reassembly). Short Channel PDUs of 9 bytes carry DLC control information such as ARQ acknowledgements and resource requests.

In order to compute the maximum throughput achievable in the H/2 system, we made the following assumptions:

1. There is only one connection (uplink) in all the cell.
2. The MT has always data to send to the AP
3. A single SCH per frame transmitted in mode BPSK 1/2 is allocated for the signalling of the connection.

Moreover when we simulate the performance of the H/2 MAC with a raw bit rate of 216 Mbit/s, we assume that the transmission and reception buffers capacity is scaled to support an increased number of LCH per frame, that the additional signalling is negligible. We also assume that LCH PDUs can be properly mapped on the symbols of the new PHY. For instance, in the current PHY at 54 Mbit/s, a LCH is carried by exactly 2 OFDM symbols. At 216 Mbit/s with the same symbol duration, an LCH could be carried by half a symbol, and since the maximum number of LCH per MAC frame is large, we neglect the potential loss of half a symbol. Therefore, the only padding bits required are inserted by the Convergence Layer which segments the payload into an integer number of LCHs. The MAC overhead is computed using the figures provided in Table 2.

Channel	**Value (OFDM symbols)**
BCH+Preamble*BCH*	5+4=9
FCH*MIN*	6
ACH	3
RCH+Preamble*RCH*	3+4=7
Uplink overhead (SCH)	$4+\lceil 9/Bps \rceil=4+3=7$

Table 2: Length of the HIPERLAN/2 control channels

The MAC frame duration equals 500 times the OFDM symbol duration, but according to Table 2, only 500-9-6-3-7-7=468 OFDM symbols will carry useful data. A packet of *x* bytes is segmented by the H/2 Convergence Layer into $\left\lceil \frac{x}{48} \right\rceil$ LCHs. The number of bytes transmitted per LCH is thus $\frac{x}{\left\lceil \frac{x}{48} \right\rceil}$. The availavable number of LCHs of MAC payload per frame is $\left\lfloor \frac{468 \cdot N_{dbps}}{54 \cdot 8} \right\rfloor$.

Combining all the above mentioned expressions, we get the MAC throughput:

$$T = \frac{\left\lfloor \frac{468 \cdot N_{dbps}}{54 \cdot 8} \right\rfloor}{t_{frame}} \cdot \frac{8 \cdot x}{\left\lceil \frac{x}{48} \right\rceil}$$

The throughput is plotted on Figure 7 for raw bit rates of 54 Mbit/s and 216 Mbit/s.

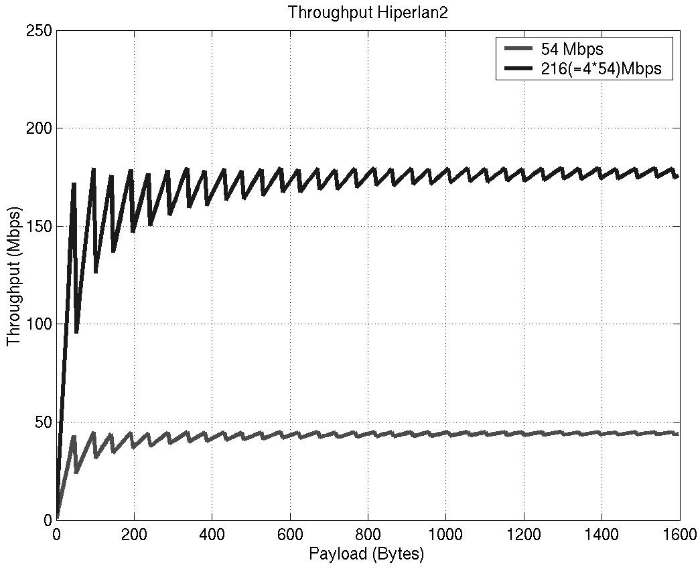

Figure 7: Maximum throughput of a HIPERLAN/2 link vs payload size for 54 Mbit/s and 216 Mbit/s physical layer rates

The TDD/TDMA transmission of H/2 offers by far the highest throughput and a decent overhead ratio of about 20% at 216 Mbit/s Phy rate, as long as the transmission and reception windows are adjusted. This represents a 60 Mbit/s increase compared to 802.11e. Besides, the efficiency is maintained even for smaller packet sizes (the oscillating behavior of the throughput is due to the segmentation and reassembly process). This is important for applications such as Voice over IP, as mentioned before. The higher efficiency can be explained by the fact that in H/2 packets are grouped without any SIFS between them.

Note that the comparison above was performed only for one link. If several simultaneous links were considered, contention-based access techniques like DCF and EDCF would suffer an additional penalty compared to TDD/TDMA.

In this section, we showed that the MAC efficiency of 802.11 as is would significantly reduce the impact of a physical layer bit rate increase on the effective throughput. This is by the way the reason why the Study Group was dubbed “High Throughput” SG rather than “High Rate”. Protocols with an improved efficiency such as the TDD/TDMA approach adopted in the H/2 MAC and to a lesser extent the 802.11e Group Acknowledgement feature of HCF would better support higher physical bit rates. Therefore, in the next section, the proposed physical layer improvements will be evaluated in combination with a specific MAC layer.

4. Impact of Physical Layer techniques on the throughput

In this section, we present physical layer techniques which have the potential to bring either higher peak bit rate or extended range compared to the current 802.11a standard. Prior to the creation of the HTSG, many 802.11 participants have given their view on what a future standard should look like. Bit rates in the order of 100-200 Mbit/s and physical layer techniques such as multiple antennas, turbo-codes, higher-order constellations were mentioned. In the following, we will discuss these three ones as well as channel bundling. In addition to pure PHY layer proposals, a better integration of the MAC and the PHY (employing Hybrid ARQ for example), the reduction of MAC overhead and improved support of ad-hoc multi-hop communications are all proposals requiring careful consideration. Another key requirement was that any new standard should remain compatible with the legacy one. How to maintain compatibility between the current and future standard is not the focus of this paper, though compatibility will need to be addressed early in the standardization process.

The use of several antennas at the transmitter, at the receiver or at both sides is known to significantly increase the theoretically achievable capacity of a wireless system [8], and this, of course also in the framework of OFDM-based schemes [9]. Currently, in 802.11a, selection diversity can be applied at the Access Point by choosing between two antennas the one which experiences the best Signal to Noise Ratio (SNR). This very simple scheme improves the coverage but still relies on a single radio-frequency (RF) module and a switch for antenna selection. With the addition of a complete RF module per available antenna, more complex digital signal processing can be envisaged in order to fully exploit the multi-antenna capabilities. Spatial diversity schemes permit to increase the robustness of a link at a given bit rate, leading to an increased range for this rate. At a given transmitter-receiver distance , the link adaptation algorithm selects the bit rate which maximizes the throughput while meeting the QoS requirements. If the same set of bit rates as in 802.11a is used (6 Mbit/s to 54 Mbit/s), then their respective operating range will be increased and at large distances a higher bit rate will be achievable. However, the peak bit rate will remain 54 Mbit/s. In order to increase the peak bit rate, it is possible to introduce a new mode, using for instance a higher order constellation and requiring a higher SNR. Instead of improving the robustness of the transmission, spatial multiplexing schemes offer higher raw bit rate by transmitting simultaneously several parallel data flows, which generates additional inter-antenna interference.

For instance, a two transmit antenna (M_T=2) wireless link with two or more receive antennas ($M_R \geq 2$) can be designed to either maximize spatial diversity (e.g. via the Alamouti Space-Time Block Coding technique [10]) or to perform spatial multiplexing (e.g., via [8]). However, for a symmetric antenna configuration, when $M_T = M_R = 2$, it appears that spatial multiplexing gain is very difficult to exploit, whereas Space-Time Block Coding techniques combined with coherent receive processing can achieve significant performance improvements with low computational complexity (see [15] for instance, where the Bit Error Rate performance of the IEEE802.11a system was improved by up to 8.7 dB in the best case, compared to a single antenna system with the same total transmitted power). As said before, this 8.7 dB gain can translate into a larger range and therefore a larger throughput at a given distance. It can also be traded-off against a reduction of the transmit power, and hence an increase of battery life for portable devices, or in order to support higher order modulations to increase the peak bit-rate. However, with $M_T>2$ and $M_R>1$, transmit diversity and spatial multiplexing gains can be obtained simultaneously, but there is a fundamental tradeoff in the level of transmit diversity and multiplexing gains that can be achieved in any transmission scheme [11].

A more conventional means to increase the bit rate is to increase the bandwidth. The technique which consists in transmitting on several channels in parallel is called channel bundling, and is used for instance in GPRS. Several 802.11a chips currently on the market implement a proprietary channel bundling, although regulatory bodies disapprove this. The complexity of the receiver is naturally increased, but transmitting on two adjacent channels can be less complex than transmitting two separate streams on antennas with spatial multiplexing, because it is not necessary to duplicate the RF module. However, several issues remain to be clarified, if such a scheme is considered in a future high throughput standard:

- Several implementations are possible, which result in different throughput performance. For instance, two channels can be used to transmit either a single packet per transmission opportunity in half the normal duration, or two packets during the normal duration. The first scheme is less complex but exhibits a lower throughput since the weight of the overhead is increased, as explained in the previous section. The second scheme, on the contrary, would increase the physical bit rate without decreasing the MAC efficiency.
- In many deployment scenarios, it is likely that more than one channel will be available. However, as soon as the spectrum gets saturated, which will also be a likely scenario especially in regions like Japan where the spectrum is limited to 4 channels, channel bundling will cause problems. Therefore, just like Dynamic Frequency Selection was adopted (at least in Europe so far) to have a fair and coherent spectrum sharing, some mechanisms should be studied to enable a fair and efficient use of channel bundling at 5 GHz.

Turbo-codes [12] were adopted in third generation cellular systems and allow to approach the channel capacity in additive white gaussian noise (AWGN) channels, and were also proposed for OFDM based WLANs [13]. The gain to be expected depends on the multipath characteristics of the environment but will typically be in the order of 2 to 3 dB.

Finally the use of higher order modulations has also been proposed. Introducing a 256 QAM mode would theoretically allow the peak bit rate of 802.11a to increase from 54 Mbit/s to 72 Mbit/s. But the Signal to Noise Ratio required by such a modulation is also much higher. This degradation of the SNR could be compensated by a gain brought by for instance Space Time Coding. However, implementation and quantization requirements for such a modulation scheme will have an impact on the device complexity and have to be carefully assessed.

Simulation results

In order to assess the various technical solutions presented in the previous paragraph, we performed throughput versus range simulations in a typical indoor office environment identical to that of Figure 1, with the same packet size of 1500 bytes and transmit power of 200mW. We focused on the impact of Space Time Block Coding and Channel Bundling, as well as the improvement provided by 802.11e MAC. On Figure 8, the throughput achievable with plain 802.11a is plotted as a reference and hardly reaches 30 Mbit/s.

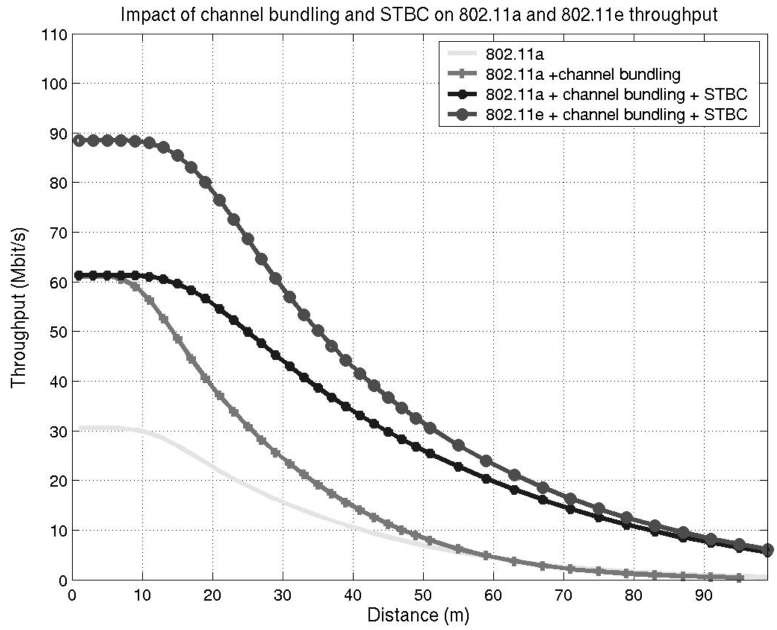

Figure 8: Impact of various Physical layer improvements of the throughput vs distance performance

Among the two channel bundling techniques we mentioned in the previous paragraph, we selected the most efficient and complex one, in which two packets are transmitted in parallel. With this scheme, not only the physical layer bit rate but also the MAC throughput are doubled. However, since in the selected scheme the two channels share the same Power Amplifier, the maximum transmitted power per channel is half that of plain 802.11a. At distances close to the effective cell range (here around 50 meters), the Signal to Noise Ratio per channel is 3 dB lower, which balances the gain of transmitting on two channels in parallel. The implementation of space time coding (here a 2x2 Alamouti STBC) in conjunction with channel bundling dramatically increases the range: at 40 meters the throughput is still higher than the maximum of 802.11a (30 Mbit/s). Finally, the higher efficiency of 802.11e allows to reach about 90 Mbit/s (the maximum physical layer bit rate being 108 Mbit/s).

Conclusions

In this paper, some hints on the next generation of IEEE802.11 networks are given. First the physical and MAC layer characteristics of the WLANs and WPANs specified by the various standardization bodies worldwide are briefly reviewed, including the 802.11a OFDM physical layer. Then we verify by analytical throughput computations that a straightforward increase of the physical layer bit rate would not lead to a significant throughput increase with the 802.11 legacy MAC, due to the heavy overhead. However this approach would be sensible with a TDD/TDMA access technique similar to HIPERLAN/2, and to a lesser extent with the 802.11e MAC. Finally we review the various physical layer techniques which have the potential to bring a significant throughput increase, including OFDM with multiple antennae and channel bundling. We then simulate the combination of space-time coding with two antennas at each terminal plus the Group Acknowledgement features of 802.11e and a specific implementation of 2-channel bundling. Using such a combination of techniques, a threefold increase in throughput can be obtained, and the range can be doubled.

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