Evolution of 5 GHz WLAN Towards Higher Throughputs

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Abstract

A standardization effort has started within the IEEE802.11 Working Group to define the next generation of 802.11 Wireless LANs. This article illustrates how throughput achieved above the MAC layer of 5 GHz WLANs can be increased from an existing 30 Mbit/s maximum with 802.11a to rates exceeding 90 Mbit/s. After a brief review of ongoing WLAN standardization activities, the support of a higher physical layer bit rate by various standardized MAC protocols (802.11, 802.11e and HIPERLAN/2) is discussed, showing that PHY and MAC layers must be considered jointly in order to achieve a significant throughput increase. Various physical layer techniques are compared in terms of performance and complexity. Especially, simulations show that by relying on MAC layers with good efficiency like 802.11e and HIPERLAN/2, a combination of space-time block coding with a possibility of channel bundling could bring a peak throughput increase from 30 to 90 Mbit/s as well as a significant cell range increase.

Introduction

The past 5 years have witnessed the emergence of Wireless Local and Personal Area Networks (WLAN/WPAN) in the home, enterprise, and public access environments. The wide variety of WLAN products currently available in the market is quickly leading to a scenario in which a WLAN/PAN interface will become as ubiquitous as a standard Ethernet or USB port. In particular, the IEEE802.11 protocol operating in both the 2.4 GHz ISM and 5.2 GHz UNII bands has enjoyed spectacular market success under the WiFi name. However, the wide range of operational environments and application QoS requirements envisaged will lead to some significant challenges in the future for WLAN standards. In the enterprise, high speed WLAN represents a flexible alternative or complement to wired Ethernet. This provides motivation for continuing to increase the available data rate beyond 100 Mbit/s, along with stringent security requirements. In public access scenarios, WLANs have the capability to provide high-speed Internet access, requiring an optimal tradeoff between bit rates and range. Further, the home environment represents a number of significant challenges, namely the simultaneous distribution of High Definition video, high speed Internet, and telephony inside the house. Such applications demand efficiency, robustness and QoS from the underlying WLAN.

These applications rely on the WLAN standards developed by the IEEE802.11 Working Group in the United States, the ETSI BRAN in Europe and the ARIB MMAC in Japan. The physical (PHY) data rate of 802.11 has already been extended from the original 2 Mbit/s to 11Mbit/s for 802.11b and 54Mbit/s for 802.11a [1]. Europe (ETSI BRAN HIPERLAN/2) [2] and Japan (ARIB MMAC HiSWANa) have also adopted a 5GHz OFDM PHY layer almost identical to that of 802.11a. Products based on the new 802.11a PHY layer will progressively coexist with 802.11b networks, as chipset vendors develop multi-mode products capable of operating in any 802.11 network.

Several WPAN specifications such as Bluetooth or 802.15 have also been issued. Wireless PANs typically have shorter range, lower transmit power, and lower data rates than Wireless LANs. The 802.15 Working Group, responsible for WPAN standardization within the IEEE, has based the 802.15.1 standard on Bluetooth. Data rates similar to those of WLANs are now studied in 802.15.3 and 802.15.3a, blurring the traditional distinction between WPAN and WLAN.

Although Quality of Service (QoS) and security are now clear concerns, the priority when introducing a new generation WLAN has generally been to increase the PHY data rate in isolation. The 802.11 Working Group has recently commenced an activity to determine the technical requirements to enhance the current 802.11 standard. This activity, which takes place in the 802.11 High Throughput Study Group, is an excellent opportunity to review technical solutions for achieving higher data rates taking into account additional requirements including: throughput effectively offered to higher layers, range, implementation complexity and power consumption. This paper addresses these issues, and presents simulation results that illustrate the advantage of combining various PHY and MAC improvements.

The evolution of 802.11 should be examined in the context of ongoing worldwide standardization processes, which is outlined in the next section, with a special emphasis on the 802.11a PHY layer. Afterwards, we perform a relative throughput performance analysis of 802.11a, 802.11e, and HIPERLAN/2 (H/2) and verify that the MAC protocol seriously limits the impact of PHY layer improvements in raw data rate. Next, we examine various physical layer solutions suitable for achieving future WLAN requirements, including channel bundling and multiple antennas. The impact of these techniques on the different MAC layers is assessed by throughput simulations.

Overview of WLAN standards

The most common WLAN standard today is 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 defined a MAC based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), two PHY layers in the 2.4 GHz band, and a third PHY based on Infrared (IR). The 2.4 GHz PHY's employ 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 Mb/s. This is clearly the most successful WLAN standard to date.

Following 802.11b was 802.11a [1][3] that specified a new PHY for the 5GHz UNII band. It 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. 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 PHY layer can be varied from 6 to 54 Mbit/s, and adapted to the link quality. This mechanism is illustrated by Figure 1, where the throughput of a single 802.11a connection is plotted as a function of the distance from the access point. The transmitted power is 200mW, which is the maximum level tolerated for indoor use in the lower band in Europe and in the middle band in the US. 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 is assumed to be 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 even when the terminals transmit data at 54 Mbit/s and are close to the Access Point. This limitation is due to the MAC overhead, and will be further investigated in the following section.

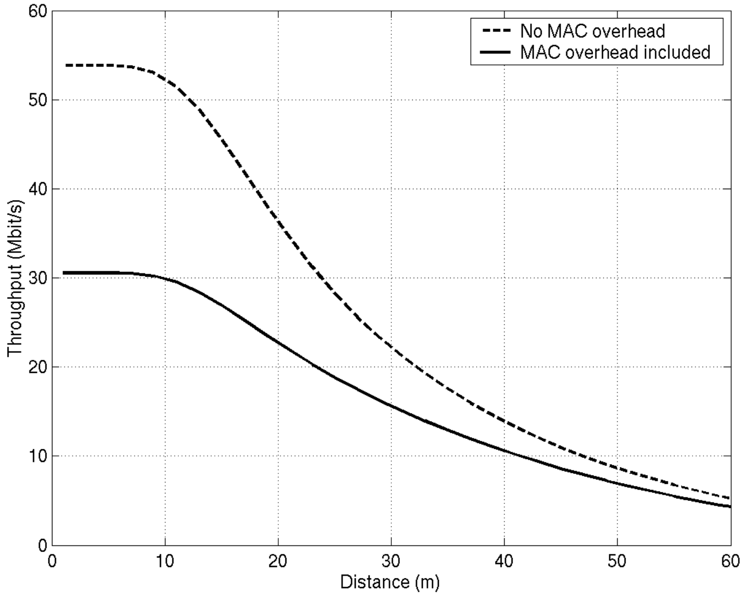

Figure 1: 802.11a achievable throughput vs. distance, typical indoor office environment.

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 PHY 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 PHY 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 to enhance the 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 CSMA/CA access technique of the Distributed Coordination Function (DCF), a Hybrid

Coordination Function (HCF) is introduced which defines a Contention Free Period (CFP) and a Contention Period (CP). During the CFP, the Hybrid Coordinator (typically located in the Access Point) schedules the transmission opportunities of the terminals, based on individual requests. The Enhanced DCF (EDCF), which is the contention based channel access mechanism of HCF, supports soft QoS by introducing Access Categories (ACs): packets are delivered through multiple backoff instances per station, each backoff instance being parameterized with AC specific parameters. A mapping of the priorities on ACs is performed. 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 IEEE so far has issued new PHY (802.11b, a, g, …) and MAC (802.11e, i, …) specifications separately, whereas in Europe the ETSI/BRAN group produced PHY and MAC layer specifications almost simultaneously for its new HIPERLAN specification, called HIPERLAN type 2. 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 when considering a higher throughput standard, as the following section will illustrate.

The difficulties of extending 802.11a

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 PHY layer. Xiao and Rosdahl [10] have derived formulas of the theoretical maximum throughput for the existing CSMA/CA 802.11 MAC. This result implies that a straightforward increase in PHY bit rate will not necessarily lead to a corresponding increase in throughput. In [4], the same authors compare the throughput performance of 802.11 and 802.11e group acknowledgement mode as a function of new PHY 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 PHY bit rates. In this section, we extend this work and show that compared to the H/2 protocol, the MAC efficiency of 802.11e remains limited at high PHY bit rates by the Inter Frame Spaces, which reduces the effect of increasing the group size.

It is well known that the 802.11 protocol uses the CSMA/CA mechanism to access the medium. The fundamental mechanism is referred to as *Distributed Coordination Function* (DCF). DCF 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 transmission of a positive acknowledgement (ACK) by the destination node 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. Still, neither CSMA/CA nor RTS/CTS solves the exposed terminal 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 the priority.

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

1. Basic Access Mode is used (there is no RTS/CTS, which would lead to an even higher overhead)
2. The channel is ideal (error-free transmissions)
3. There are only two nodes in the cell and at any transmission cycle there is one and only one active station that has always a packet to send and the other station can only accept packets and provide acknowledgement

Therefore, the transmitter never has to contend with any other station to access the medium. Under these assumptions and considering a transmission cycle made of a DIFS deferral, a backoff, a data transmission, a SIFS deferral and an ACK transmission, Xiao and Rosdhal showed in [10] that the throughput is maximized and equal to:

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

All numerical values and meanings of the terms used in (1) are explicitely detailed in Table 1. More specifically, terms T_{d_data} and T_{d_ack} represent the durations needed for the transmission of a packet and of an acknowledgement respectively. Their values are directly proportional to the length of the payload (fixed to 14 bytes for the ACK) and inversely proportional to the number of data bits transmitted per OFDM symbols (N_{dbps} refer to Table 2). In addition to that, physical layer constraints related to the use of OFDM have been taken into account, i.e. the duration of preambles and of the physical header

Parameter	**Value**	**Comment**
$CW_{\min}$	16	Minimum value of the Contention Window used in the back off mechanism
T_{slot}	$9\mu s$	Duration of a time slot
T_{difs}	$34\mu s$	Duration of a Distributed Inter Frame Space (DIFS)
T_{sifs}	$16\mu s$	Duration of a Short Inter Frame Space (SIFS)
	$1\mu s$	Propagation delay
L_{h_data}	36 bytes	Payload size for the CF-Polling message
$L_{g\_a\_r}$	22 bytes	Payload size for the Group Acknowledgment Request
L_{g_a}	56 bytes	Payload size for the Group Acknowledgment

Table 1: Time parameters for 802.11a/e

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 2: Parameters for the various 5 GHz PHY modes

When PHY layer bit rate goes to infinity, N_{dbps} goes to infinity as well but still at least one OFDM symbol is required to transmit the data and one for the acknowledgement, so that we find a throughput limit slightly different from [10]:

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

Based on the parameters of Table 1, MaxThroughput is plotted on Figure 2 for PHY layer bit rates 54 Mbit/s and 216 Mbit/s against the packet size. The maximum packet size considered is the one foreseen by the standard specification. The theoretical throughput limit when raw bit rate approaches infinity is plotted as well. At a PHY bit rate of 216 Mbit/s, which could be obtained for instance by transmitting 4 parallel bit streams of 64QAM symbols with code rate ¾ on different antennas, the throughput remains below 80 Mbit/s even for large packet sizes. 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 signaling, and not by the transmission itself. Actually, the MAC overhead at 216 Mbit/s amounts to about 75%. Another well known drawback of 802.11 is that the MAC efficiency is especially low for small packet sizes.

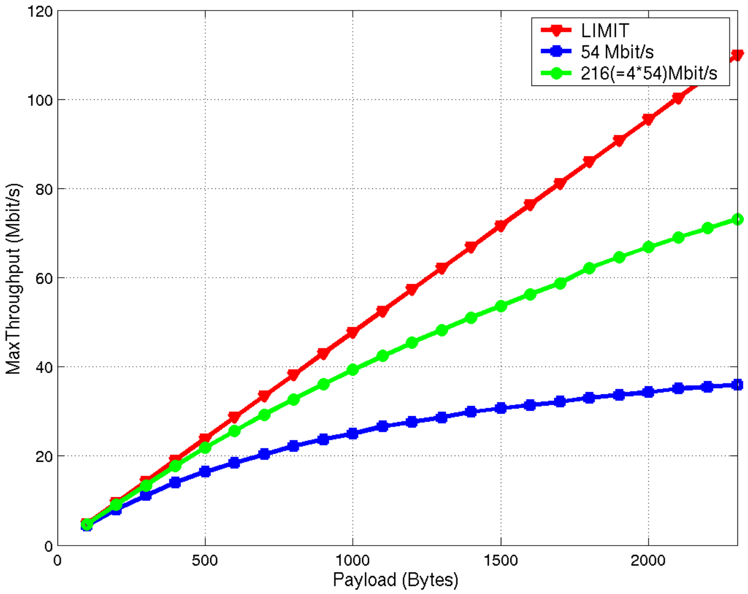

Figure 2: Maximum throughput achievable by 802.11a vs. packet size for various PHY bit rates

An improvement of this protocol is being studied in the 802.11 Task Group e. The access technique is managed by a hybrid coordinator and alternates Contention and Contention Free Period (CP and CFP respectively): the users gain the access to the channel either by contending for it (during the CP) or when the Access Point polls them (during both the CP and CFP). Once the sender is granted a transmission opportunity (TXOP) by the HCF, it is allowed to transmit a sequence of packets. Moreover, a single group-acknowledgement packet can acknowledge the fragments of up to 64 data packets (MSDU). In the following, fragmentation is not considered (i.e. an MSDU will generate a single MPDU) 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. On Figure 3, a burst of MPDU followed by a Group Acknowledgement is represented.

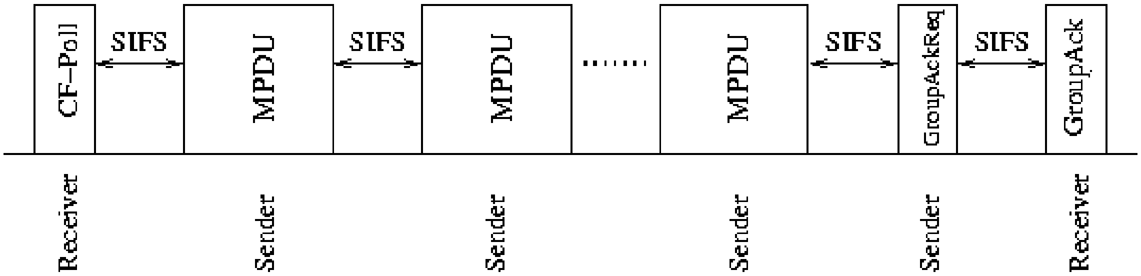

Figure 3: Group Acknowledgement mechanism in IEEE802.11e

Under the same assumptions considered for 802.11a it is possible to neglect the overhead required to obtain the TXOP and the formula for maximum throughput is given in [4] as:

$$MaxTroughput = \frac{8L_{data}N_{burst}}{T_{cf\_poll} + N_{burst}T_{d\_data} + T_{g\_a\_r} + T_{g\_a} + T_{sifs}(N_{burst} + 2)} \qquad (3)$$

where N_{burst} is the number of packets in a burst transmission and the other terms are explicitely detailed in Table 1.

Compared to the expression used for 802.11a and in accordance with the mechanism showed in Figure 3, new terms must be introduced for the throughput evaluation. On one hand, transmitting several packets in a burst improves the size of the payload by a factor N_{burst}. Moreover the mechanism specified for the 802.11e MAC protocol allows to avoid the overhead due to the backoff and to the T_{DIFS}. On the other hand, time spent for the polling and for the group acknowledgement request must be taken into account along with the increased number of SIFS.

Like in the case of 802.11a, we are investigating the efficiency of the MAC protocol assuming we can improve the raw bit rate of the physical layer indefinitely. When PHY layer bit rate goes to infinity, we find once again a slightly different formula for the throughput limit:

$$LIMIT = \frac{8L_{data}N_{burst}}{(N_{burst} + 3)(T_{preamble} + T_{h\_phy} + T_{sym}) + T_{sifs}(N_{burst} + 2)} \qquad (4)$$

In order to evaluate the limits of 802.11e, we plot on Figure 4 the maximum achievable throughput for both N_{burst} = 16 and N_{burst} = 64.

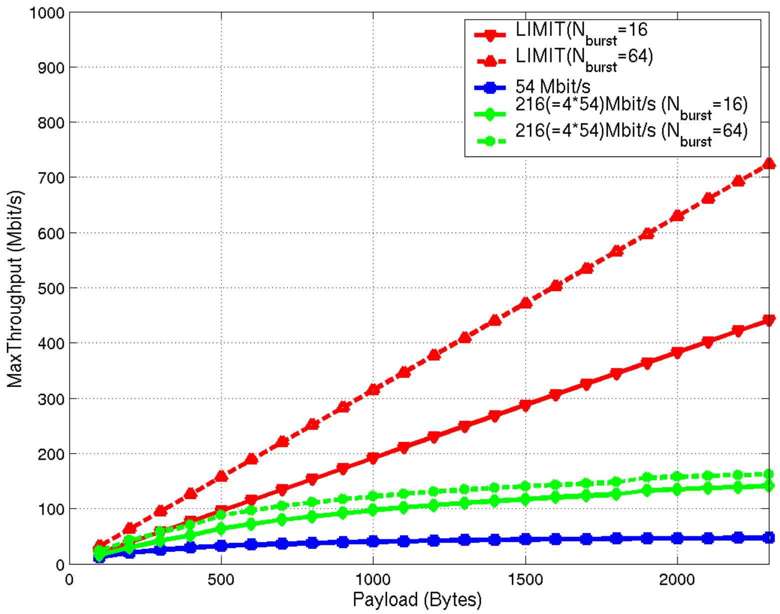

Figure 4: Maximum throughput achievable by 802.11e vs. packet size for various PHY bit rates

802.11e 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 H/2 is very similar to 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 [5]. The Access Point (AP) allocates the radio resource to the uplink, downlink and direct link connections, as described on the example of Figure 5. The Mobile Terminals (MT) can access the channel using a form of slotted Aloha during a random access phase, 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 main types of PDUs:

- Long Channel PDUs (LCH) carry mainly the payload of connections. The size of this PDU is 54 bytes, whereof 48 bytes are allocated for the payload, the remaining 6 bytes being used for CRC and Convergence Layer signaling (for Segmentation and Reassembly)
- Short Channel PDUs (SCH) of 9 bytes carry data link control information such as ARQ acknowledgements (useless in our case of error-free channel) and resource requests

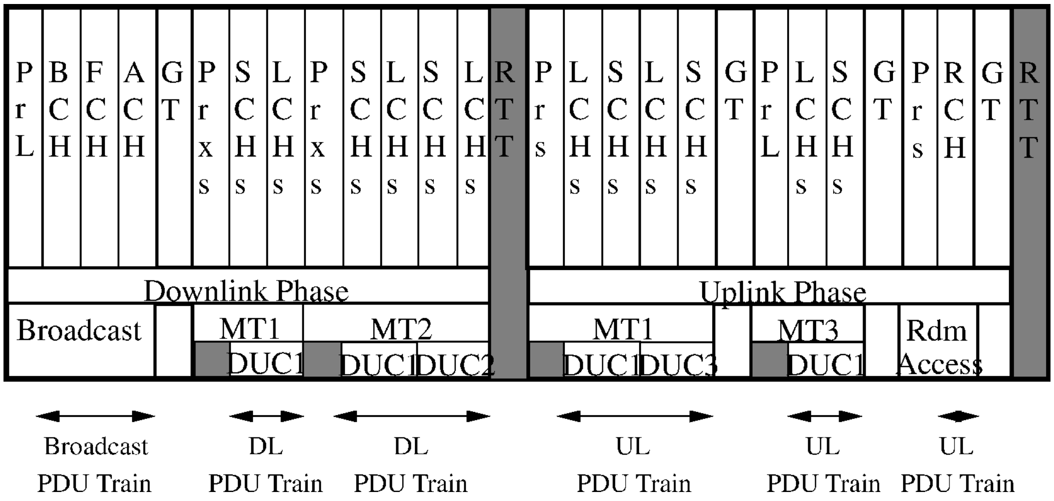

Figure 5: Layout of the HIPERLAN/2 MAC frame

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 the entire 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 signaling 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 and that the additional signaling is negligible. We finally 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, an 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 3

Channel	**Size (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 3: Length of the HIPERLAN/2 control channels

The MAC frame duration equals 500 times the OFDM symbol duration, but according to Table 3, 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 payload bytes transmitted per LCH is thus $\frac{x}{\left\lceil \frac{x}{48} \right\rceil}$. The available number of LCHs of MAC payload per frame is $\left\lfloor \frac{468 \cdot N_{dbps}}{54 \cdot 8} \right\rfloor$. Finally, the maximum MAC throughput that is plotted on Figure 6 for raw bit rates of 54 Mbit/s and 216 Mbit/s is:

$$MaxThroughput = \frac{\left\lfloor \frac{468 \cdot N_{dbps}}{54 \cdot 8} \right\rfloor}{t_{frame}} \cdot \frac{8 \cdot x}{\left\lceil \frac{x}{48} \right\rceil} \qquad (5)$$

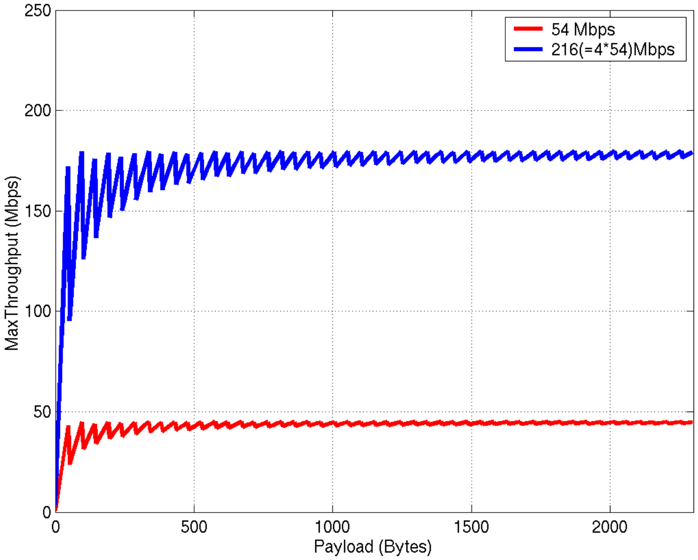

Figure 6: Throughput achievable with H/2 vs. packet size

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, in which the size of the IP packet delivered to the MAC layer may be as short as a hundred bytes. 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: the contentions (increased with the number of connections) and backoff procedures would waste channel occupancy whereas a centralized TDD/TDMA access scheme would tend to optimize this occupancy among the users.

In this section, we showed that the MAC efficiency of 802.11 DCF would significantly reduce the impact of a PHY layer bit rate increase on the effective throughput. Protocols with an improved efficiency such as the H/2 MAC layer and to a lesser extent the 802.11e HCF would better support higher PHY bit rates. In any case, the changes proposed in the PHY layer might require a modification of the MAC, in order to fully benefit from the throughput increase. In addition to the throughput criterion, power consumption, complexity and range will also have to be measured.

Technical solutions for future high throughput WLAN standards

In this section, the requirements and potential technical solutions for increasing WLAN throughput are briefly reviewed. Several proposals are also examined and assessed in terms of criteria including throughput, power-consumption, complexity and range.

Prior to the creation of the High Throughput Study Group, the first step towards the creation of a new Task Group, many 802.11 participants have given their view on what a future standard should look like. Peak bit rates of 100-200 Mbit/s and throughputs approaching 100 Mbit/s have often been stated as requirements. Several PHY and MAC techniques were also advocated. In [11], for instance, we showed that a 2x2 Alamouti Space Time Coding OFDM scheme (see below) could significantly improve the cell range compared to current 802.11a. In the next paragraph, we will successively discuss the impact of multiple antennas, bandwidth increase, turbo-codes and higher-order constellations. However, in addition to these pure PHY layer proposals, better integration of the MAC and the PHY (employing Hybrid ARQ for example), reduction of MAC overhead and improved support for ad-hoc multi-hop communications are all proposals requiring careful consideration. Another key requirement is 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 (see for instance [6]), and this, of course, also in the framework of OFDM-based schemes [7]. Indeed, in wireless communication systems, multiple antennas provide spatial diversity, which can mitigate the effects of multipath-induced fading and alternatively, multipath can also be exploited to increase link capacity with multiple-input multiple-output (MIMO) or spatial multiplexing techniques.

Currently, in 802.11a, selection diversity can be applied at the Access Point by selecting between two antennas the one that experiences the best Signal to Noise Ratio. 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 stage per available antenna, more complex digital signal processing can be envisaged in order to fully exploit the multi-antenna capabilities in terms of diversity or multiplexing gains. With the objective of increasing the peak bit-rate, spatial diversity can be used in order to increase the robustness of the transmission of higher order modulations that are costly in terms of RF requirements, whereas spatial multiplexing enables to transmit simultaneously several parallel data flows with lower modulation order, but with additional inter-antenna interference. The latter can be reduced by interference cancellation techniques such as BLAST.

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 [8]) or to perform spatial multiplexing (e.g., via [6]). 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 improvement of the Bit Error Rate performance with low computational complexity[1] . This 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 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

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[1] In European project FITNESS (http://www.ist-fitness.org/) the Bit Error Rate performance of the 802.11a 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

transmission scheme. Thus, the performance of specific transmission and reception strategies for achieving both diversity and multiplexing gains is an interesting area of research which needs to be carefully considered.

A more conventional means to achieve a higher bit rate is to increase the bandwidth. The technique that consists in transmitting on several channels in parallel is called channel bundling. 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 all the RF components. 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, the bundling of two channels makes it possible 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 PHY 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 can be studied to enable a fair and efficient use of channel bundling at 5 GHz.
- It should be kept in mind that channel bundling, contrary to multiple antennas, does not provide higher system capacity since it does not improve the spectral efficiency

Turbo-codes were adopted in third generation cellular systems and allow approaching the channel capacity in additive white Gaussian noise (AWGN) channels. In multi-path environments such as those encountered in WLANs, the application of turbo-codes to an OFDM PHY typically brings a 2 to 3 dB gain [9]

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 Block 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.

In order to evaluate 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 two-channel bundling, as well as the improvement provided by 802.11e and H/2 MAC. The results are plotted on Figure 7. The throughput achievable with plain 802.11a is plotted as a reference and hardly reaches 30 Mbit/s. With the first channel bundling strategy mentioned in the previous paragraph, the reduction of the useful transmission time increases the weight of the MAC overhead, making 802.11e less efficient than H/2. With the second and most efficient channel bundling scheme, in which two packets are transmitted in parallel, not only the PHY layer bit rate but also the MAC throughput are doubled. In both cases however, we assume that the two channels share the same Power Amplifier, therefore 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 block coding (here a 2x2 Alamouti coding) in conjunction with channel bundling drastically increases the range: at 40 meters the throughput is still higher than the maximum of 802.11a (30 Mbit/s). Finally, the highest efficiency of 802.11e and H/2 allows to reach about 90 Mbit/s (the maximum PHY layer bit rate being 108 Mbit/s).

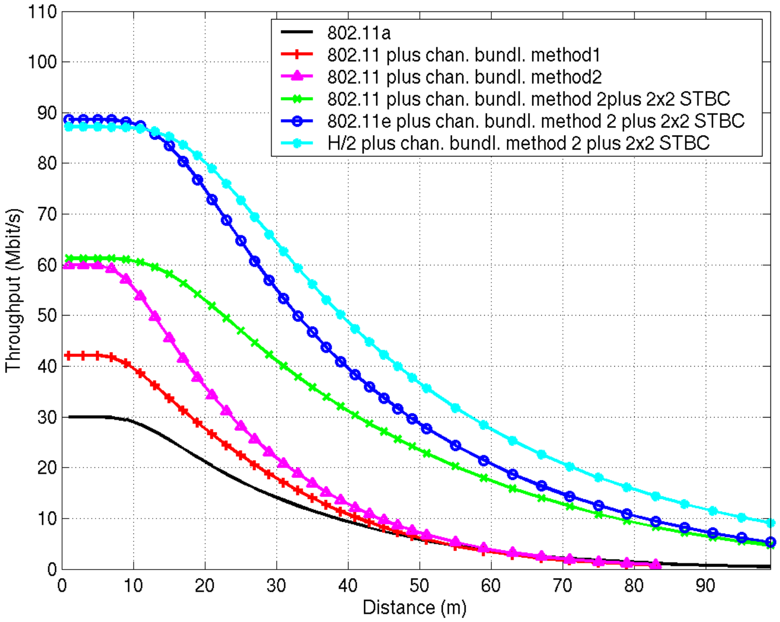

Figure 7: Impact of channel bundling and space-time coding on throughput vs distance performance

Conclusions

In this paper, some hints on the next generation of WLANs are given. First the PHY and MAC layer characteristics of the WLANs and WPANs specified by the various standardization bodies worldwide are briefly reviewed, including the 802.11a OFDM PHY layer. Then, we verify by analytical throughput computations that a straightforward increase of the PHY 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 PHY layer techniques that have the potential to bring a significant throughput increase, including OFDM with multiple antennas and channel bundling. The latter opens the way to a variety of implementations that have very different performance. However, we show by simulations that by cleverly bundling two channels and implementing space-time block coding with two antennas at each terminal, the maximum throughput could be tripled and the range doubled.

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