IEEE 802.11n: Enhancements for higher throughput in wireless LANS

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IEEE 802.11N: ENHANCEMENTS FOR HIGHER THROUGHPUT IN WIRELESS LANS

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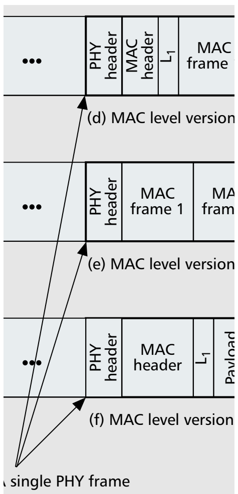


The authors introduce a new standardization effort, IEEE 802.11n, an amendment to IEEE 802.11 standards that it is capable of much higher throughputs, with a maximum throughput of at least 100Mb/s, as measured at the medium access control (MAC) data service access point.

ABSTRACT

This article introduces a new standardization effort, IEEE 802.11n, an amendment to IEEE 802.11 standards that it is capable of much higher throughputs, with a maximum throughput of at least 100 Mb/s, as measured at the medium access control data service access point. The IEEE 802.11n will provide both physical layer and MAC enhancements. In this article we introduce some PHY proposals and study the fundamental issue of MAC inefficiency. We propose several MAC enhancements via various frame aggregation mechanisms that overcome the theoretical throughput limit and reach higher throughput. We classify frame aggregation mechanisms into many different and orthogonal aspects, such as distributed vs. centrally controlled, ad hoc vs. infrastructure, uplink vs. downlink, single-destination vs. multi-destination, PHY-level vs. MAC-level, single-rate vs. multirate, immediate ACK vs. delayed ACK, and no spacing vs. SIFS spacing.

INTRODUCTION

Wireless local area networks (WLANs) are becoming more popular and increasingly relied on. The IEEE 802.11 WLAN is accepted as a complementary technology to high-speed IEEE 802.3 (Ethernet) for portable and mobile devices. One reason for such success is that it keeps increasing data transmission rates while maintaining a relatively low price. The IEEE 802.11, 802.11b, and 802.11a/g specifications provide up to 2 Mb/s, 11 Mb/s, and 54 Mb/s data rates [1, 2], respectively. Furthermore, the IEEE 802.11 Working Group is pursuing IEEE 802.11n, an amendment for higher throughput and higher speed enhancements. Different from the goal of IEEE 802.11b/.11a/.11g, i.e., to provide higher-speed data rates with different physical layer (PHY) specifications, IEEE 802.11n aims at higher throughput instead of higher data rates with PHY and medium access control (MAC) enhancements.

The IEEE 802.11 MAC employs a mandatory contention-based channel access function called the distributed coordination function (DCF) and an optional centrally controlled channel access function, the point coordination function (PCF) [1]. The DCF adopts carrier sense multiple access with collision avoidance (CSMA/CA) with binary exponential backoff, and the PCF adopts a polling mechanism. To support MAC-level quality of service (QoS), the IEEE 802.11 Working Group is currently working on the standardization of IEEE 802.11e. The IEEE 802.11e MAC employs a channel access function called the hybrid coordination function (HCF), which includes contention-based channel access, enhanced distributed channel access (EDCA), and contention-free centrally controlled channel access, HCF controlled channel access (HCCA).

To provide better QoS, especially for multimedia applications, increasing data rates is also highly desirable. The rationale is the same as Ethernet, which dramatically increases data rates from 10/100 Mb/s to 10 Gb/s. Data-rate-intensive applications exist such as multimedia conferencing, MPEG video streaming, consumer applications, network storage, file transfer, and simultaneous transmission of multiple HDTV signals, audio, and online gaming. Furthermore, there is a great demand for higher-capacity WLAN networks in the market in such areas ass hotspots, service providers, and wireless backhaul. Therefore, increasing data rates is crucial, and the IEEE 802.11 Working Group was seeking higher data rates over 100 Mb/s for IEEE 802.11a extension [2]. However, we proved that a theoretical throughput limit exists due to MAC and PHY overhead [2]. In other words, the theoretical throughput limit, about 75 Mb/s for IEEE 802.11a with a payload size of 1500 bytes [2], upper bounds any obtained throughput even when the data rate goes infinitely high. Therefore, increasing transmission rate cannot help a lot. Both reducing overhead and pursuing higher data rates are therefore necessary and important [2]. In July 2002 the IEEE 802.11 High Throughput Study Group (HTSG) was established, emphasizing higher throughput for data rates over 100 Mb/s in WLANs. The first official meeting of the IEEE 802.11n Task Group took place in September 2003, replacing the IEEE High Throughput Study Group (HTSG). The scope of IEEE 802.11n is to define an amendment to the IEEE 802.11 standards to enable much higher throughputs, with a maximum throughput of at least 100 Mb/s, as measured at the MAC data service access point (SAP). IEEE 802.11n will provide both PHY and MAC enhancements. Note that even though IEEE 802.11e also provides some mechanisms for efficient MAC enhancements such as Direct Link Protocol and Block Acknowledgment Protocol, its major goal is still to provide QoS services, whereas the goal of IEEE 802.11n is to provide higher throughput via PHY and MAC enhancements.

In this article we first introduce the history and current status of IEEE 802.11n, as well as some PHY proposals. Then we study the theoretical throughput limit and provide an overhead analysis for IEEE 802.11, and compare this aspect with HIPERLAN/2. Finally, we propose several MAC enhancements via various frame aggregation mechanisms. We adopt the original IEEE 802.11 MAC in this article, but the mechanisms can easily be applied to IEEE 802.11e.

IEEE 802.11N

In this section we provide an up-to-date survey on the efforts to produce the IEEE 802.11n standard, including its history and current status. The IEEE 802.11n standard process has three phases: phase 1 is the preparation stage from January to September 2002; phase 2 was the of IEEE 802.11 HTSG from September 2002 to September 2003; phase 3 is the IEEE 802.11n Task Group (TGn), which began in September 2003 and is expected to finish in March 2007.

Phase 1: Preparation

The first formal presentation at IEEE 802 meetings about 802.11a higher data rate extension was at the IEEE 802.11 interim meeting at Dallas, Texas, in January 2002 [2]. In this presentation Jones *et al.* described the high demand for data rates over 100 Mb/s through IEEE 802.11, and described some potential approaches to achieve higher data rates: modulation and coding enhancements, spatial diversity techniques, spatial multiplexing, and double bandwidth solutions with underlying IEEE 802.11a waveforms. Later on at the meeting, a straw poll for a call for interest on 802.11a higher rate extension was conducted in the IEEE 802.11 working group, and received tremendous interest among hundreds of committee members.

At the St. Louis IEEE 802 plenary meeting in March 2002, we provided a throughput analysis for higher data rates over 100 Mb/s [2]. Tzannes *et al.* proposed a bit-loading (BL) approach [2]. One of the drawbacks is that BL may require feedback from the receiver to the transmitter, and the communication from the receiver to the transmitter must happen faster than channel changes. Hori *et al.* compared four different potential approaches: the double clock rate approach, the double subcarrier number approach, the 4096-quadrature amplitude modulation (QAM)-orthogonal frequency-division multiplexing (OFDM) approach, and the OFDM/space-division multiplexing (SDM) (multicarrier multiple-input multiple-output [MIMO]) system approach [2]. Coffey suggested some criteria for higher data rates, and that higher data rates should emphasize throughput with consideration for backward compatibility rather than data rate [2].

At the Sydney, Australia, IEEE 802 interim meeting in May 2002, we showed that a theoretical throughput upper limit exists for IEEE 802.11 protocols [2]. Therefore, increasing transmission rate cannot help much. Both reducing overhead and pursuing higher data rates are therefore necessary and important [3]. The IEEE 802.11 HTSG was established in July 2002 emphasizing higher throughput for higher data rates over 100 Mb/s WLANs.

Phase 2: IEEE 802.11 HTSG

The IEEE 802.11 HTSG began operations in September 2002 and ended in September 2003. During this phase, a Project Authorization Request (PAR) and Five Criteria for Standards Development were established.

The scope of the MAC and PHY enhancements assume a baseline specification to support higher throughput. The amendment seeks to improve the peak throughput to at least 100 Mb/s, measured at the MAC data SAP. This represents an improvement of at least four times the throughput obtainable using existing 802.11 systems. The highest throughput mode shall achieve a spectral efficiency of at least 3 b/s/Hz. The Task Group (IEEE 802.11n) will undertake the following steps:

- Identify and define usage models, channel models, and related MAC and application assumptions.
- Identify and define evaluation metrics that characterize the important aspects of a particular usage model.

Initial usage models include hotspot, enterprise, and residential. Evaluation metrics include throughput, range, aggregate network capacity, power consumption (peak and average), spectral flexibility, cost/complexity flexibility, backward compatibility, and coexistence.

The Five Criteria for Standards Development are:

- **Broad market potential**: It shall have a broad market potential; that is, broad sets of applicability, multiple vendors and numerous users, and balanced costs (LAN vs. attached stations).
- **Compatibility**: Keeping the MAC SAP interface the same as for the existing 802.11 standards is required for compatibility. New enhancements shall be defined in a format and structure consistent with existing 802.11 standards.
- **Distinct identity**: Each IEEE 802 standard shall have a distinct identity from other IEEE 802 standards.
- **Technical feasibility**: Those introduced in phase 1 and later parts of this subsection can provide technical feasibility. Furthermore, there are currently reliable WLAN solutions.
- **Economic feasibility**: Economic feasibility includes known cost factors, reasonable cost for performance, and consideration of installation costs.

Next, we introduce some additional proposals for technical feasibility. In [4] the authors proposed exploring space diversity through multiple

We showed that a theoretical throughput upper limit exists for IEEE 802.11 protocols. Therefore increasing transmission rate cannot help much. Both reducing overhead and pursuing higher data rates are therefore necessary and important antennae other than frequency diversity via bit interleaved coded modulation, and claimed that OFDM is very well suited for use with multiple antennae, for example, as an optional mode in IEEE 802.16, with the cost of an additional antenna and a radio frequency (RF) front-end. In [5] the authors proposed a combined scheme of BL and trellis-coded modulation (TCM). BL is the process of modulating a different number of bits on each carrier based on the signal-to-noise ratio (SNR) of the carriers. IEEE 802.11a adopts an equal number of bits per carrier, which is the simplest form of BL. BL is better suited to a multipath channel. However, it requires feedback from the receiver to the transmitter, and the communication from the receiver to the transmitter must happen faster than channel changes. On the other hand, TCM combines coding and modulation functions to provide improved performance. Coded modulation schemes combine with BL to encode all information bits. The advantages include:

- It does not have a preset maximum data rate.
- It is optimally suited to a multipath channel.
- It is based on mature and widely understood technology, such as asymmetric digital subscriber line (ADSL).
- It requires a relatively small standardization effort.

In [6] the author proposed a MIMO-OFDM solution. In [7] the authors claimed that 250 Mb/s data rate is achievable. In [8] the authors showed some experimental results based on MIMO-OFDM for high-throughput WLANs. In [9] the author proposed using smart antennas to improve SNR, increase coverage/range and data rate, reduce interference and multipath, and increase network capacity and battery life.

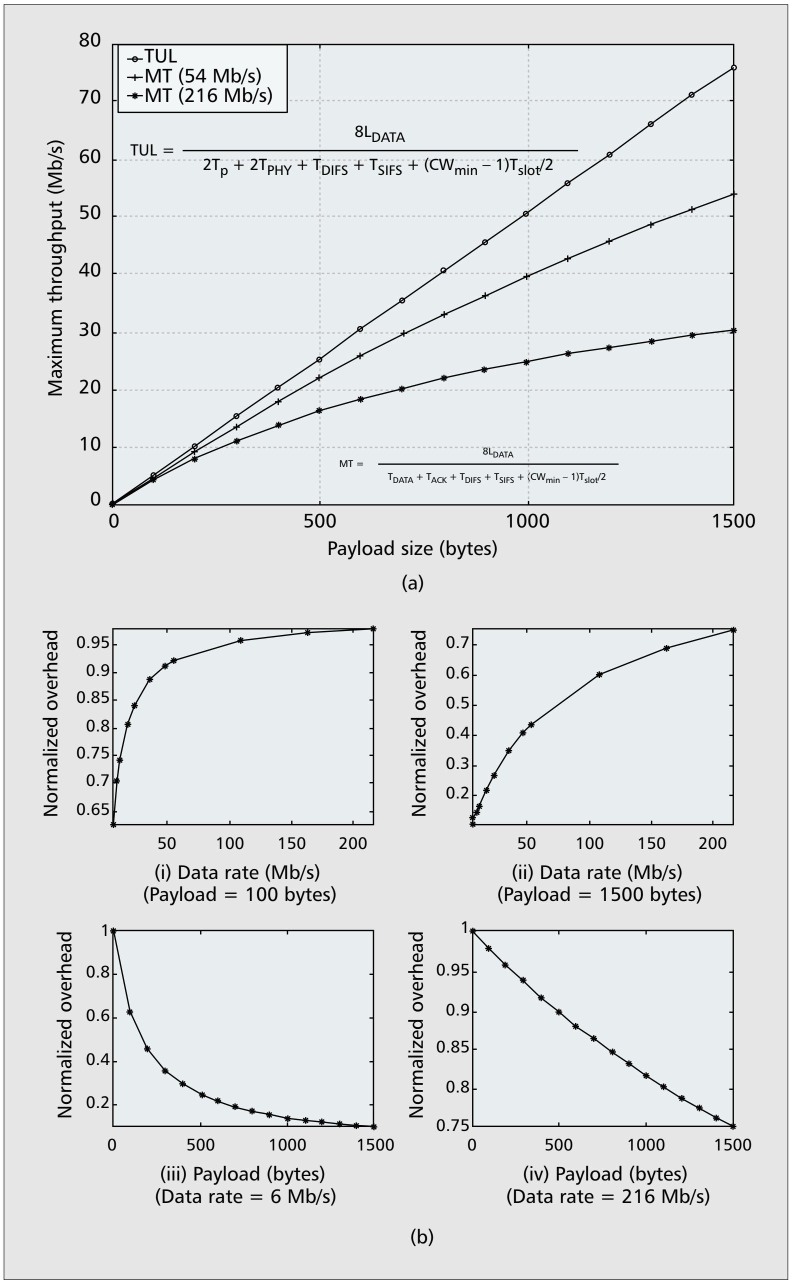


Figure 1. *a) The MT and TUL for IEEE 802.11a; b) normalized overhead vs. data rate and payload.*

Phase 3: IEEE 802.11n TGn

The first official meeting of the IEEE 802.11n Task Group took place September 2003 in Singapore. The IEEE 802.11n standard is planned to be published in March 2007. The TGn will further go through the following steps: establishing the proposal selection process and criteria, call for proposals, combination of proposals, several letter ballots, standard approval, and finally standard publication. We will see more contributions in future IEEE 802.11n meetings. So far, most contributions in IEEE 802.11n meetings focus on PHY enhancements. Instead, this article serves a good purpose in discussing MAC enhancements.

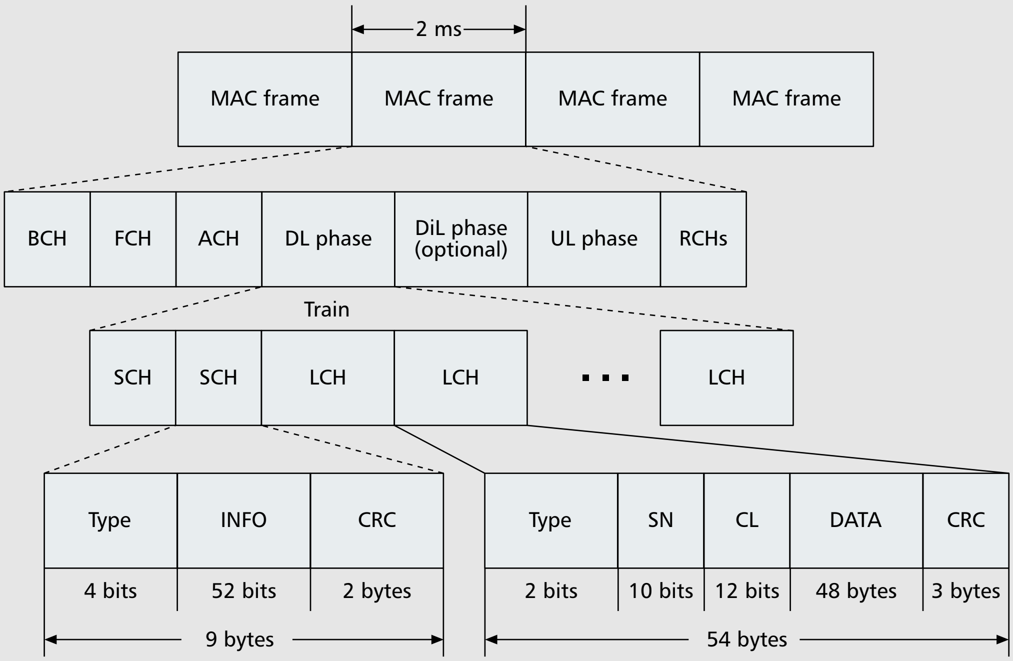
Theoretical Limit and Overhead Analysis of the IEEE 802.11 MAC

The achievable maximum throughput (MT) can be met when the system is in the best case scenario:

- The channel is ideal, without errors.
- At any transmission cycle, there is one and only one active station that always has a frame to send, and other stations can only accept frames and provide acknowledgments (ACKs).

The throughput upper limit (TUL) [2] is defined as the maximum throughput when the raw data rate goes infinitely high.

As indicated in [3], overhead is the major fundamental issue for inefficient MAC, and it includes headers (MAC header, frame check sequence [FCS], and PHY header), interframe spaces (IFSs), backoff time, and ACKs. Define overhead as the difference between data rate and throughput, and define normalized overhead as overhead divided by data rate. We further assume that all higher data rates are compatible with IEEE 802.11a. Let T_{slot}, T_{SIFS}, T_{DIFS}, and CW_{min} denote a slot time, a short IFS (SIFS) time, a differentiated IFS (DIFS) time, and the minimum backoff contention window size, respectively. Let T_P and T_{PHY} denote transmission times of a physical preamble and a PHY header, respectively. Let T_{DATA} and T_{ACK} denote transmission times of a data frame and an ACK, respectively. Let L_{DATA} denote the payload length in bytes.



(a)

$$T_O = T_{BCH+Pre} + 26_{NDown} + 32_{NUP} + T_{ACH} + T_{RCH+Pre} + (N_{Down} + 2_{NUP})T_{SCH} + T_{Turn}$$

$$\text{Throughput}_{HIPERLAN/2} = \frac{[(2000 - T_O)/T_{LCH}] \cdot 48 \cdot 8}{2000} \text{ (b/s)}$$

(b)

Figure 2. *a) HIPERLAN/2 MAC frame; b) equations for overhead and throughput.*

The wireless LAN standards, ETSI BRAN HIPERLAN/2 and IEEE 802.11a/11g, offer transmission rates up to 54 Mb/s in the 5 GHz or 2.4GHz band. The two standards differ primarily on the MAC layer. The actual throughputs achieved are also highly dependent on MAC protocols.

According to our previous contributions in [2], the MT and TUL are shown in Fig. 1a.

Figure 1a shows the MT and TUL for IEEE 802.11a. As illustrated in the figure, the TUL upper bounds the MT at a 54 Mb/s data rate and the MT at a 216 Mb/s data rate. When the payload size is 1500 bytes, the TUL is about 75.24 Mb/s. The existence of the TUL shows that by simply increasing the data rate without reducing overhead, the enhanced throughput is bounded even when the data rate goes infinitely high. In other words, reducing overhead is necessary for IEEE 802.11 standards to achieve higher throughput.

Figure 1b(i) and (ii) show normalized overhead vs. data rate. The normalized overhead increases as the data rate increases. The normalized throughput almost reaches 1 after 180 Mb/s when the payload size is 100 bytes. The normalized throughput reaches 70 percent after 180 Mb/s when the payload size is 1500 bytes. Figure 1b(iii) and (iv) show normalized overhead vs. payload size. The normalized overhead decreases as the payload size increases. The normalized throughput almost reaches 1 when the payload size is very small.

In summary, the normalized overhead is extremely large when either the data rate is high or the frame is small.

HIPERLAN/2

The wireless LAN standards, European Telecommunications Standards Institute (ETSI) Broadband Radio Access Network (BRAN) HIPERLAN/2 [10] and IEEE 802.11a/11g, offer transmission rates up to 54 Mb/s in the 5 GHz or 2.4 GHz band. In this section we compare IEEE 802.11a and HIPERLAN/2 in terms of throughput upper limit. The two standards differ primarily in the MAC layer. The actual throughputs achieved are also highly dependent on MAC protocols. HIPERLAN/2 employs centralized control, where a scheduler at an AP allocates resources in a MAC frame. Another difference in MAC protocols is the packet length adopted: HIPERLAN/2 adopted fixed length packets, and IEEE 802.11 adopted variable length packets.

In HIPERLAN/2 a MAC frame is transmitted in a period of 2 ms (Fig. 2a). Each MAC frame comprises time slots for broadcast control (BCH), frame control (FCH), access feedback control (ACH), data transmission in downlink (DL), direct link (DiL), and uplink (UL) phases, and random channels (RCHs). DL and UL are used when data has to be transmitted. DL, UL, and DiL phases consistent of two types of protocol data units (PDUs): the short transport chan-

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