IEEE 802.11n Development: History, Process, and Technology

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ABSTRACT

This article provides insight into the IEEE 802.11n standard amendment development process, beginning with a general overview of the IEEE 802.11 process. Development of requirements and usage models in the study group and task group is discussed. The lengthy proposal down selection process used by 802.11n is described and critiqued. We also discuss the expected time to develop a standard from a market perspective. An overview of the physical layer technology used to achieve the 600 Mb/s data rate is presented. We outline the medium access layer features employed to enhance usable throughput to over 400 Mb/s. The added robustness afforded by techniques in the standard and issues with backward compatibility with legacy IEEE 802.11a/g devices are addressed.

INTRODUCTION

In 2002 discussions began in the IEEE 802.11 Working Group (WG) to extend the data rates of the physical layer beyond those of IEEE 802.11a/g in order to address higher throughput wired applications that would benefit from the flexibility of wireless connectivity. The WG proceeded through the typical steps in developing a standard. The high throughput study group (HT SG) was formed with great interest, with participants at the meetings numbering well over 100. The group introduced new antenna technology, such as multiple-input multiple-output (MIMO).

Subsequently the IEEE 802.11n Task Group (TGn) began to develop an amendment to the IEEE 802.11 standard (i.e., IEEE 802.11n). Initially there was large participation in TGn. Often votes on TGn proposals caused other task groups to temporarily recess their meetings, and garnered on the order of 250 votes. As the technology and the draft matured, interest in TGn has declined to a few core participants resolving comments. Now the excitement in TGn has shifted from the standards body to the marketplace, where numerous draft IEEE 802.11n products are becoming available to the consumer. These new products enhance basic networking in the home and office. Also, new types of products are beginning to become available, such as IEEE 802.11n-based wireless multimedia and gaming systems.

As described in the subsequent section, the standard amendment process seems straightforward and benign — for IEEE 802.11n it has been everything but so. The process has turned out to be as challenging as the technology itself. The history that brought us to the current phase of the process is described in the sections on study group and task group activity. The proposal process specific to IEEE 802.11n and its associated issues is outlined. We describe how compromise was finally reached, leading to the first draft of the amendment. In the next section of the article market expectations regarding the time to complete the IEEE 802.11n standard are discussed. Following that we provide an overview of the physical layer (PHY) and medium access layer (MAC) enhancements in IEEE 802.11n. Lastly, we highlight some lessons learned and propose changes to the process that may reduce the duration of amendment development.

As a note, in the remainder of the article the notation 802.11 will be used as a simplification of IEEE 802.11 with the same intended meaning.

802.11 PROCESS TO AMEND THE STANDARD

The 802.11 WG follows five steps to amend the 802.11 standard:

- Initial discussion of new ideas in the Wireless Next Generation Standing Committee (WNG SC)
- Formation of an SG to formulate the purpose and scope of the amendment
- Creation of a TG to develop a draft of the amendment that addresses the purpose and scope
- Approval of the draft by the WG, and opening of a Sponsor Ballot pool for review of the draft by the IEEE Standards Association (IEEE-SA)
- Ratification of the draft by the IEEE-SA Standards Board

To elaborate on the five steps above, the standard amendment process begins in the WG with presentations of a new concept to the WNG

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SC. If there is broad interest for the new idea, the WNG SC participants vote to request the WG to create a new SG. Presentations can all be made in one 802.11 meeting or span multiple meetings. The WG then votes on whether to create a new SG, which requires 75 percent approval. Unlike other organizations where each company gets a single vote, in 802.11 each individual participant who has achieved voting member status gets a vote (status achieved through meeting attendance).

With a passing vote, a new SG is created. The SG prepares a document called the Project Authorization Request (PAR), which contains the purpose and scope of the amendment. These will become the guiding requirements for the TG. The SG must also address five criteria demonstrating the need for the new amendment. These criteria include:

- Broad market potential
- Compatibility with the family of IEEE 802 standards
- Distinct identity from other IEEE 802 standards
- Technical feasibility
- Economic feasibility

The SG then votes to approve the PAR and five criteria, and request the WG to create a TG. This step also requires 75 percent approval. Typically the WG briefly discusses the PAR and five criteria, and often requests modifications from the SG. Eventually the WG votes to approve the PAR and five criteria, which again requires 75 percent approval. The WG then requests the IEEE 802 Executive Committee (EC) and after that the IEEE-SA Standards Board to approve the PAR and formation of a new TG. The SG typically lasts six months to a year. On formation of the TG, the SG dissolves. If either the WG or the EC do not approve the PAR and five criteria, a TG is not created.

The primary goal of the TG is to create a draft amendment. The TG can either "design by committee" or issue a call for proposals. With the "design by committee" approach, individuals present submissions on new features. With a 75 percent vote by the TG members, the new feature is adopted as part of the draft. On the other hand, with a call for proposals, typically groups of individuals or companies form proposal teams and create a proposal that on acceptance would become the initial draft of the amendment. This approach requires a down selection procedure since typically numerous proposals are submitted for consideration. Details of the down selection procedure are decided by the TG, but a confirmation vote by the TG of the winning proposal is required. The confirmation vote requires 75 percent approval for the final proposal to become the initial draft.

After a draft is created, a letter ballot pool is formed from all the voting members of the WG. The members review the draft, and a letter ballot vote occurs on whether the draft is acceptable for submission to the IEEE-SA as a Sponsor Ballot. As part of the voting process, the members create comments regarding their issues with the draft. If there is not 75 percent approval, the TG goes back to work on a new draft addressing all the comments. This is the comment resolution phase of the TG. If the vote exceeds 75 percent approval but with voters still generating many new comments, the TG works on a revision of the specific sections of the draft that addresses the new comments. Subsequent votes are termed recirculation votes. Finally, when no new no votes and comments are received from the WG, the draft is submitted to IEEE-SA for a Sponsor Ballot.

The Sponsor Ballot pool is made up of members of the IEEE-SA. Any member of the IEEE may join the IEEE-SA as an addition to annual IEEE membership. This process provides a broad review of the draft, beyond just the participants of 802.11.

The Sponsor Ballot process is similar to the letter ballot process. The Sponsor Ballot vote occurs, and the TG receives comments and generates updates to the draft that address the comments. When the Sponsor Ballot pool finally approves the draft amendment with no new no votes or comments, the draft is ratified by the IEEE-SA Standards Board. Optimistically, creation of a new amendment, starting with TG formation to final ratification, takes two to three years.

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WNG SC AND SG ACTIVITY

In January 2002 a presentation was given to WNG SC expressing interest in a high-data-rate extension to 802.11a [4]. The interest was in part based on increasing data rates in wired Ethernet and wireless products emerging on the market with proprietary extensions to 802.11a/g. Subsequently, other presentations were given calling for greater than 100 Mb/s data rates by spatial multiplexing and/or doubling the bandwidth in addition to improving MAC efficiency. Claims were made that new markets and applications would require higher throughput (e.g., wireless home entertainment). It is important to note that a presentation was made describing a MIMO prototype and actual measurements [2]. The goal of standards development is to foster new commercially successful markets by interoperable products, not to perform research. Proof of feasibility of new technology by prototyping is a reasonable starting point for standards development. For market success, the goal should be that by the time standard development is complete (or mature), manufacturers are capable of low-cost silicon implementation of the system.

The new High Throughput (HT) SG was formed in September 2002. Beyond development of the PAR and five criteria, work also began in HT SG on usage model development, channel model development, and selection procedures. The work was then continued in TGn. A committee was formed to define various market-based usage models that were used to define network simulation scenarios for the performance evaluation of the proposals. The usage models were to be relevant to the expected uses of the technology. Furthermore, they were to require higher throughput than was available with 802.11a/g. The components of the usage models included applications, environments, and use cases [7]. The applications included various forms of video and audio, Internet and local file

With MIMO being one of the primary physical layer candidate technologies, new standardized channel models were required in order to benchmark different proposals. A channel model ad hoc committee was created to develop indoor MIMO channel models.

transfer, and VoIP. Requirements in terms of offered load, maximum packet loss rate, maximum delay, and network protocol were captured for each application. The main environments included home, office, and hot spots. Use cases were collected that gave a description of how someone uses the application in a particular environment (i.e., multiple TVs running throughout the home getting their content from a single remotely located media server). The various use cases were merged together to create a small number of realistic usage models, but each capable of stressing the system. Each usage model contained an access point (AP) and a defined number of stations running a mix of applications based on the use cases. The environment thus dictated the channel model. The usage models were then converted into simulation scenarios.

With MIMO one of the primary physical layer candidate technologies, new standardized channel models were required in order to benchmark different proposals. A channel model ad hoc committee was created to develop indoor MIMO channel models. The channel modeling effort incorporated a literature search for existing models and measurements, new measurements, and the development of new models [1].

TGn Proposal Process

TGn officially began in September 2003. TGn decided to proceed with a call for proposals rather than a design by committee approach. The first order of business was to complete the creation of the selection procedure. As a first step in the selection criteria, functional requirements and comparison criteria were defined [6]. The Functional Requirements document was created containing a list of mandatory features, performance, and behavior [8]. The Comparison Criteria document defined the simulation results that were required of a complete proposal [9]. A complete proposal was one that did not violate the PAR and met all the functional requirements addressing the comparison criteria.

Once the usage models, channel models, functional requirements, and comparison criteria were adopted, the task group issued a call for proposals in May 2004. The selection criteria called for a series of down selection votes to one proposal. After each down selection vote, the proposal with the least number of votes was eliminated. The final proposal was required to pass a confirmation vote by 75 percent. If the confirmation vote failed, the last three proposals would be brought back and the process restarted. As can be seen, only 25 percent of the group can force this process to repeat forever (or at least until the defined duration of the TG expires).

In 802.11n five complete proposals were submitted for consideration along with a large number of partial proposals. Three of the proposals were created by individual companies. The other two proposals were each created by a team of companies: TGn Sync (started by Intel, Cisco, Agere, and Sony) and WWiSE (started by Broadcom, Conexant, Texas Instruments, and Airgo Networks). Many other companies were involved in the proposal process, and most ended up joining one of these two proposal teams. The first round of proposal presentations was in Sept 2004, two years after the start of the study group. Partial proposals were given time to present, but were required to merge with complete proposals for further consideration.

After a series of down selection votes, in March 2005 TGn had its final down selection vote and first failed confirmation vote of the TGn Sync proposal. In May 2005, the second failed confirmation vote took place and selection procedure reset to the last three proposals. The down selection process naturally creates a contentious environment. Companies expend a tremendous amount of resources developing technology and a proposal. A long drawn out down selection process increases the tension between camps, and makes compromise more and more difficult. An attempt was made to create a joint proposal between the three proposals, but the effort was unsuccessful due to the acrimony and lack of trust between the participants. The basic features and technologies in the various proposals were actually the same. All proposals included MIMO, 40 MHz bandwidth channels, frame aggregation, and enhanced block acknowledgment. For the most part, the difference between the proposals was the implementation details of these features. But due to the process, it became impossible to negotiate within the IEEE standards development environment.

In light of the stagnation of the proposal selection process, a group of silicon providers (started by Intel and Broadcom) went outside the IEEE and formed the Enhanced Wireless Consortium (EWC) special interest group to craft a basic interoperable specification such that they could start implementing interoperable devices. The specification picked pieces from each of the top two proposals to create the first draft. Ultimately the EWC felt it was beneficial to the industry for the specification to become an IEEE standard. Since EWC had no formal standing in the IEEE, EWC was required to convince others to adopt the EWC specification as the TGn joint proposal. This required passing the confirmation vote with 75 percent. Negotiations with more companies to garner support resulted in many new optional features to the EWC specification. The final EWC specification was adopted as a joint proposal and submitted for confirmation in TGn, where it passed unanimously in January 2006.

Interestingly, more optional features ended up in the EWC/joint proposal than were in either the TGn Sync or WWiSE proposals. Such is the nature of compromise necessary to achieve the 75 percent confirmation vote. For example, TGn Sync had implicit beamforming and WWiSE had no beamforming. Yet the joint proposal contained implicit beamforming, explicit beamforming, and antenna selection.

In hindsight, there are a number of ways the down selection process could have been streamlined. The top two proposals (TGn Sync and WWiSE) received the largest number of votes at each down selection. Furthermore, the top proposal (TGn Sync) received the largest number of votes at each down selection vote. TGn could have held just two down selection votes, one to reduce the number of proposals to two and a final down selection vote to select a winner. Considering the basic technology was the same between proposals, the down selection winner could have been converted to a first draft of the standard amendment, bypassing confirmation votes. In essence, the first draft would be selected based on the proposal receiving greater than 50 percent vote rather than 75 percent. Such an approach would completely change the dynamics of the proposal process. To achieve the extra 25 percent for confirmation, proposal teams (and EWC) were required to incorporate features from various companies that had little general support and in many cases were no more than research ideas.

The letter ballot vote on the draft requires 75 percent, so a super-majority vote is still required to approve the draft. One may argue that the first letter ballot would be guaranteed to fail if the winning proposal only achieved 50 percent approval. On the other hand, the TGn joint proposal achieved unanimous support in the confirmation vote, but still failed the first letter ballot and generated thousands of comments in large part due to all the extra features. Once these features are in the draft, a 75 percent vote is required to remove them, which is almost impossible. Therefore, a great deal of time is required to fix all the extraneous features and address their associated letter ballot comments. A draft based on a proposal with only 50 percent support may also fail the letter ballot, but would be guaranteed to have far fewer comments due to the smaller number of optional features. Furthermore, new features would then be required to achieve 75 percent support, resulting in higher-quality additions to the draft.

MARKET EXPECTATIONS AND TIMESCALES

As the technology of 802.11a/b/g matured, silicon and system providers were looking for new technology to incorporate into new products to refresh product lines. In 2004 Atheros developed a proprietary 40 MHz mode built on 802.11g. In 2005 and 2006 the market saw the first wave of proprietary MIMO-based wireless LAN products. These were typically called "pre-n." Interoperability between different products was only guaranteed by falling back to 802.11a/g operation.

Looking back at the history of TGn, the initial schedule put forth by HT SG called for completing the PAR in November 2002, completing the first draft in July 2003, completing the second draft in September 2003, going to sponsor ballot in March 2004, and final approval in July 2004. Obviously this was a bit optimistic, but even an additional year or two would have met the needs of manufacturers with an IEEE standard, rather than having to produce proprietary and non-interoperable modes of operation.

Turning back to the down selection process of TGn, the issue with incorporating so many "pet features" as part of a compromise is the time it takes to thoroughly review, edit, check, and test each feature. This is illustrated by the number of comments TGn received in its first three letter ballots. Six thousand unique comments were received in the letter ballot for draft 1.0. Three thousand unique comments were received in letter ballot for draft 2.0. Nine hundred comments were received in letter ballot for draft 3.0. With comment resolution for draft 3.0 expected to be completed in March 2008, comment resolution has thus far taken two years. The current projected completion date is June 2009, approaching eight years after the first presentation in WNG SC.

With the exception of coexistence between 40 and 20 MHz channel bandwidth modes of operation, the basic functionality of the PHY and MAC layer stabilized between drafts 1.0 and 2.0. Beyond draft 2.0, the vast majority of the comments and most of the time spent creating resolutions have been on the numerous optional features. The nature of the down selection process that results in adding many options to garner 75 percent confirmation vote greatly extends the comment resolution process.

Having realized the market demand for standards-based interoperable products, the Wi-Fi Alliance considered certifying devices based on an 802.11n draft due to the slow development of the 802.11n amendment. Wi-Fi certified products provide consumers with assurance of interoperability of core functionality that was not guaranteed by proprietary modes in pre-n products. The Wi-Fi Alliance developed a certification program based on a subset of features in 802.11n draft 2.0 and began certification of 802.11n draft 2.0 devices in June 2007. Part of the rationale was that the core functionality of the draft was stable, with draft 2.0 being a major enhancement over draft 1.0. Considering the current timeline for 802.11n, early release by IEEE of the 802.11n draft 2.0 amendment and Wi-Fi certification of draft 2.0 was a significant step forward in speeding up the adoption of 802.11n-based WLAN technology. Additional optional features may be certified as the draft matures or reaches final approval.

Early release of a draft of the standard and draft-based certification changed the dynamics in TGn. Participants in TGn whose employer produced draft 2.0 certified products are now motivated to maintain interoperability between their current certified products and later final standard-based products. It is now unlikely that any changes will occur to the core features certified based on draft 2.0. The focus of the comment resolution process has shifted to refining the optional features that were not part of the draft 2.0 based certification.

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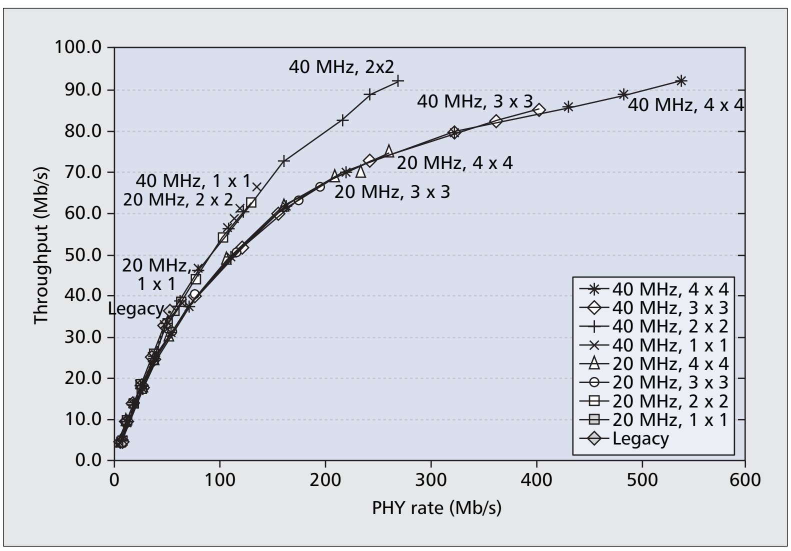
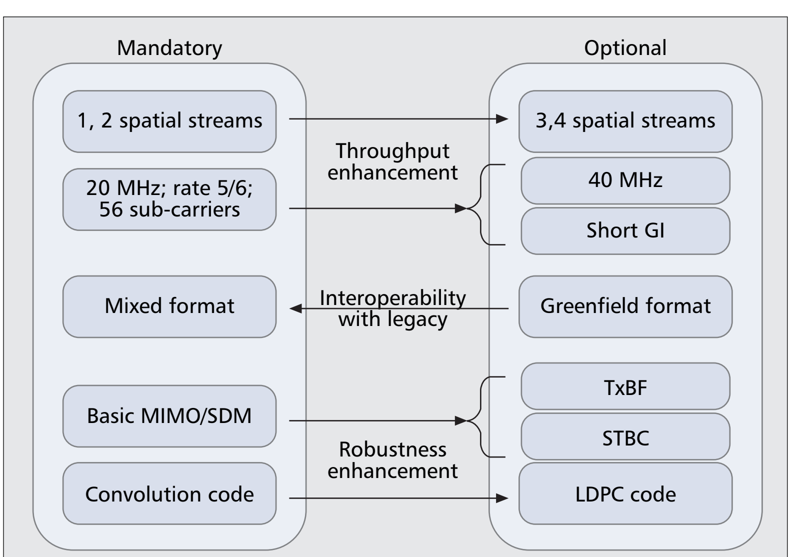
OVERVIEW OF 11N ENHANCEMENTS

The key requirement that drove most of the development in 802.11n is the capability of at least 100 Mb/s MAC throughput. Considering that the typical throughput of 802.11a/g is 25 Mb/s (with a 54 Mb/s PHY data rate), this requirement dictated at least a fourfold increase in throughput. Defining the requirement as MAC throughput rather than PHY data rate forced developers to consider the difficult problem of improving MAC efficiency. Figure 1 demonstrates the achievable throughput when the PHY data rates are increased with an unmodified 802.11e-based MAC. The inability to achieve a throughput of 100 Mb/s necessitated substantial improvements in MAC efficiency when designing the 802.11n MAC.

Two basic concepts are employed in 802.11n to increase the PHY data rates: MIMO and 40 MHz bandwidth channels. Increasing from a single spatial stream and one transmit antenna to four spatial streams and four antennas increases the data rate by a factor of four. (The term *spatial stream* is defined in the 802.11n standard [3] as one of several bitstreams that are transmitted over multiple spatial dimensions created by the use of multiple antennas at both ends of a communications link.) However, due to the inherent increased cost associated with increasing the number of antennas, modes that use three and four spatial streams are optional, as indicated in Fig. 2. And to allow for handheld devices, the two spatial streams mode is only mandatory in an access point (AP). As shown in Fig. 2, 40 MHz bandwidth channel operation is optional in the standard due to concerns regarding interoperability between 20 and 40 MHz bandwidth devices, the permissibility of the use of 40 MHz bandwidth channels in the various regulatory domains, and spectral efficiency. However, the 40 MHz bandwidth channel mode has become a core feature due to the low cost of doubling the data rate from doubling the bandwidth. Almost all 802.11n products on the market feature a 40 MHz mode of operation. Other minor modifications were also made to the 802.11a/g waveform to increase the data rate. The highest encoder rate in 802.11a/g is 3/4. This was increased to 5/6 in 802.11n for an 11 percent increase in data rate. With the improvement in radio frequency (RF) technology, it was demonstrated that two extra frequency subcarriers could be squeezed into the guard band on each side of the spectral waveform and still meet the transmit spectral mask. This increased the data rate by 8 percent over 802.11a/g. Lastly, the waveform in 802.11a/g and mandatory operation in 802.11n contains an 800 ns guard interval between each orthogonal frequency-division multiplexing (OFDM) symbol. An optional mode was defined with a 400 ns guard interval between each OFDM symbol to increase the data rates by another 11 percent.



■ **Figure 1.** *Throughput vs. PHY data rate assuming no MAC changes. Reproduced with permission from [5].*



■ **Figure 2.** *Mandatory and optional 802.11n PHY features. Reproduced with permission from [5].*

Another functional requirement of 802.11n was interoperability between 802.11a/g and 802.11n. The TG decided to meet this requirement in the physical layer by defining a waveform that was backward compatible with 802.11a and OFDM modes of 802.11g. The preamble of the 802.11n mixed format waveform begins with the preamble of the 802.11a/g waveform. This includes the 802.11a/g short training field, long training field, and signal field. This allows 802.11a/g devices to detect the 802.11n mixed format packet and decode the signal field. Even though the 802.11a/g devices will not be able to decode the remainder of the 802.11n packet, they will be able to properly defer their own transmission based on the length specified in the signal field. The remainder of the 802.11n Mixed format waveform includes a second short training field, additional long training fields, and additional signal fields followed by the data. These new fields are required for MIMO training and signaling of the many new modes of operation. To ensure backward compatibility between 20 MHz bandwidth channel devices (including 802.11n and 802.11a/g) and 40 MHz bandwidth channel devices, the preamble of the 40 MHz waveform is identical to the 20 MHz waveform and is repeated on the two adjacent 20 MHz bandwidth channels that form the 40 MHz bandwidth channel. This allows 20 MHz bandwidth devices on either adjacent channel to decode the signal field and properly defer transmission. The preamble in 802.11a has a length of 20 μs; with the additional training and signal fields, the 802.11n mixed format packet has a preamble with a length of 36 μs for one spatial stream up to 48 μs for four spatial streams.

Unfortunately, MIMO training and backward compatibility increases the overhead, which reduces efficiency. In environments free from legacy devices (termed *greenfield*) backward compatibility is not required. As illustrated in Fig. 2, 802.11n includes an optional greenfield format. By eliminating the components of the preamble that support backward compatibility, the greenfield format preamble is 12 μs shorter than the mixed format preamble. This difference in efficiency becomes more pronounced when the packet length is short, as in the case of VoIP traffic. Therefore, the use of the greenfield format is permitted even in the presence of legacy devices with proper MAC protection, although the overhead of the MAC protection may reduce the efficiency gained from the PHY.

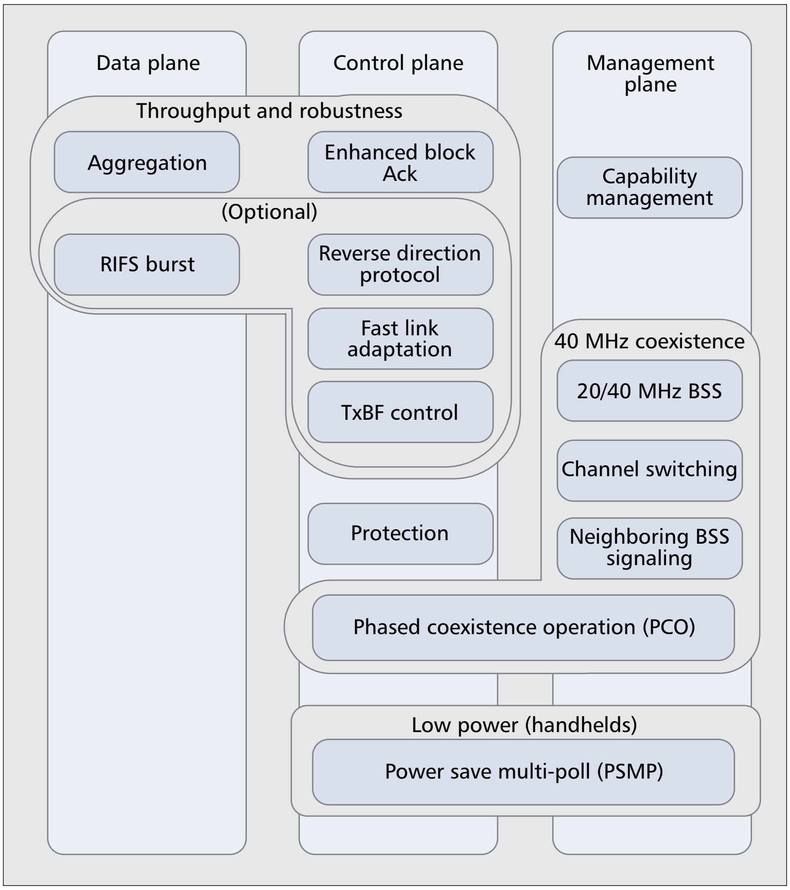
Range was considered as a performance metric in the PAR and comparison criteria. To increase the data rate at a given range requires enhanced robustness of the wireless link. 802.11n defines implicit and explicit transmit beamforming (TxBF) methods and space-time block coding (STBC), which improves link performance over MIMO with basic spatial-division multiplexing (SDM). The standard also defines a new optional low density parity check (LDPC) encoding scheme, which provides better coding performance over the basic convolutional code.

To break the 100 Mb/s throughput barrier, frame aggregation was added to the 802.11n MAC (as illustrated in Fig. 3) as the key method of increasing efficiency. The issue is that as the data rate increases, the time on air of the data portion of the packet decreases. However, the PHY and MAC overhead remain constant. This results in diminishing returns from the increase in PHY data rate, as illustrated in Fig. 1. Frame aggregation increases the length of the data portion of the packet to increase overall efficiency.

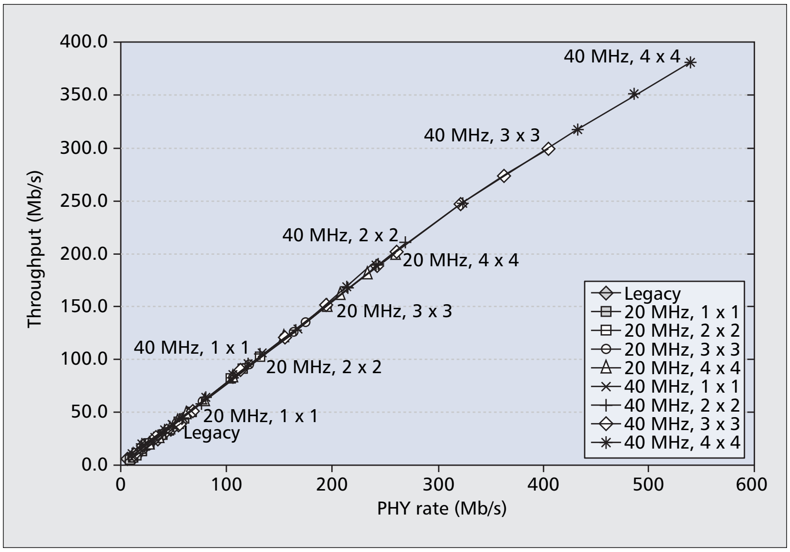
Two forms of aggregation exist in the standard: MAC protocol data unit aggregation (A-MPDU) and MAC service data unit aggregation (A-MSDU). Logically, A-MSDU resides at the top of the MAC and aggregates multiple MSDUs into a single MPDU. Each MSDU is prepended with a subframe header consisting of the destination address, source address, and a length field giving the length of the SDU in bytes. This is then padded with 0 to 3 bytes to round the subframe to a 32-bit word boundary. Multiple such subframes are concatenated together to form a single MPDU. An advantage of A-MSDU is that it can be implemented in software. A-MPDU resides at the bottom of the MAC and aggregates multiple MPDUs. Each MPDU is prepended with a header consisting of a length field, 8-bit CRC, and 8-bit signature field. These subframes are similarly padded to 32-bit word boundaries. Each subframe is concatenated together. An advantage of A-MPDU is that if an individual MPDU is corrupt, the receiver can scan forward to the next MPDU by detecting the signature field in the header of the next MPDU. With A-MSDU, any bit error causes all the aggregates to fail.

MAC throughput with frame aggregation increases linearly with PHY data rate with traffic conducive to aggregation, as illustrated in Fig. 4. With a PHY data rate of 600 Mb/s, a MAC throughput of over 400 Mb/s is now achievable with 802.11n MAC enhancements.

When using block acknowledgment from 802.11e, a station transmits a burst of packets before receiving an acknowledgment. A simple increase in efficiency when not employing frame



■ **Figure 3.** *Summary of 802.11n MAC enhancements. Reproduced with permission from [5].*



■ **Figure 4.** *Throughput Vs PHY data rate with frame aggregation. Reproduced with permission from [5].*

The 802.11 WG has formed a new study group to investigate "very high throughput" potentially providing throughput in the order of giga-bits per second. Hopefully the lessons learned from 802.11n will result in improvements of the processes of future task groups.

aggregation is reducing the interframe spacing (RIFS) between packets, which is possible since the station no longer requires additional time to switch between transmit and receive states. Additional enhancements to the block acknowledgment (BA) mechanism in 802.11e include compressing the BA frame by eliminating support for fragmentation. The reverse direction protocol was incorporated, which allows a station to share its transmit opportunity (TXOP) with another station. This increases throughput with traffic patterns that are highly asymmetric, for example, when transferring a large file with FTP operating over TCP. Time is borrowed during the TXOP to send the short TCP Acknowledgment in the reserve direction. Depending on the usage model, TCP traffic throughput may improve up to 40 percent.

Many new methods of control and management were added to 802.11n, as illustrated in Fig. 3. In order to more rapidly track changes in the channel, fast link adaptation assists in the selection of the optimal modulation and coding scheme (MCS). Transmit beamforming may be considered a PHY technique, but it requires a great deal of control in the MAC for channel sounding, calibration, and the exchange of channel state information or beamforming weights. Protection mechanisms had to be devised to ensure that legacy 802.11a/g devices are not harmed by the new modes of operation and vice versa. These new modes, which may require protection, include RIFS bursting and greenfield format transmissions.

With the introduction of the 40 MHz bandwidth channel came the complexity of managing coexistence between 40 MHz bandwidth 802.11n devices and 20 MHz bandwidth 802.11n and 802.11a/g devices. This becomes especially difficult when operating in the 2.4 GHz band where the channel numbering is incremented by 5 MHz, causing complicated partial overlapping channel conditions between neighboring APs. Rules were put in place mandating that an AP scan for neighboring basic service sets (BSSs) prior to establishing a 40 MHz BSS and preventing the establishment of a 40 MHz BSS when neighboring BSSs are detected in overlapping channels. Furthermore, during the operation of a 40 MHz BSS in the 2.4 GHz band, active 40 MHz bandwidth stations must periodically scan overlapping channels. If conditions change disallowing 40 MHz operation (i.e., a new 20 MHz BSS appears in an overlapping channel), the AP must switch the BSS to 20 MHz bandwidth channel operation.

With the increased interest in Wi-Fi enabled handheld devices, Power Save Multi-Poll (PSMP) was incorporated in the 802.11n MAC to provide a minor improvement of channel utilization and reduction in power consumption when transmitting and receiving small amounts of data periodically. These conditions arise with multiple voice over IP (VoIP) sessions in the BSS. Downlink transmissions are grouped together, and uplink transmissions are scheduled. The schedule for the downlink transmission is provided at the start of the PSMP phase, which allows for devices to power down their receivers until needed.

Summary and Lessons Learned

As indicated by the rate of Wi-Fi certification of new wireless products, 802.11n is showing the beginnings of being a resounding market success. Over 100 devices were certified in the first few months, three times as many as with 802.11b, 802.11a, or 802.11g. Consider that just 10 years ago data rates were on the order of just a few megabits per second. Now products are available to the consumer capable of hundreds of megabits per second and able to support wireless video (e.g., two 20 Mb/s HTDV streams between adjacent rooms). These devices include the latest advances in wireless networking technology, including MIMO, frame aggregation, and 20/40 MHz bandwidth channels.

That said, initial expectations in HT SG were for a completed standard amendment a few years ago. Fundamentally we need to avoid lengthy adversarial processes. The participants in IEEE 802.15.3a went through years of fighting and political maneuvering before disbanding without completing a standard. Fortunately, in 802.11n the technical issues did not cause as wide a divide, and a few companies from both sides of the fence were able to come together and form EWC. This led to a broadly accepted compromise and ended the contentious proposal process. Mergers outside the often politically charged standards body should be encouraged earlier in the proposal process.

With a call for proposals and down selection approach, changes need to be made to the proposal process to guarantee conclusion and disallow endless loops. As described, a possible approach to speeding up the process is to reduce the number of down selection votes and eliminate the confirmation vote.

When initially proposed, many of the new features in 802.11n were no more than new research ideas, such as PSMP or coexistence of 20 and 40 MHz bandwidth channel devices. On initial adoption there were no presentations containing simulation results of these features within an 802.11 system. Proposed features should be more mature before being adopted into a draft of the standard to shorten the standardization process. This avoids continual improvements to the feature during the development of the draft.

For the time to develop a standards amendment to meet market needs, the scope of an amendment should be narrowed. 802.11n tried to address a wide scope of diverse environments. For example, to keep pace with the increasing data rates of Ethernet requires much higher data rates emphasizing features that provide high throughput, whereas serving VoIP handheld devices in an outdoor Wi-Fi hotspot requires features with a focus on low power and small form factor. As witnessed, each new feature, be it mandatory or optional (and especially new research ideas), results in hundreds of letter ballot comments that lengthen the letter ballot and comment resolution phase. The number of new features in an amendment should be limited within a narrow scope to shorten the time to market.

The 802.11 WG has formed a new study group to investigate "very high throughput" potentially providing throughput on the order of gigabits per second. Hopefully the lessons learned from 802.11n will result in improvements in the processes of future task groups.

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