1 Introduction

Wireless local area networking has experienced tremendous growth in the last ten years with the proliferation of IEEE 802.11 devices. Its beginnings date back to Hertz's discovery of radio waves in 1888, followed by Marconi's initial experimentation with transmission and reception of radio waves over long distances in 1894. In the following century, radio communication and radar proved to be invaluable to the military, which included the development of spread spectrum technology. The first packet-based wireless network, ALOHANET, was created by researchers at the University of Hawaii in 1971. Seven computers were deployed over four islands communicating with a central computer in a bi-directional star topology.

A milestone event for commercial wireless local area networks (WLANs) came about in 1985 when the United States Federal Communications Commission (FCC) allowed the use of the experimental industrial, scientific, and medical (ISM) radio bands for the commercial application of spread spectrum technology. Several generations of proprietary WLAN devices were developed to use these bands, including WaveLAN by Bell Labs. These initial systems were expensive and deployment was only feasible when running cable was difficult.

Advances in semiconductor technology and WLAN standardization with IEEE 802.11 led to a dramatic reduction in cost and the increased adoption of WLAN technology. With the increasing commercial interest, the Wi-Fi Alliance (WFA) was formed in 1999 to certify interoperability between IEEE 802.11 devices from different manufacturers through rigorous testing. Shipments of Wi-Fi certified integrated circuits exceeded a billion units per year in 2011 (ABIresearch, 2012) and are expected to exceed 2.5 billion units per year by 2016 (ABIresearch, 2012), as illustrated in Figure 1.1.

Such large and sustained growth is due to the benefits WLANs offer over wired networking. In existing homes or enterprises, deploying cables for network access may involve tearing up walls, floors, or ceilings, which is both inconvenient and costly. In contrast, providing wireless network connectivity in these environments is often as simple as installing a single wireless access point. Perhaps more importantly though, the proliferation of laptops and handheld devices has meant that people desire connectivity wherever they are located, not just where the network connection is located. Network connectivity in a conference room or while seated on the sofa in the living room are just two examples of the flexibility afforded by WLANs.

There has been a proliferation of small scale deployments providing Internet access in coffee shops, airports, hotels, etc., which have come to be known as hotspots. In recent

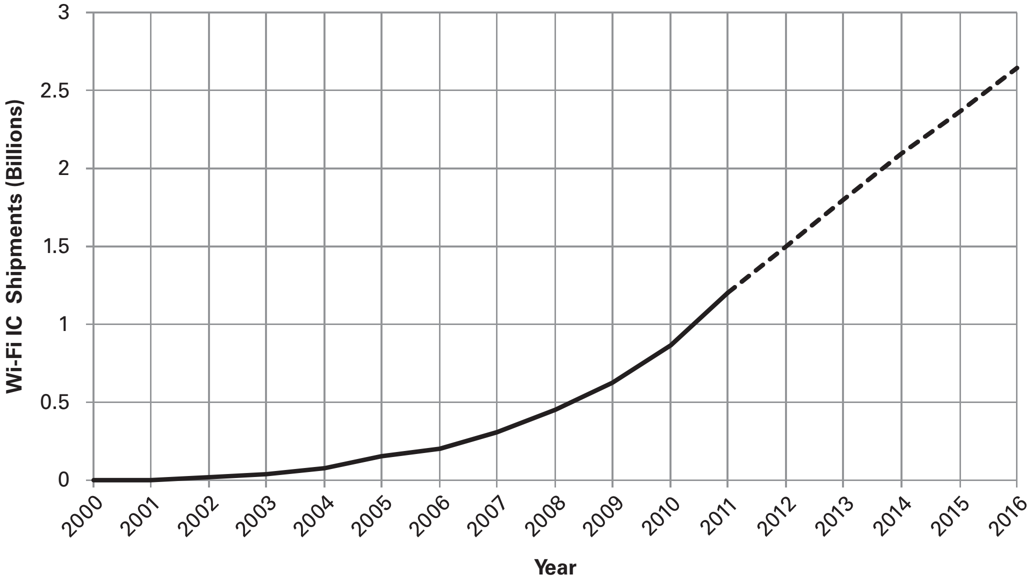

Figure 1.1 Wi-Fi IC shipments.Source: ABIresearch (2007, 2012).

years, carriers with heavily congested cellular networks are deploying hotspots to offload traffic from their cellular networks. Additionally, when these networks are used in conjunction with virtual private network (VPN) technology, employees can securely access corporate networks from almost anywhere.

WLAN products and systems started with 802.11b, 802.11g, and 802.11a standard amendments, which provided throughput enhancements over the original 802.11 PHYs. Progress in WLAN technology continued with the development of 802.11n. Increased data rates were achieved with the multiple-input multiple-output (MIMO) concept, with its origins by Foschini (1996) at Bell Labs. In 2004, Atheros demonstrated that 40 MHz devices could be produced at almost the same cost as 20 MHz devices. During a similar time frame, the FCC and ETSI adopted new regulations in the 5 GHz band that added an additional 400 MHz of unlicensed spectrum for use by commercial WLANs.

These events paved the way for the broad acceptance of 40 MHz operating modes in 802.11n. When spectrum is free, increasing the channel bandwidth is the most cost effective way to increase the data rate.

Typically product development lags standardization efforts and products are released after the publication of the standard. An interesting event occurred in 2003 when Broadcom released a chipset based on a draft version of the 802.11g amendment, prior to final publication. This set a precedent for the flurry of “pre-n” products in 2005 and 2006, as industry players rushed to be first to market. Most of these products were either proprietary implementations of MIMO, or based on draft 1.0 of 802.11n, and thus unlikely to be compliant with the final standard.

Through early 2007, major improvements and clarifications were made to the 802.11n draft resulting in IEEE 802.11n draft 2.0. To continue the market momentum and forestall interoperability issues, the IEEE took the unusual step of releasing 802.11n D2.0 to the public while work continued toward the final standard. This allowed the Wi-Fi Alliance (WFA) to begin interoperability testing and certification of devices based on a subset of the 802.11n D2.0 features in May 2007. Wi-Fi certified 802.11n D2.0 products provide consumers the assurance of interoperability between manufacturers that was not guaranteed by previous “pre-n” products. At the end of 2009, 802.11n was finally approved and the WFA updated the certification program to reflect support for the approved standard. Full interoperability was maintained between 802.11n D2.0 and the approved standard products. These were major steps in speeding up the standardization and certification process of new technology.

As this process was successful for the industry and beneficial for the consumers, 802.11ac will follow a similar path. It is expected that 802.11ac products based on an early draft will be certified and on the market in early 2013. Completion of the 802.11ac is expected by the end of 2013.[1] Certification based on the approved standard will take place in a similar time frame.

1.1 An overview of IEEE 802.11

The IEEE 802.11 standard defines multiple physical layers (PHYs) and a common medium access control (MAC) layer for wireless local area networking. As a member of the IEEE 802 family of local area networking (LAN) and metropolitan area networking (MAN) standards, 802.11 inherits the 802 reference model and 48-bit universal addressing scheme. The 802 reference model is based on the OSI reference model described in Table 1.1. In this model, the 802.11 MAC and 802.2 logical link control (LLC) sublayers form the data link layer and the 802.11 PHY the physical layer.

1.1.1 The 802.11 MAC

The initial version of the 802.11 standard was completed in 1997. Influenced by the huge market success of Ethernet (standardized as IEEE 802.3), the 802.11 MAC adopted the same simple distributed access protocol, carrier sense multiple access (CSMA). With CSMA, a station wishing to transmit first listens to the medium for a predetermined period. If the medium is sensed to be “idle” during this period then the station is permitted to transmit. If the medium is sensed to be “busy,” the station has to defer its transmission. The original (shared medium) Ethernet used a variation called CSMA/CD or carrier sense multiple access with collision detection. After determining that the medium is “idle” and transmitting, the station is able to receive its own transmission and detect collisions. If a collision is detected, the two colliding stations backoff for a random period before transmitting again. The random backoff period reduces the probability of a second collision.

With wireless it is not possible to detect a collision with one’s own transmission directly in this way: thus 802.11 uses a variation called CSMA/CA or carrier sense

[1] The reader is referred to http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm for the latest update on the timeline of 802.11ac

Table 1.1 OSI reference model (adapted from ISO/IEC 7498-1, 1994)

OSI reference model layers	Description	Examples	Layer categories
Application	Interacts with the software applications that implement a communicating component	HTTP, FTP, SMTP	Application
Presentation	Establishes context between application-layer entities	MIME, TLS, SSL	
Session	Establishes, manages, and terminates communication sessions	Named pipe, NetBIOS	
Transport	Provides an end-to-end reliable data transfer service, including flow control, segmentation/desegmentation and error control	TCP, UDP	
Network	Provides the means for transferring variable length data sequences from a source device to a destination device. Maintains the quality of service requested by the transport layer	IP (IPv4, IPv6), ICMP, IPsec	
Data link	Provides the means for transferring data between devices	LLC 802.11 MAC	Data transport
Physical	Provides the electrical and physical specifications for devices	802.11 PHY	

multiple access with collision avoidance. With CSMA/CA, if the station detects that the medium is busy, it defers its transmission for a random period following the medium going "idle" again. This approach of always backing off for a random period following another station's transmission improves performance since the penalty for a collision is much higher on a wireless LAN than on a wired LAN. On a wired LAN collisions are detected electrically and thus almost immediately, while on wireless LAN collisions are inferred through the lack of an acknowledgement or other response from the remote station once the complete frame has been transmitted.

There is no doubt that the simplicity of this distributed access protocol, which enables consistent implementation across all nodes, significantly contributed to Ethernet's rapid adoption as the industry LAN standard. Likewise, the adoption by the industry of 802.11 as the wireless LAN standard is in no small part due to the simplicity of this access protocol, its similarity to Ethernet, and again the consistent implementation across all nodes that has allowed 802.11 to beat out the more complex, centrally coordinated access protocols of competing WLAN technologies such as HyperLAN.

1.1.2 The 802.11 PHYs

The original (1997) 802.11 standard included three PHYs: infrared (IR), 2.4 GHz frequency hopped spread spectrum (FHSS), and 2.4 GHz direct sequence spread spectrum (DSSS). This was followed by two standard amendments in 1999: 802.11b built upon DSSS to increase the data rate in 2.4 GHz and 802.11a to create a new PHY in 5 GHz. 802.11b enhanced DSSS with complementary code keying (CCK), increasing the data rate to 11 Mbps. With higher data rates, IEEE 802.11b devices achieved significant market success, and markets for IR and FHSS PHYs did not materialize.

The development of 802.11a introduced orthogonal frequency division multiplexing (OFDM) to 802.11. Even though 802.11a introduced data rates of up to 54 Mbps, it is confined to the 5 GHz band and, as a result, adoption has been slow. New devices wishing to take advantage of the higher rates provided by 802.11a but retain backward compatibility with the huge installed base of 802.11b devices would need to implement two radios, one to operate using 802.11b in the 2.4 GHz band and one to operate using 802.11a in the 5 GHz band. Furthermore, international frequency regulations in the 2.4 GHz band uniformly allowed commercial use, whereas in 1999 and 2000 the non-military use of the 5 GHz band was limited to select channels in the United States.

In 2001, the FCC permitted the use of OFDM in the 2.4 GHz band. Subsequently, the 802.11 working group developed the 802.11g amendment, which incorporates the 802.11a OFDM PHY in the 2.4 GHz band, and adopted it as part of the standard in 2003. In addition, backward compatibility and interoperability is maintained between 802.11g and the older 802.11b devices. This allows for new 802.11g client cards to work in existing 802.11b hotspots, or older 802.11b embedded client devices to connect with a new 802.11g access point (AP). Because of this and new data rates of up to 54 Mbps, 802.11g experienced large market success. A summary of the high level features of each PHY is given in Table 1.2.

With the adoption of each new PHY, 802.11 has experienced a five-fold increase in data rate. This rate of increase continues with 802.11n with a data rate of 300 Mbps in 20 MHz and 600 Mbps in 40 MHz. Furthermore, in the 5 GHz band, 802.11ac provides a data rate of 1733 Mbps with 80 MHz and four spatial streams, and a maximum data rate of 6933 Mbps with 160 MHz and eight spatial streams. The exponential increase in data rate is illustrated in Figure 1.2.

Table 1.2 Overview of 802.11 PHYs

	802.11	802.11b	802.11a	802.11g	802.11n	802.11ac
PHY technology	DSSS	DSSS/ CCK	OFDM	OFDM DSSS/ CCK	SDM/OFDM	SDM/OFDM MU-MIMO
Data rates (Mbps)	1, 2	5.5, 11	6–54	1–54	6.5–600	6.5–6933.3
Frequency band (GHz)	2.4	2.4	5	2.4	2.4 and 5	5
Channel spacing (MHz)	25	25	20	25 MHz	20 and 40	20, 40, 80, and 160

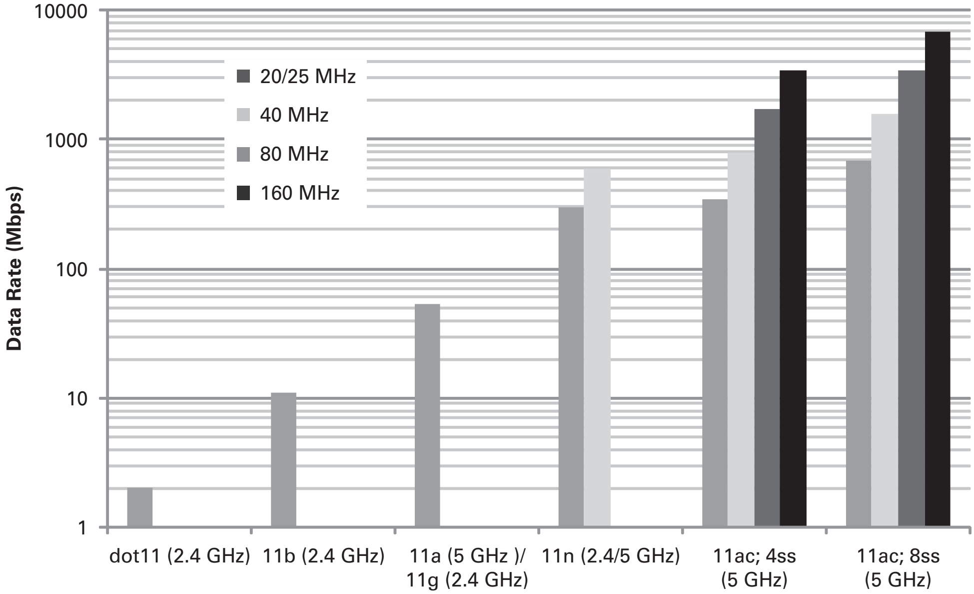

Figure 1.2 Increase in 802.11 PHY data rate.

1.1.3 The 802.11 network architecture

The basic service set (BSS) is the basic building block of an 802.11 LAN. Stations that remain within a certain coverage area and form some sort of association form a BSS. The most basic form of association is where stations communicate directly with one another in an ad-hoc network, referred to as an independent BSS or IBSS. This is illustrated as BSS 1 in Figure 1.3.

More typically, however, stations associate with a central station dedicated to managing the BSS and referred to as an access point (AP). A BSS built around an AP is called an infrastructure BSS and is illustrated by BSS 2 and BSS 3 in Figure 1.3. Infrastructure BSSs may be interconnected via their APs through a distribution system (DS).

The BSSs interconnected by a DS form an extended service set (ESS). A key concept of the ESS is that stations within the ESS can address each other directly at the MAC layer. The ESS, being an 802.11 concept, encompasses only the 802.11 devices and does not dictate the nature of the DS. In practice, however, the DS is typically an Ethernet (802.3) LAN and the AP functions as an Ethernet bridge. As such, stations in a BSS can also directly address stations on the LAN at the MAC layer.

1.1.4 Wi-Fi Direct

Recognizing the need for improved peer-to-peer operation, the Wi-Fi Alliance has developed a specification for direct communication between Wi-Fi devices without being associated with an infrastructure BSS. Such communication is possible using an

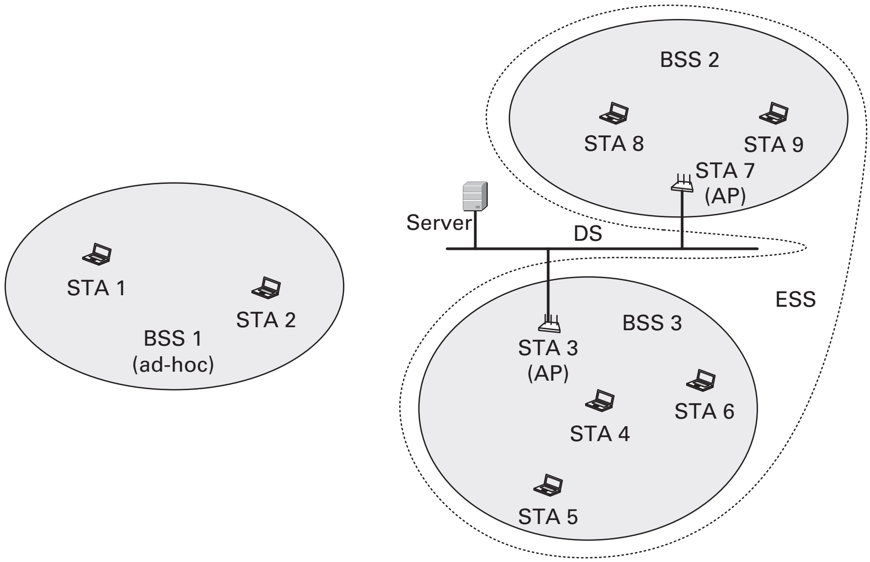

Figure 1.3 BSS, DS, and ESS concepts.

independent BSS, as defined in the 802.11 specification; however, it was preferable to create a mode of operation closer to that of the infrastructure BSS.

In a Wi-Fi Direct network, one device, called the group owner (GO), assumes a role similar to that of an AP while the other devices associate with that device as they would an AP. The Wi-Fi Direct network is thus similar to an infrastructure BSS except that (1) the GO does not provide access to a distribution system, and (2) like its peers, the GO could be a mobile, battery powered device, and thus also need to enter a low power sleep state when idle.

The Wi-Fi Direct standard builds on the 802.11 specification, specifying protocols by which devices can discover each other, how a device assumes the role of group owner and the protocol for absence from the session channel (for power management or to visit an infrastructure BSS channel).

1.2 History of high throughput and 802.11n

1.2.1 The High Throughput Study Group

Interest in a high data rate extension to 802.11a began with a presentation to the Wireless Next Generation Standing Committee (WNG SC) of IEEE 802.11 in January 2002. Market drivers were outlined, such as increasing data rates of wired Ethernet, more data rate intensive applications, non-standard 100+ Mbps products entering the market, and the need for higher capacity WLAN networks (Jones, 2002). The presentation mentioned techniques such as spatial multiplexing and doubling the bandwidth as potential approaches to study for increasing data rate.

After many additional presentations, the High Throughput Study Group (HTSG) was formed with its first meeting in September 2002. The primary objective of HTSG was to complete two documents necessary for the creation of the High Throughput Task Group (TGn). These are the project authorization request (PAR) form and five criteria form. The PAR defined the scope and purpose of the task group as follows:

The scope of this project is to define an amendment that shall define standardized modifications to both the 802.11 physical layers (PHY) and the 802.11 medium access control layer (MAC) so that modes of operation can be enabled that are capable of much higher throughputs, with a maximum throughput of at least 100 Mbps, as measured at the MAC data service access point (SAP). IEEE (2006)

By this statement, the standard amendment developed by TGn must contain modes of operation that are capable of achieving at least 100 Mbps *throughput*. Throughput is the measure of "useful" information delivered by the system and by using throughput as the metric, both MAC and PHY overhead must be considered. 802.11a/g systems typically achieve a maximum throughput of around 25 Mbps; thus this statement required at least a four-fold increase in throughput. Meeting this requirement would in essence mandate PHY data rates well in excess of 100 Mbps as well as significant enhancements to MAC efficiency.

Additional explanatory notes were included with the PAR outlining many evaluation metrics. These include throughput at the MAC SAP, range, aggregate network capacity, power consumption, spectral flexibility, cost complexity flexibility, backward compatibility, and coexistence (IEEE, 2006).

The five criteria form requires that the study group demonstrate the necessity of creating an amendment to the standard. The criteria include (1) broad market potential, (2) compatibility with existing IEEE 802.1 architecture, (3) distinct identity from other IEEE 802 standards, (4) technical feasibility, and (5) economic feasibility (Rosdahl, 2003). The goal is to create a standard amendment which results in marketable products, but that will also be differentiated from other potentially similar products.

In addition to completing the PAR and five criteria forms, HTSG also began development of new multipath fading MIMO channel models (Erceg *et al*., 2004) and usage models (Stephens *et al*., 2004). The channel models and usage models were used to create a common framework for simulations by different participants in the standard development process.

1.2.2 Formation of the High Throughput Task Group (TGn)

The PAR was accepted and approved by the 802 working group, creating Task Group n (TGn) with the first meeting of the task group held in September 2003. The standard amendment developed by the task group would be proposal driven, meaning that members of the task group would make partial or complete technical proposals, with the complete proposals proceeding through a down-selection process culminating in a single proposal upon which the standard amendment would be based. Partial proposals would be informative and could be incorporated in a complete proposal along the way. To that end, the task group began development of the functional requirements (Stephens, 2005) and comparison criteria (Stephens, 2004) documents. These two documents would provide, respectively, the technical requirements complete proposals must meet and criteria by which complete proposals would be compared.

The task group began with nine functional requirements. One of the functional requirements was a catch-all, requiring that proposals meet the PAR and five criteria. A second requirement was a reiteration of the PAR requirement to achieve 100 Mbps throughput at the top of the MAC.

Furthermore, since it was expected that not all regulatory domains would allow a single device to use multiple 20 MHz channels (an easy way to achieve the throughput objective), the second requirement added a restriction that 100 Mbps throughput be achieved in a single 20 MHz channel. To enforce efficient use of spectrum, another requirement was added for a mode of operation with a spectral efficiency of at least 3 bps/Hz.

Four functional requirements addressed operational bands and backward compatibility. One of these requirements was that the protocol should support operation in the 5 GHz band due to the large availability of spectrum there. Another requirement was that at least some modes of operation be backward compatible with 802.11a systems. Noteworthy was the fact that there was no requirement to support operation in the 2.4 GHz band. However, if a proposal did support 2.4 GHz band operation, it was required that there be modes of operation that were backward compatible with 802.11g systems. In this context, some flexibility was given, allowing an 802.11n AP to be configured to accept or reject associations from legacy stations.

The 802.11e amendment to the standard, nearing completion at the time, added many features for improving the quality of service (QoS) in 802.11 systems. Many of the perceived applications for 802.11n involved real time voice and video which necessitate QoS. Therefore a functional requirement was included which mandated that a proposal allow for the implementation of 802.11e features within an 802.11n station.

The comparison criteria in Stephens (2004) outlined metrics and required disclosure of results which would allow for comparison between proposals under the same simulation setup and assumptions. The comparison criteria incorporated the simulation scenarios and usage models defined in Stephens *et al*. (2004). During the development of the comparison criteria, the task group realized that members of the task group did not always share the same definitions for common terms. Therefore definitions for goodput, backward compatibility, and signal-to-noise ratio (SNR) were provided. The comparison criteria covered four main categories: marketability, backward compatibility and coexistence with legacy devices, MAC related criteria, and PHY related criteria.

Under marketability, the proposal must provide goodput results for residential, enterprise, and hotspot simulation scenarios. Goodput is defined by totaling the number of bits in the MAC service data units (MSDU) indicated at the MAC service access point (SAP), and dividing by the simulation duration (Stephens, 2004). Two optional criteria included describing the PHY and MAC complexity. The PHY complexity was to be given relative to 802.11a.

To ensure backward compatibility and coexistence with legacy devices, a proposal was required to provide a summary of the means used to achieve backward compatibility with 802.11a and, if operating in 2.4 GHz, 802.11g. Simulation results demonstrating interoperability were also required. The goodput of a legacy device in an 802.11n network and the impact of a legacy device on the goodput of 802.11n devices were also to be reported.

The MAC related criteria included performance measurements and changes that were made to the MAC. In the residential, enterprise, and hotspot simulation scenarios a number of different metrics were to be captured and reported. These included the ability to support the service requirements of various applications, including QoS requirements. Measurements of aggregate goodput of the entire simulation scenario were required to indicate network capacity. MAC efficiency was to be provided, which is defined as the aggregate goodput divided by the average PHY data rate. To ensure reasonable range for the new modes of operation, throughput versus range curves were also to be provided.

The PHY related criteria included PHY rates and preambles, channelization, spectral efficiency, PHY performance, and PHY changes. In addition, the comparison criteria also defined PHY impairments to be used in combination with channel models for PHY simulations. Each proposal was required to generate simulation results for both additive white Gaussian noise (AWGN) and non-AWGN channels. Furthermore, simulation conditions to analyze the impact on packet error rate (PER) of carrier frequency offset and symbol clock offset were also defined.

1.2.3 Call for proposals

The TGn call for proposals was issued on May 17, 2004, with the first proposals presented in September 2004. Over the course of the process two main proposal teams emerged, TGn Sync and WWiSE (world wide spectral efficiency). The TGn Sync proposal team was founded by Intel, Cisco, Agere, and Sony with the objective of covering the broad range of markets these companies were involved in, including the personal computer (PC), enterprise, and consumer electronics markets. The WWiSE proposal team was formed by Airgo Networks, Broadcom, Conexant, and Texas Instruments. These semiconductor companies were interested in a simple upgrade to 802.11a for fast time to market. Many other companies were involved in the proposal process and most ended up joining one of these two proposal teams.

The key features of all the proposals were similar, including spatial division multiplexing and 40 MHz channels for increased data rate, and frame aggregation for improved MAC efficiency. The proposals differed in scope (TGn Sync proposed numerous minor improvements to the MAC while WWiSE proposed limiting changes) and support for advanced features such as transmit beamforming (initially absent from the WWiSE proposal).

A series of proposal down-selection and confirmation votes took place between September 2004 and May 2005. During that time, mergers between proposals and enhancements to proposals took place. The TGn Sync proposal won the final down-selection vote between it and WWiSE, but failed the confirmation vote in May 2005.

1.2.4 Handheld devices

During this period interest arose in a new emerging market of converged Wi-Fi and mobile handsets. The shipment of dual mode Wi-Fi/cellular handsets had grown significantly from 2005 to 2006. Some participants in the proposal process believed that handsets would be the dominant Wi-Fi platform within a few years (de Courville *et al.*, 2005). At the time, converged mobile devices were projected to grow worldwide at a compound annual growth rate of 30% (IDC, 2007).

A contentious issue for handheld proponents was the high throughput requirement for 100 Mbps throughput. This, in essence, would force all 802.11n devices to have multiple antennas. This is a difficult requirement for converged mobile devices, since they already contain radios and antennas for cellular 2G, 3G, Bluetooth, and in some cases GPS. Concern was raised that mandating 802.11n devices to have multiple antennas would force handset manufacturers to continue to incorporate single antenna 802.11a/g into handsets and not upgrade to 802.11n. Not only does this diminish the capabilities of the handset device, it burdens all future 802.11n deployments with continued coexistence with 802.11a/g embedded in these new handset devices.

For this reason an ad-hoc group was formed to create functional requirements supporting single antenna devices. Two new requirements were added to the functional requirements document in July 2005. The first requirement mandated that a proposal define single antenna modes of operation supporting at least 50 Mbps throughput in a 20 MHz channel. The second requirement dictated that an 802.11n AP or station interoperate with client devices that comply with 802.11n requirements but incorporate only a single antenna. This requirement resulted in 802.11n making mandatory at least two antennas in an AP, but only one antenna in a non-AP device.

1.2.5 Merging of proposals

After the failed confirmation vote, a joint proposal effort was started within the task group to merge the two competing proposals. Due to entrenched positions and the large membership of the group, the joint proposal effort proceeded very slowly. As a result, Intel and Broadcom formed the Enhanced Wireless Consortium (EWC) in October 2005 to produce a specification outside the IEEE that would bring products to market faster. With much of the task group membership ultimately joining the EWC, this effort had the effect of breaking the deadlock within the IEEE, and the EWC specification, which was essentially a merger of the TGn Sync and WWiSE proposals, was adopted as the joint proposal and submitted for confirmation to TGn where it was unanimously passed in January 2006.

1.2.6 802.11n amendment drafts

The joint proposal was converted to a draft 802.11 standard amendment for higher throughput (TGn Draft 1.0), and entered letter ballot. In letter ballot, IEEE 802.11

 https://doi.org/10.1017/CBO9781139061407.004

working group members (not just task group members) vote to either adopt the draft as is or reject it with comments detailing changes needed. The draft requires at least a 75% affirmative vote within the IEEE 802.11 working group in order to proceed to sponsor ballot where it is considered for adoption by the broader IEEE standards association. TGn Draft 1.0 entered letter ballot in March 2006 and, not unusually, failed to achieve the 75% threshold for adoption. Comment resolution began May 2006 on the roughly 6000 unique technical and editorial comments submitted along with the votes.

With resolution of the TGn Draft 1.0 comments, TGn Draft 2.0 went out for letter ballot vote in February 2007 and this time passed with 83% of the votes. However, there were still 3000 unique technical and editorial comments accompanying the letter ballot votes. It is typical for the task group to continue comment resolution until a minimum number of negative votes are received; thus comment resolution for TGn Draft 2.0 continued between March 2007 and September 2007, resulting in TGn Draft 3.0. Since TGn Draft 2.0 passed, TGn Draft 3.0 through TGn Draft 7.0 only required a recirculation ballot in which comments may only address clauses that changed between the drafts. Sponsor ballot began in January 2009 with completion of the 802.11n standard amendment based on Draft 11.0 in September 2009. The submissions contributed by the task group participants in the development of the standard are publicly available on the World Wide Web.[2] The final 802.11n standard amendment was published in 2009 and then incorporated into the 2012 revision of the IEEE 802.11 standard, both of which are available for purchase from the IEEE.[3]

Of great value to someone investigating the 802.11n PHY is the transmit waveform generator developed by Metalink. The description of the generator, developed in MATLAB®, is given in Anholt and Livshitz (2006). The actual source code is publicly available and is included in Anholt and Livshitz (2007). Most, if not all, transmit waveform features are supported by the generator.

1.3 Environments and applications for 802.11n

In the development of 802.11n, three primary environments were considered for studying system performance and capabilities: residential, enterprise, and hotspot. Within each of these environments a different mix of existing and new applications was envisioned. Use cases were defined (Stephens *et al.*, 2004) that describe how an end user uses an application in a specific WLAN environment. Examples include watching television remotely from the cable or set-top box within the home, or talking on the telephone remotely from one's desk at work. Additionally, usage models were developed for each environment which combined multiple use cases and applications.

Finally, a simulation scenario was created for each usage model and environment. These simulation scenarios were used to stress MAC capability when comparing proposals. Each simulation scenario includes a channel model associated with the particular environment. In addition, the location of the AP and stations were defined, giving a

[2] http://grouper.ieee.org/groups/802/11/ [3] http://standards.ieee.org/getieee802/

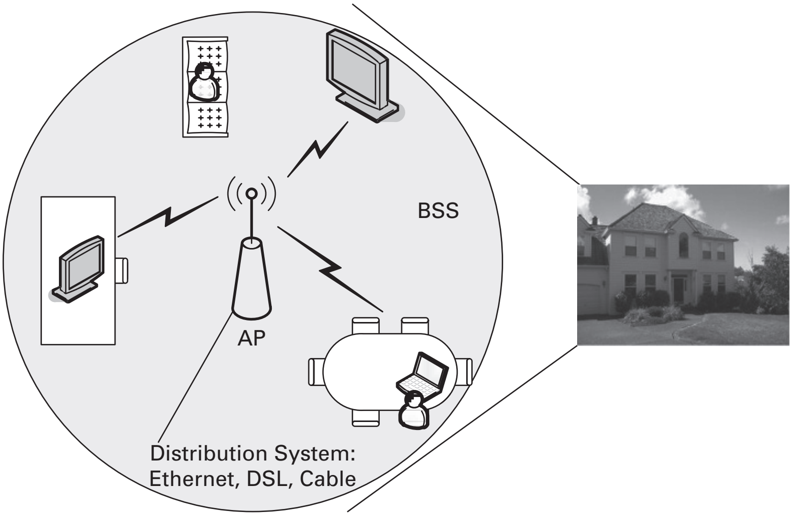

Figure 1.4 Residential usage model.

spatial component to the usage model in terms of the distance between the AP and the stations. For each application, system parameters were defined such as packet size, maximum packet loss rate tolerated by the application, maximum delay, network-layer protocol running (e.g. UDP or TCP), and offered load.

The residential usage model consists of a single BSS, as illustrated in Figure 1.4. This model typically includes only one AP and many client stations. In a typical AP-station configuration, applications include Internet access and streaming audio and video. Furthermore, user experience with applications like intra-networking for local file transfer, backups, and printing is enhanced with higher data rates. New applications such as voice over IP (VoIP) and video phones were also incorporated into the residential usage model.

The high throughput task group envisioned an AP that could also take the form of a wireless home media gateway. Such a device would distribute audio and video content throughout the home, such as DVD and standard and high definition TV. Other residential applications benefiting from higher wireless data rates include content download from a video camera or photo camera. Interactive gaming has recently begun to incorporate wireless technology. Gamers benefit from the freedom of not being tethered by wires when the connections between the controller and the console, the console and the display, and the console to internet access are made wireless.

The usage model for an enterprise environment emphasizes network connectivity supported by multiple BSSs to cover larger buildings and floor plans, as illustrated in Figure 1.5. The BSSs are interconnected via the distribution system, typically Ethernet, creating an extended service set (ESS). As in a cellular deployment, each additional AP increases the total network coverage and capacity.

Networking applications such as file transfer and disk backup will benefit greatly from the higher data rates of 802.11n. Higher data rates will increase network capacity providing support for a larger number of clients. Higher throughputs will also enable new applications such as remote display via a wireless connection between a laptop and

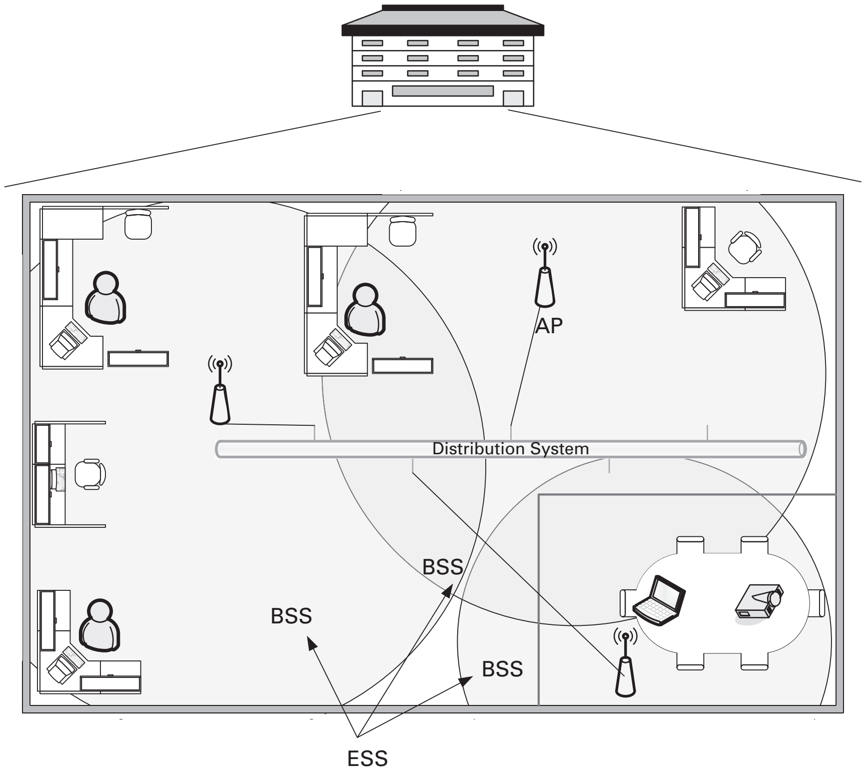

Figure 1.5 Enterprise usage model.

projector, simplifying presentations in conference rooms. Additionally, wireless video conferencing and VoIP may be supported (Stephens *et al.*, 2004).

The hotspot model envisions locations such as an airport lounge (illustrated in Figure 1.6), coffee shop, library, hotel, or convention center. Some municipalities have also blanketed downtown areas with Wi-Fi coverage. A hotspot could be located either indoors or outdoors and could cover a large open area. Therefore the propagation model could be substantially different from either residential or enterprise. In a hotspot, most traffic goes through the Internet and a session is typically limited to less than two hours (Stephens *et al.*, 2004). Applications include web browsing, Internet file transfer, and email. Also, new hotspot applications are envisioned such as the ability to watch a TV program or movie on a laptop or other display. This would involve the streaming of audio and video content over the Internet or the redistribution of standard or high definition TV signals.

1.4 Major features of 802.11n

PHY data rates in 802.11n are significantly improved over 802.11a and 802.11g primarily through the use of spatial multiplexing using MIMO and 40 MHz operation. To take

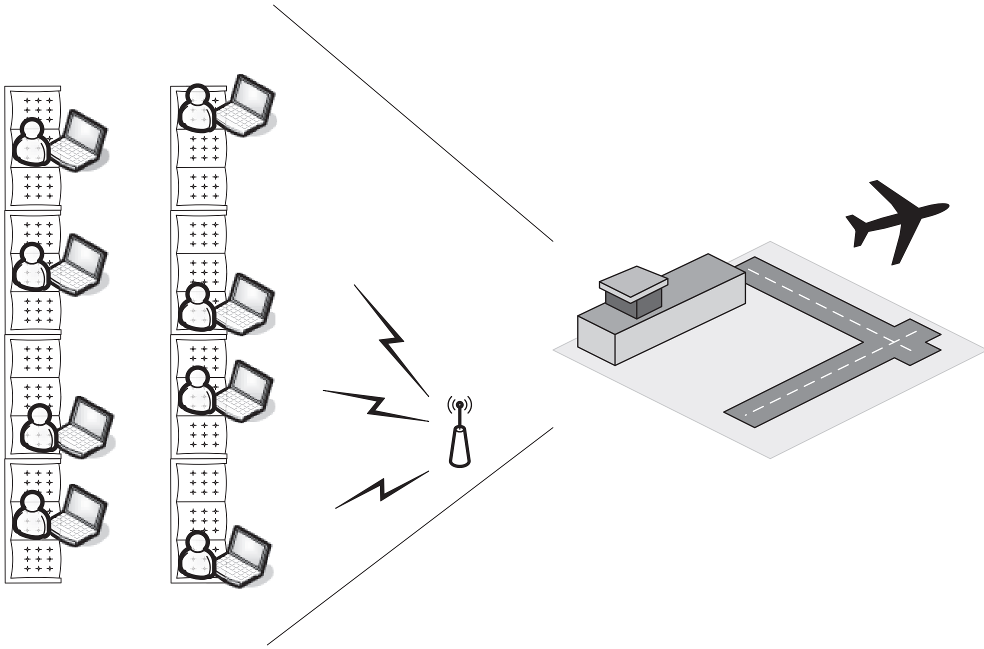

Figure 1.6 Hotspot usage model.

advantage of the much higher data rates provided by these techniques, MAC efficiency is also improved through the use of frame aggregation and enhancements to the block acknowledgement protocol. These features together provide the bulk of the throughput enhancement over that achievable with 802.11a and 802.11g.

Robustness is improved inherently through the increased spatial diversity provided by the use of multiple antennas. Space-time block coding (STBC) as an option in the PHY further improves robustness, as does fast link adaptation, a mechanism for rapidly tracking changing channel conditions. More robust channel codes are adopted in the form of low density parity check (LDPC) codes. The standard amendment also introduces transmit beamforming, with both PHY and MAC enhancements to further improve robustness.

A number of other enhancements provide further gains. In the PHY, these include a shorter guard interval, which may be used under certain channel conditions. The PHY also includes a Greenfield preamble, which is shorter than the mandatory mixed format preamble. However, unlike the mixed format, it is not backward compatible with existing 802.11a and 802.11g devices without MAC protection. In the MAC, the reverse direction protocol provides a performance improvement for certain traffic patterns, by allowing a station to sublease the otherwise unused portion of its allocated transmit opportunity to its remote peer and thus reducing overall channel access overhead. A reduced interframe space (RIFS) used when transmitting a burst of frames reduces overhead in comparison to the existing short interframe space (SIFS).

An overview of the mandatory and optional features of the 802.11n PHY is given in Figure 1.7. The first generation of products typically operate in the 2.4 GHz band only,

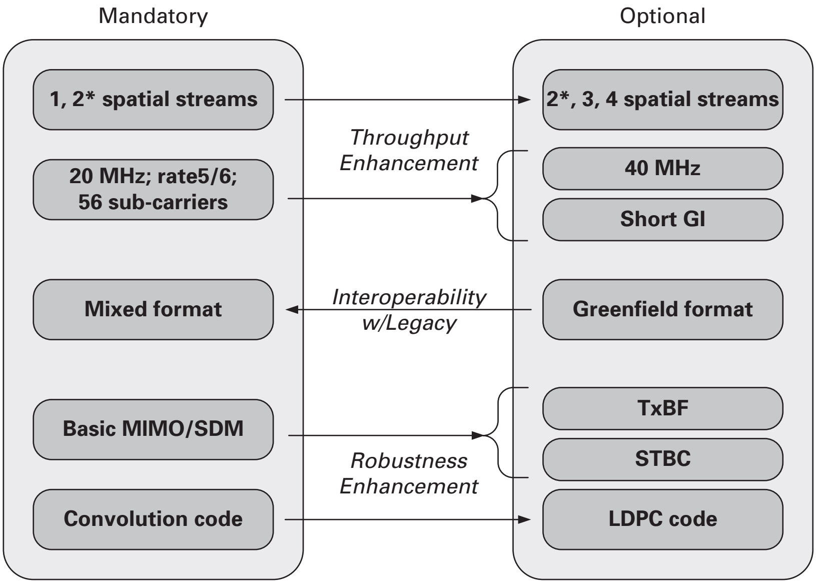

Figure 1.7 Mandatory and optional 802.11n PHY features. (* 2 spatial streams mandatory for AP only.)

with up to two spatial streams and 40 MHz channel width. In this book the term spatial streams is used to refer to one or more independent data streams transmitted from the antennas. A device requires at least as many antennas as spatial streams. When using the short guard interval, these initial products are able to achieve a PHY data rate of 300 Mbps. With second generation products, we begin to see dual-band 2.4 GHz and 5 GHz products. These products also achieve 300 Mbps, but several incorporate an extra receive antenna chain for additional receive diversity. Some products also support the Greenfield preamble format. Third generation devices added another transmit antenna chain to support three spatial streams and 450 Mbps. For robustness, devices began employing STBC. Due to the number of sub-options with TxBF, it was difficult to select a common set of sub-options to certify. This greatly limited the deployment of TxBF in third generation devices.

An overview of the features added to the MAC in 802.11n and 802.11ac is given in Figure 1.8. In addition to the throughput and robustness enhancing features already mentioned, the MAC is extended in a number of other areas.

The numerous optional features in 802.11n and 802.11ac mean that extensive signaling of device capability is required to ensure coexistence and interoperability. For example, whether a device supports certain PHY features such as the Greenfield format preamble or MAC features such as the ability to participate in a reverse direction protocol exchange.

The existence of wide channel operation (40 MHz or greater) also creates a number of coexistence issues. The AP needs to manage the wide channel BSS so that different channel width devices, both legacy and (very) high throughput, are able to associate with the BSS and operate. Because wide channel operation uses two or more 20 MHz channels, mechanisms are needed to mitigate the effect this might have on neighboring

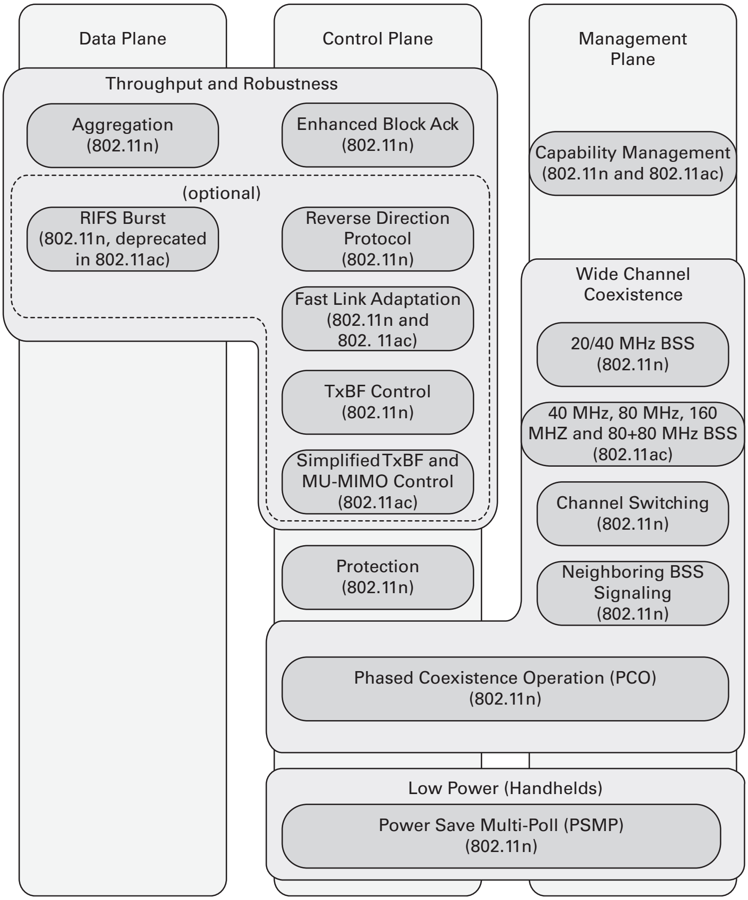

Figure 1.8 Summary of 802.11n and 802.11ac MAC enhancements.

20 MHz BSSs operating independently on any of these channels. Coexistence is primarily achieved through careful channel selection, i.e. choosing a pair of channels that have little or no active neighborhood traffic. To this end, the 802.11n and 802.11ac amendments add scanning requirements to detect the presence of active neighborhood BSSs as well as the ability to actively move the BSS to another pair of channels should a neighboring 20 MHz BSS become active.

In recognition of the growing importance of handheld devices, 802.11n added a channel access scheduling technique called power-save multi-poll (PSMP) to efficiently support a large number of stations.

1.5 History of Very High Throughput and 802.11ac

As the 802.11n standard amendment development matured and associated products became popular in the market, 802.11 initiated a new study group in May 2007 to investigate Very High Throughput (VHT) technologies. Initially the study group was started to address IMT-advanced operation, in the hopes of such new spectrum in bands <6 GHz being allocated to unlicensed usage. However, this initial objective was dropped and the focus of the study group shifted to enhancing 802.11n in the 5 GHz band.

The Wi-Fi Alliance was solicited to provide usage models to help develop requirements (Myles and de Vegt, 2008). The general categories of the usage models included wireless display, distribution of high definition TV, rapid upload/download, backhaul, outdoor campus, auditorium, and manufacturing floor. Specific usages that will be most prevalent in the market place include compressed video streaming around a house, rapid sync-and-go, and wireless I/O. With streaming around the home, it is envisioned that TVs and DVRs around the home will have wireless capability and that 100+ Mbps aggregate of videos from a DVR can be displayed wirelessly on TVs in different rooms. This is similar to the 802.11n residential usage model illustrated in Figure 1.4, with emphasis on high resolution video with minimal interference in the 5 GHz band as opposed to the 2.4 GHz band. With rapid sync-and-go, users can quickly sync movies or pictures between mobile devices such as a phone, a laptop, or a tablet. With a 1 Gbps radio link, a 1 GB video file will take much less than a minute to transfer between devices. Data rates exceeding 1 Gbps will provide the capability for a wireless desktop, with wireless connections between a computer and peripherals such as monitors, printers, and storage devices.

With this input, the Very High Throughput study group developed two Project Authorization Requests (PARs), one for the 5 GHz band (802.11ac) and one for the 60 GHz band (802.11ad). The scope for 802.11ac includes: (1) single link throughput supporting at least 500 Mbps, (2) multi-station throughput of at least 1 Gbps, (3) exclusion of 2.4 GHz band, and (4) backward compatibility and coexistence with legacy 802.11 devices in the 5 GHz band. The PAR was approved in September 2008 and the 802.11ac task group began in November 2008.

The task group initially developed a specification framework document (Stacey *et al.*, 2011), a functional requirements and evaluation methodology document (Loc and Cheong, 2011), an amendment to 802.11n channel model document (Breit *et al.*, 2010), and a usage model document (De Vegt, 2009). This process was purposely different than the proposal down-selection process of 802.11n. After the challenging experience in 802.11n, the group opted for the less contentious approach of developing a specification as a group based on a specification framework. Through its various revisions, the specification framework document built a list of features that would be included in the draft specification, with detail added to the features as the document evolved.

An initial Draft 0.1 was developed based on the specification framework and approved by the task group in January 2011. This draft went through an internal task group comment and review cycle, resulting in a Draft 1.0 released to the 802.11 working group for letter ballot in May 2011. The task group addressed the comments on Draft 1.0 coming out of the letter ballot to produce Draft 2.0 which was released in January 2012. Comment resolution on Draft 2.0 completed in May 2012, resulting in Draft 3.0. Comment resolution on Draft 3.0 completed in September 2012, resulting in Draft 4.0.

At the time this book went to press, the standard amendment was in recirculation letter ballot on Draft 3.0 and would continue there until a minimum number of negative votes and comments were received. It will then proceed to sponsor ballot. Whereas letter ballot includes only voting members in IEEE 802.11, the sponsor ballot pool may include members from all of the IEEE 802 Standard Association, providing a broader review of the draft.

It is expected that sponsor ballot will begin in March 2013. Final approval of the 802.11ac standard amendment is expected in December 2013.[4] However, as was the case with 802.11n, initial products with basic 802.11ac features based on a draft will be certified and emerge on the market well before final approval.

The submissions contributed by the task group participants in the development of the standard are publicly available on the World Wide Web.[5] The drafts of the standard are only available to voting members of 802.11, but, Draft 3.0 of 802.11ac was released to the public. Draft 3.0 is currently available for purchase from the IEEE.[6] Once approved, the final standard amendment would be available there as well.

A transmit waveform generator was also implemented for 802.11ac, this time by CSR. The description of the generator, developed in MATLAB®, is given in Tong and Popescue (2011). The actual source code is publicly available and is embedded in the document. Most, if not all, 802.11ac transmit waveform features are supported by the generator.

The new PHY enhancements in 802.11ac to increase the data rate include channel bandwidth expansion to 80 and 160 MHz. In addition, a new feature in 802.11ac is the use of non-contiguous channels, whereby two non-adjacent 80 MHz channels may be used to form a 160 MHz transmission, termed 80+80 MHz. This allows more flexible channel assignment with the wider bandwidth to avoid heavily occupied channels or even to avoid radars. Furthermore, the number of spatial streams is increased to eight, double that of 802.11n. Modulation size is increased to 256-QAM for a 33% increase in data rate, when link quality permits. Lastly, 802.11ac expands on MIMO in 802.11n to enable multi-user MIMO (MU-MIMO). By allowing simultaneous transmissions to multiple devices, network capacity improves.

The techniques introduced in 802.11n to improve robustness, TxBF, STBC, and LDPC code are also employed in 802.11ac. However, modifications have been made to each of the techniques to simplify operation and reduce the number of sub-options, which should result in increased adoption of these features in the market.

As opposed to 802.11n, 802.11ac has only one preamble. Like the 802.11n mixed format preamble, the VHT preamble contains a legacy compatible portion of the preamble for compatibility with 802.11a/n devices. In addition, the VHT preamble supports both single user and multi-user operation.

An overview of the mandatory and optional features of the 802.11ac PHY is given in Figure 1.9. It is expected that the first generation 802.11ac devices will have one, two,

[4] The reader is referred to http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm for the latest update on the timeline of 802.11n.

[5] http://grouper.ieee.org/groups/802/11/ [6] http://standards.ieee.org/getieee802/

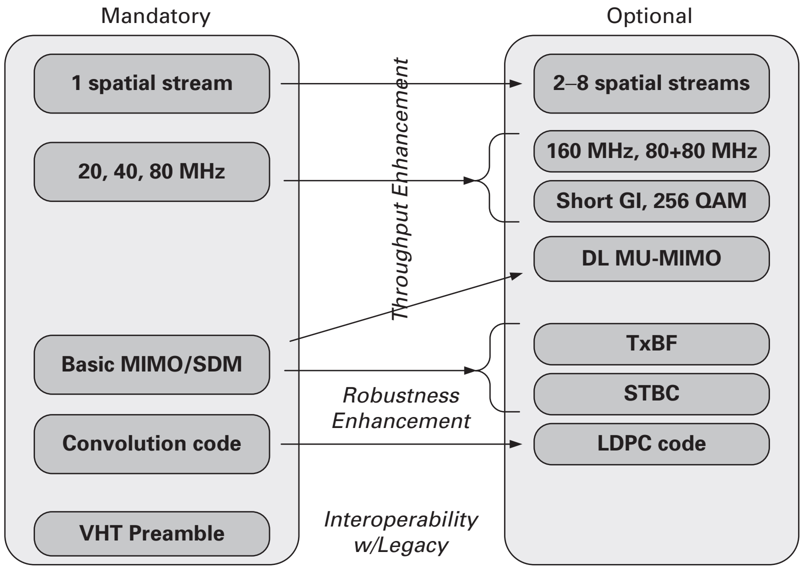

Figure 1.9 Mandatory and optional 802.11ac PHY features.

or three spatial streams, as with current 802.11n devices. The major enhancement in data rate enhancement in these devices will be 80 MHz. It is also expected that most devices will include 256-QAM. With the simplification of TxBF in 802.11ac, this feature may be included in first generation 802.11ac devices. Some of these devices may also employ STBC and LDPC. Features like more than three spatial streams, 160 MHz, and MU-MIMO will only see prominence in future generation devices.

With 802.11ac, the MAC includes enhancements in aggregation, and improved wide channel operation in the presence of hidden nodes through a dynamic and static RTC/CTS bandwidth signaling mechanism. An enhanced power save operation with the presence of a station identifier in the PHY header is included, as well as a mechanism for signaling a station's operating mode (channel bandwidth and number of active receive chains).

A new sounding protocol is introduced to support TxBF and MU-MIMO. Significantly, there are a minimal number of implementation options with this protocol, which should promote industry adoption.

Since the wider channel width could occupy a significant potion of the available spectrum in the 5 GHz band, there are new scanning rules for detecting overlapping BSS operation with requirements and recommendation for channel selection when establishing a VHT BSS.

1.6 Outline of chapters

The book is divided into three parts. The first part, Chapters 2–6, covers the PHY and provides a comprehensive review of all mandatory and optional PHY features in

802.11n. Chapter 7 covers the 802.11ac PHY features. The second part, Chapters 8–12, covers the MAC, an overview of existing MAC features, and a detailed review of the new features introduced in 802.11n and 802.11ac. The last part, Chapters 13–15, covers transmit beamforming, MU-MIMO, and fast link adaptation.

Chapter 2 gives a brief overview of orthogonal frequency division multiplexing (OFDM). Chapter 3 begins with a description of multiple-input multiple-output (MIMO) basics and spatial division multiplexing (SDM). This is followed by a discussion of the MIMO environment and the 802.11n MIMO multipath fading channel and propagation models. The chapter concludes with an explanation of linear receiver design and highlights of maximum likelihood estimation. Included in the discussion of MIMO and receiver design are capacity based performance curves.

Chapter 4 details the design of the mixed format (MF) preamble used for interoperability with legacy 802.11a/g OFDM devices. The chapter begins with a review of 802.11a preamble design. Included in the review are illustrations of the waveform. A description of the 802.11a/g packet encoding process and receive procedure is presented, which includes a receiver block diagram. This leads into a discussion of the legacy part of the MF preamble. Next, the high throughput (HT) portion of the preamble is described. Following this, the encoding of the Data field is presented. The chapter ends with a discussion of the receive procedure and a block diagram for basic modes of operation. Tables of parameters of the modulation and coding scheme (MCS) for basic modes of operation are given in an appendix.

Chapter 5 outlines all the PHY techniques employed in the 802.11n specification to increase the data rate. The first section of the chapter details the new 40 MHz channel and waveform. This includes a plot illustrating throughput as a function of range. This is followed by a brief discussion of the extra subcarriers which were added to the 802.11n 20 MHz waveform. The next part of the chapter gives the MCS definitions. This includes several waterfall curves illustrating the packet error rate (PER) versus SNR performance in additive white Gaussian noise (AWGN) and in the 802.11n MIMO multipath fading channel models. A description of the shorter Greenfield (GF) preamble is also provided in this chapter. This also includes discussion on the debate of how much the GF preamble actually improves performance. The last topic covered in this chapter is on the short guard interval (GI).

Chapter 6 covers the subject of improving the robustness of the system. Four techniques are described. The first method is receive diversity, where PER versus SNR waterfall curves are provided along with throughput curves to demonstrate the gain achieved from receive diversity in a MIMO system. The next technique is a straightforward one involving spatial expansion (SE), which provides a small amount of transmit diversity gain. Waterfall curves are provided for SE as well. This is followed by a detailed description of space-time block coding (STBC). Transmit antenna configurations are presented, along with an approach for implementing a receiver and equalizer. Again performance curves are presented that illustrate which system configurations benefit the most from STBC. In the last part of the chapter, low density parity check (LDPC) codes are discussed. The specific characteristics of the LDPC encoding process in the 802.11n standard amendment are detailed. Waterfall curves for LDPC are provided to compare performance with the mandatory binary convolutional code.

The new VHT PHY is described in Chapter 7. The new channelization for 802.11ac is illustrated. This chapter focuses on the SU aspects of the new VHT format preamble and data field.

The MAC section begins in Chapter 8 with a functional description of the 802.11 MAC as background for the remaining chapters. This chapter covers the basic contention-based access protocol including the 802.11e quality of service (QoS) extensions, channel access timing, the concept of a transmit opportunity, and the basic acknowledgement and block acknowledgement protocols.

Chapter 9 describes why changes are necessary in the MAC to improve throughput and then details the two key throughput enhancing features: aggregation and enhancements to the block acknowledgement protocol.

Beyond the basic contention-based access protocol, the 802.11 MAC includes additional channel access mechanisms. Chapter 10 provides an overview of these mechanisms, including the point coordination function (PCF) from the original 802.11 specification and the hybrid coordinated channel access (HCCA) function from the 802.11e amendment. The chapter then provides details on the power-save multi-poll (PSMP) channel access technique and the reverse direction protocol, both of which are new in 802.11n.

Coexistence and interoperability is a critical issue with 802.11n and 802.11ac and Chapter 11 provides details on this broad topic. The chapter covers capability signaling and BSS control. The chapter then covers wider channel operation, managing HT and VHT BSS operation, and maintaining interoperability with narrower bandwidth devices. The critical topic of coexistence between neighboring BSSs occupying each other's secondary channel is also discussed. Finally, the chapter covers protection mechanisms.

To round out the MAC section, Chapter 12 provides details on MAC frame formats. This chapter is intended as a reference for the discussions in the other chapters.

The final part of the book deals with the complex topics of transmit beamforming, MU-MIMO, and fast link adaptation. Chapter 13 provides details on both the PHY and MAC aspects of single user transmit beamforming for both 802.11n and 802.11ac. Chapter 14 covers both PHY and MAC aspects of MU-MIMO. Lastly, Chapter 15 describes fast link adaptation for both 802.11n and 802.11ac.

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