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Comparitive Study of IEEE 802.11 a, b, g & n Standards

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***Abstract*— Wireless Local Area Networks (WLANs) provides location independent network access between computing devices using radio waves as medium of communication. IEEE 802.11 based WLANs are becoming popular in various environments primarily due to their lower cost of implementation and higher data rates. This paper discusses popular WLAN standards, namely IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and IEEE 802.11n and makes a comprehensive comparison between each of them. This comparison will help in understanding the pro and cons of each standard and their usability in different scenarios.**

Keywords—IEEE 802.11; 802.11 a/b/g/n; WLANs; IEEE Standards; Comparison of IEEE Standards; Wi-Fi Standards

I. INTRODUCTION

Use of WLAN technologies started in late 1990, with the introduction of various products by different manufacturers that operated within the 900 MHz frequency band. These non-standard solutions had proprietary designs and provided data rates up to 1Mbps. These technologies were considerably slower than the most wired LANs at that time, which provided 10 Mbps.

Since then, WLANs have evolved rapidly into a crucial technology for millions of users worldwide. Even today, this technology continues to evolve. The latest generation of high-speed WLAN solutions, based on the Institute of Electrical and Electronics Engineers (IEEE) Draft 802.11 standard, are now available. These standards offer several advantages over other existing technologies such as improved reliability and greater application data throughput.

The wider acceptance and popularity of IEEE 802.11 standards is due to low-cost of end-user equipment and high-speed data rates offered by theses standards. IEEE 802.11 standard initially specified data rates of 1Mbps and 2Mbps based on Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS) and Infrared (IR) techniques for three different PHY layers. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is the basis of MAC protocol in IEEE 802.11 WLAN, which allows only one user to utilize radio channel at a certain time. Thereafter several new PHY layer specifications were added while the MAC specification remained largely unchanged.

II. EVOLUTION OF IEEE 802.11 WLAN STANDARDS

TABLE I. LIST OF CURRENT AND FUTURE IEEE STANDARDS. [6]

No.	Standard	Year	Description
1	802.11a	1999	Speed 54 Mbps and 5 GHz band
2	802.11b	1999	Enhancements to support 5.5 & 11 Mbps speed
3	802.11c	2001	Bridge operation procedures
4	802.11d	2001	International roaming extensions
5	802.11e	2005	Enhancements: QoS, including packet bursting
6	802.11f	2003	Inter-Access Point Protocol
7	802.11g	2003	54 Mbps, 2.4 GHz standard
8	802.11h	2004	Spectrum Managed 802.11a (5 GHz) for Europe
9	802.11i	2004	Enhanced security
10	802.11j	2004	Extensions for Japan
11	802.11k	2008	Radio resource measurement enhancements
12	802.11n	2009	Higher throughput improvements using MIMO
13	802.11p	2010	WAVE
15	802.11r	2008	Fast BSS transition (FT)
16	802.11s	2011	Mesh Networking, ESS
17	802.11u	2011	Improvements related to Hot Spots
18	802.11v	2011	Wireless network management
19	802.11w	2009	Protected Management Frames
20	802.11x	-	Extensible authentication network
21	802.11y	2008	3650–3700 MHz Operation in the U.S.
22	802.11z	2010	Extensions to DLS
23	802.11aa	2012	Robust streaming of AV Transport Streams
24	802.11ad	2012	Very High Throughput 60 GHz
25	802.11ae	2012	Prioritization of Management Frames

III. IEEE 802.11A

Introduced in 1999, IEEE 802.11a standard uses the 5 GHz spectrum and provides a maximum theoretical data rate of 54 Mbps. The data rate automatically lowers down to (54/48/36/24/12/9/6 Mbps) to maintain the connectivity with the increased distance or attenuation. The 5 GHz spectrum has higher attenuation (more signal loss due to obstacles or noise in the channel) than lower frequencies, such as 2.4 GHz. Penetrating walls degrades the performance compared to 2.4 GHz. 802.11a based products are typically used in large organizations or with wireless ISPs in outdoor backbone networks.

Spectrum allocation in the 5 GHz band is subject to regulatory bodies responsible for geographic-specific regulatory domains. The channelization used for this standard dependent on such allocation, as well as the associated rules for use of these allocations. In the USA, the FCC is responsible for the allocation of the 5 GHz U-NII bands.

A. OFDM

IEEE 802.11a standard uses a method called Orthogonal Frequency Division Multiplexing (OFDM). OFDM divides a radio channel into a large number of smaller channels. Each of these channels have their own subcarrier signal, which can independently transmit information.

OFDM partitions the comparatively wideband 20 MHz 802.11a channel into 64 subcarriers of 312.5 kHz each. Partitioning is such that, each subcarrier becomes an independent narrowband channel. Same modulation, coding scheme and transmit power is used for sending data on these subcarriers. Modulation schemes used in this standard varies from BPSK, QPSK, QAM-16 and QAM-64.

Division of channels increases the symbol time per channel, as many slow symbols will be sent in parallel instead of many fast symbols in sequence. 802.11a utilizes the frequency diversity provided by OFDM by coding across the data carried on the subcarriers. A fraction of redundant information can be used to correct errors that occur when fading reduces the SNR on some of the subcarriers.

IV. IEEE 802.11B

Introduced in July 1999, IEEE 802.11b provides a maximum theoretical data rate of 11 Mbps in the 2.4 GHz Industrial, Scientific and Medical (ISM) band. It specifies High Rate extension of the PHY for the DSSS system, also called as the High Rate PHY to be used for ISM applications in the 2.4GHz band.

High Rate PHY extension provides capabilities of 5.5 Mbps and 11 Mbps of payload data rates in addition to the 1Mbps and 2 Mbps rates. Additionally, a number of optional features allow the performance of the radio frequency LAN system to be improved as technology allows the implementation of these options to become cost effective.

A. DSSS

Direct-Sequence Spread Spectrum (DSSS) is a modulation technique in which the transmitted signal utilizes more bandwidth than the information signal that is to be transmitted. It uses a single channel to send data across all frequencies within that channel. Complementary Code Keying (CCK) is used for encoding communications at data rates of 5.5 and 11 Mbps, alongside providing backward compatibility with the original 802.11 standard operating at 1 and 2Mbps.

- The following 11-chip Barker sequence is used for modulation at 1 and 2 Mbps:

$$+1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1 \qquad (1)$$

- For CCK modulation at 5.5 and 11 Mbps, the spreading code length is 8 and is based on complementary codes. The chipping rate is 11 Mchip/s. The 8-bit CCK code words are derived from the following formula:

$$c = \{e^{j(\phi1 + \phi2 + \phi3 + \phi4)}, e^{j(\phi1 + \phi3 + \phi4)}, e^{j(\phi1 + \phi2 + \phi4)}, e^{j(\phi1 + \phi4)}, e^{j(\phi1 + \phi2 + \phi3)}, e^{j(\phi1 + \phi3)}, e^{j(\phi1 + \phi2)}, e^{j\phi1}\} \qquad (2)$$

B. PBCC

Packet binary convolutional coding (PBCC) is an optional coding scheme used in IEEE 802.11b. It uses a 64-state Binary Convolutional Code (BCC), rate R=1/2 code and a cover sequence.

V. IEEE 802.11G

IEEE 802.11g standard, ratified in 2003, provided a maximum theoretical 54 Mbps data rate in the 2.4 GHz ISM band. It specifies further rate extension of the PHY for the DSSS system. It is also called as the Extended Rate PHY (ERP).

IEEE 802.11g is backward compatible with the 802.11b standard. However, when 802.11b and 802.11g clients are connected to an 802.11g router, lower data rates will be experienced by 802.11g clients. Many routers provide the option of allowing mixed 802.11b/g clients or they may be set to either 802.11b or 802.11g clients only.

A. ERP

ERP systems implements all mandatory modes of IEEE 802.11b standard, except it operates the 2.4 GHz ISM band but uses channelization plan of IEEE 802.11a.

The ERP builds on the payload data rates of 1 and 2 Mbps use DSSS modulation and builds on the payload data rates of 1, 2, 5.5, and 11 Mbps use DSSS, CCK, and optional PBCC modulations. It also provides additional payload data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. Two additional optional ERP-PBCC modulation modes with payload data rates of 22 and 33 Mbps are defined.

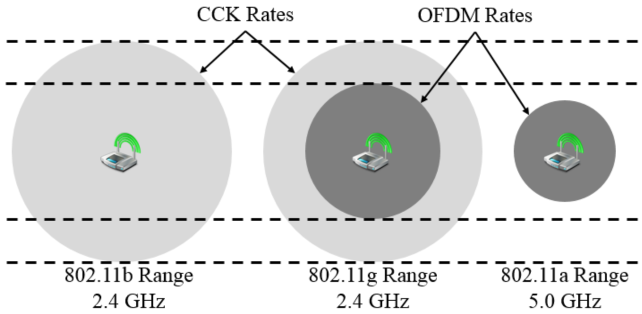

Fig. 1. Relative Range of 802.11b, 802.11g, and 802.11a Devices [15]

VI. IEEE 802.11N

IEEE 802.11n standard aims to significantly increase the data throughput rates in the WLANs. It incorporates a number of technical changes, the important ones are the addition of Multiple-Input Multiple-Output (MIMO) and Spatial Multiplexing. 802.11n operates on both 2.4 GHz and 5 GHz bands. The 802.11n specifications provide both 20 MHz and 40 MHz channel options. By bonding two adjacent 20 MHz channels, 802.11n provides double the data rate in utilization of 40 MHz channels.

There are minor differences between 802.11a/g and 802.11n. In 802.11a/g there are 48 data subcarriers, 4 pilot tones for control, and 6 unused guard subcarriers at each edge of the channel. In 802.11n, there are only 4 guard subcarriers at each edge of the channel, and two adjacent 20 MHz channels can be merged into a single 40 MHz channel.

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A. MIMO

Multiple-Input Multiple-Output (MIMO) exploits a radio-wave phenomenon called multipath, i.e., transmitted information bouncing off various obstacles, reaching the receiving antenna multiple times via different routes and at different intervals. Uncontrolled multipath distorts the original signal thus degrading the overall performance of the system.

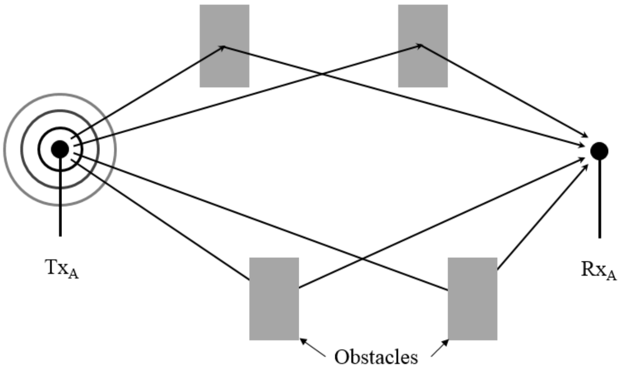

Fig. 2. Multipath Interference

MIMO harnesses multipath with a technique called as Space-Division Multiplexing. A MIMO radio transmits multiple signals simultaneously and takes advantage of multipath. Each signal is known as a spatial stream. Each of these spatial stream is transmitted from a dedicated antenna, using its own transmitter. Since antennas are separated by a small space, each signal takes a slightly different path to the receiver. This phenomenon is knows as spatial diversity.

B. Spatial Multiplexing (SM)

It subdivides an outgoing signal stream into multiple pieces, which are transmitted through different spatial streams. If the individual streams arrive at the receiver with sufficiently different spatial signatures, the receiver can easily reassemble them to generate the original signal stream. Multiplexing two spatial streams onto a single channel effectively doubles capacity and thus maximizes data rate.

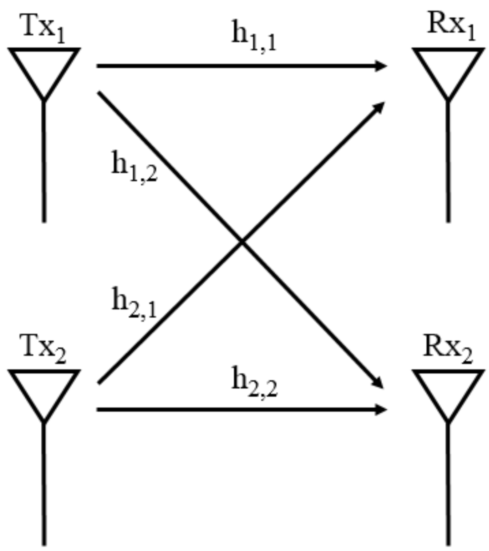

Fig. 3. Spatial Multiplexing

VII. COMPARISON TABLE

TABLE II. COMPARISON OF IEEE STANDARDS [1] [2] [3] [4] [5] [9]

	IEEE 802.11a	**IEEE 802.11b**	**IEEE 802.11g**	**IEEE 802.11n**	**Remarks / Inference**
Overview	Operates at 5GHz U-NII band	Specifies High Rate extension of PHY for 2.4GHz band used for ISM applications	Rate extension of PHY for DSSS. Supports DSSS-OFDM (optional)	Offers throughput up to 600Mpbs using MIMO, SM, STBC and ASEL	Operation of IEEE 802.11a, g & n are defined in 5GHz band while IEEE 802.11b operates at 2.4GHz
Scope	PHY services are provided by the 5 GHz OFDM system.	Specifies PHY entity for HR/DSSS extension	Specifies ERP entity and the deviations from earlier standards	Defines the services provided to the MAC by the HT-PHY.	IEEE 802.11n offers highest throughput through the use of HT greenfield mode
Modulation Schemes	BPSK OFDM, QPSK OFDM, 16-QAM OFDM, 64-QAM OFDM	BDSK, DQPSK, CCK, PBCC	ERP-DSSS, ERP-CCK, ERP-OFDM, ERP-PBCC, DSSS-OFDM	HR/DSSS, ERP-PBCC, DSSS-OFDM, ERP OFDM, OFDM, HT	OFDM offers higher speeds in comparison with DSSS; however compatibility with legacy system needs support for DSSS
Coding Rate	1/2, 2/3, 3/4	NA (FEC is not used in DSSS)	1/2, 2/3, 3/4	3/4, 2/3, 5/6	Higher coding rate allows 802.11n to achieve higher throughput.
Subcarriers	48 data, 4 pilot	1 (DSSS)	48 data, 4 pilot	52 data, 4 pilot /108 data, 6 pilot	More subcarriers marginally increases the data rate up to 65/130Mbps in 802.11n
Guard Interval	0.8µs	NA (GI is not present in DSSS)	0.8µs	0.4µs	Lower GI increases throughput by 10% in 802.11n
Channel Spacing	20MHz	22MHz	20MHz	20, 40MHz(Channel Bonding)	Spectral Efficiency [12] of 802.11n standard increases due to the use of channel bonding.

Symbol Duration	4µs	1-2Mbps: 11 chips. 5-11Mbps: 8 chips	4µs	4µs	802.11b/g uses DSSS in which symbols are absent.
Preamble	OFDM	Long/Short(Optional)	Long/Short/OFDM	HT PHY for 2.4 & 5 GHz	Frame Aggregation reduces the preamble in 802.11n which boosts the throughput.
Channel Bonding	Absent	Absent	Absent	Present	Present in 802.11n which doubles the data rate.
Transit Beamforming	Absent	Absent	Absent	Present (Due to use of MIMO)	Helps in increasing the signal strength at the RX. However not useful in Broadcast or Multicast mode.
Data Aggregation	Absent	Absent	Absent	Present	Increases the overall throughput but leads to queuing and compression delays.
Communication	SISO	SISO	SISO	MIMO	Improved SNR due to transmit beamforming [12].
Operational Speeds (Mbps)	6, 9, 12, 18, 24, 36, 48, 54	1, 2, 5.5, 11	1, 2, 5.5, 11, 6, 9, 12, 18, 24, 36, 48, 54	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2, 15, 30, 45, 60, 90, 120, 135	Data rate increases as the range of the standard decreases.
Streams	1	1	1	Streams vary from 1-4.	Higher number of streams results in higher throughput
Slot Time	9µs	5µs	20µs, 9µs (BSS)	9µs (5GHz), 20µs (2.4GHz)	Higher slot time increase the waiting period in 2.4 GHz channel reducing the efficiency of the system.
Duplex	Half	Half	Half	Full	Full duplex implies shorter waiting time, leading to higher data speeds in IEEE 802.11n.
Operational Modes	OFDM	DBPSK, DQSK, CCK, PBCC	ERP-DSSS, ERP-OFDM, ERP-PBCC, DSSS-OFDM	HT(Greenfield), Non-HT, HT-Mixed	Variation in Operational modes allows working with legacy systems in IEEE 802.11 g & n.
Spreading Sequence	NA (It only uses OFDM)	Barker sequence, CCK	Same as IEEE 802.11b standard	Same as IEEE 802.11b standard	Spreading sequence provides noise immunity in 802.11b
Operating Frequency Range	5 GHz band (USA).	2.4-2.4835GHz (US & Europe), 2.471–2.497 GHz (Japan).	Operation follow IEEE 802.11b standard.	Operates in 5 GHz band and/or 2.4 GHz band.	Lower frequency spectrum provides larger range. However, the 2.4GHz channel is more prone to noise from other devices.
Channel Center Frequency	$F = 5000 + 5 \times n_{ch}$ MHz Where $n_{ch} = 0, 1 \ldots 200$.	2.4-2.4835 GHz (US), 2.471-2.497GHz(Japan), 2.4465-2.4835 GHz (France), 2.445-2.475GHz (Spain)	$F = 2407 + 5 \times n_{ch}$ MHz where $n_{ch} = 1, 2, \ldots, 13$	2.4 GHz Band: Same as IEEE 802.11a. 5 GHz band: f = Channel_start_freq + 5 $\times n_{ch}$ MHz where $n_{ch} = 0, 1, \ldots, 200$	Higher Channel Center Frequency ensures higher bandwidth in IEEE 802.11 a & n.
Channel Plan	Operating channel numbers domain is defined by FCC.	1, 6, 11(non-overlapping) 1, 3, 5, 7, 9, 11 (overlapping).	All mandatory modes of IEEE 802.11b, except it uses the 2.4 GHz frequency band.	Channelization for 802.11b/g in 20MHz band as well as 40 MHz channel.	Since 802.11n has highest number of available channels, it can gain highest throughput.
Operating temperature range	1: 0 to 40 °C, (office environments) 2: -20 to 50 °C 3: -30 to 70 °C (industrial environments)	1: 0 to 40 °C (office environments) 2: -30 to 70 °C (industrial environments)	Same as IEEE 802.11b standard.	Same as IEEE 802.11a standard.	IEEE 802.11a/n has comparatively larger number of operating temperature.
Transmit center & Symbol clock frequency tolerance	± 20 ppm max	±25 ppm max	±25 PPM max	± 20 ppm max(5 GHz), ± 25 ppm max(2.4 GHz)	It is higher for 2.4GHz band, which makes it more resistant channel noise.
Actual Throughput (Mbps)	27	4-5	20-25	160	Higher throughput achieved in 802.11n using MIMO technology.
Range (m)	35-120	38-140	38-140	70-250	802.11n has largest range, however, in legacy systems 802.11g is the winner.

Available Spectrum	300 MHz	83.5 MHz	83.5MHz	83.5MHz (2.4GHz), 300 MHz (5GHz)	Largest spectrum is available for transmission in 802.11n
Occupied Bandwidth	16.6 MHz	22 MHz	16.6 MHz	16.5 MHz	Higher occupied bandwidth results greater ICI (Refer sec 3.4)
Compatibility	IEEE 802.11 n	IEEE 802.11g/n	IEEE 802.11b/n	IEEE 802.11a/b/g	Compatibility with all the legacy devices makes 802.11n an ideal choice while upgrading WLANs.
Power Consumption	5.15-5.25: 40mW 5.25-5.35: 200mW 5.725-5.825: 800mW	1W (US), 0.1W (Europe), 0.01W (Japan)	Should meet the requirements of the local regulatory body. For example, IEEE 802.11b	Should meet the requirements of local regulatory body. For example, IEEE 802.11b	High power transmitters increases EVM [5]. Thus, increasing transmit power tends to decrease the range.
Aggregation delays	Absent	Absent	Absent	Present due to the use of Block ACK	Introduces delays in intermediate nodes due to compression and queuing of data blocks.
RSSI (dBm)	-70	-85	-85	-64 (2.4 GHz) -61 (5 GHz)	Higher RSSI in 802.11n implies higher signal strength at the receiver.
Security	Open System Authentication	WEP uses RC4 for confidentiality and CRC-32 checksum for integrity	WPA uses 40-104 bit encryption key	WPA2 introduces CCMP (AES-based encryption)	WPA & WPA2 were developed to replace weak WEP.
Major Advantages	Higher throughput	Noise Immunity, Low equipment costs	High throughput and compatibility	Very high link speeds.	IEEE 802.11n standard leads the race when it comes to throughput.
Major Drawbacks	Restricted to line of sight, large no of AP & lower range	Heavy interference from devices operating in 2.4GHz channel.	Heavily crowded 2.4 GHz channel.	Channel bonding is only possible in 5GHz band and higher cost of upgradation	Cost consideration makes IEEE 802.11g standard more useful than the others.
Applications	Reliable communication & high throughputs in small coverage areas. Supports video streaming and VoIP.	For Internet access and the DSL or cable modem service (Operating at less than 1 to 6 Mbps).	For residential, small & medium size business users which require desired signal coverage and reliability, where high throughput is not a critical decision factor.	Applications that require sharing of large files, Voice and video applications, IPTV services, CRM and ERP access, etc.	Most of the system are based on IEEE 802.11g and are replaced by IEEE 802.11n for meeting the additional demands of the users.

VIII. CONCLUSION

The primary advantage of IEEE 802.11 standards is the ability to move data at high speeds and this makes it attractive for providing the link to a remote host. This link will have the ability of higher bandwidth and a lower recurring cost than the previous systems. Also the availability of a number of variants of this standard can help users to select a technology suitable for their needs. Thus it provides a flexible way of achieving data communication among various devices.

A. IEEE 802.11a

It provides fast maximum speed and regulated frequencies. Since the 2.4 GHz frequency band is heavily used by many users and appliances, moving to the 5 GHz band gives 802.11a the advantage of less interference. The 5GHz carrier frequency restricts the use of 802.11a to almost line of sight, requiring the use of more number of access points. It also means signal penetration through various obstacles is much reduced compared to IEEE 802.11b. Also higher costs and shorter range makes this standard less attractive.

One of the biggest drawback is that it is not compatible with 802.11b. Another disadvantage of 802.11a is that it is only available in half the bandwidth in Japan, and it isn't allowed for use in Europe.

B. IEEE 802.11b

IEEE 802.11b offers a low cost replacement for IEEE 802.11a standard which has a good signal range. However, speed offered is slowest when compared to other standards. Also the 2.4 GHz frequency band is heavily congested and 802.11b suffers from interference from other networking devices, microwave ovens, cordless phones and Bluetooth.

C. IEEE 802.11g

802.11g can be viewed as a superset of 802.11b, providing all the functionality and backward compatibility with 802.11b, along with the higher performance related with OFDM transmissions. Even when operating in DSSS mode, it provides comparatively better range performance relative to the 802.11b standard. Since, 802.11g relies heavily on 2.4GHz technology, it has an added advantage of significant cost reduction engineering and economies which has resulted due to the increasing numbers of 802.11b based devices. As such, the cost of an 802.11g devices is equal to that of an 802.11b devices. Customers get increased performance, more robust security and better range for exactly the same price.

D. IEEE 802.11n

802.11n has the ability to drastically increase the capacity of a WLANs and the overall throughput of all the devices. Since, it operates in both the 2.4 & 5 GHz bands, the same channelization that is used for 802.11b and 802.11g can be used. Also, there are considerably more channels available in the 5 GHz band than in the 2.4GHz band.

With the higher data rates and the increased efficiency, it is possible that a single 802.11n access point working in a 20 MHz channel in the 2.4 GHz band and a 40 MHz channel in the 5 GHz band.

One of the important issues in this standard is the use of the 40 MHz mode of operation of 802.11n is not recommended in 2.4 GHz band, because a significant portion of the band will suffer from interference from a single 40 MHz transmitter. In addition, it is requires the second 20 MHz channel to be joined with the original 20 MHz channel to create a 40 MHz channel, must be free of any other legacy device operating in the same channel. This dramatically reduces the chance that any 40 MHz operations will be feasible in this band.

Even when all legacy 802.11 b and g devices are removed from the band, it will be difficult to deploy access points working in the 40 MHz channels. Therefore, care should be taken when selecting the 802.11n equipment to install. One should move to this new standard only if it is absolutely necessary to add a new access points, in order to satisfy the demands for additional capacity in WLANs and bring Ethernet-level speeds to the wireless clients.

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