Testing WLAN Devices According to IEEE 802.11 Standards

Application Note

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Introduction

Wireless local area networking (WLAN) capabilities are being integrated into an increasing number of products: smartphones, digital cameras, printers, tablets, HDTVs, Blu-ray players and more. This trend is leading to a greater number of simultaneous connections to any given network in a home, school or business environment. Even though each individual connection may not require a high data rate, the cumulative demand results in higher requirements for total data throughput.

To keep pace with these trends, every new generation of the various IEEE 802.11 standards—a, b, g, n, and ac—supports increased data capacity by providing greater throughput and wider bandwidths. As the standards evolve, backward compatibility remains a fundamental requirement. For example, modulation techniques used in older standards, such as DSSS and FHSS, have carried forward into newer standards of OFDM and MIMO.

The continuing evolution of 802.11 standards and products has important implications for those who test WLAN or Wi-Fi transmitters, receivers, and transceivers from R&D, through design verification and manufacturing. The testing of receivers and transceivers requires the use of vector signal generators capable of producing the complex modulated signals used by the 802.11 wireless connectivity standards. Software such as Agilent Signal Studio can be used to create test signals—with or without impairments—and then download the waveforms to a vector signal generator.

Testing transmitters and transceivers requires a signal analyzer configured with sufficient frequency coverage and analysis bandwidth. Standard-specific measurement and analysis capabilities are available in the Agilent N/W9077A WLAN measurement applications that can run inside the Agilent X-Series signal analyzers. These measurement applications provide one-button measurements with pass/fail indicators.

This application note provides a broad survey of transmitter and receiver test requirements with a focus on 802.11a, b, g, n, and ac. It also presents an overview of Agilent's test equipment, software, and measurement applications for WLAN testing.

The Evolution of IEEE 802.11

A closer look: Modulation techniques

The following modulation techniques are used in the various 802.11 standards.

Direct-sequence spread spectrum (DSSS): This spreads a single carrier over a wider spectrum by multiplying the data bits with a special bit pattern called a Barker key. Although this is typically an 11-bit pattern, 802.11b uses an 8-bit key, at an 11 MHz chip rate. The net result is a reduction in the interference caused by narrowband sources.

Complementary code keying (CCK): Used as a supplement to the Barker Code, CCK enables a 2-Mbps data rate but reduces the transmission range due to greater susceptibility to narrowband interference.

Packet binary convolution coding (PBCC): Uses forward error correction to improve link performance in the presence of excess noise. Scrambled data is fed into a convolutional encoder, which has a six-stage memory and taps that are combined to produce two outputs. The four possible output states (00, 01, 10 and 11) are mapped onto a pair of QPSK states (11 Mbps). A codeword controls how the chosen state alternates over time.

Orthogonal frequency-division multiplex (OFDM): This splits the transmission into a high-rate data stream and several lower-rate streams that are transmitted simultaneously over several subcarriers. Lower data rates in the parallel subcarriers result in longer symbol duration, which decreases the relative amount of delay spread (time dispersion) caused by multipath propagation. Because a guard interval can be inserted between successive OFDM symbols, intersymbol interference (ISI) is reduced to an almost insignificant level.

Since the release of the initial version of 802.11 in 1997, the standard has evolved to satisfy new applications and meet the need for ever-faster data rates. Along the way, a series of amendments have defined changes to the physical or PHY layer (Table 1).

Table 1. Overview of the evolution of the 802.11 standards

IEEE standard	Year released	Notes
802.11	1997	Provides 1- or 2-Mbps transmission in the 2.4 GHz band using either frequency-hopping, spread spectrum (FHSS), or direct-sequence spread spectrum (DSSS)
802.11a	1999	Uses orthogonal frequency-division multiplexing (OFDM) in the 5 GHz band and provides connections as fast as 54 Mbps
802.11b	1999	Uses DSSS in the 2.4 GHz band and provides connections as fast as 11 Mbps, with fallback to 5.5, 2 and 1 Mbps, depending on signal strength
802.11g	2003	Uses OFDM in the 2.4 GHz band and provides 54 Mbps connections
802.11n	2009	Includes many enhancements to extend WLAN range, reliability and throughput. PHY-layer examples include multiple-input/multiple-output (MIMO) and 20 or 40 MHz bandwidth. Operates in the 2.4 and 5 GHz bands and provides data rates of up to 600 Mbps. Also called High Throughput or HT LAN.
802.11ac	2012 (draft)	Expected to provide very high throughput (VHT) data rates of 1 Gbps in the 5 GHz band. Uses RF bandwidth of up to 160 MHz, higher-order modulation such as 256QAM and up to eight MIMO spatial streams.

When 802.11g was introduced, it became the preferred standard over both 802.11a and 802.11b and was widely adopted by both consumers and businesses. While 802.11a and 802.11g use the same OFDM modulation scheme, they operate on different frequency bands- 2.4 GHz and 5 GHz, respectively- however, backward compatibility is still required. Later, when the 802.11n standard was introduced, offering breakthrough benefits including enabling Wi-Fi networks to do more, faster, and over a larger area, IEEE defined three modes in the physical layer and required backward compatibility with 802.11 a/b/g gear, even though they were later designated as legacy technologies.

Three upcoming versions of the standard are also worth noting:

- 802.11p is designed for vehicular applications

- 802.11ad is for VHT in the 60-GHz frequency band

- 802.11af will support WLAN operation in the spectrum that will become available after the transition from analog to digital TV signals

Frequency Channels and Frame Structures

Each version of the 802.11 standard has a clearly defined set of channels and channel bandwidths (Figure 1). In the time domain, WLAN transmissions occur as bursts or frames that vary in length and spacing, usually in the range of a few hundred microseconds to one millisecond.
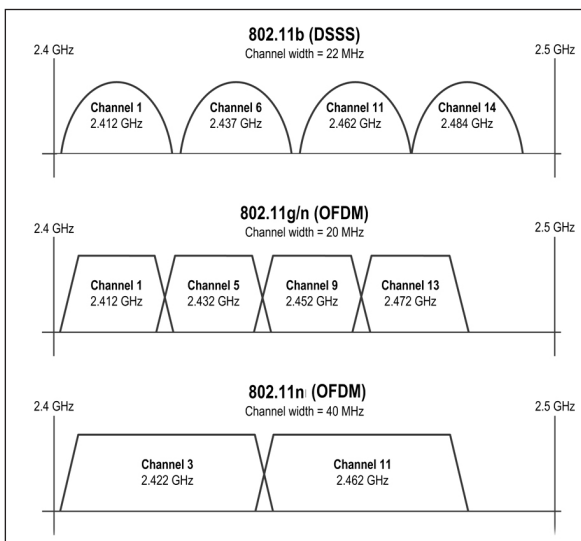

Figure 1. In the 2.4 GHz range, the 802.11b, g, and n standards use a variety of non-overlapping frequency channels.

Frame structure: 802.11a

802.11a was the first WLAN standard to use OFDM, which allows greater data transmission rates in a narrower bandwidth. OFDM uses 52 subcarriers that are spaced 312.5 kHz apart. Data is sent simultaneously on 48 subcarriers; the other four are used as pilots.

Because the 2.4 GHz industrial, scientific and medical (ISM) band was rapidly becoming overused, 802.11a was defined to operate in the 5 GHz Unlicensed National Information Infrastructure (U-NII) band. The U-NII band is not continuous, but rather contains two ranges. The first range is 5.15 GHz to 5.35 GHz and the second is 5.725 GHz to 5.825 GHz. Both ranges are separated into overlapping carriers spaced 20 MHz apart.

Figure 2 shows the OFDM frame structure used in 802.11a. Each frame starts with a training sequence (preamble) followed by the SIGNAL field and then the user data. The training sequence and 24-bit SIGNAL field are transmitted at a rate of 6 Mbps. The header (SIGNAL field) tells the receiver the transmission rate and length for the ensuing data. It also indirectly defines the modulation technique used by the subcarrier: BPSK, QPSK, 16QAM or 64QAM.

Figure 2. Frame structure used for OFDM transmissions in 802.11a.

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Frame structure: 802.11b

Figure 3 shows the DSSS frame structure used in 802.11b. In the initial version of the standard, the preamble and header were transmitted at 1 Mbps using DBPSK modulation, independent of the transmission speed. User data was transmitted at 1 Mbps using DBPSK or 2 Mbps using DQPSK.

When the standard was officially released, the complementary code keying (CCK) standard was included. This was used for data transmissions at 5.5 and 11 Mbps.

The standard also included an optional short 56-bit preamble (versus the 128-bit long version). In this mode, only the Synchronization and Start Frame Delimiter (SFD) fields are transmitted at 1 Mbps. The rest of the header is sent at 2 Mbps (DQPSK) and the data payload is sent using DQPSK at 2 Mbps or CCK at 5.5 or 11 Mbps.
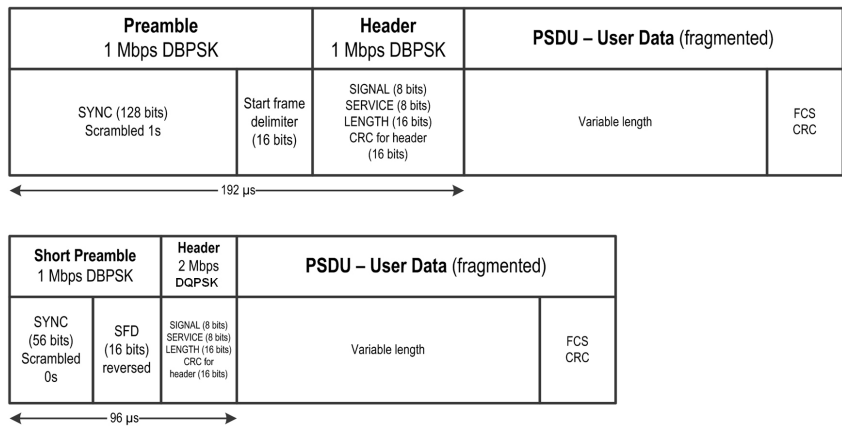
Preamble 1 Mbps DBPSK		Header 1 Mbps DBPSK	PSDU – User Data (fragmented)	
SYNC (128 bits) Scrambled 1s	Start frame delimiter (16 bits)	SIGNAL (8 bits) SERVICE (8 bits) LENGTH (16 bits) CRC for header (16 bits)	Variable length	FCS CRC

←————————————— 192 µs —————————————→

Short Preamble 1 Mbps DBPSK		Header 2 Mbps DQPSK	PSDU – User Data (fragmented)	
SYNC (56 bits) Scrambled 0s	SFD (16 bits) reversed	SIGNAL (8 bits) SERVICE (8 bits) LENGTH (16 bits) CRC for header (16 bits)	Variable length	FCS CRC

←————————— 96 µs —————————→

Figure 3. Frame structures used for DSSS transmissions in 802.11b (long and short preambles).

Frame structure: 802.11g

To maintain compatibility with the older standards, 802.11g uses both OFDM and DSSS. The ability to use both modulation techniques is achieved through provision of four physical layers. In the standard, these are defined as extended-rate physicals (ERPs) that coexist during a frame exchange. As a result, transmitters and receivers can select and use any of the four layers as long as both support it. Two of the layers are mandatory and two are optional:

- ERP-DSSS/CCK: Mandatory
  This is the 802.11b PHY layer. Data rates are 1, 2, 5.5 and 11 Mbps.

- ERP-DSSS/PBCC: Optional
  This PHY layer, which was also part of 802.11b, uses DSSS with packet binary convolutionary coding (PBCC) and supports data rates of 22 and 33 Mbps.

- ERP-OFDM: Mandatory
  This PHY layer was new in 802.11g. Data rates are 6, 9, 12, 18, 24, 36, 48 and 54 in the 2.4 GHz band.

- DSSS-OFDM: Optional
  New in 802.11g, this PHY layer combines a DSSS preamble with OFDM payload transmission. Data rates are the same as with ERP-OFDM.

As an example of an 802.11g frame structure, Figure 4 shows the long preamble format used in DSSS-OFDM.
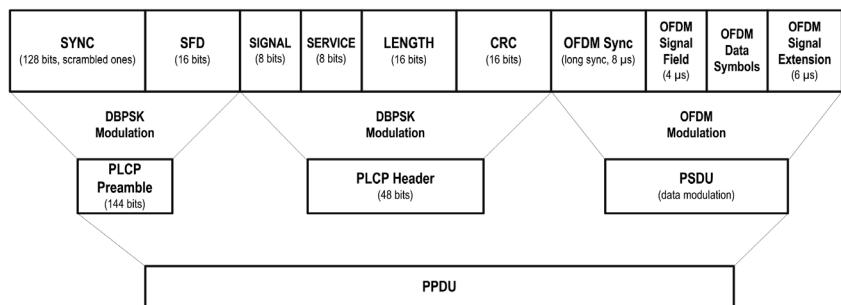
Figure 4. Frame structure used for DSSS-OFDM transmissions in 802.11g (long preamble PPDU format).

Frame structure: 802.11n

This standard defined the high-throughput physical layer (HT PHY) and added new attributes in the PHY and MAC layers. Important changes included new packet formats, 20 and 40 MHz transmission bandwidths, new modulation and coding schemes (MCS), frame aggregation in the MAC layer, and MIMO technologies. The key result is data rates as high as 600 Mbps.

As shown in Figure 5, the 802.11n standard supports three frame structures: legacy, mixed mode and green field.

In legacy mode (non-HT), frames are transmitted using the 802.11a/g OFDM format. Legacy WLAN systems and the new 802.11n MIMO-OFDM systems can and will co-exist. If 11n systems use MIMO transmission, only one transmit antenna is used and the system will act as if it were a SISO legacy system. Therefore, in this mode, transmission and reception will be typical 802.11 operations, and it is mandatory that there be backward compatibility with the existing standard.

Mixed mode packets are transmitted with a preamble that is compatible with 802.11a and g. Short training sequence (L-STF), long training sequence (L-LTF) and signal (L-SIG) description legacy elements are transmitted so that the signal can be decoded by 802.11a/g devices. The rest of the packet includes a MIMO training sequence format. In this mode, both the 11n MIMO-OFDM systems and the legacy systems co-exist. The 11n MIMO system should have the capability to generate legacy packets for the legacy systems and high throughput packets for MIMO-OFDM systems. So, the burst structure should be decodable to legacy systems and should provide better performance to MIMOsystems.

Green field mode, HT packets are transmitted without a legacy-compatible component. Transmission happens only between the 11n MIMO-OFDM systems even in the presence of legacy receivers.
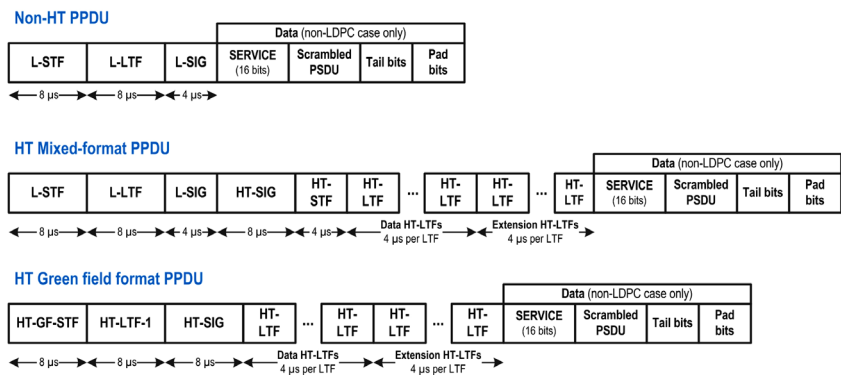

Figure 5. The three frame structures used in 802.11n.

Frame structure: 802.11ac

This emerging standard targets very high throughput (VHT) of 1 Gbps and runs only in the 5 -GHz band. To support higher data rates, it includes four key features: wider channels, higher-order modulation, more spatial streams and antennas, and multi-user MIMO.

- Channel bandwidth: 20, 40 and 80 MHz are mandatory; 160 MHz and an 80+80 MHz mode are optional.

- Modulation types: BPSK, QPSK, 16QAM and 64QAM are mandatory; 256QAM is optional.

- Spatial streams and antennas: One stream is mandatory; use of two to eight streams is optional. Transmitter beamforming and space time block coding (STBC) are optional.

- Multi-user MIMO: Increases system efficiency in the downlink by allowing simultaneous transmission to multiple users.

With these features, the maximum data rate can approach 6.9 Gbps. However, 1.5 Gbps will be more common, assuming a typical case that uses 80 MHz channels, four transmit antennas and 256QAM modulation.

Figure 6 shows the frame structure for a VHT PPDU transmission. The preamble and training fields enable the receiver to auto-detect the PHY layer standard being used. The initial legacy short and long training fields (L-STF, L-LTF) and signal field (L-SIG) are similar to those used in 802.11a, b and g; the fourth field (symbols 6 and 7) identify the frame as either 802.11n or ac.

VHT PPDU
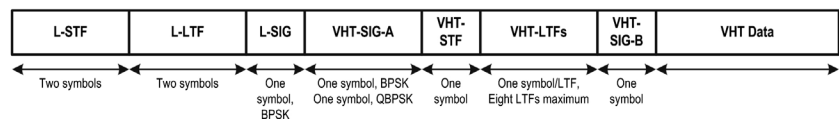
Figure 6. The VHT PPDU frame structure used in 802.11ac.

Transmitter Test

The test requirements for WLAN transmitters and receivers are defined in the 802.11 series standard. Table 2 lists the RF test requirements for 802.11a, b, g, n and ac transmitters. Where applicable, each cell of the table shows the chapter that describes each test and its requirements.

Table 2. Where to find transmitter tests in the IEEE 802.11 standard

Transmitter measurement	802.11a-1999	802.11b-1999	802.11g-2003	802.11n-2009	802.11ac-(D5.0)
Transmit power	17.3.9.1	18.4.7.1	19.4.7.1 / 18.4.7.1	20.3.21.3	—
Power control	—	18.4.7.2	—	—	—
Spectrum mask	17.3.9.2	18.4.7.3	17.3.9.2	20.3.21.1	22.3.18.1
Transmission spurious	17.3.9.3	18.4.6.8	17.3.9.3	—	—
Center frequency tolerance	17.3.9.4	18.4.7.4	19.4.7.2	20.3.21.4	22.3.18.3
Symbol (chip) clock frequency tolerance	17.3.9.5	18.4.7.5	19.4.7.3	20.3.21.6	22.3.18.3
Center frequency leakage	17.3.9.6.1	—	17.3.9.6.1	20.3.21.7.2	22.3.18.4.2
Power on/down ramp	—	18.4.7.6	—	—	—
RF carrier suppression	—	18.4.7.7	—	—	—
Spectral flatness	17.3.9.6.2	—	17.3.9.6.2	20.3.21.2	22.3.18.2
Modulation accuracy	17.3.9.7	18.4.7.8	17.3.9.6.3	20.3.21.7.4	22.3.18.4.3
Constellation error (EVM rms)	17.3.9.6.3	—	17.3.9.7	20.3.21.7.3	22.3.18.4.4

Test reference numbers starting with 17 apply to 802.11a, those that start with 18 apply to 802.11b, and those starting with 19 apply to 802.11g and some 11a and 11b items. Due to backward compatibility requirements, the test reference numbers that start with 20 and 22 only apply to 802.11n and ac single-channel.

An Agilent PXA or MXA X-Series signal analyzer, used with the N9077A WLAN measurement application, which runs inside the analyzer, offers an excellent solution for making WLAN transmitter test measurements. The N9077A WLAN measurement application supports the 802.11 a, b, g, n and ac standards, including 802.11n signals at 20 and 40 MHz as well as 802.11ac signals at 20, 40, 80, 80+80 and 160 MHz with all modulation formats. [1]

The following gallery of screen images illustrates the types of measurements, displays and results that can be produced with the N9077A WLAN measurement application.

1. The N9030A PXA can be configured with 25, 40, 85 or 160 MHz analysis bandwidth; the N9020A MXA can be configured with 25, 40, 85, 125 or 160 MHz analysis bandwidth.
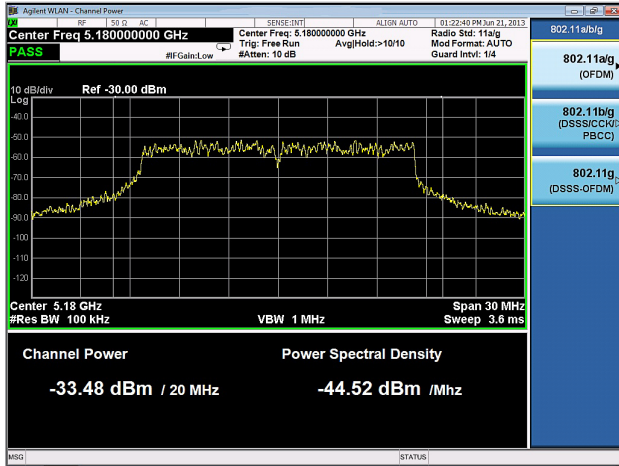
Figure 7. Channel power measurement for transmit power levels; tested signal is 802.11a OFDM at 54 Mbps.
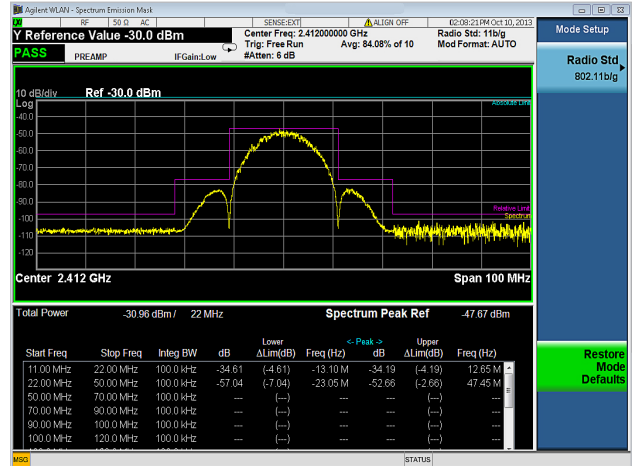

Figure 8. Transmit spectrum mask measurement; tested signal is 802.11b DSSS at 11 Mbps.
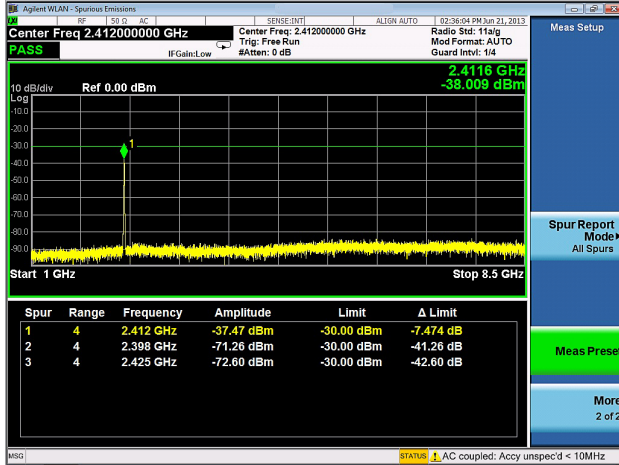

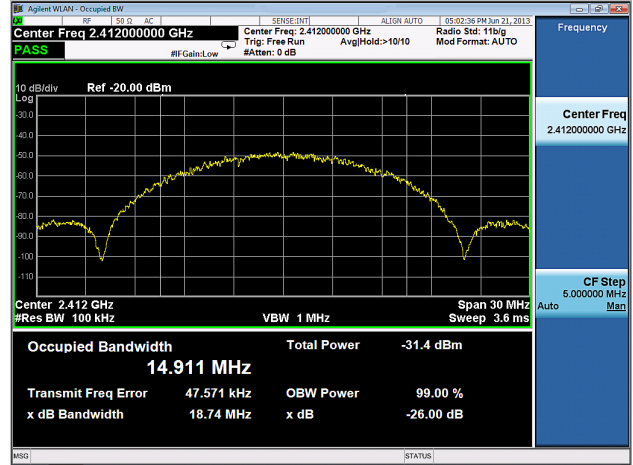Figure 9. Spurious emissions measurement; tested signal is 802.11b DSSS at 11 Mbps.

Figure 10. Transmit center frequency error measurement; tested signal is 802.11b DSSS at 11 Mbps.
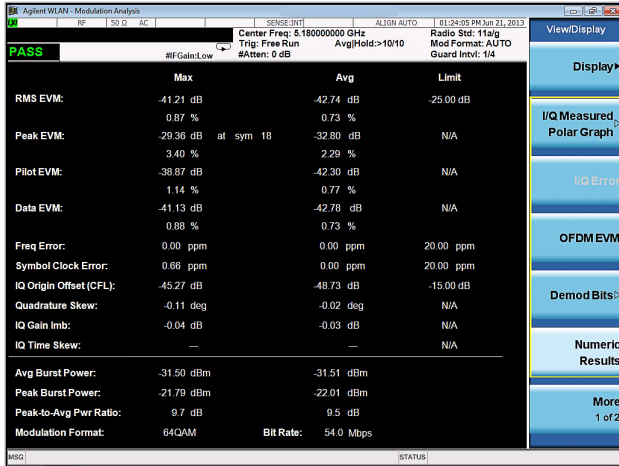
Figure 11. Symbol clock frequency tolerance measurement within modulation analysis numeric trace; tested signal is 802.11a ODFM at 54 Mbps.

Figure 12. Power-up and power-down measurement result from a power-versus-time measurement; tested signal is 802.11b DSSS at 11 Mbps.
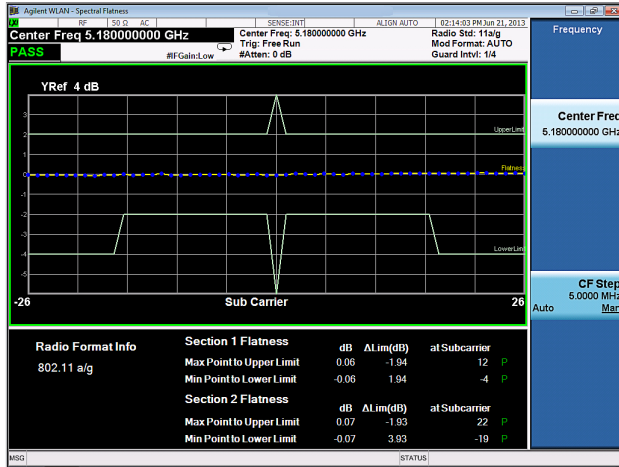
Figure 13. Spectral flatness measurement for an 802.11a signal.
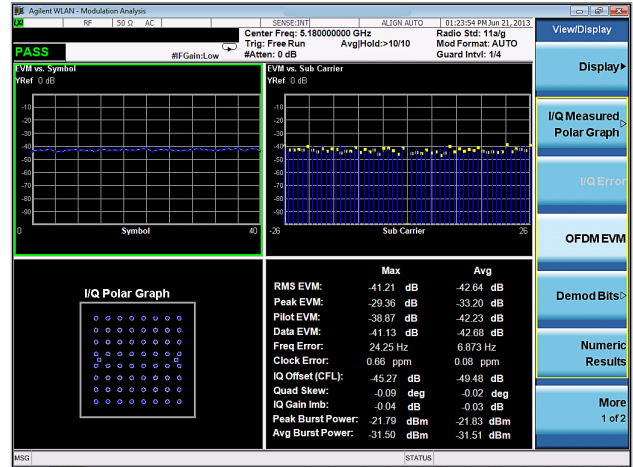
Figure 14. EVM traces and results for an 802.11a OFDM signal.

Receiver Test

Table 3 lists the RF test requirements for 802.11a, b, g, n and ac receivers. Where applicable, each cell of the table shows the chapter that describes each test and its requirements.

Table 3. Where to find receiver tests in the 802.11 standard

Receiver measurement	802.11a-1999	802.11b-1999	802.11g-2003	802.11n-2009	802.11ac-(D5.0)
Receiver minimum input level sensitivity	17.3.10.1	18.4.8.1	19.5.1 19.6.1	20.3.22.1	22.3.19.1
Adjacent channel rejection	17.3.10.2	18.4.8.3	19.5.2 19.6.2	20.3.22.2	22.3.19.2
Nonadjacent channel rejection	17.3.10.3	—	—	20.3.22.3	22.3.19.3
Receiver maximum input level	17.3.10.4	18.4.8.2	19.5.3	20.3.22.4	22.3.19.4
Clear channel assessment (CCA) sensitivity	17.3.10.5	18.4.8.4	—	20.3.22.5	22.3.19.5
Received channel power indicator (RCPI)	—	—	—	20.3.22.6	—
RSSI	—	—	—	—	22.3.19.6
Reduced interframe space (RIFS)	—	—	—	20.3.22.7	—

Receiver design can be quite difficult because the device must be able to handle a wide variety of input-signal conditions—and many of these conditions can be quite difficult to predict. The eight key specifications in the 802.11 standard are intended to characterize receiver performance when faced with non-ideal signals. Table 4 summarizes the purpose of the various tests.

Table 4. Major receiver tests and their purpose

Receiver measurement	Purpose
Receiver minimum input level sensitivity	Ensures that the WLAN device is able to receive data with a defined maximum packet error rate (PER) at a defined minimum level; measured at the antenna port
Adjacent channel rejection & Nonadjacent channel rejection	This set of tests verifies that a receiver can establish and hold a connection if other channels are occupied by other users
Receiver maximum input level	Ensures that a WLAN card can set up a connection and transmit if the distance between transmitter and receiver is very short. The receiver-under-test must be able to receive data with a defined maximum PER at a defined minimum level; measured at the antenna port
Clear channel assessment (CCA) sensitivity	CCA is used to detect if the planned transmission channel is free or in use by another WLAN connection.
Received channel power indicator (RCPI)	In the 802.11n standard, the RCPI value is used as a measure of the received RF power in the selected channel; measured at the antenna port
RSSI	In the 802.11ac standard, RSSI is measured during the preamble; it must be monotonic. The result is reported only to the receiver's MAC processor, not the signal transmitter.

The testing of receivers and transceivers requires the use of instruments capable of producing the complex modulation techniques used by the 802.11 wireless connectivity standards, such as the Agilent N5182B MXG vector signal generator. Software such as Agilent Signal Studio for WLAN (N7617B) can be used to create test signals, with or without impairments, and download the waveforms to a vector signal generator.

Conclusion

Every new generation of the IEEE 802.11 standards supports increased data capacity by providing greater speeds and wider bandwidths. The continuing evolution of the 802.11 standard and the products it supports presents a variety of challenges for testing WLAN or Wi-Fi transmitters, receivers and transceivers in R&D, design verification and manufacturing. The test solutions available from Agilent, including instrumentation and software are designed to help you keep pace today and in the future as new standards emerge.

Related Literature

Application Note 1509, Agilent MIMO Wireless PHY Layer (RF) Operation and Measurement, publication 5989-3443EN

Testing New-generation Wireless LAN, publication 5990-8856EN

Creating and Optimizing 802.11ac Signals and Measurements, publication 5991-0574EN

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