Practical Manufacturing Testing of 802.11 OFDM Wireless Devices
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Preface
The Practical Manufacturing Testing of 802.11 OFDM Wireless Devices handbook provides an introduction to the production testing of 802.11 OFDM-compliant handsets.

The preface includes the following topics:

• Who should use this guide
• What this guide contains

Who Should Use This Guide
The Practical Manufacturing Testing of 802.11 OFDM Wireless Devices handbook is intended for test engineers and other technical personnel who intend to learn about testing of 802.11 OFDM-compliant handsets.

What This Guide Contains
This document is divided into six chapters and an appendix and includes the following topics:

Chapter 1: Introduction to this document
Chapter 2: Introduction to 802.11 OFDM
Chapter 3: Transmit measurements
Chapter 4: Receive measurements
Chapter 5: Miscellaneous measurements
Chapter 6: LitePoint Offerings for 802.11 OFDM Testing
Appendix A1: Test Purpose (TP) identifiers
Chapter 1 Summary

WiFi, a technology that builds on IEEE 802.11 standards, is now becoming a common feature in many everyday devices including desktop and portable PCs, game consoles, more recently cellular handsets, TVs, home entertainment components, and set-top boxes. The advantages of WiFi for these and many more categories of commercial devices are numerous. For example in cellular handsets, WiFi offers a means to offload traffic that is negatively impacting cellular voice performance and is expected to be the key driver to mass consumer adoption of VoIP. Thanks to these and many more advantages, WiFi handset shipments have experienced strong growth over the past years, a growth that is projected to continue in 2010 and beyond.

While the technology for the mass production of WiFi devices is well established, the manufacturers of these devices are faced with the challenge of testing for 802.11 quality and reliability in a production-line environment, where cost considerations are paramount.

This document is intended to help manufacturers by offering an introduction to production testing of 802.11 devices. In particular, it describes testing of OFDM 802.11, which is becoming the standard over the DSSS 802.11 PHY-layer amendment, with a focus on OFDM 802.11n, which has required manufacturers of WiFi devices to meet tighter specifications with respect to the previous OFDM 802.11a/g amendments.

After providing a brief description of OFDM 802.11 modulation techniques, data rates, and packets, this document presents information on the measurements traditionally used in a production line to assess the minimum requirements for WiFi devices, which are then distributed in the marketplace. The significance of each of these measurements and guidelines on how to set up the measurement procedure and interpret the results is also provided.
Chapter 2 Introduction to IEEE 802.11 OFDM

IEEE 802.11 is a set of standards defining a wireless communication system in the GHz range. The original 802.11 standard and subsequent “amendments” are created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802) and include several over-the-air modulation techniques that use the same basic protocol.

The most popular modulation technique is Orthogonal Frequency Division Multiplexing (OFDM), defined for by the 802.11a amendment in the 5 GHz band. The 802.11a standard was released in 1999 and uses the same data link layer protocol and frame format as the original standard. In 2003, the use of OFDM technique was extended to the 2.4 GHz band with the release of the 802.11g amendment. 802.11g was backward-compatible with the preexisting 802.11b, which occupies the same band but is based on Direct Sequence Spread Spectrum (DSSS) modulation and thus is not discussed in this document.

The newest standard that makes use of OFDM is 802.11n (in both the 2.4 GHz band and the 5 GHz band), which improves upon the previous 802.11 standards by adding Multiple-Input Multiple-Output (MIMO) and other newer features. The IEEE has approved the amendment in October 2009; yet, chipsets and devices conforming to a 2007 draft of the 802.11n proposal were made commercially available by several wireless companies prior to the final ratification.

802.11n chipsets and devices offer higher bandwidth, as well as improved security and quality of service; as a consequence, this recent amendment has quickly become the technology of choice for many emerging multi-media applications, including but not limited to game consoles, smart phones, Mobile Internet Devices (MIDs), Wi-Fi access points, routers, and broadband gateways that integrate modem and Wi-Fi features.

Compared to the legacy devices, IEEE requires manufacturers of 802.11n devices to meet tighter specifications, in order to support 802.11n’s primary focus to improve throughput. Given the technological progresses that have occurred since 2003, when the 802.11g amendment was ratified, manufacturers of legacy devices should also refer to the latest specifications if they want to keep their legacy devices competitive in the marketplace and to minimize the likelihood of coexistence problems with 802.11n devices.

In light of the recent changes and future trends in 802.11 OFDM WiFi development, this document focuses on the specifications described in the latest IEEE amendment (known as 802.11n Specification, or, Amendment 5: Enhancement for Higher Throughput). While MIMO technology is an important part of the 802.11n standard, recently the most impressive growth has been seen in Single-Input, Single-Output (SISO) OFDM 802.11n wireless-enabled portable devices; therefore, this document is dedicated to testing such devices in a manufacturing environment.

This chapter includes the following sections:

2.1. OFDM Modulation
2.2. OFDM Coding Rates and Data Rates
2.3. OFDM Packets

2.1. Bluetooth Modulation and Data Rates

In the OFDM technique, the usable bandwidth is divided into a large number of smaller bandwidths, or “subcarriers.” The high-speed information is then divided onto these multiple lower-speed signals, which are transmitted simultaneously on different frequencies in parallel. The resulting low-data-rate carriers are more tolerant of fading because of multiple reflections. OFDM modulation is characterized by high peak-to-average power ratio (PAPR) in time, and a power distribution that resembles white Gaussian noise.

Prior to the release of the 802.11n amendment, 802.11 OFDM was based on only 52 (26x2) carriers with 312.5 kHz spacing, defining about a 16.8 MHz bandwidth in a 20 MHz channel. The OFDM format before the 802.11n amendment is known today as Legacy Mode and is shown in Figure 1-a. The recent amendment builds on previous 802.11 standards by increasing the number of carriers and by adding 40 MHz channels to the physical layer. This is accomplished in a number of modes:

• High-Throughput (HT) Mixed Mode
  • In Mixed Mode HT20, the 20 MHz channel is created by increasing the number of carriers from 52 to 56 in the HT portion, as shown in Figure 1-b. The legacy portion of the preamble still has 52 carriers.
• In Mixed Mode HT40, the 40 MHz channel is created by using two adjacent 20 MHz channels with a total of 114 (57x2) carriers in the data portion, as shown in Figure 1-c. The legacy portion of the preamble has a total of only 104 carriers (52x2). The broadcast and other control frames are sent in legacy 20 MHz channels with 26x2 carriers, to allow the legacy devices to inter-operate as well.

• High-Throughput (HT) Greenfield Mode

  • In Greenfield Mode, also available in HT20 and HT40, the number of carriers is as defined in Mixed Mode\(^1\). The main difference between Mixed Mode and Greenfield Mode is that the latter has no legacy preamble, that is, there is no provision to allow a legacy device to understand the full transmission.

A description of the structure of the PLCP\(^2\) protocol data unit in each mode is provided in Chapter 2.3.

Each carrier is modulated by BPSK, QPSK, QAM16, or QAM64 modulation, depending on the specific 802.11 PHY layer amendments and data rate. Pilots always use BPSK with a known pattern.

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1 With the exception of the HT Signal Field (HT-SIG), see Chapter 2.3
2 Physical Layer Convergence Procedure.
2.2. OFDM Coding Rates and Data Rates

In Legacy/Non-HT mode, the 802.11a/g modulation scheme is used. Here, the data rate varies depending on the specific modulation format and coding rate (R) as shown in Table 1. The symbol duration is 4 μs, equivalent to 250,000 symbols. The actual symbol is 3.2 μs, the remaining 800 ns being guard interval (GI, also called cyclic prefix) between symbols. The spectral nulls are at integer multiples of 1/3.2 μs, that is, at integer multiples of the carrier spacing (312.5 kHz).

The data is coded to improve performance, reliability, and handling of bit errors.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate (R)</th>
<th>Data Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>9 Mbps</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>12 Mbps</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>18 Mbps</td>
</tr>
<tr>
<td>QAM16</td>
<td>1/2</td>
<td>24 Mbps</td>
</tr>
<tr>
<td>QAM16</td>
<td>3/4</td>
<td>36 Mbps</td>
</tr>
<tr>
<td>OFQAM64</td>
<td>2/3</td>
<td>48 Mbps</td>
</tr>
<tr>
<td>QAM64</td>
<td>3/4</td>
<td>54 Mbps</td>
</tr>
</tbody>
</table>

Table 1. Modulation, Coding Rate, and Data Rate in 802.11a/g devices (20 MHz channel spacing).

For 802.11n communications, a continuous decision-making process is used, based on the feedback from the receiver about the channel conditions to adjust the transmit modulation. Given the conditions, the system will change the modulation rate to provide the best compromise between data rate and error rate for the payload. In addition, 802.11n provides many more combinations than 802.11a/g to allow for transmission using multiple streams and coding. The complexity of 802.11n rate adaptation gives rise to the concept of Modulation Coding Scheme (MCS), which includes variables such as the number of spatial streams, modulation, and the data rate on each stream. During communication, the optimum MCS is negotiated based on channel conditions. There are 76 MCS types specified in the 802.11n Specification document. Table 2 shows the modulation scheme (and corresponding data rate) used in the MCS with single spatial stream. The values are reported both with 800 ns GI, which is the legacy mode as well as the default mode for 802.11n devices, and with 400 ns GI, which is an optional mode for 802.11n devices.

<table>
<thead>
<tr>
<th>MCS</th>
<th>Modulation</th>
<th>Coding Rate (R)</th>
<th>Data Rate [Mbps] GI = 800 ns</th>
<th>Data Rate [Mbps] GI = 400 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>BPSK</td>
<td>1/2</td>
<td>6.5</td>
<td>7.2</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1/2</td>
<td>13</td>
<td>14.4</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>3/4</td>
<td>19.5</td>
<td>21.7</td>
</tr>
<tr>
<td>3</td>
<td>QAM16</td>
<td>1/2</td>
<td>26</td>
<td>28.9</td>
</tr>
<tr>
<td>4</td>
<td>QAM16</td>
<td>3/4</td>
<td>39</td>
<td>43.3</td>
</tr>
<tr>
<td>5</td>
<td>QAM64</td>
<td>2/3</td>
<td>52</td>
<td>57.8</td>
</tr>
<tr>
<td>6</td>
<td>QAM64</td>
<td>3/4</td>
<td>58.5</td>
<td>65.0</td>
</tr>
<tr>
<td>7</td>
<td>QAM64</td>
<td>5/6</td>
<td>65</td>
<td>72.2</td>
</tr>
<tr>
<td>32</td>
<td>BPSK</td>
<td>1/2</td>
<td>6</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Table 2. Modulation, Coding Rate, and Data Rate per MCS in single stream 802.11 devices.

The guard interval that is part of each OFDM symbol is a period of time that is used to minimize intersymbol interference.
2.3. OFDM Packets
The 802.11n Specification introduces the definition of the HT OFDM PHY, which is based on the OFDM PHY defined in the previous amendment with extensibility up to four spatial streams, for operation in 20 MHz bandwidth, and with the addition of one to four spatial streams, for operation in 40 MHz bandwidth.

In the context of the HT PHY, the structure of the PLCP protocol data unit (PPDU) is defined and can be one of the following:

- In Non-HT Format (mandatory), packets are structured exactly as in the previous amendment to ensure compatibility with legacy 802.11a/g devices;
- In HT-Mixed Format (mandatory), packets contain a non-HT preamble compatible with legacy devices to enable detection of the PPDU and acquisition of carrier frequency and timing by both HT and legacy devices. The rest of the packet, however, cannot be decoded by legacy devices;
- In HT-Greenfield Format (optional), packets do not contain a non-HT compatible part.

In the HT-Mixed Format, the non-HT portion of the preamble contains a Legacy Short Training Field (L-STF) and a Legacy Long Training Field (L-LTF), which are defined exactly as the legacy OFDM 802.11 Short Training Sequence (STS) and Long Training Sequence (LTS), respectively:

- The L-STF is for packet detection, Automatic Gain Control (AGC), coarse frequency-offset correction. The L-STF is 8 μs long (two OFDM symbols), does not contain channel coding, and is not scrambled;
- The L-LTF is for channel estimation, fine frequency-offset correction, and symbol timing. The L-LTF is 8 μs long (two OFDM symbols), does not contain channel coding, and is not scrambled.

To keep the PAPR of both the L-STF and the L-LTF in 40 MHz transmission mode comparable to that of the 20 MHz transmission mode, the upper sub-channels (sub-carriers 6-58) are phase rotated by +90º. To enable proper synchronization with the legacy devices, the sub-carriers at ±32 in 40 MHz (which are the DC sub-carriers for the legacy 20 MHz transmission) are both nulled in the L-LTF.

In addition to the L-STF and L-LTF, the non-HT portion of the HT-Mixed Format also includes the legacy-compatible Signal Field (LSIG) defined in previous amendments:

- The L-SIG is used to communicate rate and length information. It is 4 μs long (one OFDM symbol), and it is encoded, interleaved, and mapped.

The 802.11n Specification introduces the definition of the HT Signal Field (HT-SIG) contained in the HT portion of the preamble in the HT-Mixed format:

- The HT-SIG consists of two OFDM symbols and is used to carry information required to interpret the HT packet formats, such as the index into the MCS table (see Table 2) and the GI length. The HT-SIG is encoded, interleaved and mapped.

HT-SIG symbols are BPSK modulated, in which the constellation of the data tones is rotated by 90° relative to the legacy signal field. Following the HT-SIG Field are the HT-STF and HT-LTF, meant to improve communications in a MIMO system.

In the HT-Greenfield format, all of the non-HT fields are omitted from the preamble. The specific HT fields used are:

- The HT-GF-STF, for AGC convergence, timing acquisition, and coarse frequency acquisition;
- One or several HT-LTFs, provided as a way for the receiver to estimate the channel between each spatial mapper input and receive chain. The initial HT-LTFs (HT-DLTFs) are necessary for demodulation of the HT-Data portion of the PPDU and are followed, for sounding packets only, by optional HT-LTFs (HT-ELTFs) to sound extra dimensions of the MIMO channel;
- The HT-SIG, which provides all the information required to interpret the HT packet format.
Chapter 3 Transmit Measurements
This chapter describes the measurements performed during an OFDM signal transmission. The most commonly used OFDM transmit measurements can be grouped as follows:

3.1. Transmit Power Measurements
3.2. Transmit Frequency Measurements
3.3. Transmit Spectral Measurements
3.4. Transmit Modulation Measurements
3.5. I/Q Imbalance Measurements

3.1. Transmit Power Measurements
Transmit Power Measurements for the 802.11 specification include the following:

• Transmit Average Power
• Transmit Peak Power
• Channel Power
• Power vs. Time
• Packet-to-Packet Power Variation

The objective of these tests is to verify the transmit power level. If the power is too low, performance in a noisy environment is affected; if it is too high, battery life is compromised and interference issues may arise. Also, transmit power must be kept within the limit specified by regulations specific to each country. Power variations are also tested as they can compromise the quality of the transmission.

Transmit Average Power

What is it?
Transmit Average Power is the average power of complete data capture (in dBm), performed with or without removal of any gap between packets.

Why is it important?
No IEEE Transmit Average Power limit exists. IEEE requires that chipsets and devices meet the regulatory specifications in each country of operation. While the specifications in the U.S. limit peak power, in some regions such as Europe, the applicable standard requires that the Average Power be measured, corrected for duty cycle and compared to the applicable limit.

How is it measured?
Transmit Average Power is usually measured over a complete data capture, with or without removal of any gap between packets.

Where is it tested?
Testing Transmit Average Power is clearly relevant to manufacturing as most devices are specified by transmit power.

Transmit Peak Power

What is it?
Transmit Peak Power is the maximum transmit power of the DUT (in dBm), usually measured over the entire capture.

Why is it important?
Similar to the Transmit Average Power, IEEE does not specify a Transmit Peak Power limit and demands that chipsets and devices comply with the regulatory specifications in each country of operation. The regulatory standards most widely used for 802.11 devices in various countries are as follows:

• USA—FCC Part 15 Subpart E, EN 301 893 and EN 300 328.
Europe—CEPT ECC DEC (04) 08, ETSI EN301 893.
Japan—MIC Equipment Ordinance (EO) for Regulating Radio Equipment Articles 7, 49.20, 49.21a.

How is it measured?
Peak transmit power is usually measured over the transmission pulse duration of the device and averaged across symbols. This averaging must include only time intervals during which the transmitter is operating at its maximum power and must not include any time intervals during which the transmitter is off or is transmitting at a reduced power level.

Where is it tested?
Transmit Peak Power is difficult to measure because a very high bandwidth power meter is needed. Yet, testing Transmit Peak Power is relevant to manufacturing because it provides information about compression in the transmitter, and therefore about the device performance.

Channel Power

What is it?
Channel Power is a measure of the transmitted power in a selected channel over the preamble and the entire received frame.

Why is it important?
Maximum Channel Power regulations are in place in several countries worldwide. In addition, IEEE puts a limit to Adjacent Channel Power (ACP), defined as the amount of signal power that leaks into adjacent channels located above and below a desired channel.

How is it measured?
Several methods to measure the Channel Power exist. Generally, the measure is obtained by integrating the power contributions from all frequencies in the time-domain at a specified bandwidth (BW). Channel Power is not frequency-selective; that is, it does not discriminate for the presence of signals at frequencies other than the desired ones (i.e., harmonics, spurious).

Where is it tested?
Testing Channel Power is relevant to manufacturing in countries defining Power/MHz, such as for example in Japan.

Power vs. Time

What is it?
A Power vs. Time plot shows the instantaneous signal power versus time.

Why is it important?
Some wireless standards specify a mask and the signal’s instantaneous power versus time waveform must conform to this specification. The mask is typically specified during the ramp-up and ramp-down transient of the signal.

How is it measured?
Power vs. Time is measured and plotted as the time envelope of transmit power within the specified bandwidth (BW). Channel Power is the integral result of this envelope. As such, Power vs. Time is not frequency-selective.

Where is it tested?
Testing Power vs. Time is relevant to manufacturing: typically, power cannot change thought the packet or the constellation moves away from the defined point in L-LTF. This shift is usually captured by EVM unless amplitude tracking is enabled. LitePoint WiFi testers’ GUI allows measuring Power vs. Time.

Packet-to-Packet Power Variation

What is it?
Packet-to-Packet Power Variation is defined as the average peak- or RMS-power ratio between packets.

Why is it important?
The maximum power of each packet of information may degrade in time due to heating of the transmitter components or drift. Usually, the power control loop substantially reduces the heating and drift; a malfunctioning or poorly-performing power control loop will result in higher Packet-to-Packet Power Variation. This variation can affect the signal quality. Usually, it is desirable that the Packet-to-Packet Power Variation be less than 1 dB within a specified number of packets (typically, a bundle of 25 packets), as
indicated in Figure 2.

How is it measured?
Packet-to-Packet Power Variation is measured in the time-domain and may depend on data and on time. Several methods exist, based on which measure of power within a packet is considered. This is either packet average power or peak power; whatever the method, it is important that the data dependence be eliminated by the measurement procedure.

Where is it tested?
Testing Packet-to-Packet Power Variation is relevant to manufacturing. LitePoint recommends to measure packet average power, since packet peak power will vary significantly with data contents. The test should be performed only after the power control loop has settled. Finally, the test should always be performed across multiple packets, to ensure that the loop is stable; its result will be meaningless otherwise.

3.2. Transmit Frequency Measurements
Transmit Frequency Measurements for 802.11 OFDM include:

- Frequency Error (Transmit Center Frequency Tolerance)
- Clock Error
- Frequency Settling (Start of Packet)

These tests verify frequency accuracy of the transmitter. Frequency accuracy is a critical parameter in a wireless communication system since it ensures that the receiver of the transmitted signal is able to recover the information contained in it. In addition, precise frequency accuracy minimizes interference in multi-user systems.

**Frequency Error (Transmit Center Frequency Tolerance)**

What is it?
A Frequency Error measures the difference (misalignment) between the carrier frequency generated by the reference oscillators at the transmitter and the expected carrier frequency.

Why is it important?
Typically, the baseband processor can handle significant frequency error, without significant effect, if at least minimal phase tracking is activated. If phase tracking is completely deactivated, OFDM systems are sensitive to frequency errors. Here, a Frequency Error results in a shift of the frequency domain symbols relative to the receiver’s, which can lead to inter-subcarrier interference and a deteriorated quality of the channel estimation. Hence, especially for OFDM systems, it is important that the reference oscillator frequency (or local oscillator frequency in Sigma Delta PLLs) is close to the desired frequency.

IEEE specifies that the transmit center frequency error shall be ±20 PPM maximum for the 5 GHz band and ± 25 ppm maximum for the 2.4 GHz band. Typical values of Frequency Error, however, are well below 5 PPM. IEEE also specifies that the transmit center frequency and symbol clock frequency be derived from the same reference oscillator (locked). This means that the error in PPM for the carrier and the symbol timing are the same.

Contrary to DSSS systems, which are instead robust to frequency errors.
How is it measured?
A Frequency Error can be verified by analyzing an 802.11 signal from the DUT. It is often measured from the time-domain signal; however, it can also be measured using frequency-domain samples. Typically, Frequency Error is measured based on short and long training sequence (preamble).

Where is it tested?
Testing Frequency Error is clearly relevant to manufacturing. Meeting the required Frequency Error specifications ensures the accuracy of the crystal and is important to ensure interoperability.

Clock Error

What is it?
A Clock Error is the sampling clock difference at the transmitter and receiver. IEEE requires that the transmit center frequency and the symbol clock frequency for all transmit antennas shall be derived from the same reference oscillator, hence, the specifications for the Clock Error and for the Transmit Center Frequency Tolerance are the same.

Why is it important?
A sampling Clock Error introduces a phase rotation that depends on the carrier and on the symbol index. Clock Errors in the absence of frequency errors normally occur in systems which use a Sigma Delta PLL to change the center frequency of the local oscillator, rather than a reference crystal. Also, a Clock Error can result if the Analog-to-Digital Converter (ADC) and Voltage Controlled Oscillator (VCO) run each on a separate crystal, although modern architectures tend to avoid this approach precisely because of this issue. IEEE specifies that the Clock Error shall be ±20 PPM maximum for the 5 GHz band and ± 25 PPM maximum for the 2.4 GHz band.

How is it measured?
In principle, the measurement is performed during the pilot tracking period, using frequency- and time-dependent phase rotation measurements on the pilots in frequency domain. In practice, testing Clock Error during the entire duration of the packet ensures that more accurate and repeatable results are obtained. It is important to consider that most baseband processors implement symbol tracking, which compensates for clock errors. For this reason, the test system should have the option to enable symbol tracking and measure the actual degradation to be expected by the specific DUT. With a single crystal, this is generally not an issue, but will require a long packet, hence, a long test time.

Where is it tested?
If the Frequency Error is measured, testing Clock Error may not be relevant to manufacturing.

Frequency Settling (Start of Packet)

What is it?
Frequency Settling is defined as the time required for the architecture to reach a stable frequency error.

Why is it important?
When the DUT powers up, the current drawn by the device can push either the crystal or the local oscillator. Typically, if the frequency recovers fast, the local oscillator is being pushed; a slower recovery may indicate that the reference crystal is being pushed.

How is it measured?
The Frequency Settling should be calculated at the start of packet.

Where is it tested?
Testing Frequency Settling is relevant to manufacturing, since it provides a measure of decoupling of the power supply. With Greenfield packets, the time required for Frequency Settling may even affect the EVM. Typically, the Frequency Error should be fully settled at the end of the L-STF, as it defines the channel estimate. For this reason, LitePoint uses the L-STF to estimate the Frequency Error and calculate the Frequency Settling parameter. (Figure 3 shows the Frequency Error during both the L-STF and the L-LTF.)

5 Also IEEE specifies that the different transmit chain center frequencies (LO) and each transmit chain symbol clock frequency shall all be derived from the same reference oscillator.
3.3. Transmit Spectral Measurements

Transmit Spectral Measurements for 802.11 OFDM include:

- Spectral Mask
- Spectral Flatness
- Transmit Center Frequency Leakage
- Complimentary Cumulative Density Function (CCDF)

These measurements verify conformity of the distribution of signal power to the specification as well as compliance to regulatory limits. In addition, they provide information on common types of distortions that can affect the signal.

Spectral Mask

What is it?

A Spectral Mask describes the distribution of signal power across each channel.

Why is it important?

IEEE defines the permitted distribution of signal power for each 802.11 layer amendment, and to which the measured Spectral Mask must be compared:

- When transmitting in a 20 MHz channel, the transmitted spectrum must have a 0 dB relative to the maximum spectral density of the signal.

- When transmitting in a 40 MHz channel, the transmitted spectrum must have a 0 dB relative to the maximum spectral density of the signal.

- In Japan, requirements vary slightly.
For DSSS systems, measuring the spectral mask is the dominant requirement and usually sufficient; however, it cannot be used to estimate the Error Vector Magnitude (EVM, see 3.4) since noise and I/Q impairments are masked. Therefore, it is not sufficient to measure the signal quality in OFDM systems. Yet, the Spectral Mask can be and is often used as a diagnostic tool to determine whether some types of distortions are present in the signal. One common cause of such distortion is compression. Compression results from increased transmit power in the transmitter and causes spectral regrowth, which in turn may lead to signal sidebands approaching the mask limit. In addition, an improperly configured baseband signal also creates unwanted sidebands in an OFDM signal. Finally, these sidebands may jam and compromise the signal quality in adjacent channels. Another reason why measuring the Spectral Mask can be important is that some implementations deliberately increase transmit power at lower data rates, at which the mask can be violated even though the minimum EVM requirement is met (typically, this violation may happen at data rates lower than 24 Mbit/s).

**How is it measured?**
A Spectral Mask is obtained from a measurement of the Power Spectral Density (PSD) of the device; that is, from the distribution of the transmit signal power in frequency. The measurements are made using a 100 kHz resolution bandwidth and a 30 kHz video bandwidth. Usually, it is recommended to check if the Spectral Mask is met for all channels—or at least the most likely worst channel. Most likely, the worst case scenario will exist at the channel with highest output power, or where the signal is most compressed.

Assuming that the chip scales power with the data rate, the EVM usually limits the spectral mask at high bit rates, so there is no need to check the mask; on the contrary, at lower bit rates, the EVM is relaxed and the spectral mask will be the limiting factor. Normally, the test is performed by increasing the gain at lower bit rates by a predefined number. However, checking the spectral mask for modulations yielding the highest output power is advisable. For many chipsets, the bit rates from 6 Mbit/s to 18 Mbit/s use the same output power, and the spectral mask limits the transmit power for these solutions.

For OFDM Spectral Mask, there are no distinct points where the mask will be violated and therefore, the full plot must be checked. This can easily be done by analyzing the captured spectral plot against the Spectral Mask specified by IEEE.

**Where is it tested?**
Testing Spectral Mask is relevant to manufacturing as it provides a comprehensive picture of the transmitter’s spectral performance and ensures that neighboring channels will not suffer interference due to a “noisy” device. In some solutions, LitePoint provides a measure for the worst-case percentage difference between the Spectral Mask defined by IEEE standards and the measured Spectral Mask.

![IEEE 802.11 Spectral mask for 802.11 20 MHz channel.](image)

Figure 4-a. IEEE 802.11 Spectral mask for 802.11 20 MHz channel.
Spectral Flatness

What is it?
Spectral Flatness is defined as the geometric mean of the power spectrum divided by the arithmetic mean of the power spectrum.

Why is it important?
Spectral Flatness is a measure of the deviation in power in all spectral bands.

- For OFDM systems in a 20 MHz channel and in corresponding 20 MHz transmission in a 40 MHz channel, IEEE requires that the average energy of the constellations in each of the subcarriers –16 to –1 and +1 to +16 deviate no more than ±2 dB from their average energy. The average energy in each of the subcarriers –28 to –17 and +17 to +28, instead, must deviate no more than +2/–4 dB from that of subcarriers –16 to –1 and +1 to +16.
- In a 40 MHz transmission⁸, the average energy of the constellations in each of the subcarriers –42 to –2 and +2 to +42 must deviate no more than ±2 dB from their average energy. The average energy of the constellations in each of the subcarriers –43 to –58 and +43 to +58 must deviate no more than +2/–4 dB from the average energy of subcarriers –42 to –2 and +2 to +42.

How is it measured?
Spectral Flatness is derived from the channel estimate obtained from the HT-LTF(s). It is measured during the channel estimation phase of the burst, with all carriers active but after the start of a normal burst.

Where is it tested?
Testing Spectral Flatness is relevant to manufacturing. It ensures that power is spread out evenly over the channel, which could be compromised by the output filter performance.

Transmit Center Frequency Leakage

What is it?
DC offset can affect certain transmitter implementations in the up-converter path, and usually causes carrier leakage. Such leakage manifests itself in a receiver as energy in the transmit center frequency, hence the name Transmit Center Frequency Leakage.

⁸ Excluding PPDUs in MCS 32 format and non-HT duplicate format.
**Why is it important?**
The carrier leakage produces a CW tone at the carrier frequency (as shown in Figure 5), and if it is too large, it can introduce significant problems for the system. When too large, it can make the transmitter transmit significant power at the beginning and end of the packet, where the power amplifier is active, but the base band produces no modulation. For OFDM signals, no information exists at the carrier frequency, so one only need to make sure the carrier leakage does not saturate the receiver. Obviously, efficiency-conscious designs will look at very small DC offset as a very desirable characteristic of the DUT. Often OFDM-based receiver systems utilize some way to calibrate out or remove the carrier leakage.

IEEE mandates that the transmitter center frequency leakage does not exceed –15 dB relative to overall transmitted power (or, equivalently, +2 dB relative to the average energy of the rest of the subcarriers) for transmission in a 20 MHz channel width.

For transmissions in a 40 MHz channel width, the center frequency leakage must not exceed –20 dB relative to overall transmitted power (or, equivalently, 0 dB relative to the average energy of the rest of the subcarriers).

For upper or lower 20 MHz transmissions in a 40 MHz channel, the center frequency leakage (center of a 40 MHz channel) must not exceed –17 dB relative to overall transmitted power (or, equivalently, 0 dB relative to the average energy of the rest of the subcarriers).

**How is it measured?**
Testing Transmit Center Frequency Leakage is relatively easy in OFDM systems. No special transmit signal is needed. The leakage can be measured as part of any valid OFDM signal, from the channel estimate that is in turn derived from the L-LTF.

**Where is it tested?**
Testing Transmit Center Frequency Leakage in OFDM devices is generally not critical to manufacturing. DSSS devices are generally much more sensitive to Leakage; hence, meeting the Leakage requirement for the 802.11b standard (which makes use of DSSS modulation) typically ensures that the requirement is met also for OFDM-based standards.

![Figure 5. Effect of a DC offset (or, LO leakage) on the Power Spectral Density (PSD).](image)

**Complimentary Cumulative Density Function (CCDF)**

**What is it?**
CCDF is a method used to characterize the peak power statistics of a digitally modulated signal. CCDF links a percentage probability to a power level.

**Why is it important?**
Measuring the CCDF is a simple and effective method of determining the nonlinear characteristics of a transmitter. This measurement indicates how often the observed signal reaches or exceeds a specific level. Comparison of measured values and theoretical reference values (which can be determined for OFDM) not only yields information on the nonlinear response of all types of active elements, but it does so without the need to transmit complex test sequences.

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For DSSS signals, signal energy exists at the carrier frequency, so it cannot easily be removed. Carrier leakage will result in a DC component in the receiver, which can shift the constellation.
How is it measured?
In this measurement, an instrument with time-gating capability is used to select only the active portion of the burst (if time gating were not used, the periods when the burst is off would reduce the average power calculation). The measurement is made over several bursts for improved accuracy. The CCDF, which is simply the more common cumulative distribution function (CDF) subtracted from 1.0, shows the number of decibels above the average power on the horizontal axis, and percent probability on vertical axis.

Where is it tested?
Testing CCDF is typically not performed in manufacturing. It may be relevant for quality assurance or design verification.

3.4. Transmit Modulation Measurements
Transmit Modulation Measurements include the following:

- Constellation Diagram
- Error Vector Magnitude (EVM)

These tests provide critical information on the types of distortion in the entire transmit chain that can affect the signal quality.

Constellation Diagram

What is it?
The Constellation Diagram is a representation of a signal modulated by a digital modulation scheme. The plots in Figure 6 show typical constellations for an OFDM signal. The green constellation points represent the information from the pilot subcarriers; the red constellation points, the data on the subcarriers.

Why is it important?
The diagram is useful to identify some types of corruption in signal quality. Some common types of corruption are I/Q gain and phase mismatch, symbol clock error, group delay, phase noise, and compression. Each of these types of corruption has a specific effect on the QAM constellation symbols which makes it possible to identify them. Some illustrative examples are provided in Section 3.5 (on I/Q Imbalance Measurements).

How is it measured?
Each position in a QAM constellation grid represents a particular I/Q symbol state. To obtain a QAM Constellation Diagram, the transmit signal from the DUT is captured and digitized, and the symbols demodulated by the tester’s Vector Signal Analyzer. The average power of each of these symbols is then plotted on the QAM constellation grid.

Where is it tested?
Testing Constellation Diagram is typically not performed in manufacturing. The information carried by the diagram is aggregated by the EVM value.
Figure 6. Typical QAM constellations for a OFDM based signal with BPSK (top, left), QPSK (top, right), QAM16 (bottom, left), or QAM64 (bottom, right) modulation.

Error Vector Magnitude (EVM)

What is it?
The EVM is a measure of the deviation of the actual constellation points from the ideal error-free locations in the constellation diagram (in % RMS or dB). Also known as Transmit Constellation Error, the RMS error is averaged over subcarriers, OFDM frames, and packets.

Why is it important?
EVM, schematically shown in Figure 7, is a measure of the transmit quality; in that, it provides an indication of the sum of the effects that various imperfections in the device implementation have on the transmit symbols. Typical imperfections are compression, dynamic range, I/Q errors, interference and phase noise.

EVM is a statistical quantity obtained from a distribution of errors that include both deterministic and non-deterministic imperfections (as shown in Figure 8). Completely deterministic and non-varying imperfections would simply shift the signal from its ideal location; non-deterministic imperfections such as inter-symbol interference and noise, instead, are shown by repeated measurements as varying randomly about the ideal location, defining an error cloud. Compression\(^\text{10}\) and phase noise are typically the main contributors to EVM, which is typically well below -30 dB, depending on the modulation format. EVM is also allowed to degrade with data rate: less stringent EVM at lower data rates enable higher transmit power when lowering data rate.

\(^{10}\)Especially for modern designs, compression is often dominating as these devices often limit the peak-to-average-power (PAP) to enable predistortion.
Table 3 shows the maximum EVM for legacy devices and for 802.11n devices. In 802.11n, EVM requirements are stricter because the noise from each radio will add noise to the other(s) in the system, further degrading performance and EVM (a higher signal-to-noise ratio (SNR) is required to obtain the higher data rate, and 802.11n requires approximately 3 dB higher SNR than legacy a/b/g devices).

**How is it measured?**

The test is performed by instrumentation capable of converting the transmitted signals into a stream of complex samples at 40 Msample/s or more, with sufficient accuracy in terms of I/Q amplitude and phase balance, dc offsets, phase noise, and analog-to-digital quantization noise (i.e., the test receiver must be higher in performance than the DUT).

EVM performance should be verified at all transmit power levels, and measured over multiple symbols as average of the EVM for each symbol. EVM is not a fixed number and capture-to-capture variation exists that gives EVM a statistical distribution across symbols. Also, EVM shows a dependency on the analysis options (such as Phase Tracking, Channel Estimate, Symbol Timing Tracking, Frequency Sync, and Amplitude Tracking). Because analysis parameters can improve EVM, they should be chosen carefully. IEEE mandates that the test is performed over at least 20 frames (Nf), each frame being at least 16 OFDM symbols long. Random data is to be used for the symbols.

**Where is it tested?**

Testing EVM is relevant to manufacturing. If performed according to IEEE specification, EVM measurement can be time consuming especially for the lower bit-rate modulation schemes. However, EVM measurements are important and are usually performed to verify the modulation accuracy of the OFDM transmitter (EVM provides a succinct “one number” summary of a transmitter’s quality).

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**Figure 7. Graphical representation of EVM.**

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11 The same requirements apply to both 20 MHz channels and 40 MHz channels.
### Figure 8. Statistical distribution of EVM values.

<table>
<thead>
<tr>
<th>Data Rate [Mbps]</th>
<th>Coding Rate (R)</th>
<th>EVM (dB) for legacy devices</th>
<th>EVM (dB) for 802.11n devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>-8</td>
<td>-8</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>-13</td>
<td>-13</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>-16</td>
<td>-16</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>-19</td>
<td>-19</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>-22</td>
<td>-22</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>-25</td>
<td>-25</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/6</td>
<td>--</td>
<td>-28</td>
</tr>
</tbody>
</table>

Table 3. Maximum EVM versus data rate for OFDM 802.11a/g legacy devices and 802.11n devices.

### 3.5. I/Q Imbalance Measurements

I/Q Imbalance Measurements include I/Q gain mismatch and I/Q phase mismatch. In this chapter, they are described jointly since both their origin and test procedures are usually very similar.

#### I/Q Gain and Phase Mismatch

**What is it?**

Gain Mismatch originates from the two baseband modulation input signals (I and Q) having an amplitude difference at the upconverter. Phase (or Quadrature) Mismatch occurs when the two modulated baseband signals are not 100% in quadrature (90°) when being up converted by the up-converter.

**Why is it important?**

I/Q mismatch (or imbalance) is a key front-end effect for OFDM systems. Typical sources of I/Q imbalance are differential parasitic capacitances and inductances along the PCB traces, component variations, baseband or RF IC design variations.

A difference in gain or phase between the I and Q signals will cause a distortion of the constellation resulting in reduced EVM. An inspection of the constellation diagram can give an indication of the dominant mismatch: for example, the lateral separation
of the pilot tone and the twisted nature of the constellation is an indication of a phase mismatch. Typically, both gain and phase mismatches will exist, and both will contribute to EVM degradation, making it difficult to appreciate each contribution. Hence, it may be desirable to measure these parameters directly to understand the source of the impaired EVM. Usually, less than < 2% gain mismatch and less than < |2| degree phase mismatch are desirable.

Figure 9 shows the effect of I/Q mismatches on a OFDM-based QAM16 constellation diagram.

**How is it measured?**
The measurement is similar to that described for EVM. I/Q gain and phase mismatch are ideally expressed in % and degrees, respectively, as well as contribution to EVM.

**Where is it tested?**
Testing I/Q Gain and Phase Mismatch is relevant to manufacturing, even though the effect of the mismatch is captured by the EVM. With LitePoint testing solutions, I/Q Mismatch is measured automatically and its contribution to EVM is indicated.

Figure 9. Effect on the OFDM based QAM16 constellation of I/Q gain mismatch (left), I/Q phase mismatch (middle), and combined I/Q imbalance (right).
Chapter 4 Receive Measurements

This chapter describes the measurements performed during an OFDM signal reception. The most typical measurements in a production-line testing facility include:

- Receive Packet Error Rate (Receive-PER)
- Sensitivity
- Maximum Input Level
- Channel Rejection
- Receive Channel Power Indicator (RCPI)

**Receive Packet Error Rate (Receive-PER)**

**What is it?**
Receive Packet Error Rate (Receive-PER) is the number of incorrectly received data packets divided by the number of transmitted packets (sent by the test set).

**Why is it important?**
Testing Receive-PER at a given level ensures that the receiver is robust to noise, interference, distortion and other factors that might affect communication at that level. The Receive-PER typically degrades at both very low and very high signal power: Figure 10 shows a typical curve of Receive-PER performance versus the power of the signal at the input of the receiver. The lowest and highest power levels of the receiver at which the receive-PER degrades to a specified value are the Sensitivity and Maximum Input Power (described later), respectively. Receive-PER is very similar to Bit Error Rate (BER), yet much easier to measure.

**How is it performed?**
Typically, a signal generator sends a predefined number of packets at a specified power level. Most receivers can simply measure the number of good packets received; hence, when the number of sent packets is known, it is easy to calculate the PER by requesting the DUT for the number of received packets. In principle, PER should be measured over the entire input power level range.

**Where is it tested?**
Testing Receive-PER is relevant to manufacturing. Measuring PER over the entire input power level range is usually timeconsuming and generally not necessary in manufacturing. For this reason, LitePoint typically recommends determining PER at only the sensitivity level.

![Figure 10. Simplified plot of Receive-PER versus the power of the signal at the input of the receiver.](image)

**Sensitivity**

**What is it?**
Sensitivity is the minimum level of signal detected by the receiver to guarantee that a specified maximum receive packet error rate be met.
Why is it important?
Sensitivity is an important figure of merit when the receiver is in a region with very low intensity signals. It provides indirect information on the noise level of the architecture.

IEEE specifies the Sensitivity levels that must be demonstrated at different modulations and data rates, shown in Table 4 for both legacy devices (20 MHz channel, up to R=3/4 with 64-QAM modulation) and 802.11n devices.

How is it performed?
The Sensitivity of the receiver is traditionally tested by the use of a golden unit and attenuators. In this test, a packet or a frame is sent a predetermined number of times; IEEE specifies the 802.11n packet to contain 4096 bytes, and the measurement be taken at the antenna connectors as average power per receive antenna.

The manufacturer should be aware that the turbo code option available in 802.11n devices yields a lower PER, that is, it improves sensitivity performance (the sensitivity is 3-4 dB higher than with non-turbo). As a result of this, a device may pass the sensitivity test if turbo code is employed, and fail otherwise. If the DUT supports both turbo and non-turbo codes, LitePoint recommends that the latter is used during Sensitivity testing.

Where is it tested?
Testing Sensitivity is not relevant to manufacturing, since the test time can be long. However, testing a few DUTs at random in a manufacturing environment can be useful to identify quality issues. Moreover, testing at a single rate and frequency can be desirable as it allows tracking of the noise figure from device to device.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate (R)</th>
<th>Sensitivity (dB) 20MHz Channel Legacy 802.11 a/g</th>
<th>Sensitivity (dB) 20MHz Channel 802.11n</th>
<th>Sensitivity (dB) 40MHz Channel 802.11n</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>-82</td>
<td>-82</td>
<td>-79</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>-81</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>-79</td>
<td>-79</td>
<td>-76</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>-77</td>
<td>-77</td>
<td>-74</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>-74</td>
<td>-74</td>
<td>-71</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>-70</td>
<td>-70</td>
<td>-67</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>-66</td>
<td>-66</td>
<td>-63</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>-65</td>
<td>-65</td>
<td>-62</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/6</td>
<td>--</td>
<td>-64</td>
<td>-61</td>
</tr>
</tbody>
</table>

Table 4. Minimum Sensitivity at different data rates for 802.11a/g legacy devices and 802.11n devices (both 20 MHz Channel and 40 MHz Channel; applies to MCSs 0–31, 800 ns GI). Frame length 1000 packets, 1000 bytes/packet.

Maximum Input Level

What is it?
Maximum Input Level is the maximum level of signal detected by the receiver to guarantee that a specified maximum receive packet error rate be met (see Figure 10).

Why is it important?
Maximum Input Level is an important figure of merit when the receiver is very near an access point. If the power level is too high, the device can be deemed faulty by the user, while it is simply working outside of its normal operating range.

12 Turbo code is a form of error correcting, relying on soft iterative decoding to achieve high coding gains. In the past years, its advantages led to adoption in several recent digital communication standards.
IEEE specifies that a maximum Receive-PER of 10% must be achieved for a maximum input level of –30 dBm in the 5 GHz band and –20 dBm in the 2.4 GHz band for 802.11n devices\textsuperscript{13}, measured for any baseband modulation.

**How is it performed?**
The measurement procedure is very similar to that described to obtain the receiver’s Sensitivity. A frame length of 1,000 packets should be used for testing.

**Where is it tested?**
Testing Maximum Input Level is relevant to manufacturing if tested as a PER measurement at a fixed predefined level.

**Channel Rejection**

**What is it?**
Channel Rejection describes the ability to receive a wanted signal while strong interfering signals are present at a different channel. It is specified as the power difference between the interfering channel and the desired channel.

Depending on the position of the interfering signals, this performance parameter is known as Adjacent Channel Rejection (the unwanted signals are in the channels adjacent to the wanted signal\textsuperscript{14}) or Nonadjacent Channel Rejection (the unwanted signals are two or more channels away).

**Why is it important?**
Interference with signals other than the wanted one may affect the ability of the device to receive a wanted modulated signal without exceeding a given degradation.

IEEE specifies that one must meet a PER less than 10% at a power of the interfering signal (relative to the power of the desired signal) equal to the Channel Rejection values in Table 5. Note that the minimum Channel Rejection will vary with the modulation and data rate, as well as with the channel width.

**How is it performed?**
The measurement procedure is similar to that described to obtain the receiver’s Sensitivity. The test is performed by initially setting the wanted signal’s strength 3 dB above the rate-dependent sensitivity level (specified in Table 4). Then, the PER is calculated while raising the power of the interfering signals until 10% PER is met in the presence of strong interfering signals as follows:

- For all transmissions in a 20 MHz channel width, the adjacent channel center frequencies should be separated by 20 MHz when operating in the 5 GHz band and by 25 MHz in the 2.4 GHz band.
- For all transmissions in a 40 MHz channel width, the adjacent channel center frequencies should be separated by 40 MHz.
- For all transmissions in a 20 MHz channel width in the 5 GHz band, the nonadjacent channel center frequencies should be separated by 40 MHz or more.
- For all transmissions in a 40 MHz channel width in the 5 GHz band, the nonadjacent channel center frequencies shall be separated by 80 MHz or more.

The power difference between the interfering and the wanted channel when 10% PER is met is the corresponding Channel Rejection result.

Note that the Nonadjacent Channel Rejection for transmissions in a 20 MHz or 40 MHz channel width is applicable only to 5 GHz band. In all tests, the interfering signal in the adjacent channel is a conformant OFDM signal, unsynchronized with the signal in the channel under test, and with a minimum duty cycle of 50%.

\textsuperscript{13} For legacy devices in the 2.4 GHz band, Maximum Input Level specifications are less strict.

\textsuperscript{14} Adjacent Channel is defined as the non-overlapping channel which is at least 25 MHz separated from the wanted signal.
Where is it tested?
Testing Channel Rejection is typically not performed in manufacturing (it is important during the product development phase).

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate (R)</th>
<th>Adjacent Ch. Rejection (dB)</th>
<th>Nonadjacent Ch. Rejection (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>13</td>
<td>29</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>11</td>
<td>27</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>-1</td>
<td>15</td>
</tr>
<tr>
<td>64-QAM</td>
<td>5/6</td>
<td>-2 (.11n only)</td>
<td>-4 (.11n only)</td>
</tr>
</tbody>
</table>

Table 5. Minimum Channel Rejection at different modulations and coding rates. Frame length 1000 packets, 1000 bytes/packet. For 802.11n devices, levels apply to MCSs 0–31, 800 ns GI.

Received Channel Power Indicator (RCPI)

What is it?
Received Channel Power Indicator (RCPI) is a measure of the received RF power in the selected channel at the front end of the receiver. This measurement of the received signal power is usually expressed in arbitrary units.

Why is it important?
RCPI determines the amount of radio energy in the channel. Compared to other measurement, it does not provide any indication of the signal quality. Yet, it is a relatively simple measurement to obtain.

IEEE specifies that the RCPI is a monotonically increasing, logarithmic function of the received power level defined in dBm. The allowed values for the RCPI parameter consist each of an 8 bit value in the range from 0 through 220, with indicated values rounded to the nearest 0.5 dB as follows:

- 0: Power < –110 dBm
- 1: Power = –109.5 dBm
- 2: Power = –109.0 dBm
- ... and so on up to
- 220: Power > 0 dBm
- 221–254: reserved
- 255: Measurement not available, where RCPI is calculated as (Power in dBm +110)*2 for 0 dBm > Power > –110 dBm (20-90). RCPI should equal the received RF power within an accuracy of ± 5 dB within the specified dynamic range of the receiver. The received RF power is determined assuming a receiver noise equivalent bandwidth equal to the channel width multiplied by 1.1.

\(^{15}\) A similar, but not identical, metric is the RSSI (Received Signal Strength Indication), which also aims to provide some level of classification of the received signal. RSSI is acquired during the preamble stage of receiving an 802.11 frame and has (for the most part) been replaced with RCPI in the past years.
How is it performed?
The RCPI level is retrieved as reported by the DUT after a known packet level is used at the input. IEEE requires that this parameter is measured over the data portion of the received frame, and it is reported as the average of the power in all active receive chains. If the RCPI level is higher than a threshold value, the performance is considered satisfactory. The DUT often requires a minimum number of packets to average RCPI over, to compensate for signal power fluctuations due to fading.

Where is it tested?
Testing RCPI is typically not relevant to manufacturing. It may be relevant for testing UMA devices.
Chapter 5 Miscellaneous Measurements

This chapter describes measurements other than the ones necessary to test of the transmitter and receiver performance. The most useful measurements may vary depending on the particular device, yet the most commonly used ones are as follows:

- Rx/Tx Turnaround Time
- Current Consumption
- MAC Address

**Rx/Tx Turnaround Time**

**What is it?**
Rx/Tx Turnaround Time (or Timing) is defined as the time (in microseconds) that the PHY requires to change from receiving to transmitting the start of the first symbol.

**Why is it important?**
According to the Specification document, Rx/Tx Turnaround Time is the result of several contributions: first, a delay occurs when the MAC layer communicates with the PLCP through the PHY service access point; in addition, the Rx/Tx switch needs time to change status; finally, the power amplifier needs time to ramp on. Slow Rx/Tx Turnaround Time may be an indication of a MAC performance issue or of production defects; hence, verifying the correct dynamic behavior of the DUT during turnaround can be important.

Rx/Tx Turnaround Time is a component of the Short Interframe Space (SIFS), which is the time interval between the last symbol of a data frame and its acknowledgment. IEEE specifies the SIFS to be 10 μs when the DUT operates in the 2.4 GHz band and 16 μs when in the 5 GHz band.

Equally of interest to the manufacturer can be the time that the PHY requires to complete the opposite action, that is, to change from transmitting to receiving. This time is known simply as Delay.

**How is it performed?**
Typically in a manufacturing environment, the duration of the SIFS can be measured in order to verify the correct dynamic behavior of the DUT from receiving to transmitting. To do so, the tester sends a data frame to the DUT. The DUT sends an acknowledgment (ACK) of frame received back to the tester. The tester detects the ACK and measures SIFS as the interval between the end of the data frame and the start of the ACK.

Estimating the Delay is also possible. In this case, after receiving an ACK from the DUT, the tester waits for an interval of time equal to the desired delay, and then sends a new data frame. The dynamic behavior of the DUT from transmitting to receiving is verified if this second data frame is correctly received.

**Where is it tested?**
Testing Tx/Rx Turnaround Time is typically tested on random devices in the manufacturing phase. When the test is performed, generally the goal is to verify the correct dynamic behavior of the DUT. To this goal, LitePoint’s testers based on multi-packet technology can measure SIFS and estimate the delay.

**Current Consumption**

**What is it?**
Current Consumption measures the amount of current (hence, power) drawn by the DUT during operation.

**Why is it important?**
Current Consumption measurements can be difficult to perform, as a current meter is usually relatively slow. Therefore, one would need to force the DUT into modes where it is continuously transmitting, receiving, in standby and in sleep mode. This may not be needed, as current measurement during production testing does not need to be provided in detail. It is primarily intended to find shorts or other notable current consumption scenarios that clearly indicate failures in the DUT.

In many production setups, this measurement is completely omitted. In others, it can be of vital importance or can be useful to e.g.
optimize DUT performance in a power-constrained environment. In this case, the Current Consumption measurement should be included as part of the output power calibration process, such that the output power is limited to a level where the overall current consumption is within a given limit.

**How is it performed?**
A current meter is used to monitor the Current Consumption during the operation of the device. Ideally, the information on the Current Consumption is synchronized with the different modes of operation of the DUT.

**Where is it tested?**
Testing Current Consumption is relevant to manufacturing and generally performed with an external meter.

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**MAC Address**

**What is it?**
The final step of WiFi production is to write the MAC Address to the DUT, which is typically stored in an EEPROM. Testing MAC Address is verifying that this operation is performed correctly.

**Why is it important?**
Networking regulations specify that each WiFi device is given a unique MAC address. During the life of the device, the MAC header of each of the packets sent and received must contain the MAC address. If the MAC address is not stored (or, if it is written incorrectly) in the DUT, the device will not be able to communicate with other devices in the network.

**How is it performed?**
A waveform is created with the desired MAC address, loaded in the tester’s Vector Signal Generator, and sent to the DUT. If the DUT replies with an Acknowledgment (ACK), it is detected by the tester’s Vector Signal Analyzer and the DUT passes the test. In alternative, the tester can analyze a packet transmitted by the DUT in order to decode the source MAC address.

**Where is it tested?**
As all devices require a MAC address, this step is critical in manufacturing.
Chapter 6 LitePoint Offerings for 802.11 OFDM Testing

LitePoint products include a combination of hardware/software platforms, graphical user interfaces (GUI), and chipset-specific calibration and test application programs. In manufacturing, the hardware platform and chipset-specific calibration and test programs are optimized to find any manufacturing defects. Combined with support expertise, these products are key elements of LitePoint’s test system solutions.

Figure 11 shows an IQxel-M tester in a typical module test setup. LitePoint offerings for 802.11 OFDM testing included the IQxel family of testers. The turn-key application programs for manufacturing are developed in LitePoint’s IQfact+ software environment.

Figure 11. Typical module test setup based on an IQxel-M tester.

6.1. IQxel Family of Testers

IQxel
The LitePoint IQxel is the first One Box Tester (OBT) for 802.11ac devices. Its rugged design makes it simple to deploy in high-volume device manufacturing applications. IQxel delivers the quickest and easiest factory test capabilities because of its simple but robust architecture that uses a compact 2U high chassis. It requires no external PC for processing of captured measurements, and utilizes standard gigabit Ethernet communication and SCPI-compliant control commands.

IQxel-M
The LitePoint IQxel-M test system is a major advancement in the speed and efficiency for performing parallel tests on up to four wireless devices. It is the ideal solution for high-volume production environments enabling testing of numerous connectivity standards including 802.11, Bluetooth, ZigBee, Z-Wave, WiSUN, LTE-U and DECT as well as all navigation and broadcast standards, while delivering with superior reliability and test speed.

IQxel-MW
The LitePoint IQxel-MW is the world’s first test solution for 802.11ax Wi-Fi technology. Ideal for both R&D and high-volume production, IQxel-MW delivers high performance verification for the most popular wireless connectivity standards including 802.11, Bluetooth, DECT and ZigBee. Additionally, IQxel-MW offers high efficiency parallel testing for up to 16 devices. The IQxel-MW series is available in three configurations, 2 ports, 8 ports and 16 ports, which support up to 2x2 and 4x4 true MIMO testing. This can be extended to true 8x8 MIMO testing by stacking multiple testers.

6.2. IQfact+ Software Solutions

IQfact+ Manufacturing Test Software is optimized for the most popular chipsets. The test programs are a result of LitePoint’s partnership with the leading chipset manufacturers, and offer a quick, easy, and cost-effective way to develop and test chipsetspecific solutions. IQfact+ test programs run on LitePoint manufacturing test platforms to provide high-volume production testing. The software contains a flexible operator interface, a test suite with calibration and verification procedures, all tailored for the manufacturing requirements of specific chipset-based wireless products.
## Appendix A1 TP Identifiers

Included in this section is, for each test described in this document, the corresponding Test Purpose (TP) identifiers described in the Specification documents (IEEE Std 802.11™-2007 and IEEE Std 802.11n™-2009). References to additional documentation, when appropriate, are provided.

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