Introduction to Wireless LAN Measurements

From 802.11a to 802.11ac

NATIONAL INSTRUMENTS

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1. *History of Wireless LAN*

A basic Wireless Local Area Network (WLAN) network design uses the idea of an access point and clients. The access point or router is the equivalent of a base station in a cellular network. It acts as a bridge between the wired backbone and the wireless client traffic. Examples of client devices include desktops, laptops, smart phones, game consoles and printers.

In 1997, the IEEE 802.11 Working Group approved IEEE 802.11 as the world's first WLAN standard, which supported data rates of 1 Mb/s and 2 Mb/s. In 1999, two important amendments to the original 802.11 standard were ratified.

- IEEE 802.11a-1999, known as 802.11a, allowed data rates of up to 54 Mb/s in the 5 GHz band using OFDM technology.
- IEEE 802.11b-1999, known as 802.11b, allowed for up to 11 Mb/s in the 2.4 GHz unlicensed band by extending the use of direct sequence spread spectrum (DSSS) technology.

802.11a was the basis for the 802.11g amendment released in 2003, which used an identical orthogonal frequency division multiplexing (OFDM) physical layer structure but in the 2.4 GHz band. The need for 802.11g was driven by the slow adoption of 802.11a in the 5 GHz band, which contained limited channels for commercial use.

The Wi-Fi Alliance (WFA), a consortium of industry-leading companies, was formed in 1999 to facilitate better interoperability, quality, and user experience for IEEE 802.11 devices from a broad range of vendors. Manufacturers of such devices can pursue the Wi-Fi certification with the alliance, which allows them to use the Wi-Fi logo, shown in **Figure 1.1**, on WLAN devices.

Figure 1.1. Wi-Fi Logo

Since the late 1990s, the IEEE 802.11 family of standards has continued to evolve to serve consumers with increasingly higher data rates. IEEE 802.11n was officially released in 2009, though products based on the draft specification were available as early as 2006. This standard marked a substantial data rate increase over the existing 802.11a, b, and g amendments. IEEE 802.11n allowed for wider channel bandwidths (40 MHz versus 20 MHz) and was the first WLAN standard to use multiple antennas for data streams: up to 4x4 multiple input, multiple output (MIMO). As a result, 802.11n increased the theoretical data throughput from 54 Mb/s to 300 Mb/s in a 20 MHz channel, and 600 Mb/s in a 40 MHz channel.

In January 2012, a finalized 802.11ac draft amendment was released, outlining substantial improvements in data rates over 802.11n. The 802.11ac amendment provides a maximum theoretical data throughput of 6.93 Gb/s using channel bandwidths of up to 160 MHz, higher order modulation schemes, such as 256-QAM, and MIMO configurations of up to 8x8. **Table 1.1** illustrates a brief summary of the evolution of the 802.11 standard.

Year	Amendment	Throughput[1]	Purpose
1997	802.11	2 Mb/s	Original release. Included 1 Mb/s and 2Mb/s data rates in the 2.4GHz ISM band based on a physical layer (PHY).
1999	802.11a	54 Mb/s	Added an OFDM-based PHY in the 5 GHz band.
1999	802.11b	11 Mb/s	Extended the DSSS PHY from the original standard in the ISM band to a maximum of 11 Mb/s.
2003	802.11g	54 Mb/s	Implemented the ODFM-based PHY (up to 54 Mb/s) introduced in 802.11a in the 2.4GHz ISM band.
2007	802.11-2007		Consolidated the 802.11 amendments with the base standard.
2009	802.11n	600 Mb/s	Added MIMO options in both 2.4GHz and 5GHz bands. The maximum data rate can range from 54 Mb/s (mandatory) to 600 Mb/s (optional).
2012	802.11-2012		Consolidated the 802.11 amendments with the base standard.
TBD	802.11ac	6.93 Gb/s	Extended the HT (802.11n) specification in the 5GHz band to offer increased throughput through wider channel bandwidths, higher density modulation, and additional MIMO streams. Using an aggregate of stations, in conjunction with optional specifications, a theoretical throughput of 6.77 Gb/s is achievable.
TDB	802.11ad	7 Gb/s	A new standard to offer incredibly high theoretical throughput (7 Gb/s) in a 60 GHz band.

Table 1.1 History of WLAN Standard Introduction

802.11 Naming Conventions

Although engineers have long referred to the specific IEEE 802.11 amendments such as 802.11a,b, g, n, and ac to identify the specific technology they were using, the 2012 revision of the 802.11 specifications established specific naming criteria for each amendment. **Table 1.2** lists the alternate name for each of these technologies.

Amendment	Alternative Amendment Name	Enabling Technologies
802.11b	DSSS or HR/DSSS	DSSS, CCK
802.11a	OFDM	OFDM
802.11g	OFDM	OFDM
802.11n	HT	OFDM, MIMO
802.11ac	VHT	OFDM, MIMO, MU-MIMO

Table 1.2. Alternate Names for 802.11 Standards

As shown in **Table 1.2**, the 802.11a and 802.11g amendments are referred to collectively as part of the OFDM amendment.

[1] The listed throughput is the maximum possible, including optional specifications not mandatory in the standards.

2. WLAN Physical Layer Characteristics

Bands and Channels

WLAN is designed to operate in the unlicensed industrial, scientific and medical (ISM) radio bands around 2.4 GHz and 5 GHz. The 2.4 GHz band, which is used by 802.11b, 802.11g, and 802.11n, consists of 14 channels ranging from 2.412 GHz to 2.484 GHz, as shown in **Table 2.1**. Not all channels can be used in all regions, and local restrictions govern which channels are available.

Channel	Frequency
1	2.412 GHz
2	2.417 GHz
3	2.422 GHz
4	2.427 GHz
5	2.432 GHz
6	2.437 GHz
7	2.442 GHz
8	2.447 GHz
9	2.452 GHz
10	2.457 GHz
11	2.462 GHz
12	2.467 GHz
13	2.472 GHz
14	2.484 GHz

Table 2.1. Frequency Allocations For 802.11 Channels

By contrast, 802.11a, 802.11n, and 802.11ac amendments all utilize the 5 GHz band ranging from 5.15 GHz to 5.875 GHz. The radio bands available for WLAN in 5 GHz are a mix of ISM and Unlicensed National Information Infrastructure (U-NII) bands. **Table 2.2** illustrates the 5 GHz WLAN bands.

U-NII	Band
U-NII Low (U-NII-1)	5.15 – 5.25 GHz
U-NII Mid (U-NII-2)	5.25 – 5.35 GHz
U-NII Worldwide (U-NII-2e)	5.47 – 5.725 GHz
U-NII Upper (U-NII-3)	5.725 – 5.825 GHz
ISM	5.725 – 5.875 GHz

Table 2.2. WLAN 5 GHz Bands

Similar to the 2.4 GHz band, each country has specific regulations that determine how much of these bands are made available. Since the ISM and U-NII bands contain unlicensed spectrum, devices operating in this band should be able to tolerate interference from other devices.

Bandwidth Configurations

Although the original 802.11 specification allowed for channel bandwidths of 20 MHz, subsequent revisions expanded channel bandwidths to 40 MHz, 80 MHz, and 160 MHz, as shown in **Table 2.3**.

PHY	Amendment	Operating Band (GHz)	Channel Bandwidth (MHz)	Maximum MIMO	Higest Order Modulation Scheme	Theoretical Maximum Throughput (Mb/s)
DSSS	802.11 b	2.4	20	N/A	DQPSK	11
OFDM	802.11 a/g	5 / 2.4	20	N/A	64 QAM	54
HT	802.11 n	5 / 2.4	20/40	4x4	64 QAM	600
VHT	802.11 ac	5	20/40/80/160	8x8	256 QAM	6933

Table 2.3. Bandwidth Configurations for 802.11 Amendments

As shown in **Table 2.3**, the use of DSSS technology is limited to the 2.4 GHz band as part of the 802.11b amendment. In addition, the VHT specification is available only in the 5 GHz band.

Bandwidth Configurations for 802.11n and 802.11ac

802.11n allows the use of 20 MHz and 40 MHz modes. 802.11ac allows the use of 20 MHz, 40 MHz, 80 MHz, 80+80 MHz, and 160 MHz configurations. The 802.11ac amendment contains a wide range of channel bandwidth allocation options, as shown in **Figure 2.1**. Note that the 802.11ac amendment is available only in the 5 GHz band, and not in the 2.4 GHz band.

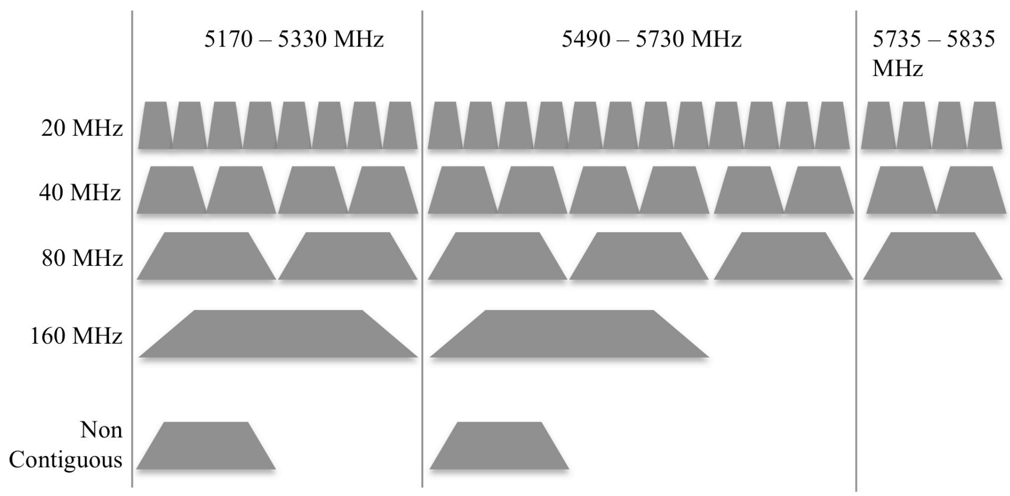

Figure 2.1. Bandwidth Allocation Options for 802.11ac and 802.11n (20 MHz, 40 MHz only)

802.11ac offers both contiguous and noncontiguous 160 MHz bandwidth configurations. The noncontiguous 160 MHz transmission is typically referred to as 80+80 mode. In the contiguous 160 MHz transmission, the signal is structured such that two 80 MHz transmissions are placed side-by-side to occupy 160 MHz of contiguous spectrum, as shown in **Figure 2.2.**

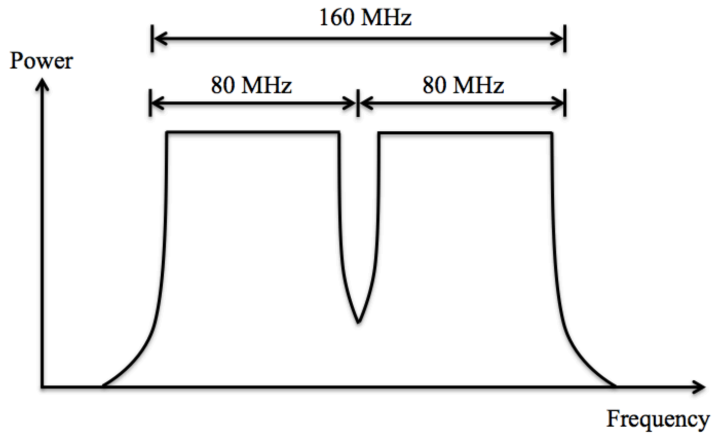

Figure 2.2. Spectral Signature of 802.11ac 160 MHz Bandwidth Transmission

As we observe in **Figure 2.2**, the 160 MHz signal is structured as the combination of two 80 MHz carriers. As a result, each of these carriers can be demodulated independently.

In addition to a contiguous 160 MHz bandwidth mode, 802.11ac also supports the 80+80 noncontiguous 160 MHz mode. When using this bandwidth option, a device can utilize any two 80 MHz channels for a combined transmission bandwidth of 160 MHz. In noncontiguous 160 MHz mode, channels can be spaced by 80 MHz or even wider, as shown in **Figure 2.3**. In the 80+80 configuration, WLAN devices typically use two RF transceivers.

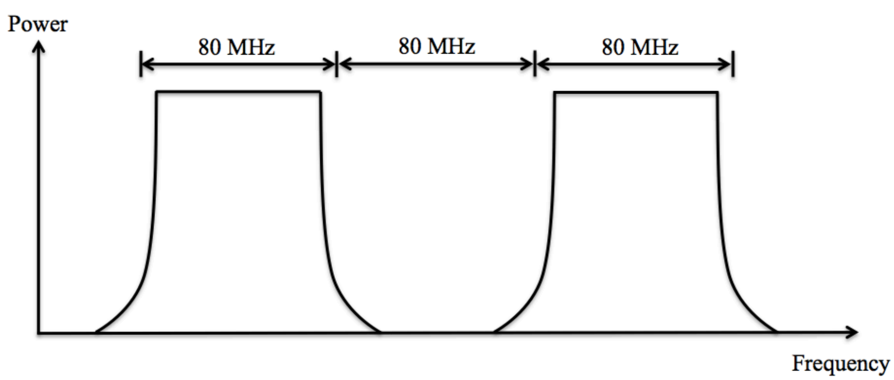

Figure 2.3. Spectral Signature of 802.11ac with 80+80 MHz Transmission

Systems using two transceivers to support the 80+80 option can also support the 160 MHz mode by default because the 160 MHz transmission is structured as the combination of two adjacent 80 MHz carriers.

Key WLAN Enabling Technologies

The 802.11 specifications use a range of key technologies that enable them to robustly achieve high data rates with reasonable spectrum utilization. For example, DSSS offers greater resilience to interference in the 2.4 GHz spectrum, which is also utilized by other wireless technologies. In addition, the 802.11a-1999 revision of the 802.11

standard was one of the first commercial wireless standards to utilize OFDM. The 802.11n amendment was also one of the first commercial standards allowing for up to 4x4 MIMO. The following sections discuss key WLAN technologies in greater detail and explain their specific implementation in WLAN.

DSSS

At the time of development of the original (1997) 802.11 standard, there was great concern over the growing number of wireless standards using the ISM spectrum at 2.4 GHz. As a result, the IEEE 802.11 committee adopted the use of DSSS technology to protect against interference. In DSSS transmissions, the modulated signal is effectively multiplied by a pseudorandom spreading code and the receiver is only able to demodulate the signal by applying the same spreading code in its tracking of the signal. The use of a spreading code effectively enhances the signal power of the desired signal and attenuates the signal power of signals that do not use the proper spreading code. This makes the receiver resilient to both narrow and wide-band interference because the receiver can effectively ignore interference.

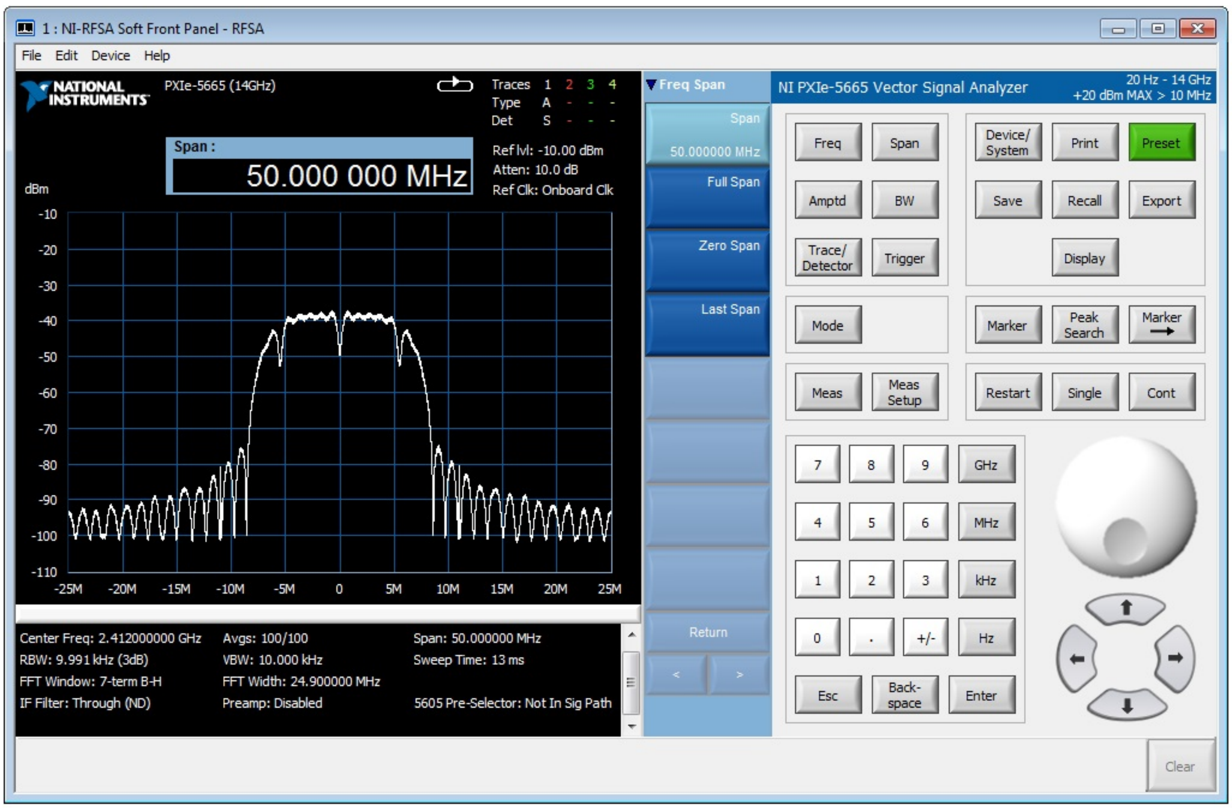

Figure 2.4. It would be nice to show an image of DSSS in the frequency domain

An 11-bit Barker sequence was used as spreading code for 1 Mb/s and 2 Mb/s data rates. The 5.5 Mb/s and 11 Mb/s data rates use complementary code keying (CCK), which uses an 8-bit spreading code. Today, the 802.11b standard is alternatively referred to as DSSS HR/DSSS. HR refers to high rate, which corresponds to the 5.5 Mb/s and 11

Mb/s data rates in 802.11b.

OFDM

With a few exceptions, the majority of WLAN flavors utilize OFDM transmission. OFDM was first adopted as part of the 802.11a specification, and then as part of the 802.11g specification. The most recent 802.11 standard collectively refers to the 802.11a and 802.11g amendments as the OFDM specification. Subsequent to 802.11a/g, all major revisions of the 802.11 standard, including 802.11n, and 802.11ac are based on OFDM technology.

The fundamental design of OFDM transmissions uses a large number of narrowband, orthogonal subcarriers to independently handle data transmissions in parallel, instead of using a single, wideband carrier. A unique feature of OFDM is that the mechanism for modulating multiple orthogonal subcarriers is accomplished through an inverse discrete Fourier transform (IDFT), as shown in **Figure 2.5**.

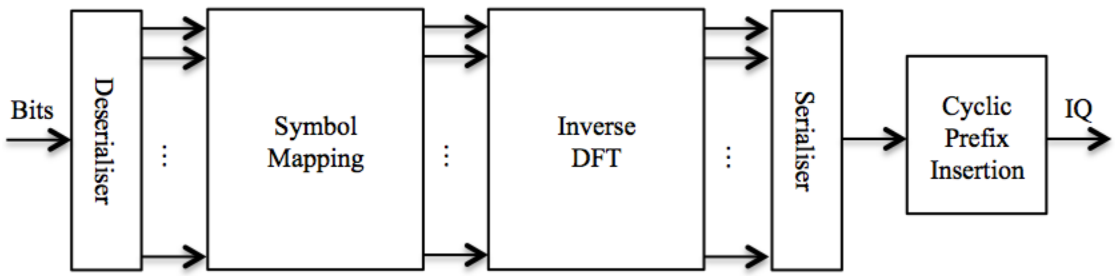

Figure 2.5. Block Diagram of a Basic OFDM Transmission.

Figure 2.5 shows that each subcarrier is modulated independently. While it is theoretically possible for OFDM transmissions to use a unique modulation scheme for each subcarrier (implemented in mobile communications standards such as LTE), WLAN transmissions require the same modulation scheme on all subcarriers. Also notice in **Figure 2.5** that a cyclic prefix is inserted after the inverse DFT. The cyclic prefix functions as a guard interval in the time domain, which minimizes the impact of intersymbol interference (ISI) between consecutive OFDM symbols and maintains the orthogonality between the sub-carriers.

The inverse DFT of an OFDM transmission effectively modulates symbols onto partially-overlapping subcarriers. However, not all subcarriers are used for data transmission, as shown in **Figure 2.6**. Pilot subcarriers are spaced throughout the channel in addition to the many data subcarriers. The pilot subcarriers are used for synchronization and channel estimation.

Notice in **Figure 2.6** that there are a few areas in the channel where subcarriers are forbidden. Typically, these areas are referred to as null carriers. Null carriers are placed on the edges of the channel to guard against inter-channel interference. Most notable is the use of a null carrier at the center of the channel. This eliminates issues related to the center frequency contaminating the OFDM modulation in that area, namely LO leakage from the mixer.

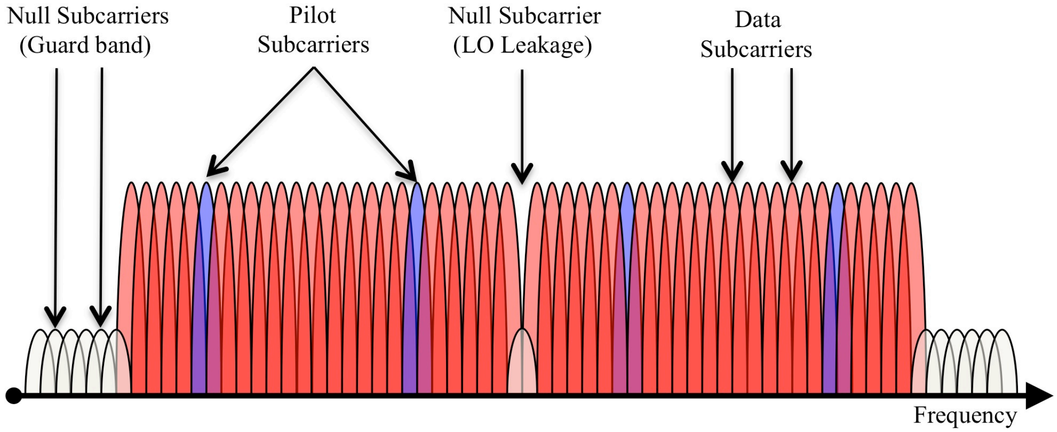

Figure 2.6. OFDM Subcarriers in the Frequency Domain.

The use of multiple narrowband carriers in OFDM systems has several benefits over the use of a single wideband carrier. One of the most significant benefits is the reduction in ISI, which greatly simplifies the complexity of channel equalization.

As the channel bandwidth of a single-carrier modulation scheme increases, the symbol period correspondingly decreases. In mobile communications environments, lower symbol periods can lead to significant ISI because multipath reflections can potentially arrive at a receiver at an exact time that is delayed relative to the signal arriving from the direct path. OFDM reduces ISI in wideband channels by using a large number of narrowband subcarriers with a relatively long symbol period. As shown in **Figure 2.7,** transmissions with a relatively long symbol period are less susceptible to intersymbol interference than those with a short symbol period.

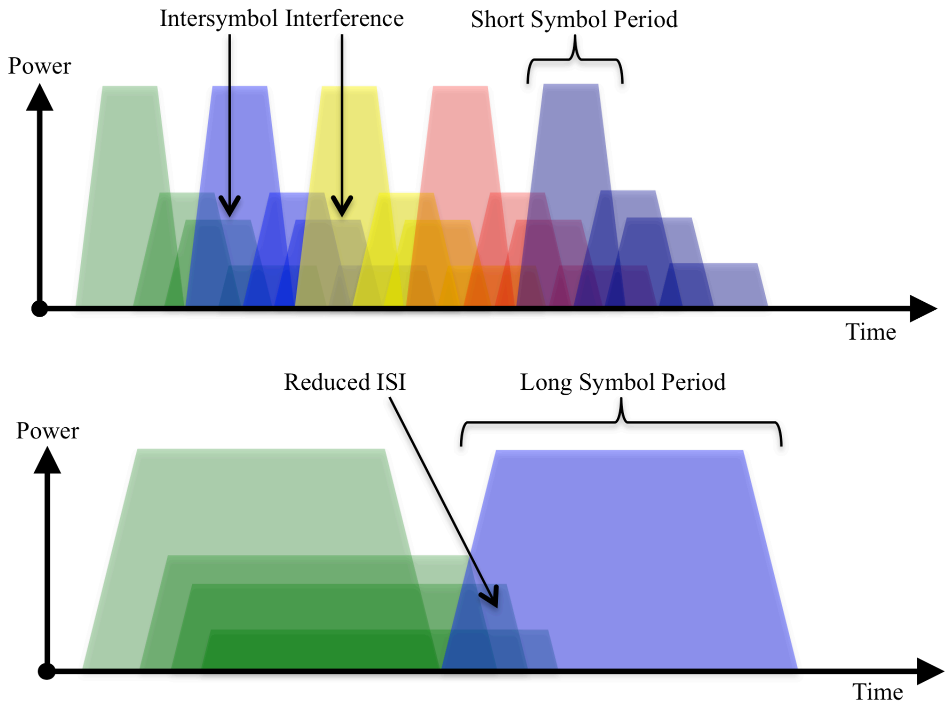

Figure 2.7. Transmissions with Longer Symbol Periods Are Less Susceptible to ISI

In WLAN transmissions, the OFDM subcarriers have a relatively low symbol rate (312.5 kHz) and the symbol period is relatively long. The combination of longer symbol periods and the implementation of the cyclic prefix reduce ISI in OFDM transmissions versus wideband single carrier transmission.

For the most common 802.11 implementations used in Wi-Fi, such as 802.11a/g, 802.11n, and 802.11ac, the OFDM transmission uses a constant symbol rate (and therefore constant subcarrier spacing) for all bandwidth configurations. **Table 2.4** shows how wider bandwidth options are implemented by using a larger number of subcarriers through a larger FFT size.

Bandwidth	**FFT Size**	**Data Subcarriers**	**Pilot Subcarriers**
20 MHz	64	52	4
40 MHz	128	108	6
80 MHz (VHT only)	256	234	8
160 MHz (VHT only)	512	468	16

Table 2.4. Bandwidth Configurations and FFT Sizes for HT and VHT PHY.

MIMO

MIMO technology, which involves multiple antennas at the transmitter and receiver, is an important technology featured in the WLAN standard. MIMO offers the option to improve the reliability and the throughput of communication over wireless channels. MIMO was first adopted in WLAN as part of the 802.11n standard, and later expanded in 802.11ac. 802.11n supports antenna configurations ranging from single input, single output (SISO) to 4x4 MIMO, with 802.11ac extending the capability to 8x8 MIMO.

Large order MIMO deployments, such as 4x4 or 8x8, are typically reserved for access points, due to both their complexity of associated cost as well as physical size limitations. End devices, such as cell phones, computers, and tablets have historically employed only a single antenna. However, with advances in integration techniques, many end devices are now using simple MIMO configurations, such as 2x2 or 3x3.

PHY	Amendment	MIMO Configurations	Note
DSSS	802.11b	SISO	
OFDM	802.11 a/g	SISO	
HT	802.11n	SISO to 4x4 MIMO	Single User-MIMO
VHT	802.11ac	SISO to 8x8 MIMO	Single-User MIMO Multi-User MIMO

Table 2.5. Bandwidth Configurations for 802.11 Standards.

As shown in **Table 2.5**, the 802.11ac amendment supports both single-user and multi-user (MU) MIMO. MU-MIMO allows for an access point to broadcast to multiple clients simultaneously using varying numbers of spatial streams per client list.

Wi-Fi access points and clients can utilize MIMO and multi-antenna technologies in various ways. One of the most well known uses of MIMO in WLAN is to enable higher data rates through the use of multiple spatial streams. This technique, known as spatial multiplexing, allows devices to transmit or receive unique data streams on different antennas simultaneously.

A second major use case for MIMO technology is to increase the diversity or redundancy of the transmission through spatial diversity. Wi-Fi systems can employ greater spatial diversity with multiple antennas at the transmitter, the receiver, or both. Spatial diversity does not increase the number of spatial streams, although it generally does allow for increased data rates in more difficult signal propagation environments through the receiver's increase in effective signal-to-noise ratio (SNR). In practical use, Wi-Fi systems often implement a combination of spatial multiplexing and spatial diversity for a combination of higher data rates and improved robustness.

Spatial Multiplexing

The mechanism by which MIMO allows for higher data rates is through the principle of spatial multiplexing. Spatial multiplexing is the transmission and reception of multiple data streams at the same time, into the same channel, using multiple antennas. The basic concept is that the receiver is able to reconstruct each transmit stream using knowledge of the wireless environment, as shown in **Figure 2.8**.

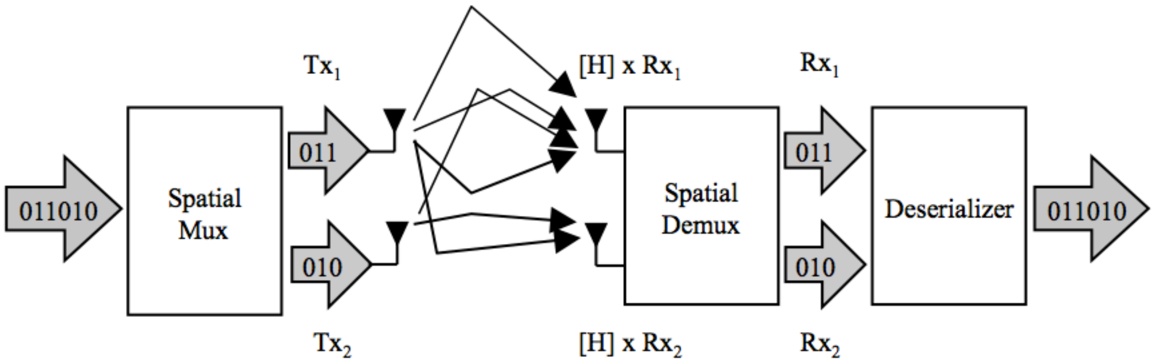

Figure 2.8. MIMO System Uses Spatial Multiplexing to Increase Data Rate

In **Figure 2.8**, both the transmitter and the receiver use multiple antennas. In addition, at any point in time, each transmit antenna will generate a different symbol. The transmissions from each antenna would appear to interfere with one other, as shown in **Figure 2.9**.

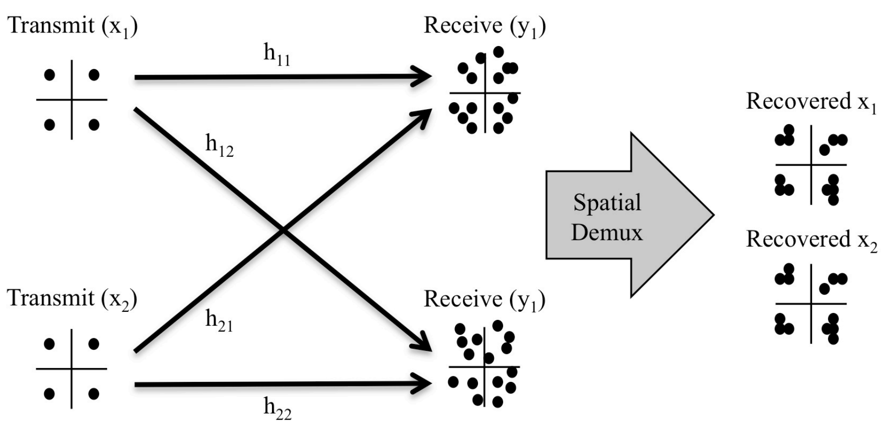

Figure 2.9. Constellation Diagram for a MIMO Channel [2]

As **Figure 2.9** also illustrates, both transmissions can be simultaneously recovered using sophisticated signal processing (spatial demultiplexing) at the receiver. As a result, each of the transmitted streams can be mapped to ideal symbols on a constellation plot. The ability to reconstruct each of the transmitted streams requires an accurate estimation of the channel through the use of multiple receive antennas.

Spatial multiplexing in MIMO systems fundamentally allows for increased data rates by allowing multiple data streams to transmit and receive in parallel. In general, you can determine highest theoretical data rate for a MIMO system by multiplying the highest data rate in a SISO system by the number of spatial streams. For example, if a SISO system were able to achieve a data rate of 100 Mb/s, an 8x8 MIMO system with 8 spatial streams could achieve a maximum data rate of 800 Mb/s.

In order to understand MIMO systems mathematically, first consider that the received signal at each antenna is the combination of each transmit antenna. In addition, the received signal is also influenced by the channel characteristics, as shown in **Figure 2.10**.

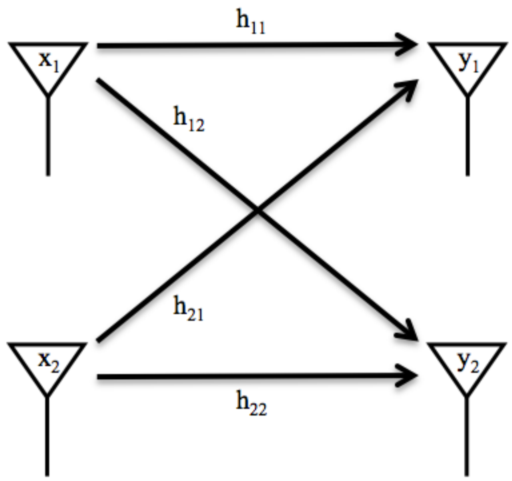

Figure 2.10. Receive Signal is a Combination of the Transmit Signal and the Channel Characteristics

Based on **Figure 2.10**, the channel model can mathematically be described using the following equations, as illustrated in **Equation 2.1 and 2.2**.

$$y_{1=}h_{11}x_1 + h_{21}x_2 + n_1$$
$$y_{2=}h_{12}x_1 + x_{22}x_2 + n_2$$

Equation 2.1 and 2.2. MIMO Channel Equations [2]

Where x_i is the signal transmitted from transmit antenna i
h_{ij} is the channel from transmit antenna i to receive antenna j
y_i is the signal received at receive antenna i
n_i represents the additive noise at receive antenna i

Equations X and Y can further be simplified in matrix form, as illustrated in **Equation 2.3 and 2.4**.

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

$$y = Hx + n$$

Equation 2.3 and 2.4. Matrix Representation of a MIMO Channel [3]

As the previous series of equations illustrates, the receiver can recover a signal that is a function of both the transmitted stream and the channel characteristics as long as the channel matrix, [H], is known. Thus, for a MIMO system to operate, it is important to accurately estimate the phase and gain characteristics of each set of channel descriptors. In practical use, the channel matrix is first estimated through the combination of known preamble sequences and/or pilot subcarriers. Once known, this matrix can be applied to the data subcarriers on subsequent transmissions.

Spatial Diversity

Achieving higher data rates is not the only use for MIMO technology. The 802.11 standards also use MIMO to implement spatial diversity at the transmitter, the receiver, or both.

One of the simplest implementations of receive diversity is the use of the maximum combining ratio (MCR) in the 1x2 single input, multiple output (SIMO) configuration. In this scenario, shown in **Figure 2.11**, the receiver simply combines the acquired signal from each of its received antennas.

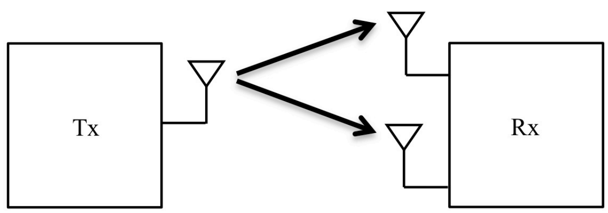

Figure 2.11. Receive Diversity in 1x2 SIMO Configuration

By combining the acquired signal from each receive antenna, the receiver increases the effective SNR of the received signal. The implementation of receive diversity improves receiver performance in low signal strength environments.

A second commonly implemented spatial diversity technique in WLAN systems is space time block coding (STBC). In STBC transmissions, each antenna is configured to transmit a different symbol in time, but each symbol is effectively transmitted multiple times. One of the simplest STBC techniques is the Alamouti code, designed by Siavash Alamouti in the late 1990s. As shown in **Figure 2.12**, a 2x1 MIMO configuration allows a transmitter to effectively generate each symbol twice.

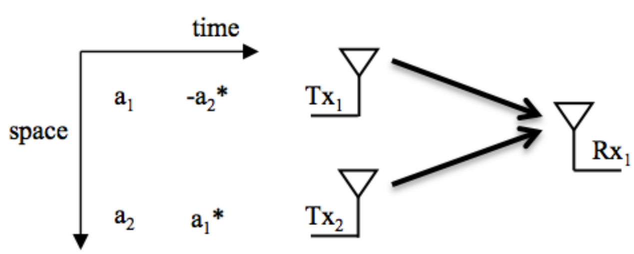

Figure 2.12. Alamouti STBC

In **Figure 2.12**, each symbol is effectively transmitted once by each transmit antennas. In the first time slot, antennas Tx_1 and Tx_2 transmit symbols a_1 and a_2, respectively. In the second timeslot, however, antenna Tx_1 transmits the negative complex conjugate of symbol a_2 and Tx_2 transmits the complex conjugate of symbol a_1. This simple open-loop coding scheme provides a more robust transmission that is more resilient to channel fading, even when there is only one receive antenna.

Multi User (MU) MIMO
In addition to its use in spatial multiplexing, MU-MIMO can optimize the available resources of the system. Although performance gains using spatial multiplexing are significant, they come at the expense of additional hardware, namely antennas and filters. This hardware typically may not be included on cost sensitive commodities such as cell phones, tablets, printers, or any other Wi-Fi connected end device. However, base stations and access points are much more likely to include this additional hardware for full MIMO capability. MU-MIMO allows the base station to dynamically use *N* antennas to independently communicate with a subset of end devices.

Figure 2.13 illustrates a MU-MIMO configuration with 8 antennas in the access point. Two of the antennas are dedicated for the bandwidth intensive needs of the media server, which is also equipped with two antennas for improved throughput. The additional antennas on the access point can each be dedicated to simpler devices with a single antenna. Multiple end devices can share a single antenna stream from the access point.

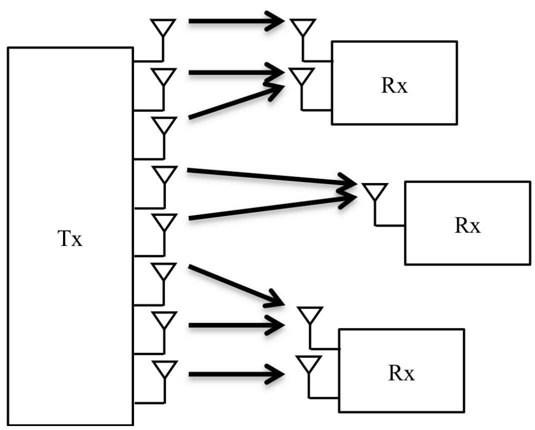

Figure 2.13. MU-MIMO Configuration

There are advantages to separating communication into a MU-MIMO transmission when possible. For example, the data streams for each user can be independent, and the power levels can be maintained independently. As a result, the access point can ramp up power transmission for the devices that need it while minimizing the transmitted power for those devices that have a less lossy channel. This allows the access point to consume less total power and minimizes the total amount of radiated energy, which in turn results in better communication channels for all users.

Theoretical Data Rate Calculation

As the wireless LAN technology evolved from the original 802.11 standard, subsequent amendments to the standard produced higher data rates using a combination of higher order modulation schemes, higher bandwidths, and MIMO technology. **Table 2.6** illustrates the maximum data rate for each of the most common iterations of the 802.11 standard.

Standard	Maximum Data Rate
802.11	2 Mb/s
802.11b	33 Mb/s
802.11a	54 Mb/s
802.11g	54 Mb/s
802.11n	600 Mb/s
802.11ac	6.933 Gb/s

Table 2.6. Maximum WLAN Data Rates

Although 802.11a/g delivered 54 Mb/s based on a SISO link in 20 MHz of bandwidth, 802.11n and 802.11ac deliver orders of magnitude improvements in data throughput by implementing advanced features such as MIMO, higher order modulation schemes, and wider channel widths (through more OFDM subcarriers). Determining the maximum data rate is a straightforward calculation, as shown in **Equation 2.5**.

Max Data Rate = $(Data\ Carriers \times Spatial\ Streams \times Bits\ per\ Symbol \times Code\ Rate)\ /\ Symbol\ Duration$

Equation 2.5. Maximum throughput of a digital communications link

One important note on nomenclature is that each combination of spatial streams, modulation type, and code rate is described differently within various revisions of the 802.11 standard. For example, with 802.11a/b/g, it is typical for one to refer to a particular combination of modulation rate and coding scheme by its data rate, as shown in **Table 2.7**.

Standard	Data Rates (Mb/s)
802.11b	1,2,5.5,11
802.11a/g	6,9,12,18,24,36,48,54

Table 2.7. WLAN Legacy Data Rates

Newer 802.11 amendments such as 802.11n and 802.11ac use the term modulation and coding scheme (MCS) because there are multiple combinations of spatial streams, modulation type, and coding rate that can yield the same theoretical data rate.

The MCS index in 802.11n extends all the way from MCS0 to MCS76, and the relatively large number of MCS indices is primarily a result of unequal modulations being supported in 802.11n. An example of unequal modulations is MCS33 which has 16-QAM for stream 1 and QPSK modulation for stream 2. The number of spatial streams is also captured as part of the MCS index in 802.11n.

In 802.11ac, the number of spatial streams is not captured in the MCS index. As a result, the MCS index in 802.11ac only extends from MCS0 to MCS9. A separate term is used to capture the spatial streams. Unequal modulations are not supported in 802.11ac.

802.11a/g Data Rate Calculations

802.11a and 802.11g use nearly identical signal structures (though in different bands), and each standard uses the same number of data carriers, symbol rates, and code rates. You can calculate a theoretical data rate for either of these standards using the parameters in **Table 2.8**.

Attribute	**Value**	**Note**
Data Subcarriers	48	Uses an FFT size of 64
Spatial Streams	1	True for all SISO links
Bits Per Symbol	6	$\log_2 64 = 6$
Code Rate	¾	Code rate at highest order modulation scheme
Symbol Duration	4 µs	Includes a guard interval of 800 ns

Table 2.8. Parameters Affecting 802.11a/g Data Rate

Given the data in **Table 2.8**, you can derive the maximum data rate for an 802.11a/g system using **Equation 2.6**.

$$\text{Maximum 802.11a/g Data Rate} = (48\times1\times6\times\tfrac{3}{4})/4\ \mu\text{s} = 54\ Mbps$$

Equation 2.6. 802.11a/g Data Rate Calculation

802.11n Data Rate Calculation

By contrast to 802.11a/g, 802.11n adds a larger number of subcarriers through its 40 MHz bandwidth high throughput (HT) option. The number of data subcarriers in the 20 MHz bandwidth is also increased to 52 as opposed to 48 in 802.11 a/g. By implementing 4x4 MIMO, 802.11n expands the number of spatial streams from 1 (SISO) to 4. Calculate the data throughput for 802.11n using the settings in **Table 2.9**.

Attribute	**Value**	**Note**
Data Subcarriers	108	Uses an FFT size of 128
Spatial Streams	4	Assuming 4x4 MIMO
Bits Per Symbol	6	$\log_2 256 = 6$
Code Rate	5/6	Code rate at highest order modulation scheme
Symbol Duration	3.6 µs	Includes a guard interval of 400ns

Table 2.9. Parameters Affecting 802.11n Data Rate

Using the attributes in **Table 2.9**, you can calculate the maximum theoretical data rate for 802.11n using **Equation 2.7**.

$$\text{Maximum Data Rate} = (108\times4\times6\times\tfrac{5}{6})/3.6\mu\text{s} = 600\ Mbps$$

Equation 2.7. 802.11n Maximum Data Rate Calculation

As shown in **Equation 2.7**, 802.11n delivers roughly one order of magnitude faster throughput than 802.11a/g. **Table 2.10** lists the types of MCS ranges supported in 802.11n.

MCS	Streams	Maximum Data Rate (40 MHz)	Note
0-7	1, Equal	150 Mb/s (MCS 7)	BPSK to 64-QAM
8-15	2, Equal	300 Mb/s (MCS 15)	BPSK to 64-QAM
16-23	3, Equal	450 Mb/s (MCS 23)	BPSK to 64-QAM
24-31	4, Equal	600 Mb/s (MCS 31)	BPSK to 64-QAM
32	1, Equal	6.7 Mb/s	BPSK and SISO
33-38	2, Unequal	225 Mb/s (MCS 38)	
39-52	3, Unequal	360 Mb/s (MCS 52)	
53-76	4, Unequal	495 Mb/s (MCS 76)	

Table 2.10. WLAN 802.11n Data Rates

802.11ac Data Rate Calculation

By contrast, to 802.11a/g and 802.11n, 802.1ac adds a larger number of subcarriers through the 160 MHz bandwidth very high throughput (VHT) option. Added spatial streams, use of the 256-QAM modulation scheme, and a higher code rate also contribute to maximum data throughput. You can use calculate the maximum data throughput for 802.11ac using key attributes of the standard, which are shown in **Table 2.11**.

Attribute	Value	Note
Data Subcarriers	468	Uses an FFT size of 512
Spatial Streams	8	Assuming 8x8 MIMO
Bits Per Symbol	8	$\log_2 256 = 8$
Code Rate	5/6	Code rate at highest order modulation scheme
Symbol Duration	3.6 µs	Includes a guard interval of 400ns

Table 2.11. Parameters Affecting 802.11ac Data Rate

Using the settings from **Table 2.11**, you can calculate the maximum theoretical data rate for 802.11ac using **Equation 2.8**.

$$\text{Maximum Data Rate} = (468 \times 8 \times 8 \times \tfrac{5}{6}) / 3.6\mu\text{s} = 6.933\ Gbps$$

Equation 2.8. 802.11ac Maximum Data Rate Calculation

Although 6.933 Gb/s is the maximum theoretical data rate of 802.11ac, a wide range of data rates are possible given number of supported bandwidths and spatial streams. **Table 2.12** illustrates several of these configurations for 802.11ac.

Channel BW	Spatial Streams	Modulation Scheme	Code Rate	Data Subcarriers	Maximum Data Rate
20 MHz	1	256 QAM	3/4	52	86.7 Mb/s
40 MHz	2	256 QAM	5/6	108	400 Mb/s
80 MHz	4	256 QAM	5/6	234	1.733 Gb/s
160 MHz	8	256 QAM	5/6	468	6.933 Gb/s

Table 2.12. WLAN 802.11ac Data Rates

The maximum data rates in **Table 2.12** define only a theoretical maximum data rate. In practice, actual devices will achieve rates that are often substantially lower than the theoretical maximum due to factors such as packet overheads, and medium sharing.

WLAN Physical Layer Measurements

Understanding the physical layer measurements is critical for both the device manufacturing process and the design process. Throughout the design process of a WLAN device, you use a wide range of physical layer measurements to better understand and characterize device performance. This section describes two types of WLAN measurements: transmit measurements, which describe the signal output from the device, and receiver measurements, which characterize the ability of a device to demodulate a received signal.

PHY layer testing of 802.11 devices is described in the 802.11 specifications. While many of the measurements for 802.11 amendments are similar, each of these is defined individually in the corresponding section of the specification document. **Table 2.13** describes which sections of the 802.11 specification document define transmitter (Tx) and receiver (Rx) specifications for WLAN devices for each technology.

Amendment	PHY	Tx Specifications	Rx Specifications
802.11b	DSSS	Sections 16.4.7, 17.4.7	Sections 16.4.8, 17.4.8
802.11a	OFDM	Section 18.3.9	Section 18.3.10
802.11g	OFDM	Section 18.3.9	Section 18.3.10
802.11n	HT	Section 20.3.20	Section 20.3.21
802.11ac	VHT	Section 22.3.18	Section 22.3.19

Table 2.13. Key to 802.11 Specifications

Note that the sections listed in **Table 2.13** for 802.11ac transmitter and receiver measurements are based on the 2013 D5 draft revision of the 802.11 specification.

Instrument Configuration for WLAN Measurements

Test and measurement of fully integrated WLAN devices generally requires a combination of a vector signal generator (VSG) and a vector signal analyzer (VSA). In some instances, both products are combined into a single instrument known as a wireless test set. National Instruments offers an integrated VSG and VSA with a userprogrammable FPGA, known as a vector signal transceiver (VST).

When testing a fully assembled WLAN device, the transmit and receive functionality of the device are combined into a single port. As a result, the test setup requires an RF switch or a combiner/splitter to connect the WLAN device to both the VSG and VSA, as shown in **Figure 2.14**.

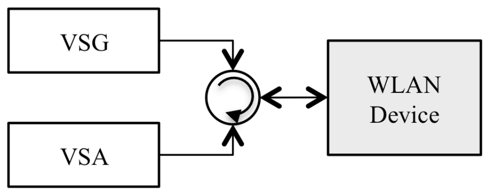

Figure 2.14. Typical test setup for a WLAN device

When testing a WLAN power amplifier (PA), the test configuration is substantially simpler than the example shown in **Figure 2.14**. In this case, the VSG sources a WLAN signal, and the VSA is connected to the output of the PA, as shown in **Figure 2.15**.

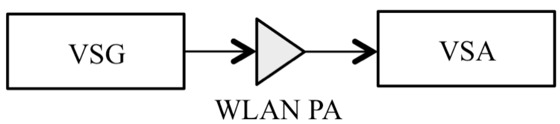

Figure 2.15. Typical test setup for a WLAN PA

In general, transmit measurements are applicable to the validation of integrated WLAN devices and discrete components such as PAs and low noise amplifiers (LNAs). However, receiver measurements are only required when testing an integrated WLAN device containing a full receiver.

When selecting a signal analyzer for WLAN testing, keep in mind that the WLAN transmitter measurements include metrics of spectral leakage and modulation quality. As a result, the signal analyzer must have corresponding vector analysis capabilities in order to appropriately demodulate the signal.

3. *Transmit Measurements*

There are three categories of WLAN transmitter measurements, including measurements of power, modulation quality, and spectral quality. Many of the measurements for various 802.11 technologies are similar, though not all measurements apply to all standards. **Table 3.1** shows which measurements apply to specific 802.11 standards and the section within the 802.11 specification where the measurement is defined. This document interchangeably uses the alternate names (DSSS, OFDM, HT, and VHT) to describe 802.11 amendments that include 802.11b, 802.11a/g, 802.11n, and 802.11ac.

Measurement Category	Measurement	DSSS (802.11b)	OFDM (802.11a/g)	HT (802.11n)	VHT (802.11ac)
Power	Transmit Power	Defined by Local Regulations			
	Power-on and Power-down ramp (DSSS)	16.4.7.8	N/A	N/A	N/A
Modulation Quality	Modulation Accuracy	16.4.7.10	18.3.9.7.4	20.3.20.7.3	22.3.18.4.3
	Chip Clock Frequency Tolerance (DSSS)	16.4.7.7	N/A	N/A	N/A
	Symbol Clock Frequency Tolerance (OFDM)	N/A	18.3.9.6	20.3.20.6	22.3.18.3
	Center Frequency Tolerance	16.4.7.6,	18.3.9.5	20.3.20.4	22.3.18.3
Spectrum	Spectrum Mask	16.4.7.5, 17.4.7.4	18.3.9.3	20.3.20.1	22.3.18.1
	Spectral flatness	N/A	18.3.9.7.3	20.3.20.2	22.3.18.2
	Carrier Suppression (DSSS)	16.4.7.9	N/A	N/A	N/A
	Center Frequency Leakage (OFDM)	N/A	18.3.9.7.2	20.3.20.7.2	22.3.18.4.2

Table 3.1. 802.11 Specifications for Transmit Measurements

Note that the sections listed in **Table 3.1** for 802.11ac transmitter and receiver measurements are based on the 2013 D5 draft revision of the 802.11 specification.

Maximum Transmit Power

Maximum transmit power values are not included in the transmit specifications shown in **Table 3.2** because the maximum transmit power of a WLAN device is by the local governmental regulatory body of the country in which the device is certified. The maximum output power is specified as a maximum equivalent isotropically radiated power (EIRP) and is dependent on the transmitter output power and the antenna gain. In general, the maximum transmitted output power in most countries ranges from 60 mW to 1W (EIRP). These limits are generally specified by band and often differ for devices intended for indoor and outdoor use. **Table 3.2** shows maximum limits for several countries.

Country	Band	Maximum Transmit Power mW (Radio Tx+Antenna Gain=EIRP)	Indoor/ Outdoor Use
United States	a	200	Indoor
	b/g	1,000	Both
Brazil	a	200	Indoor
	b/g	1,000	Both
South Africa	a	N/A	N/A
	b/g	1,000	Both
France	a	200	Indoor
	b/g	100	Both
China	a	600	Both
	b/g	600	Both

Table 3.2. Maximum Transmit Power by Country

Although the 802.11 specification does not specifically prescribe maximum power requirements for WLAN devices, power measurements serve as an important characteristic for indexing other transmit measurements. For example, modulation quality measurements such as error vector magnitude (EVM) are often heavily influenced by the linearity of the transmitter, which is output power dependent.

Average Power

Average power is perhaps the most commonly used power measurement. Average power is the time-averaged power level of an 802.11 packet over the duration of a burst. Modern test equipment has a variety of ways to specify average power level. One of the most common is time-gated average power, which measures the average power over a burst. You can also measure power such that the burst power and idle time are included. In this metric, the duty cycle of the burst has a substantial effect on the power result.

Because average power of a WLAN transmission is usually a gated power measurement, a VSA is typically required for this measurement. Average power is often referred to as the transmit power and is a primary index for all of the other measurements. When performing receiver tests, the average power is the description of the input power level to the DUT. In addition, for MIMO measurements, an average power is measured for each physical channel.

Peak Power

802.11 signals, especially the higher order OFDM types, can often exhibit extremely large peak-to-average-power-ratios (PAPR). Measure the PAPR of a signal by measuring the peak power of a transmitted signal in conjunction with the average power.

OFDM signals have relatively high PAPR characteristics because of the structure of the signal itself. In OFDM transmissions, a large number of subcarriers are transmitted in parallel, which allows subcarriers to either add or subtract from one another at each point in time. As a result, the power statistics of an OFDM transmission are almost Gaussian in nature, leading to PAPRs that typically range from 10 dB to 12 dB.

Although the actual PAPR of a transmitted WLAN signal should remain relatively constant over the operating range of the device, this is not always the case. At higher output power levels of the transmitter, when the output PA is operating in its nonlinear region, the PAPR will begin to decrease because of clipping. As a result, PAPR remains an important troubleshooting metric for a transmitter that exhibits poor modulation quality. If the poor modulation quality (EVM) is due to the nonlinearity of the output PA, you can usually correlate this source of error with a lower PAPR result.

The PAPR of the signal also has a significant impact on the measurement settings of the signal analyzer. When making 802.11 measurements, the reference level of the VSA must be set appropriately to capture the amplitude range of the transmitted packet in its entirety. Typically, packet power levels are specified as an average power. In this case, the reference level should be set greater than the average power plus the expected PAPR of the packet. For better visualization into the statistics of the PAPR, refer to the CCDF measurements section. For MIMO measurements, an average power is measured for each physical channel.

Power Versus Time

Power versus time trace describes the instantaneous power of a transmitted signal versus time. Power versus time provides a visualization of the signal for troubleshooting purposes, rather than a metric of transmitter performance. Correlating the measured power with a specific time portion of the burst can help identify time-dependent power issues.

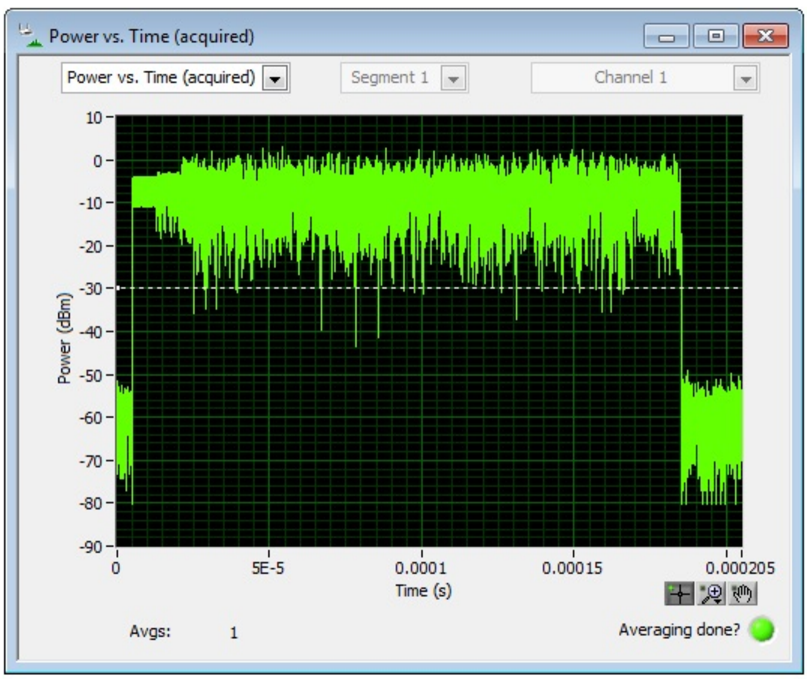

Figure 3.1. Power Versus Time Trace

For example, zooming in on a power vs. time measurement can help to detect burst rise and fall times and determine whether a valid burst has been captured.

Cross Power (MIMO)

The cross power measurement is specific to MIMO configurations. Cross power is a metric of how much power from one stream is bleeding into another channel. Consider the simple case of direct channel mapping for a 4x4 MIMO configuration with mapping matrix *M*:

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Equation 3.1. Direct Mapping Matrix for a 4x4 MIMO Configuration

In reality, the null elements outside of the diagonal, the cross terms, in *M* will have a small but finite value. As the cross terms increase, the power on a given channel due to interference from a different channel can begin to interfere with the intended operation, leading to a decrease in channel-based metrics. The ideal cross power, denoted as *CPid,* and the measured cross power, denoted *CPms,* are compared in **Equation 3.2.**

$$CP_{id} = \begin{bmatrix} NA & -\infty & -\infty & -\infty \\ -\infty & NA & -\infty & -\infty \\ -\infty & -\infty & NA & -\infty \\ -\infty & -\infty & -\infty & NA \end{bmatrix}, \text{and } CP_{ms} = \begin{bmatrix} NA & CP_{2,1} & CP_{3,1} & CP_{4,1} \\ CP_{1,2} & NA & CP_{3,2} & CP_{4,2} \\ CP_{1,3} & CP_{2,3} & NA & CP_{4,3} \\ CP_{1,4} & CP_{2,4} & CP_{3,4} & NA \end{bmatrix}.$$

Equation 3.2. CPid and CPms Comparison for a 4x4 MIMO Configuration

In both cases, the diagonal elements *CPi,i* are undefined and the cross elements are measured in dB. In the ideal case, the cross elements would all be equal to – ∞ dB - which would describe the case where no power from any given stream leaks into any unintended channel. In the real measured case, *CPi,j* (dB) represents the relative power from stream *i* leaking into channel *j*. In cases where the cross power deteriorates, focus on channel isolation in the DUT to solve the issue.

Power-On and Power-Down Ramp

One specific dynamic power characteristic that is defined by the 802.11 specification is the power-on and power-down ramp. Because WLAN devices operate in a time division duplexed (TDD) manner, fast ramp-up and ramp-down times are required to enable faster transmission and reception. The power-on and power-down requirements apply only to the DSSS or 802.11b amendment.

According, the 802.11 specifications, the transmit power-on ramp, defined as the time for a burst to go from 10% to 90% of the maximum power, shall be no greater than 2 µs. The transmit power-down ramp, defined as the time for a signal to go from 90% to 10% of its maximum power, will be no greater than 2 µs. When measuring the power-on and power-down ramp, the signal analyzer's acquisition length should include the entire packet.

Modulation Quality

The modulation quality of a WLAN transmission affects the likelihood it can be demodulated without incurring significant frame or bit errors. Modulation quality includes the following categories: modulation accuracy (EVM), chip and symbol clock frequency tolerance, and center frequency tolerance.

Error Vector Magnitude

Error Vector Magnitude (EVM) is the primary metric of modulation quality for an 802.11 transmitter. Because EVM captures a wide range of impairments of a modulated transmission, it is also one of the most useful metrics of transmitter performance. When reporting EVM, the RF signal analyzer first measures the phase and magnitude error of modulated symbols. In this measurement, the error vector is based on the error in phase and magnitude between the ideal symbol's phase and magnitude and the measured result. To compute EVM, the error vector is divided by the magnitude vector of the ideal symbol. The resulting ratio is the EVM. **Figure 3.2** shows the relationship between the measured vector, the ideal vector, and the error vector.

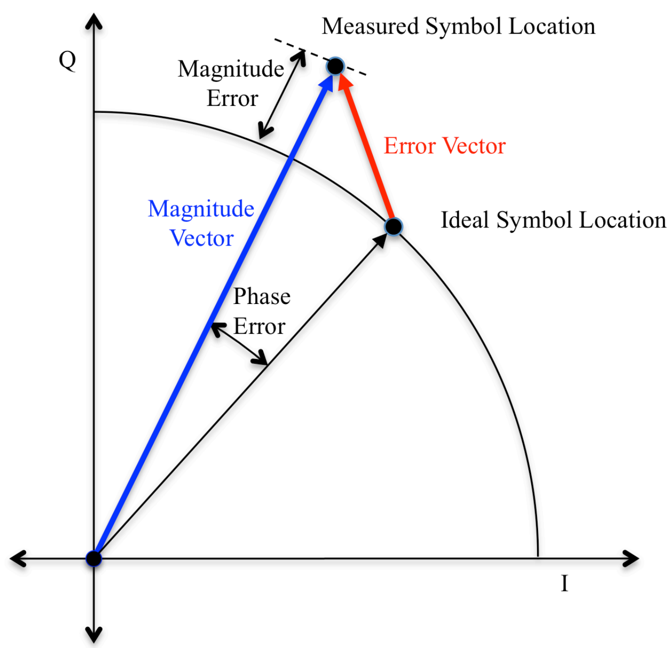

Figure 3.2. Error Vector and its Components

Although EVM is described as a ratio between an error vector and a magnitude vector, the result can be depicted either in percent (%) or in dB. You can convert EVM calculations from percent to dB using **Equation 3.3**.

$$EVM_{dB} = 20\log(EVM_{\%})$$

Equation 3.3. EVM Conversion From Percent to dB

Wireless standards using single carrier modulation typically prescribe an EVM limit in percent, while OFDM systems typically prescribe an EVM limit in dB. Because EVM is fundamentally a metric of modulation quality for only one symbol, this metric is typically represented either as a peak value or as a root mean square (RMS) value over a large number of symbols.

For DSSS transmissions, the highest order modulation scheme is DQPSK (Differential Quadrature Phase Shift

Keying). As shown on the constellation diagram in **Figure 3.3**, all symbols have the same amplitude, from the origin, and the same phase offset from each other. As a result, 802.11 specifications provide a peak EVM limit for DSSS transmissions.

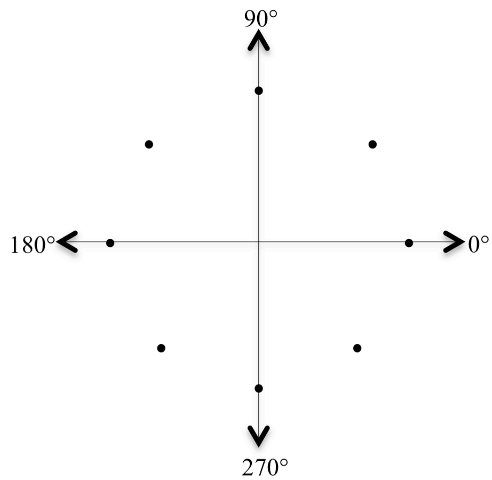

Figure 3.3. DQPSK Constellation.

Although the DSSS subsection specifies the EVM value to be the peak error out of the symbols, OFDM, HT, and VHT transmissions provide EVM requirements that are based on an RMS value. As shown in **Figure 3.4**, the magnitude vector for higher order modulation schemes such as 64-QAM varies widely from one symbol location to the next.

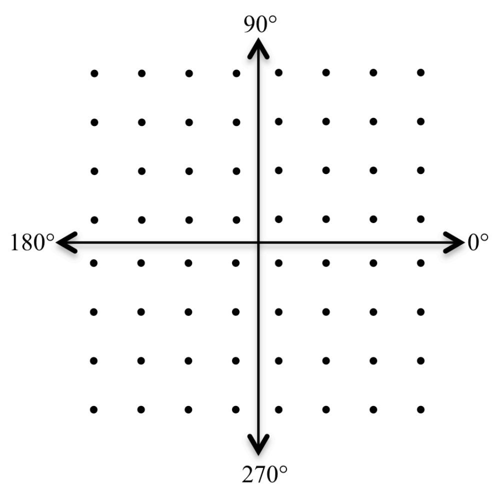

Figure 3.4. 64-QAM Constellation.

In **Figure 3.4**, a peak EVM measurement would be dominated by symbols closer to the origin, which have smaller magnitudes. As a result, a peak EVM metric is not as useful as an RMS EVM metric. Thus, OFDM-based transmissions such as 802.11a/g/n/ac specify EVM requirements as an RMS value.

In addition, the 802.11 specifications prescribe different RMS EVM limits for each modulation scheme a transmitter might use for a transmission. Each amendment has a similar EVM requirement for various combinations of modulation scheme and code rate, though not all combinations of modulation scheme and code rate are supported by the standard, as shown in **Table 3.3**.

Modulation Scheme	**Code Rate**	**EVM Limit (802.11a/g)**	**EVM Limit (802.11n)**	**EVM Limit (802.11ac)**
BPSK	½	-5 dB	- 5 dB	- 5 dB
BPSK	¾	-8 dB	N/A	N/A
QPSK	½	-10 dB	-10 dB	-10 dB
QPSK	¾	-13 dB	- 13 dB	- 13 dB
16-QAM	½	-16 dB	-16 dB	-16 dB
16-QAM	¾	-19 dB	-19 dB	-19 dB
64-QAM	2/3	-22 dB	-22 dB	-22 dB
64-QAM	¾	-25 dB	-25 dB	-25 dB
64-QAM	5/6	N/A	-27 dB	-27 dB
256-QAM	¾	N/A	N/A	-30 dB
256-QAM	5/6	N/A	N/A	-32 dB

Table 3.3. EVM Limits for OFDM, HT, and VHT

In **Table 3.3**, there is a very clear relationship between the modulation quality of a transmission and the complexity of the modulation scheme. For example, higher order modulation schemes such as 256-QAM require better modulation quality than lower order schemes such as BPSK. In Figure 3.5, observe the specification limits superimposed on a constellation plot for a 256-QAM 5/6 code rate transmission. In this instance, the EVM limit is -32 dB and the measured EVM is -dB.

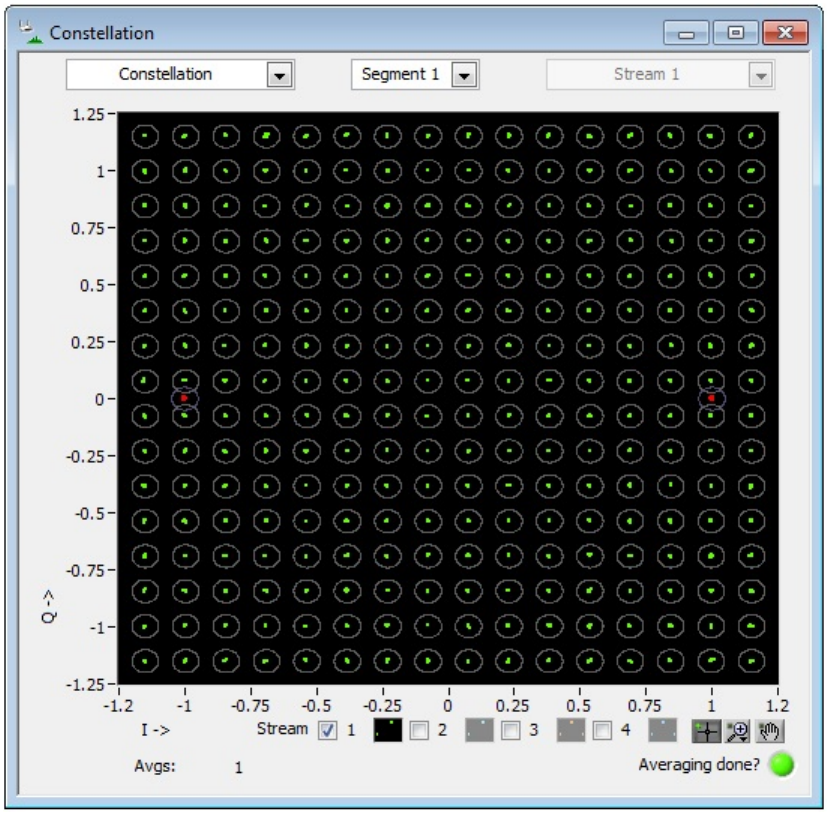

Figure 3.5 Constellation Plot of 802.11ac

Note that the modulation quality of a transmission is a function of transmitter impairments and is usually independent of the modulation scheme of the transmission. For example, a transmitter that delivers an EVM of -36 dB for 16-QAM, will generally deliver the same EVM performance when transmitting a signal using 256-QAM. Transmitters that are required to produce 256-QAM (802.11ac devices) transmissions have higher modulation quality requirements than those required to produce 64-QAM (802.11a/g/n).

Constellation Error

While the dominant EVM measurements are also derived from the symbol constellation, they are general aggregates of all the contributing errors. The constellation also contains information pointing to the source of the error. Additional metrics that are extracted from the constellation are common pilot error (CPE), IQ gain imbalance, quadrature skew and timing skew.

Timing Skew (OFDM)

Timing skew is the difference between the sampling instants of in-phase (I) and quadrature-phase (Q) components of the complex baseband signal.

Quadrature Skew

Quadrature Skew is the deviation in angle from 90 °between the in-phase (I) and quadrature-phase (Q) signals.

I/Q Gain Imbalance
I/Q gain imbalance is the ratio, in dB, of the mean amplitude of the in-phase (I) signal to the mean amplitude of the quadrature-phase (Q) signal.

Chip Frequency Tolerance (DSSS) and Symbol Clock Frequency Tolerance (OFDM)
This measurement is the difference between the Sample Clocks of each of the digital-to-analog converters (DAC) producing the I and Q signals.

Center Frequency Tolerance
A final characteristic relating to the modulation quality of a transmission is the center frequency tolerance. Ideally, if a transmitter is designed to output a signal at 2.412 GHz, the precise center frequency of that signal will be 2.412 GHz. However, impairments in the clocking circuitry of the transmitter can result in a transmission that is slightly offset in frequency from the desired location. Poor frequency accuracy in either the transmitter or receiver in a WLAN system can lead to a scenario where the receiver is unable to demodulate an over-the-air transmission.

The 802.11 specifications require a specific frequency accuracy in parts per million (PPM) and this result is measured using a VSA. For example, if the carrier frequency offset is 4 KHz and the center frequency is 2412 MHz, this corresponds to 1.658 ppm ((4 KHz/2,412 MHz) * 1 * 10e6). **Table 3.4** lists the frequency accuracy requirement, ranging from 10 to 25 ppm, for each 802.11 PHY.

PHY	+/- ppm
DSSS	25
OFDM	20
HT 2.4 GHz Band	25
HT 5 GHz Band	20
VHT	20

Table 3.4. Carrier Frequency Offset Limits

Spectrum Measurements
The final measurements that characterize the performance of WLAN transmitters are spectrum measurements. Unlike modulation accuracy measurements, which are designed to ensure that a compatible receiver can demodulate the transmitted signal successfully, frequency domain measurements are intended to certify that the signal will not interfere with others. Many frequency domain measurements do not require the phase content of the captured signal. Thus you can use a spectrum analyzer for these measurements if a VSA is unavailable.

Spectrum Mask
The spectrum mask measurement prescribes a set of limits superimposed on the power spectral density of a transmitted packet. Because the spectrum mask is a metric of the interference in adjacent channels, these limits become more stringent farther from the center of the transmitted channel. Unlike cellular communications such as UMTS and LTE, which specify an integrated power transmitted, the spectrum mask of WLAN is meant only to evaluate the peak offending frequency bin.

Spectrum mask is a pass/fail measurement that involves the comparison of a mask with the spectrum of the signal.

For DSSS, the spectrum mask measurement uses a resolution bandwidth (RBW) of 100 kHz and a video bandwidth (VBW) of 30 kHz. For OFDM technologies, the spectrum mask measurement requires an RBW and VBW of 100 kHz each.

DSSS Spectrum Mask

For DSSS transmissions, the spectrum mask profile defines the maximum emitted power in bandwidths that are between 11 MHz and 22 MHz offset from the carrier, and greater than 22 MHz offset from the carrier. In **Figure 3.6**, the DSSS mask defines the reference point, 0 dBr, as 0 dB relative to a specific reference point. The reference point is defined as the maximum spectral density of the transmission.

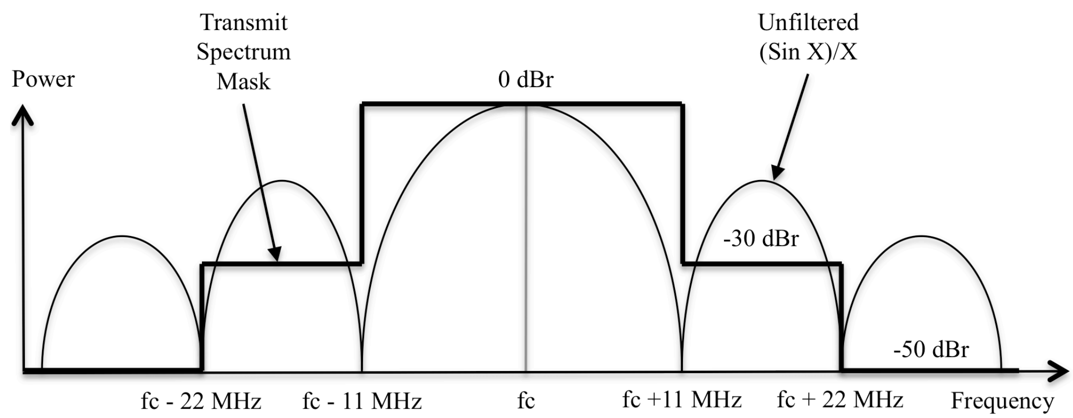

Figure 3.6. DSSS Spectrum Mask Limits

As shown in **Figure 3.6**, a DSSS transmission cannot exceed -30 dBr between 11 MHz and 22 MHz offset from the carrier. In addition, the power spectrum density of a transmission cannot exceed -50 dBr at offsets greater than 22 MHz from the carrier frequency.

OFDM, HT, and VHT Spectrum Mask

For 802.11a/g/n/ac, the spectrum mask follows a similar profile, but with appropriate accommodations for wider bandwidths or the 80+80 bandwidth configuration of 802.11ac. To generalize the spectrum mask limits for OFDM, HT, and VHT, investigate the spectrum mask for OFDM. As shown in **Figure 3.7**, key mask limits are -20 dBr, -28 dBr, and -40 dBr for an OFDM transmission.

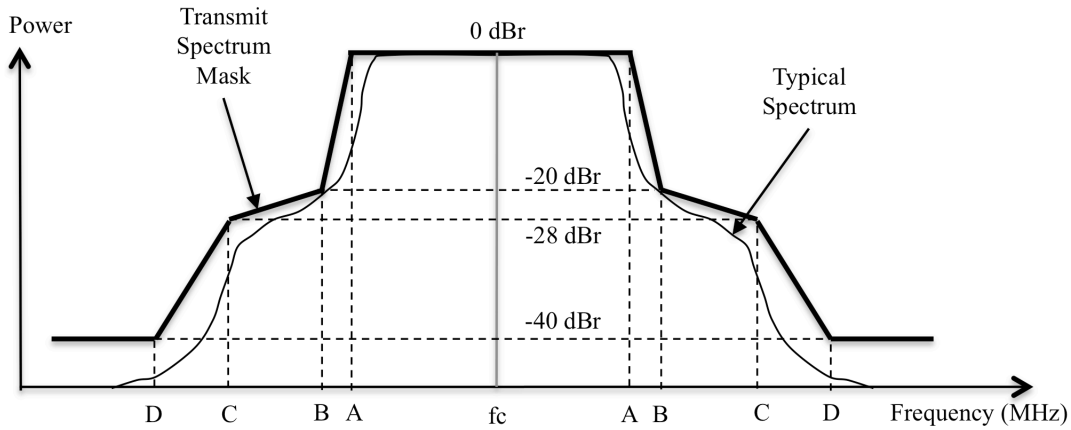

Figure 3.7. OFDM Spectrum Mask for 802.11a

Key offsets for a 20 MHz bandwidth signal are 9 MHz, 11 MHz, 20 MHz, and 30 MHz. **Table 3.5** describes key offset for signals of various bandwidths.

Signal Bandwidth	Offset A	Offset B	Offset C	Offset D
20 MHz	± 9 MHz	± 11 MHz	± 20 MHz	± 30 MHz
40 MHz	± 19 MHz	± 21 MHz	± 40 MHz	± 60 MHz
80 MHz	± 39 MHz	± 41 MHz	± 80 MHz	± 120 MHz
160 MHz	± 79 MHz	± 81 MHz	± 160 MHz	± 240 MHz

Table 3.5. Frequency Offsets for 802.11 Masks

Another distinction between various 802.11 amendments is the maximum emissions outside of the farthest offset from carrier. The limit of -40 dBr for the farthest offset applies to all transmissions except for HT 2.4 GHz. For HT 2.4 GHz, the maximum emissions for all transmissions outside the farthest offset is -45 dBr.

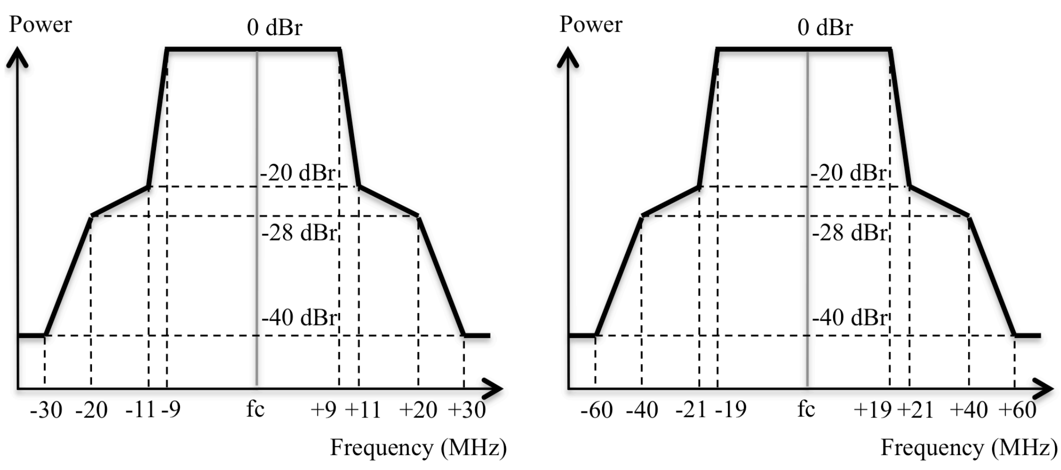

Figure 3.8. 20 and 40 MHz Emissions Masks for HT in 5 GHz band

For the 80+80 mode of 802.11ac, the transmitted spectrum mask computation is the linear sum of the two 80 MHz masks, as shown in **Figure 3.9**.

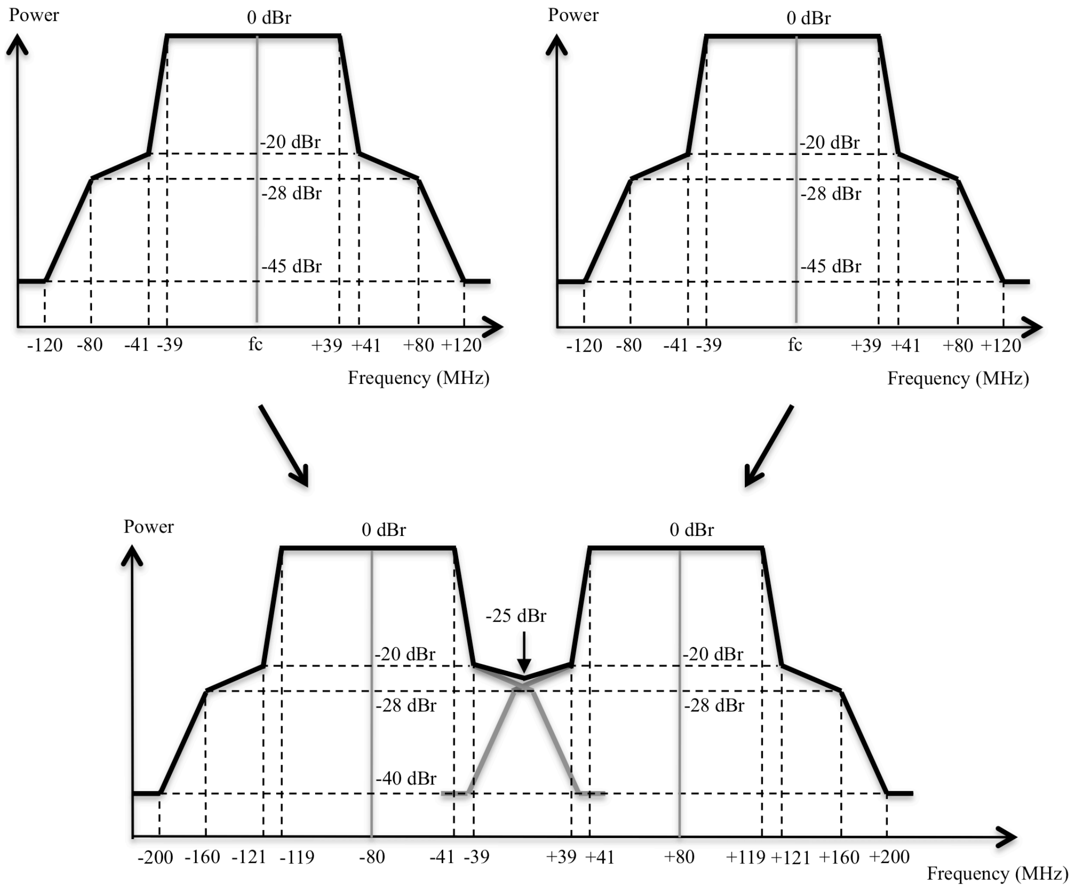

Figure 3.9 VHT 80+80 MHz Channel Spectrum Mask Limits

In **Figure 3.9**, the outer edges of the spectrum mask for the 80+80 configuration match that of the 80 MHz bandwidth option. However, the requirements for the overlapping sections are higher because they are the sum of the two limits. For example, at the -39 MHz and +39 MHz frequency offsets the limit is -25 dBr because -28 dBr + -28 dBr = -25 dBr.

Carrier Suppression (DSSS)

Although the local oscillator (LO) in an ideal quadrature modulator would not produce leakage at the RF output, this is not the case in practice. Any DC offset in a quadrature modulator will produce a spur at the output of the device that occurs at the precise frequency of the LO. This spur is the center frequency leakage or LO leakage. For DSSS transmissions in 802.11b, LO leakage is captured in the carrier suppression measurement. RF carrier suppression, measured at the channel center frequency, shall be at least 15 dB below the peak SIN(x)/x power spectrum. Because DSSS is a single carrier modulation scheme, carrier leakage can only be measured when the transmitter is generating a repeating symbol pattern.

For example, by setting the transmitter to generate a repetitive 01 data sequence with the scrambler disabled, the transmitter will effectively generate at the same symbol repeatedly. In the frequency domain, the spectrum will appear as a single tone that is offset from the center frequency of the transmission. As a result, the LO leakage can readily be characterized by measuring the emitted power at the center frequency. You can measure emitted power at the center frequency with a spectrum analyzer or a VSA, using a resolution bandwidth of 100 kHz.

Center Frequency Leakage (OFDM, HT and VHT)

Transmissions in 802.11a/g/n/ac use OFDM technology and are based on the principle of producing overlapping modulated subcarriers. OFDM technologies attempt to avoid the challenges of LO leakage by keeping the center subcarrier null. As a result, you can measure LO leakage even when the transmitter is generating data by measuring the emitted power in the center subcarrier, as shown in **Figure 3.10**.

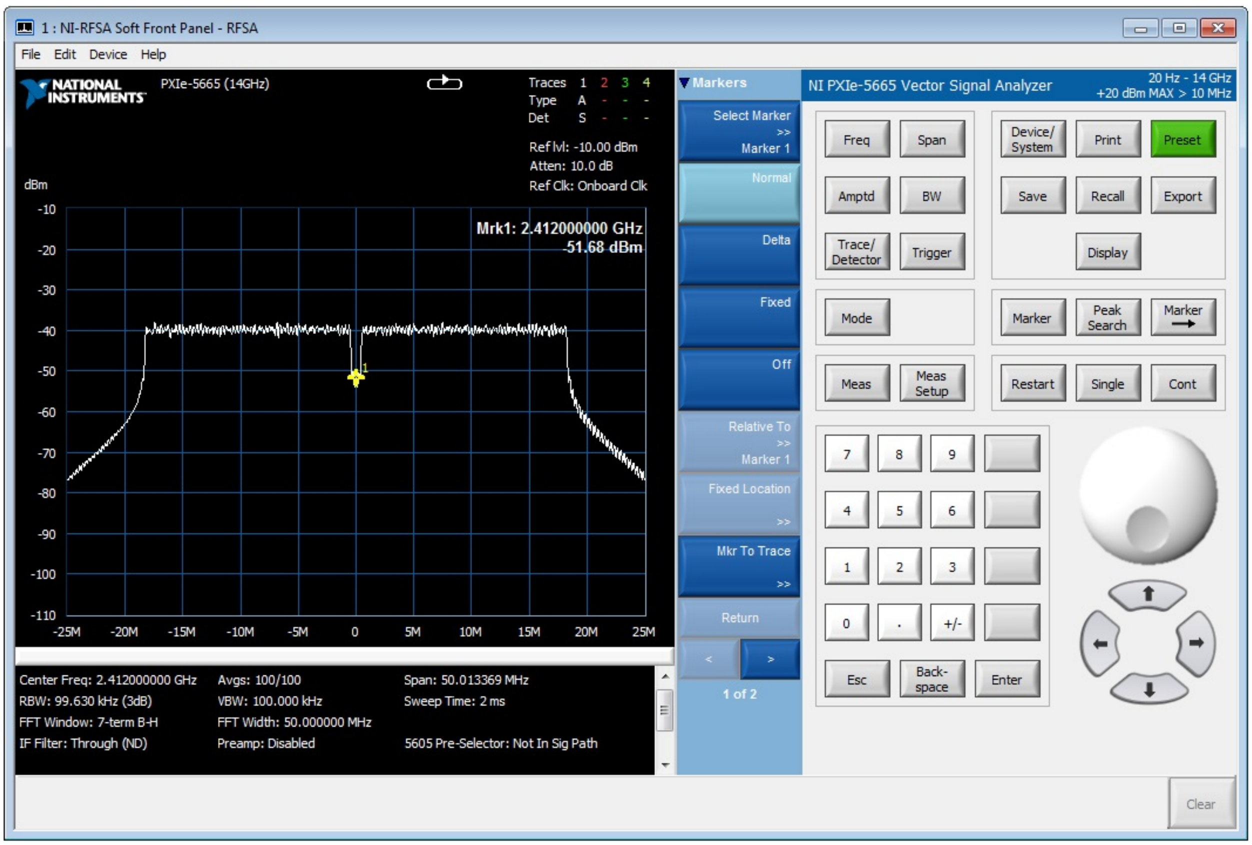

Figure 3.10. Measuring LO Leakage in the Frequency Domain

Strictly defined, carrier frequency leakage is the ratio, in dB, of the energy in the DC subcarrier to the total energy of all the subcarriers. For 20 MHz 802.11a/g/n transmissions, the maximum LO leakage shall not exceed –15 dB relative to overall transmitted power or, equivalently, +2 dB relative to the average energy of the remaining subcarriers. For 40 MHz 802.11n transmissions, the leakage shall not exceed -20 dB relative to overall transmitted power or, equivalently, 0 dB relative to the average energy of the remaining subcarriers. The LO leakage requirements for the VHT amendment are unique. For all VHT bandwidth configurations other than the 80+80 MHz transmission, the maximum LO leakage must be less than the average power for each subcarrier.

WLAN devices can implement the 80+80 MHz transmission in one of two methods, and the LO leakage requirements are different for each scenario. In the case where the signal is transmitted from a single modulator, the LO appears in the center of the transmission. In this scenario, the power measured at the center of the transmission BW using RBW 312.5 kHz shall not exceed the average power per-subcarrier.

The 80+80 MHz transmission can also be implemented using two transmitters. In this case, LO leakage appears at the center frequency of each transmitter and is not present in the center of the channel. In this case, power measured at the center of the transmission bandwidth shall not exceed the maximum of -20 dBm and -32 dB relative to total transmit power. Note that in cases where the LO leakage falls outside of both frequency 80 MHz transmissions, the RF LO shall follow the spectral mask requirements.

Spectral Flatness

Spectral flatness and applies only to OFDM-based transmissions of 802.11a/g/n/ac. Spectral flatness describes variation of the subcarrier power levels. The average energy of the constellations in each of the subcarriers shall not deviate more than a certain range from the average energy of all subcarriers, with upper and lower margins. The worst case of these two values is the spectral flatness margin.

Format	Bandwidth (MHz)	Averaging Subcarrier Indices (Inclusive)	Tested Subcarrier Indices (Inclusive)	Maximum Deviation (dB)
VHT	20	-16 to -1 and +1 to +16	-16 to -1 and +1 to +16	±4
			-28 to -17 and +17 to +28	+4/-6
	40	-42 to -2 and +2 to +42	-42 to -2 and +2 to +42	±4
			-58 to -43 and +43 to +58	+4/-6
	80	-84 to -2 and +2 to +84	-84 to -2 and +2 to +84	±4
			-122 to -85 and +85 to +122	+4/-6
	160	-172 to -130, -126 to -44,+44 to +126, and +130 to +172	-172 to -130, -126 to -44, and +44 to +126, +130 to +172	±4
			-250 to -173, -43 to -6, and +6 to +43, +173 to +250	+4/-6
Non-HT Duplicate	40	-42 to -33, -31 to -6, +6 to +31, and +33 to +42	-42 to -33, -31 to -6, and +6 to +31, +33 to +42	±4
			-58 to -43 and +43 to +58	+4/-6
	80	-84 to -70, -58 to -33, -31 to -6, +6 to +31, +33 to +58, +70 to +84	-84 to -70, -48 to -33, -31 to -6, and +6 to +31, +33 to +58, +70 to +122	±4
			-122 to -97, -95 to -85 and +85 to +95, +97 to +122	+4/-6
	160	-172 to -161, -159 to -134, -122 to -97, -95 to -70, -58 to -44, +44 to +58, +70 to +95, +97 to +122, +134 to +159, +161 to +172	-172 to -161, -159 to -134, -122 to -97, -95 to -70, -58 to -44, +44 to +58, +70 to +95, +97 to +122, +134 to +159, +161 to +172	±4
			-250 to -225, -223 to -198, -186 to -173, -43 to -33, -31 to -6, +6 to +31, +33 to +43, +173 to +186, +198 to	+4/-6

Table3.6. Spectral Flatness Limits for OFDM, HT, and VHT[2]

The spectral flatness upper margin is the difference between the upper spectral flatness mask and the relative magnitude of the channel frequency response. The lower spectral flatness margin is the difference between the relative magnitude of the channel frequency response and the lower spectral flatness mask. The relative magnitude of the channel frequency response is relative to the mean power of a few subcarriers around the DC subcarrier. In the first row of the previous table, the few subcarriers correspond to 16 subcarriers from -16 to -1. The relative magnitude of the channel frequency response is the difference between this average and the average energy of each subcarrier. The limits for the 20 MHz channel above apply also to OFDM and HT. The limits for the 40 MHz channel above also apply to HT.

[2] Recreated From Table 22-23 of Draft 5.1 of the 802.11ac Specifications

4. *Receiver Measurements*

WLAN devices are also subject to stringent receiver performance characteristics. Each receiver measurement characterizes a receiver's ability to demodulate a transmitted signal under a range of conditions, including low power, high power, and in the presence of interference.

Similar to transmitter measurements, WLAN receiver measurements are specified in several unique sections of the 802.11 specifications, including sections 16.4.8, 18.3.10, 20.3.21, and 22.3.19. In **Table 4.1**, the 2012 revision of the 802.11 specification applies to all standards except 802.11ac. The 2013 D5 draft revision of the 802.11 specification applies to 802.11ac.

Measurement	DSSS	OFDM	HT	VHT
Minimum Input Sensitivity	16.4.8.2, 17.4.8.2	18.3.10.2	20.3.21.1	22.3.19.1
Maximum Input Level	16.4.8.3, 17.4.8.3	18.3.10.5	20.3.21.4	22.3.19.4
Adjacent Channel Rejection	16.4.8.4, 17.4.8.4	18.3.10.3	20.3.21.2	22.3.19.2
Nonadjacent Channel Rejection	N/A	18.3.10.4	20.3.21.3	22.3.19.3
Received Channel Power Indicator	16.4.8.6, 17.4.8.6	18.3.10.7	20.3.21.6	N/A

Table 4.1. 802.11 Specifications for Receiver Measurements

Minimum Input Sensitivity

Minimum input sensitivity characterizes the receiver's performance in scenarios where the received signal strength is low. Excellent sensitivity performance ensures that a receiver can successfully demodulate transmissions when it is located far from the transmitter.

Sensitivity Test Setup

The test setup for WLAN receiver sensitivity involves a VSG configured to transmit the WLAN signal at a certain data rate at a known power level. A typical test configuration also uses a fixed attenuator between the instrument and the DUT, as shown in **Figure 4.1**.

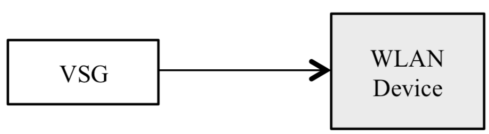

Figure 4.1. Test Setup for WLAN Sensitivity

The fixed attenuator ensures that the output noise level of the instrument does not contribute to the noise level of the receiver. The attenuator also allows you to provide a more accurate power level to the DUT. Because VSGs are generally capable of better power accuracy at higher power levels where they can be calibrated with a power meter, using a fixed attenuator allows you to use the VSG in its more accurate power range. Placing the attenuator between the VSG and the receiver allows for a better impedance match at the DUT, as well.

Sensitivity Specification

WLAN receiver sensitivity is specified as a packet error rate (PER) reported by the DUT through a digital interface. The minimum PER that a receiver must achieve is 8% for DSSS and 10% for OFDM, HT, and VHT standards.

Minimum input sensitivity is strictly defined as the lowest power level at which a receiver can achieve the prescribed PER criteria. Minimum requirements for DSSS are illustrated in **Table 4.2**.

DSSS Type	PER Threshold (%)	Minimum Sensitivity (dBm)
DSSS 2 Mb/s	8	-80
DSSS 11 Mb/s	8	-76

Table 4.2. DSSS Receiver Minimum Input Sensitivity Limits

For WLAN standards using OFDM-based technology, minimum input sensitivity is a combination of the modulation scheme, code rate, and input bandwidth. As shown in **Table 4.3**, the minimum requirements are fairly consistent across the OFDM, HT, and VHT specifications.

Modulation Scheme	Code Rate	Minimum Sensitivity (20 MHz BW)	Minimum Sensitivity (40 MHz BW)	Minimum Sensitivity (80 MHz BW)	Minimum Sensitivity (160 MHz BW)
BPSK	½	-82 dBm	-79 dBm	-76 dBm	-73 dBm
BPSK[1]	¾	-81 dBm	N/A	N/A	N/A
QPSK	½	-79 dBm	-76 dBm	-73 dBm	-70 dBm
QPSK	¾	-77 dBm	-74 dBm	-71 dBm	-68 dBm
16-QAM	½	-74 dBm	-71 dBm	-68 dBm	-65 dBm
16-QAM	¾	-70 dBm	-67 dBm	-64 dBm	-61 dBm
64-QAM	$^{2}/_{3}$	-66 dBm	-63 dBm	-60 dBm	-57 dBm
64-QAM	¾	-65 dBm	-62 dBm	-59 dBm	-56 dBm
64-QAM[2]	$^{5}/_{6}$	-64 dBm	-61 dBm	-58 dBm	-55 dBm
256-QAM[3]	¾	-59 dBm	-56 dBm	-53 dBm	-50 dBm
256-QAM[3]	$^{5}/_{6}$	-57 dBm	-54 dBm	-51 dBm	-48 dBm

1. BPSK with a ¾ code rate is supported only in the OFDM standard – and is not supported in HT or VHT
2. 64-QAM with a $^{5}/_{6}$ code rate is supported only by the HT and VHT standards and is not supported in OFDM
3. 256-QAM is supported only by the VHT standard and is not supported in OFDM or HT

Table 4.3. WLAN Receiver Sensitivity for OFDM, HT, and VHT

Table 4.3 shows a strong correlation between the complexity of the modulation scheme and the required receiver sensitivity. For example, higher-order modulation schemes such as 256-QAM require a higher SNR at the receiver to achieve the same frame error rates as more robust schemes, such as BPSK. The Wi-Fi devices are designed to use adaptive modulation techniques that employ more robust modulation schemes in low SNR environments and higher throughput schemes in scenarios where the channel environment can support it.

Maximum Input Level

The maximum input level characterizes the performance of a receiver in scenarios where the receive strength is high. This measurement ensures that the receiver functions as expected when it is located close to the transmitter. In these cases, though the receive signal SNR might be quite high, the high input power of the received signal could potentially drive the receiver's front-end components into compression, which distorts the signal.

The maximum input level measurement criteria for device performance are identical to the criteria for minimum input sensitivity. The test configuration for maximum input level requires introducing a high-power signal to the DUT, as shown in **Table 4.4**.

PHY	PER Threshold (%)	Power (dBm) at 2.4 GHz	Power (dBm) at 5 GHz
DSSS 2 Mb/s	8	-4	N/A
DSSS 11 Mb/s	8	-10	N/A
OFDM	10	-30	-30
HT	10	-20	-30
VHT	10	N/A	-30

Table 4.4. Receiver Maximum Input Level Limits

To measure maximum input level, configure a VSG to introduce a modulated signal to the receiver at a power level that is slightly less than the required input level. Slowly increase the VSG power level from a known power level until the PER threshold is reached. The highest input power level at which the receiver can still achieve its PER threshold (8% or 10%) is the receiver maximum input level. The dynamic range of the receiver is strictly described as the difference between the minimum input sensitivity and the maximum input level.

Adjacent Channel Rejection

In practical use, Wi-Fi products are designed to operate in wireless environments that are shared with a broad range of wireless devices, including, but not limited to, other Wi-Fi devices. As a result, WLAN receivers are required to achieve minimum performance criteria in scenarios where signal power is present in the adjacent band. The adjacent channel rejection (ACR) measurement characterizes a receiver's performance in the scenario where a relatively high-power signal is present in the channel directly adjacent to the reference channel.

The test setup for measuring ACR requires two RF VSGs and a power combiner. As shown in **Figure 4.2**, the primary VSG produces a WLAN signal for demodulation by the receiver. The secondary VSG produces an interfering signal that is higher in power than the reference signal.

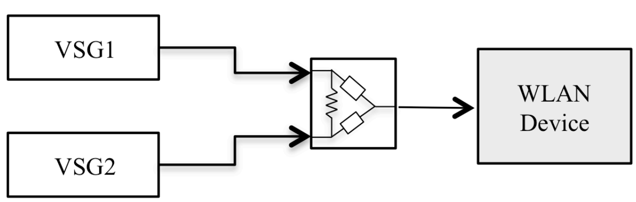

Figure 4.2. Hardware Block Diagram of ACR Measurement

Figure 4.3 shows the test configuration for ACR, which introduces two WLAN signals simultaneously to the DUT.

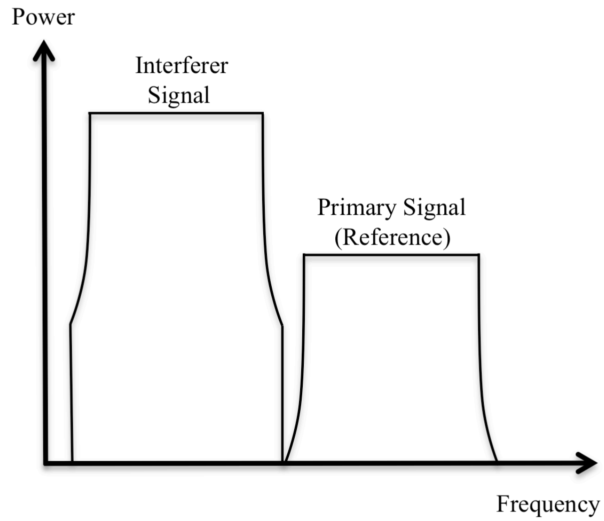

Figure 4.3. Spectral View of Signals Introduced to the DUT

To test ACR, slowly increases the power level of the interferer signal until the PER threshold is reached. The difference in power level between the primary signal and the interferer signal is the ACR performance of the receiver.

The receiver PER performance criteria for ACR is of the same as the criteria for the minimum input sensitivity and the maximum input level for DSSS, OFDM, HT, and VHT standards. For DSSS ACR measurements, the receiver must achieve 8% frame error rate. OFDM, HT, and VHT transmissions must achieve a frame error rate of 10%.

When measuring ACR for DSSS transmissions, set the reference signal to a power level that is 6 dB higher than the sensitivity limit. Under this configuration, the receiver must achieve an ACR of greater than 35 dB, as shown in **Table 4.5**.

Transmission	Input Reference Channel Power	Adjacent Channel Rejection
DSSS	Sensitivity + 6 dB	35 dB

Table 4.5. ACR Requirements for DSSS Transmissions

The required ACR criteria for OFDM, HT, and VHT standards depends on a combination of modulation scheme and code rate. **Table 4.6** provides a specific list of required performance criteria.

Modulation Scheme	Code Rate	Input Reference Channel Power	Adjacent Channel Rejection (OFDM)	Adjacent Channel Rejection (HT, VHT – Except 80+80)	Adjacent Channel Rejection (VHT 80+80)
BPSK	½	Sensitivity + 3 dB	28 dB	16 dB	13 dB
BPSK[1]	¾		27 dB	N/A	N/A
QPSK	½		25 dB	13 dB	10 dB
QPSK	¾		23 dB	11 dB	7 dB
16-QAM	½		20 dB	8 dB	5 dB
16-QAM	¾		16 dB	4 dB	1 dB
64-QAM	$^2/_3$		12 dB	0 dB	-3 dB
64-QAM	¾		11 dB	-1 dB	-4 dB
64-QAM[2]	$^5/_6$		N/A	-2 dB	-5 dB
256-QAM[3]	¾		N/A	-7 dB	-10 dB
256-QAM[3]	$^5/_6$		N/A	-9 dB	-12 dB

1. BPSK with a ¾ code rate is supported only in the OFDM standard and is not supported in HT or VHT
2. 64-QAM with a $^5/_6$ code rate is supported only by the HT and VHT standards and is not supported in OFDM
3. 256-QAM is supported only by the VHT standard and is not supported in OFDM or HT

Table 4.6. Performance Criteria for ACR

In **Table 4.6**, the precise reference channel power for the primary (demodulated) signal depends on the modulation scheme, code rate, and bandwidth of the signal. More precisely, this power level is 3 dB above the minimum receiver input sensitivity listed in **Table 4.3.**

Nonadjacent Channel Rejection

Nonadjacent channel rejection places the interferer signal in a non-adjacent channel. Nonadjacent channel rejection is only specified for OFDM, HT, and VHT standards. The DSSS transmissions do not have a nonadjacent channel rejection requirement.

Nonadjacent channel rejection is strictly defined as rejection of channels that occur more than two channel bandwidths away from the center transmission. For example, in the case of a 20 MHz channel, the nonadjacent channel center frequency is at least 40 MHz away from the center frequency of the reference channel. Similarly, the center frequency of a nonadjacent channel for a 40 MHz transmission is at least 80 MHz away from the center frequency of the reference channel.

The requirements for nonadjacent channel rejection are 14-16 dB higher than that of ACR, given that the interferer is not as close in frequency to the reference channel. The primary signal reference signal used for nonadjacent channel rejection is 3 dB above the reference channel power. **Table 4.7** illustrates specific nonadjacent channel rejection requirements for each combination of modulation scheme and code rate.

Modulation Scheme	Code Rate	Input Reference Channel Power	Nonadjacent Channel Rejection (OFDM)	Nonadjacent Channel Rejection (HT, VHT – Except 80+80)	Nonadjacent Channel Rejection (VHT 80+80)
BPSK	½	Sensitivity + 3 dB	42 dB	32 dB	29 dB
BPSK[1]	¾		41 dB	N/A	N/A
QPSK	½		39 dB	29 dB	26 dB
QPSK	¾		37 dB	27 dB	24 dB
16-QAM	½		34 dB	24 dB	21 dB
16-QAM	¾		30 dB	20 dB	17 dB
64-QAM	$^2/_3$		26 dB	16 dB	13 dB
64-QAM	¾		25 dB	15 dB	12 dB
64-QAM[2]	$^5/_6$		N/A	14 dB	11 dB
256-QAM[3]	¾		N/A	9 dB	6 dB
256-QAM[3]	$^5/_6$		N/A	7 dB	4 dB

1. BPSK with a ¾ code rate is supported only in the OFDM standard and is not supported in HT or VHT
2. 64-QAM with a $^5/_6$code rate is supported only by the HT and VHT standards and is not supported in OFDM
3. 256-QAM is supported only by the VHT standard and is not supported in OFDM or HT

Table 4.7. Nonadjacent Channel Rejection Requirements for OFDM, HT, and VHT

Received Channel Power Indicator

Received channel power indicator (RCPI) is a metric of the receive strength of the signal and is reported by the receiver using an 8-bit register. The 8-bit register produces a numeric value that ranges from 0 to 220 with a resolution of 0.5 dB and allows the receiver to report a receive strength ranging from -110 dBm (register value of 0) to 0 dBm (register value of 220).

To measure RCPI, configure a VSG to generate an RF signal at a known power level. Next, compare that power level to the RCPI result returned from the DUT. WLAN devices are generally required to report RCPI values that are within a certain +/- dB of the known VSG power level, as shown in **Table 4.8**.

PHY	RCPI Accuracy
DSSS	± 5 dB
OFDM	± 5 dB
HT	± 5 dB
VHT	N/A

Table 4.8. Received Channel Power Indicator Limits

As shown in **Table 4.8**, DSSS, OFDM, and HT transmissions have specific RCPI requirements. However, the VHT specification does not have an RCPI requirement.