



Wireless LAN at 60 GHz - IEEE 802.11ad Explained

Application Note

Introduction

The first popular standards for wireless LAN (IEEE 802.11a and b) were designed primarily to serve the needs of a laptop PC in the home and office, and later to allow connectivity “on the road” in airports, hotels, Internet cafes, and shopping malls. Their main function was to provide a link to a wired broadband connection for Web browsing and email. Since the speed of the broadband connection was the limiting factor, a relatively low-speed wireless connection was sufficient – 802.11a provided up to 54 Mb/s at 5 GHz, and 802.11b up to 11 Mb/s at 2.4 GHz, both in unlicensed spectrum bands. To minimize interference from other equipment, both used forms of spread-spectrum transmission and were heavily encoded. A later revision of the standard, 802.11g in 2003, consolidated use in the 2.4 GHz band but maintained the maximum data rate at 54 Mb/s. However, by the same time, new usage models with the need for higher throughput had been recognized: data sharing amongst connected devices in the home or small office and wireless printing as examples. A study project was set up which produced 802.11n in 2009. As well as improving the maximum single-channel data rate to over 100 Mb/s, this new standard introduced MIMO (multiple input, multiple output or spatial streaming), where up to 4 separate physical transmit and receive antennas carry independent data that is aggregated in the modulation/demodulation process. Agilent’s measurement and application expertise helps you anticipate increasing technical and operational complexities so you can accelerate your ability to achieve both engineering and business goals.



Introduction

Today, there are further usage models, summarized in Table 1, that require even higher data throughput to support today's "unwired office".

Table 1. New WLAN usage models.

Category	Usage Model
Wireless Display	<ul style="list-style-type: none"> • Desktop storage and display • Projection to TV or projector in conference room or auditorium • In-room gaming • Streaming from camcorder to display • Professional HDTV outside broadcast pickup
Distribution of HDTV	<ul style="list-style-type: none"> • Video streaming around the home • Intra-large-vehicle applications (e.g. airplane, ferry) • Wireless networking for office • Remote medical assistance
Rapid upload/download	<ul style="list-style-type: none"> • Rapid file transfer/sync • Picture-by-picture viewing • Airplane docking (manifests, fuel, catering, . . .) • Downloading movie content to mobile device • Police surveillance data transfer
Backhaul	<ul style="list-style-type: none"> • Multi-media mesh backhaul • Point-to-point backhaul
Outdoor campus / auditorium	<ul style="list-style-type: none"> • Video demo/tele-presence in auditorium • Public safety mesh (incident presence)
Manufacturing floor	<ul style="list-style-type: none"> • Automation

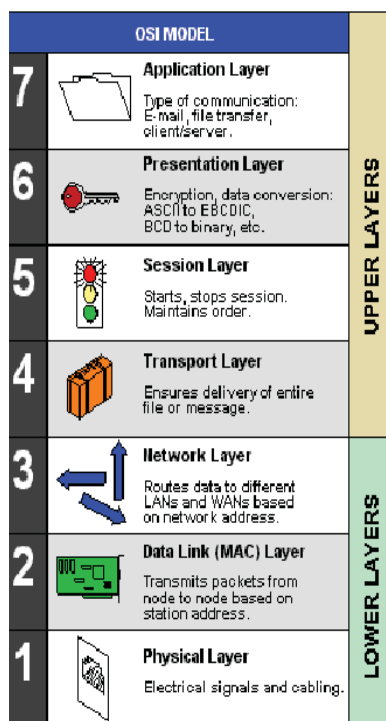


Figure 1. OSI 7-layer model.

To cater for these, two new IEEE project groups aimed at providing "Very High Throughput" (VHT) were established in late 2008. Working Group TGac is currently putting the finishing touches to 802.11ac, an extension of 802.11n, providing a minimum of 500 Mbit/s single link and 1 Gbit/s overall throughput, running in the 5 GHz band. Working Group TGad has since completed its work with the publication of 802.11ad, providing up to 6.75 Gbps throughput using approximately 2 GHz of spectrum at 60 GHz over a short range. (60 GHz transmission suffers from large attenuation through physical barriers.) Bearing in mind the number of existing devices, backward compatibility with existing standards using the same frequency range is a "must". The goal is for all the 802.11 series of standards to be backward compatible, and for 802.11ac and ad to be compatible at the Medium Access Control (MAC) or Data Link layer, and differ only in physical layer characteristics (see Figure 1). Devices could then have three radios: 2.4 GHz for general use which may suffer from interference, 5 GHz for more robust and higher speed applications, and 60 GHz for ultra-high-speed within a room – and support session switching amongst them. IEEE 802.11ad-2012 was published in December 2012 and products based on this technology are now commercially available. 802.11ac is scheduled to be finalized by February 2014, and devices complying with the draft 11ac standard have already been announced.

Why 60 GHz?

Table 1 gives examples of the demand for Gigabit data rates over wireless connections for a range of consumer applications. Data capacity is ultimately tied to modulation bandwidth, so the extreme gigabit data-rates required for uncompressed high-definition multimedia transmissions must be accommodated, including known futures such as 2048 x 1080 and 4096 x 2160 (Digital Cinema) or 3D. Such data rates demand large spectrum allocation, and simplicity of high-volume manufacturing demands that this spectrum bandwidth should be a small percentage of the transmission frequency. The global unlicensed band that already exists at around 60 GHz, where multi-GHz modulation bandwidths are practical, meets the requirement.

The unlicensed frequency allocations at around 60 GHz in each region do not match exactly, but there is substantial overlap; at least 3.5 GHz of contiguous spectrum is available in all regions that have allocated spectrum. Unlike the 2.4 GHz and 5 GHz unlicensed bands, the 60 GHz area is also relatively uncongested.

Transmission at 60 GHz covers less distance for a given power, mainly due to the increased free space path loss (loss over 1 m at 60 GHz is 68 dB, which is 21.6 dB worse than at 5 GHz), compounded by propagation losses through materials and human body shadowing (losses from a few dB to 30 dB+).

The substantial RF absorption peak in the 60 GHz band due to a resonance of atmospheric oxygen molecules is often cited as a limitation on range in this band, but this absorption effect only starts to become significant at >100 m range, which is not really relevant to the low-power transmissions being discussed here.

So low-power transmissions will not propagate very far, but this is considered an advantage. It reduces the likelihood of co-channel interference and increases the possible frequency re-use density. Another perceived advantage of limited range is the reduced opportunity for “theft” of protected content by eavesdropping on nearby transmissions. (In fact, 60 GHz was first proposed for battlefield communications just for this reason.)

A further enabler for consumer devices operating in this frequency range is the emergence of low-cost microwave component fabrication technologies. High-yield, micron-geometry components make 60 GHz devices and subsystems a commercial reality for consumer technology today, where only a few years ago they would have been unthinkable. Chips using CMOS, InP and SiGe IC technologies will be used extensively in 60 GHz wireless LAN devices.

High path loss can be mitigated by increasing antenna gain. The small geometries required at 60 GHz permit the use of fabrication techniques such as Low-Temperature Co-fired Ceramic (LTCC) and thermoplastic substrates to create suitable, physically small, high-gain directional antennas.

Multiple-antenna configurations using beam-steering are an optional feature of the specifications. Beam-steering can be employed to circumnavigate minor obstacles like people moving around a room or a piece of furniture blocking line-of-sight transmission, but longer free-space distances (e.g. > 10 m) and more substantial obstructions (e.g. walls, doors, etc.) will prevent transmission. It would be unlikely, for example, for a media server in one room to be able to reliably transmit HD video directly to a display in another.

Regulatory Overview

Since 1994, when the US Federal Communications Commission (FCC) first proposed to establish an unlicensed band at 59-64 GHz, radio regulatory organizations around the world have been legislating appropriate frequency allocations and modulation parameters to enable similar unlicensed bands in their respective jurisdictions.

At the time of writing, the US and Canada, the European Union, Japan, South Korea, Australia and China have all finalized and approved an unlicensed spectrum allocation in the 60 GHz region. The situation is summarized in Figure 2.

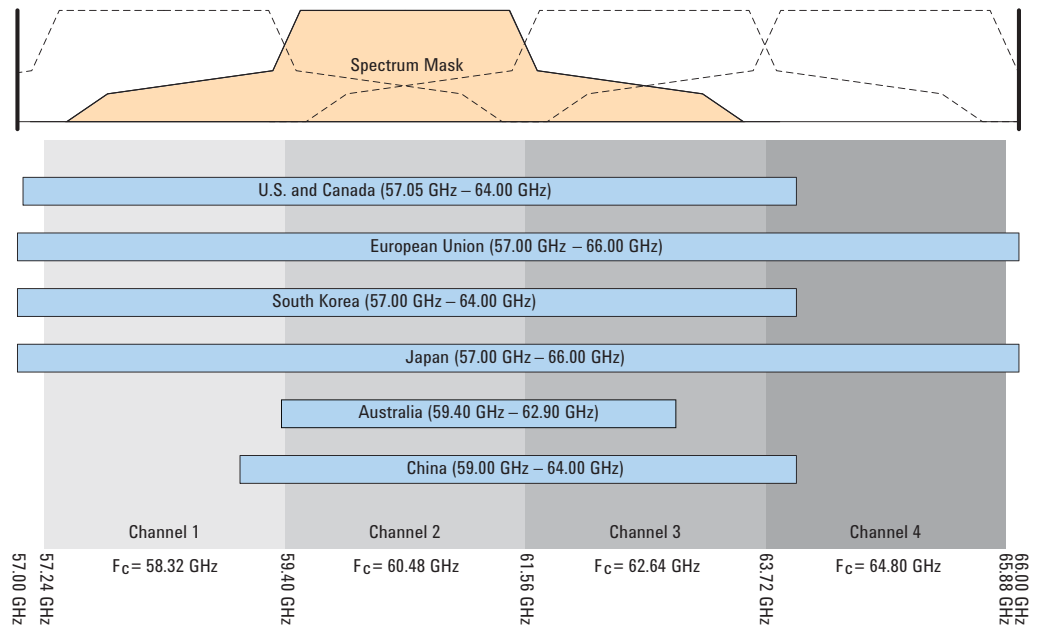


Figure 2. 60 GHz Band Channel Plan and Frequency Allocations by Region

Figure 2 also documents the channelization of the 57-66 GHz band that has emerged by consensus from technical specification development work in the IEEE, Ecma, the WirelessHD Consortium and the Wireless Gigabit Alliance. In November 2011 this channelization and a corresponding spectrum mask for the occupying signal was approved by ITU-R WP 5A for global standardization.

The ITU-R recommended channelization comprises four channels, each 2.16 GHz wide, centered on 58.32 GHz, 60.48 GHz, 62.64 GHz and 64.80 GHz respectively. As Figure 2 illustrates, not all channels are available in all countries. Channel 2, which is globally available, is therefore the default channel for equipment operating in this frequency band.

Regulatory Overview

The spectrum mask, shown to scale at the top of Figure 2, is expressed in decibels relative to the signal level at the band center (dBr); as shown more precisely in Figure 3.

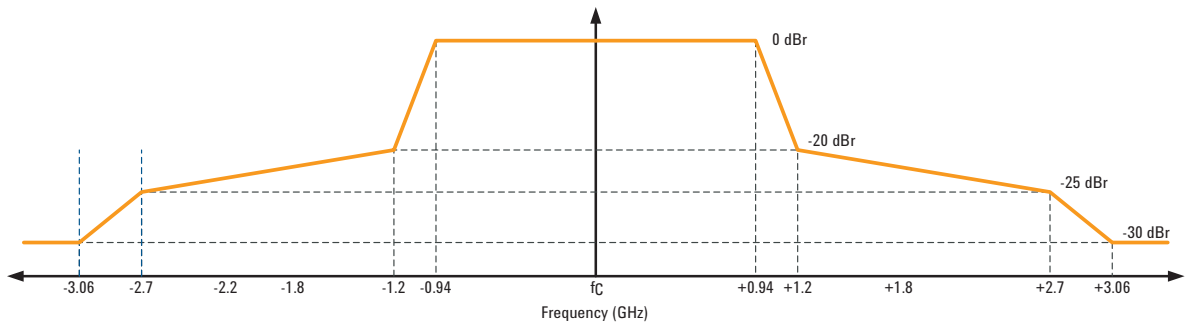


Figure 3. IEEE 802.11ad Spectrum Mask

The spectrum mask in Figure 3 is the final version, as defined by 802.11ad. This supersedes the more stringent mask that was approved by ITU WPA5. This mask is significantly different to the masks specified at lower frequencies. The breakpoints at -20 dBr have been pushed out slightly to accommodate both OFDM and Single Carrier modulations, and the adjacent channel requirements have been considerably relaxed, specifically to ease the circuit design challenges at 60 GHz by permitting higher levels of out of band distortion.

The maximum permitted transmitter power varies by country, but in general +10 dBm can be taken as a practical limit.

A History of Specifications Targeting the 60GHz Band

IEEE 802.15.3c (2005 – 2009)

The IEEE 802.15 Working Group develops standards for Wireless Personal Area Networks (WPAN).

Within the IEEE 802.15 working group, Task Group 3 (TG3) was tasked with developing high-rate (>20 Mbps) WPANs, and the outcome was IEEE 802.15.3-2003. Following the completion of that specification Task Group 3c (TG3c) was formed, in March 2005, to develop a millimeter-wave-based alternative physical layer (PHY) for the IEEE 802.15.3-2003 standard and the result was IEEE 802.15.3c-2009.

IEEE 802.15.3c-2009 endeavours to address a wide range of applications by having three distinct PHYs; a “single carrier” (SC) mode, a “high speed interface” (HSI) mode and an “audio/visual” (AV) mode, all of which are significantly architecturally different.

The single carrier SC and HSI modes use PSK/QAM modulation and so can trade reduced peak data rates for improved peak/average power ratios when compared with the OFDM-based AV mode. The SC/HSI modes are thus considered to be a better fit to the power limitations of the battery operated equipment that typically participates in a PAN (phones, cameras, MP3 players etc.).

The OFDM-based AV mode is better able to deal with multipath distortions and so can offer greater range than SC-based modes, albeit at the expense of power consumption. In this specification, the AV mode is exactly the same as the HRP PHY in WirelessHD 1.0 (although the MAC layers are different between the two specifications).

At the time of writing, no commercially available equipment employs the IEEE 802.15.3c standard.

A History of Specifications Targeting the 60GHz Band

WirelessHD® (2006 – present)

In April 2006, the WirelessHD Consortium was founded to develop and promote an industry-standard next-generation wireless digital interface specification for consumer electronics, PC and portable products.

The consortium was founded by SiBEAM Inc. in collaboration with LG Electronics Inc., Panasonic Corporation, NEC Corporation, Samsung Electronics, Co., Ltd, Sony Corporation, and Toshiba Corporation. Subsequently this core group of founding companies was expanded to include Intel Corporation (Jan 2008), Broadcom Corporation (August 2008) and Royal Philips Electronics N.V. (September 2009). These original ten companies had elevated status within the consortium as Promoter Companies and the membership was augmented by several Adopter Companies. The WirelessHD Consortium is still in existence and actively promoting WirelessHD technology, but the roster of Promoter Companies has evolved and the Adopter membership has declined in recent years, reflecting a general shift of focus in the industry towards 802.11ad.

The WirelessHD specification defines an architecture and technology for short-range (10 m) wireless interchange of high-definition multimedia data between audio-visual devices over an ad-hoc network in the 60GHz unlicensed band.

Version 1.0 of the WirelessHD specification was published in January 2008, followed by version 1.1 in April 2010.

The multimedia optimised protocol is underpinned by a physical layer capable of high speed data transmission; originally (v1.0) at rates up to 3.81Gbps, laterly (v1.1) at rates up to 7.138 Gbps, and, in principle, up to $4 \times 7.138 = 28.552$ Gbps if using 4×4 spatial multiplexing (MIMO) .

The ad-hoc network is established and managed through bi-directional protocol exchanges over the Low Rate PHY (LRP) while bulk data transfer takes place over the unidirectional Medium Rate PHY (MRP) or High Rate PHY (HRP). All three PHYs employ beam-steering techniques for Non Line Of Sight (NLOS) operation.

LRP, MRP and HRP transmissions share a common frequency channel using Time Division Multiple Access (TDMA) techniques managed by the protocol layer. LRP, MRP and HRP are all RF burst transmissions starting with a synchronization preamble followed by packet-structured OFDM modulated data.

A History of Specifications Targeting the 60GHz Band

ECMA-387 and ISO/IEC 13156 (2008 – present)

Ecma International is a not-for-profit industry association based in Geneva that was established in 1961 for the purpose of developing and publishing standards and technical reports in the areas of Information and Communication Technology (ICT) and Consumer Electronics (CE).

In December 2008 Ecma published the first edition of the ECMA-387 High Rate 60 GHz PHY, MAC and HDMI PAL Standard for short range unlicensed communications. This document subsequently passed through the ISO/IEC fast-track approval procedure to become ISO/IEC 13156:2009.

More recently, in December 2010, Ecma published a second edition of ECMA-387, which also passed through the ISO/IEC fast-track approval procedure to become ISO/IEC 13156:2011.

At the time of writing, no commercially available equipment employs the ECMA-387 standard or its ISO/IEC equivalent.

NGmS (2007 – 2009)

In October 2007, representatives of leading wireless and consumer electronics companies from around the World met to consider a proposal to develop a unified “Next Generation millimeter-wave Specification” (NGmS)¹.

Some of the participants in that meeting went on to collaborate in identifying and documenting market requirements, and creating an early draft specification. The NGmS group was disbanded in 2009 with the formation of the Wireless Gigabit Alliance and the work of the NGmS was carried forward by the new organization.

Wireless Gigabit Alliance/ WiGig™ (2009 – 2013)

On April 1, 2009, the Wireless Gigabit Alliance (WGA) was incorporated with the intent to develop specifications that define transmission of audio, video, and data in the millimeter wave frequency band operating in both Line Of Sight (LOS) and Non-Line Of Sight (NLOS) environments. The WGA also own the trademark and brand “WiGig” to describe this technology.

Version 1.0 of the WGA MAC and PHY Specification was published under the “WiGig” brand in February 2010 and this was followed by version 1.1 in April 2011. A proposal based on the WGA MAC and PHY version 1.0 Specification was contributed to IEEE 802.11 Task Group ‘ad’ (TGad) as a complete proposal specification (IEEE document 10/433r2) and was approved as TGad D0.1 on 20 May 2010.

Since then, up until the eventual publication of IEEE 802.11ad-2012 in December 2012, the WGA and IEEE maintained alignment between the evolving WGA and IEEE MAC and PHY specifications, so that the published IEEE 802.11ad and WiGig v1.2 MAC/PHY final specifications are essentially identical.

In December 2012, the Wi-Fi Alliance and WGA executed a Memorandum of Understanding (MOU) outlining their plans to consolidate activity in Wi-Fi Alliance, this intent was confirmed by a finalized agreement in March 2013 to consolidate WiGig technology and certification development in Wi-Fi Alliance. This transfer should be complete by June 2013 and all further development of this technology, particularly the protocol adaptations, will be conducted by Wi-Fi Alliance in collaboration with other organizations such as VESA, PCI-SIG and USB-IF.

1. <http://techon.nikkeibp.co.jp/article/HON-SHI/20071219/144407>

A History of Specifications Targeting the 60GHz Band

IEEE 802.11.ad (2009 – 2012)

The IEEE 802.11 Working Group develops standards for Wireless Local Area Networks (WLAN).

Within the IEEE 802.11 working group, Task Group 'ad' (TGad) was tasked with defining modifications to the 802.11 MAC and PHY to enable operation in the 60 GHz frequency band capable of Very High Throughput (VHT), where VHT was defined as capable of a maximum throughput of at least 1 Gbps.

The Project Activation Request was approved in December 2008 and the working group was formed in January 2009.

In response to the TGad call for proposals (IEEE document 09/1206r0) issued in November 2009, a proposal based on the WGA MAC and PHY version 1.0 Specification was contributed to IEEE 802.11 Task Group 'ad' (TGad) as a complete proposal specification (IEEE document 10/433r2) and was approved as TGad D0.1 on 20 May 2010. As required by the PAR, the 802.11ad specification defines a backwards-compatible extension to the IEEE 802.11-2012 specification that extends the MAC and PHY definitions as necessary to support short-range (1m - 10m) wireless interchange of data between devices over an ad-hoc network at data rates up to 6.75 Gbps in the 60GHz unlicensed band. It also supports session switching between the 2.4GHz, 5GHz and 60GHz bands.

The ad-hoc network is established and managed through bi-directional protocol exchanges using a low data-rate control channel (MCS 0) while bulk data transfer takes place over an appropriate higher-rate mode (MCS1..31). The higher rate modes employ beam-steering techniques for NLOS operation.

802.11ad uses RF burst transmissions that start with a synchronization preamble (common to all modes) followed by header and payload data. The preamble is always single-carrier modulation, the header and data may use single-carrier (SC) or OFDM modulation depending on the target bit rate.

The final IEEE 802.11ad-2012 specification was published, on schedule, in December 2012 and Task Group TGad held its final meeting in March 2013.

Looking forward

At the time of writing (May 2013), it seems highly likely that IEEE 802.11ad will become the most widely deployed 60 GHz technology, however the WirelessHD technology that pioneered the commercialization of this band may endure in some high-performance niche applications.

In the rest of this document we will refer to IEEE 802.11ad only, but (at the PHY level) this can be taken as a synonym for WiGig 1.2.

Overview of IEEE 802.11ad-2012 PHY

Introduction

This section provides a brief summary of the mmWave PHY layer defined in clause 21 of the IEEE 802.11ad-2012 amendment to IEEE Std. 802.11™-2012. To maintain generality in the specification text, and to simplify functional descriptions in future, the IEEE has introduced new terminology to identify the higher performance PHYs;

- VHT, which is short for very high throughput, is any frequency band that has a starting frequency below 6 GHz excluding the 2.4 GHz band.
- DMG, which is short for directional multi-gigabit, pertains to operation in any frequency band that contains a channel with a channel starting frequency above 45 GHz.

These terms replace the previous, more frequency-specific terms LB (Low Band at 2.4GHz), HB (High Band at 5GHz), and UB (Ultra Band at 60GHz).

So, using the new terminology, clause 21 of IEEE 802.11ad-2012 defines the DMG PHY, which is normally deployed in the “60 GHz” band from 57 GHz to 66 GHz; subject to the regional variations documented in Figure 2.

Packet structure

The IEEE 802.11ad-2012 DMG PHY supports three distinct modulation methods:

- Spread-spectrum modulation; the Control PHY.
- Single carrier (SC) modulation; the Single Carrier PHY and the Low Power Single Carrier PHY.
- Orthogonal Frequency Division Multiplex (OFDM) modulation; the OFDM PHY.

Each PHY type has a distinct purpose and packet structure, shown in Figure 4, but care has been taken to align the packet structures, and in particular the preambles, to simplify signal acquisition, processing and PHY type identification in the receiver.

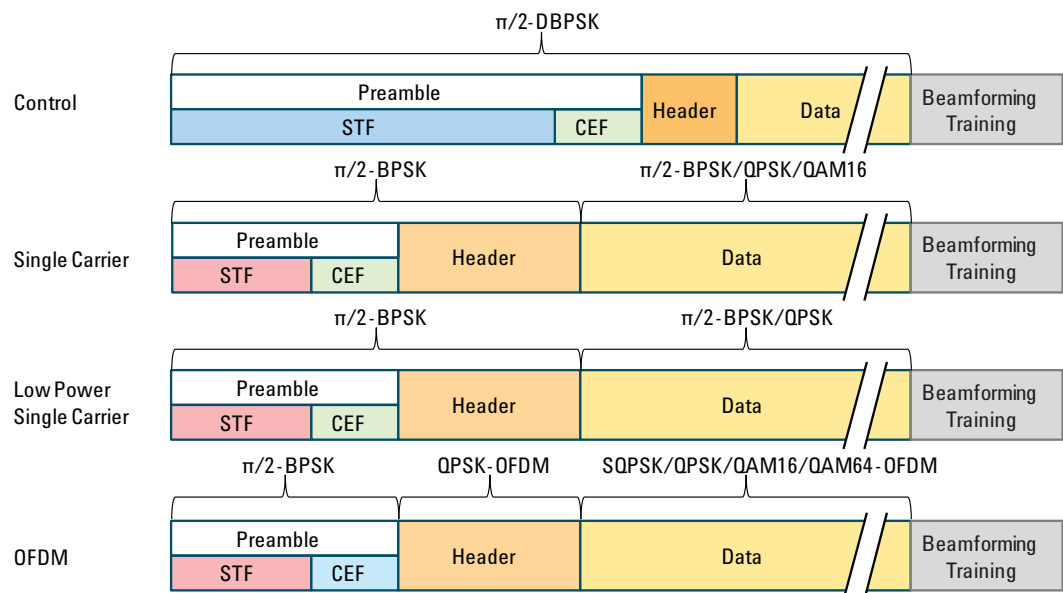


Figure 4. Packet structures for each of the three modulation types

Overview of IEEE 802.11ad-2012 PHY

Packet structure

Preamble

The three packet types share an essentially common preamble structure comprising a Short Training Field (STF) followed by a Channel Estimation Field (CEF). These fields are constructed from $\pi/2$ -BPSK modulated repeating Golay sequences that are described in more detail below.

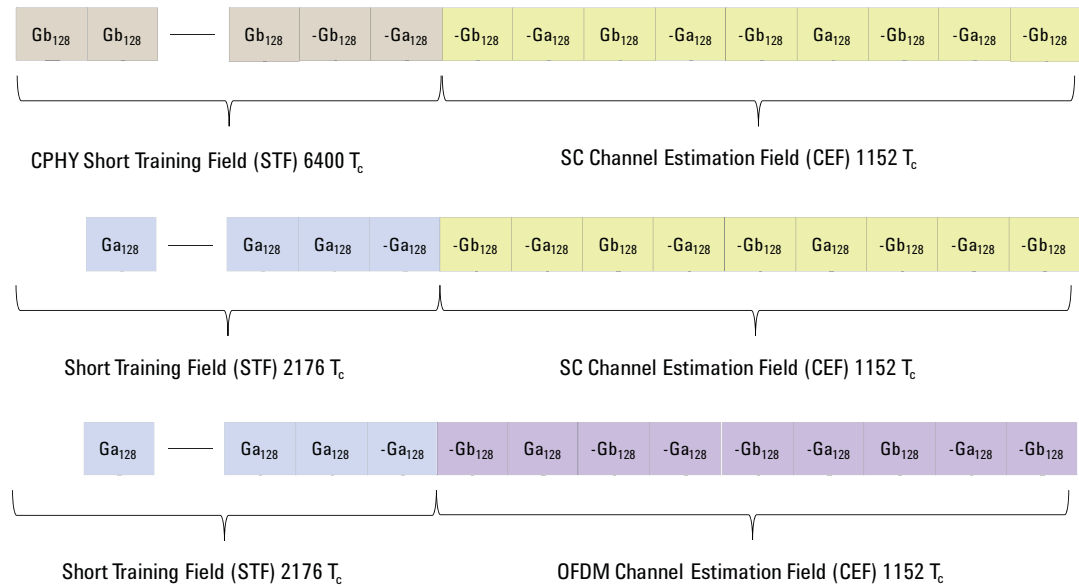


Figure 5. Preamble Variants Expressed in terms of G_{a128} and G_{b128} sequences

Figure 5 shows the structure of the three different preamble types in more detail, illustrating that the basic building blocks are the Golay complementary sequences G_{a128} and G_{b128} .

Overview of IEEE 802.11ad-2012 PHY

Packet structure

Golay complementary sequences

Golay complementary sequences are sequences of bipolar symbols (± 1) that have been mathematically constructed to have very specific autocorrelation properties. The 'a' and 'b' indicate that the Ga_{128} and Gb_{128} sequences form a complementary pair and the suffix indicates the sequence length. 802.11ad also uses Ga_{32} , Ga_{64} and Gb_{64} sequences.

The mathematics behind the sequence constructions is beyond the scope of this note, but three important attributes of these sequences are,

1. The autocorrelation of each sequence has low false peaks and low DC content under $\pi/2$ rotation
2. The sum of the very good but imperfect autocorrelation functions of the Ga and Gb sequences is perfect (the false peaks cancel exactly)
3. The Ga and Gb autocorrelations can be performed in parallel using a single, hardware efficient (and therefore fast) correlator.

A suitable fast correlator architecture is illustrated generically in Figure 6.

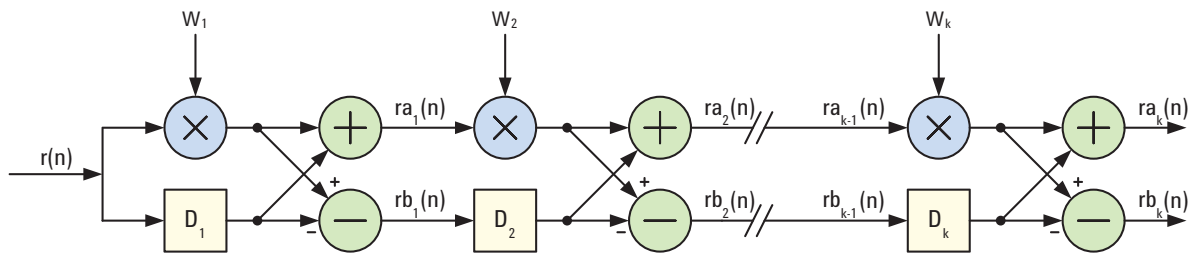


Figure 6. Fast correlator architecture

Notice that the correlator performs both 'a' and 'b' correlations in parallel. It has a single input, but two outputs, one for the 'a' sequence and one for the 'b' sequence. If the Ga_{128}/Gb_{128} version of this correlator receives a 802.11ad preamble short training field (STF) at the input $r(n)$, the $ra_7(n)$ output will produce a sequence of positive going correlation spikes for an SCPHY or OFDMPHY STF, whereas positive correlation spikes on the $rb_7(n)$ output signal the arrival of a CPHY STF.

In both cases, The periodicity of the spikes gives a direct measure of the reference sample rate, the spike amplitude can drive an AGC function, and a negative spike on the $ra_7(n)$ output signals the end of the STF. The complementary nature of the 'a' and 'b' sequences is not used in the STF (other than the benefit of having a correlator that can perform both correlations in parallel and thereby signal whether or not a CPHY packet is being received).

Overview of IEEE 802.11ad-2012 PHY

Packet structure

Golay complementary sequences

The construction of the CEF is more mathematically sophisticated and does take advantage of the complementary property; the first four and second four $G_{a_{128}}/G_{b_{128}}$ complementary sequences are logically grouped into 512-symbol groups labelled $G_{u_{512}}$ and $G_{v_{512}}$ as illustrated in Figure 7.

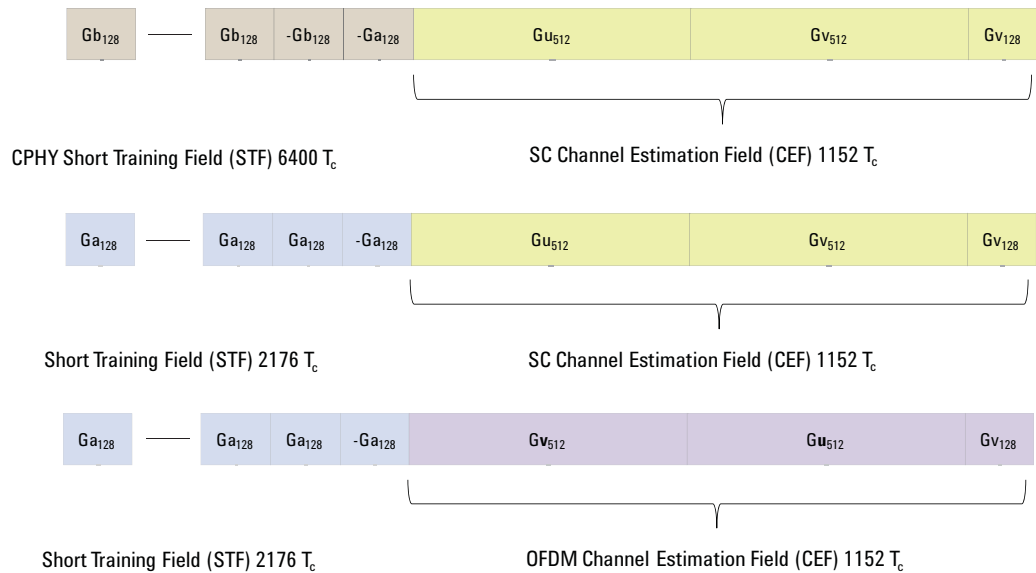


Figure 7. The preambles redrawn to show the CEF structure

The $G_{u_{512}}$ and $G_{v_{512}}$ blocks can be used to perform two independent channel estimations and the results can be summed to give a composite estimate. The basic principle behind the structure of the channel estimation fields is illustrated in Figure 8.

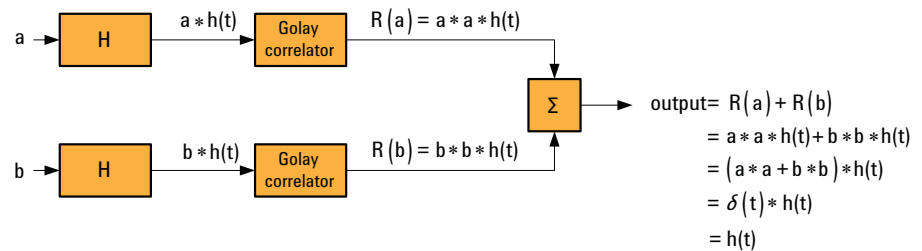


Figure 8. The principle behind the channel estimation field

We have two time sequences, 'a' and 'b'. If we pass sequence 'a' through the channel H we convolve the sequence and the channel impulse response, h(t).

If we pass the received signal through a Golay correlator for the known input sequence then we get the autocorrelation of sequence 'a' convolved with the channel impulse response.

If sequence 'b' is processed similarly, we get the autocorrelation of sequence 'b' convolved with the same channel impulse response.

If we add the two results together then, because sequences 'a' and 'b' are Golay complementary sequences, the sum of their autocorrelations is an impulse response and we are left with the channel response, h(t).

Overview of IEEE 802.11ad-2012 PHY

Packet structure

Golay complementary sequences

For satisfactory channel estimation we need to use a longer sequence than 128 samples. Therefore, in the $G_{u_{512}}$ block for example, the 'a' sequence is provided by the concatenation of $-G_{b_{128}}$ and $-G_{a_{128}}$, with the concatenation of $G_{b_{128}}$ and $-G_{a_{128}}$ providing the complementary 'b' sequence. There is a similar complementary pairing in the $G_{v_{512}}$ block.

Also, to eliminate channel estimation errors caused by signal dispersion through multipath channels, the CEF is always preceded by a $-G_{a_{128}}$ sequence as the last sequence in the STF and similarly followed by a $-G_{b_{128}}$ sequence (annotated as $G_{v_{128}}$). The polarities of these sequences, taken together with those in the G_u and G_v blocks, are defined in a way that allows dispersive errors, such as $G_{a_{128}}$ leaking into $G_{b_{128}}$, to be cancelled when the 'a' and 'b' correlator outputs are combined.

Also by comparing Figure 5 and Figure 7, we can see that the $G_{u_{512}}$ and $G_{v_{512}}$ group definitions are the same in all three modes, but they are time reversed for the OFDM PHY compared with the CPHY and SCPHY.

The time order of $G_{u_{512}}$ and $G_{v_{512}}$ is unimportant for channel estimation since each produces an independent estimate, but the reversal of these fields is used to signal that the subsequent payload is OFDM rather than Single Carrier modulated.

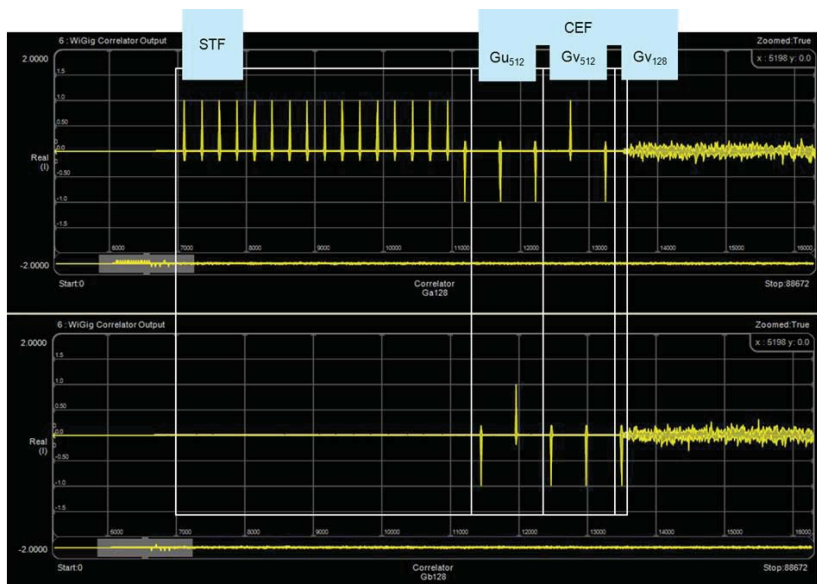


Figure 9. the $G_{a_{128}}$ and $G_{b_{128}}$ correlator outputs for the SCPHY preamble of an ideal signal.

Looking at Figure 9, for the STF field we can see the correlation spike for each of the 16 repetitions of $G_{a_{128}}$ followed by a single negative spike for the terminating $-G_{a_{128}}$. This is followed by the sequence of 9 pulses across $G_{a_{128}}$ and $G_{b_{128}}$ that constitute the CEF.

Overview of IEEE 802.11ad-2012 PHY

Packet structure

Header

In all cases the preamble is followed by a header field that conveys information about the rest of the packet. Most importantly it signals the Modulation and Coding Scheme (MCS) being used for the payload part of the packet.

The information encoded in the header is very similar for Single Carrier and OFDM packets, except that the OFDM header defines a couple of additional OFDM-specific fields; the Tone Pairing Type and Dynamic Tone Pairing (DTP) Indicator flags.

The Control packet header is an abbreviated but otherwise consistent version of the standard header. The header field structures are illustrated in Figure 10.

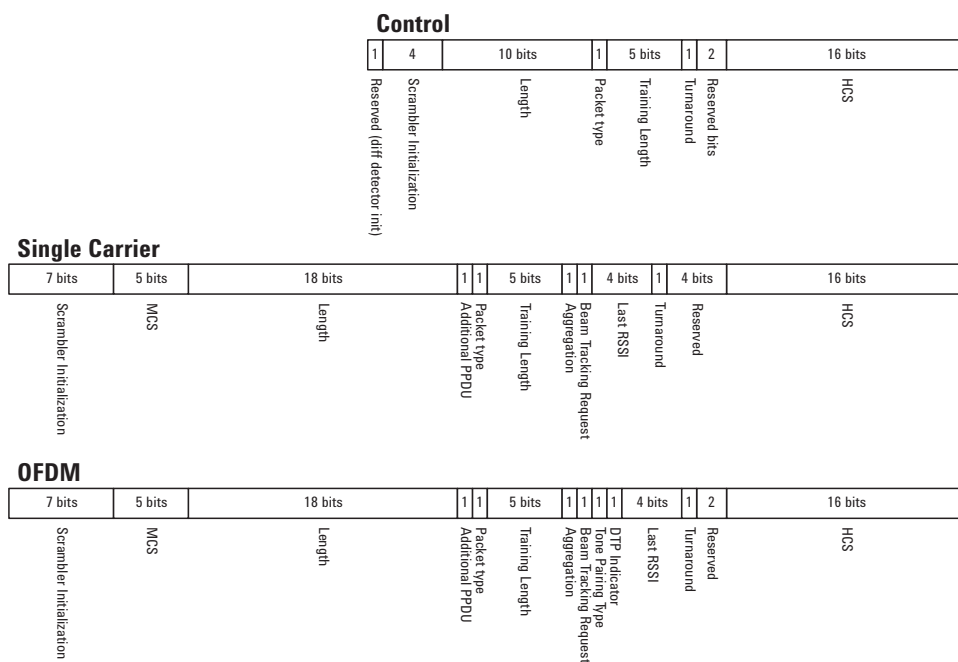


Figure 10. Header field structures

Some of the more important fields are,

- **Scrambler Initialization:** This field seeds the scrambler which is applied to the remainder of the header and the payload for data whitening purposes.
- **MCS:** This field indicates the modulation and coding scheme employed in the payload part of the packet.
- **Length:** This field indicates the number of octets of data in the payload.
- **Training Length:** This field indicates the length of the optional beam forming training field at the end of the packet.
- **Packet Type:** This flag indicates whether the optional beam forming training field is configured for transmitter or receiver training.
- **HCS:** This is a CRC-32 checksum over the header bits.

Payload

The packet payload content is a stream of octets. As mentioned, the header Length field quantifies the useful content of the payload. Prior to encoding, the payload data, depending on the chosen length, may be extended by a small amount, using “stuffing bits”, so that the encoding process will produce a whole number of modulation blocks or symbols. These dummy data are discarded by the decoding process.

Overview of IEEE 802.11ad-2012 PHY

Modulation and coding schemes

The specification tabulates 32 different modulation and coding schemes. However, as we have seen in the preceding paragraphs, there are just a few variations in the modulation and encoding of the preamble and header fields across all 32 MCS.

The packet type, and therefore the modulation of the header field is signalled by modest variations in the preamble's fields; the use of $G_{b_{128}}$ rather than $G_{a_{128}}$ sequences in the STF signals a Control packet, while the ordering of the $G_{u_{512}}$ and $G_{v_{512}}$ fields in the CEF signals whether this is an SC or OFDM packet.

Thus we can quickly simplify the picture by dividing the MCS list into four basic classifications.

Table 2. Summary of P802.11ad Modulation and Coding Schemes (MCS)

Control (CPHY)		
Coding	Modulation	Raw Bit Rate
Shortened 3/4 LDPC, 32x Spreading	$\pi/2$ -DBPSK	27.5 Mbps
Single Carrier (SCPHY)		
Coding	Modulation	Raw Bit Rate
1/2 LDPC, 2x repetition	$\pi/2$ -BPSK,	385 Mbps
1/2 LDPC,	$\pi/2$ -QPSK,	to
5/8 LDPC	$\pi/2$ -16QAM	4620 Mbps
3/4 LDPC		
13/16 LDPC		
Orthogonal Frequency Division Multiplex (OFDMPHY)		
Coding	Modulation	Raw Bit Rate
1/2 LDPC,	OFDM-SQPSK	693 Mbps
5/8 LDPC	OFDM-QPSK (DCM)	to
3/4 LDPC	OFDM-16QAM	6756.75 Mbps
13/16 LDPC	OFDM-64QAM	
Low-Power Single Carrier (LPSCPHY)		
Coding	Modulation	Raw Bit Rate
RS(224,208) + Block	$\pi/2$ -BPSK,	625.6 Mbps
Code(16/12/9/8,8)	$\pi/2$ -QPSK	to 2503 Mbps

Table 2 illustrates the underlying order and purpose in such an apparently large choice of MCS.

It is clearly important, for the reliable establishment and maintenance of connectivity, that the control channel should be as robust as possible. The purpose of the control PHY, and the reasons for its emphasis on reliability over raw speed are considered evident.

It is perhaps less clear why so many MCS are required.

Given the anticipated diversity of device type that will want to support 802.11ad there are persuasive arguments for and against both OFDM and Single Carrier based modulations, and for seriously constrained devices there is a further argument in favour of trading the strength of LDPC-based error correction for further power savings.

Within each of the SC, OFDM and LPSC categories, the specific MCS selects a different pairing of error protection coding and modulation depth, which taken together provide the user with a logical progression of link quality versus throughput operating points.

Overview of IEEE 802.11ad-2012 PHY

Modulation and coding schemes

Control PHY

Modulation and Coding Scheme 0 (MCS0) is by far the most robustly coded (and consequently, lowest throughput) mode. Its purpose is exclusively to transmit control channel messages and it is referred to as the Control PHY (CPHY). Support for MCS0 is mandatory.

The CPHY robustness is evident from its use of differential encoding, code spreading and BPSK modulation. Differential encoding eliminates the need for carrier tracking, 32x spreading contributes a theoretical 15 dB gain to the link budget, and BPSK is, of course, very noise tolerant.

A Ga_{32} Golay complementary code is used as the spreading code, so we can see the result of the despreading process directly by looking at the Ga_{32} correlator output.

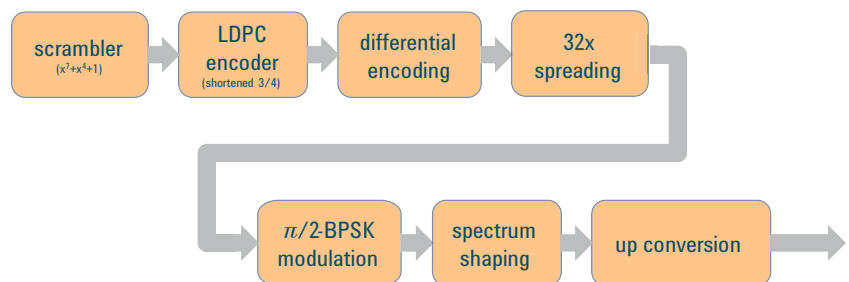


Figure 11. Summary block diagram of CPHY encoding and modulation steps

Single carrier PHY

Modulation and Coding Schemes 1 through 12 (MCS1 – MCS12) employ single-carrier modulation; specifically BPSK, QPSK or 16-QAM modulation of a (suppressed) carrier at the channel center frequency, at a fixed symbol rate of 1.76 Gsym/s. All 12 modes are essentially identical in their channel encoding steps, they differ only in the choice of error protection ratio and modulation density, to allow the appropriate tradeoff between throughput and robustness to be determined operationally (by mode selection). These 12 modes are collectively referred to as the Single Carrier PHY (SCPHY). Support for modes MCS1 to MCS4 is mandatory, to ensure that all compliant devices are capable of data interchange at rates in excess of 1Gbps as required by the original TGad PAR.

The Low-Density Parity Check (LDPC) error correcting coding technique that is common to the CPHY, SCPHY and OFDMPHY MCS is based on a common codeword length of 672 bits each carrying either 336, 504, 420 or 546 payload bits to achieve rate 1/2, 3/4, 5/8 or 13/16 as required.

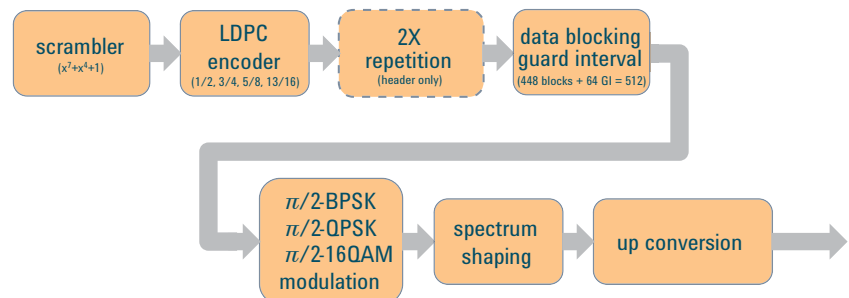


Figure 12. Summary block diagram of SCPHY encoding and modulation steps

Overview of IEEE 802.11ad-2012 PHY

Modulation and coding schemes

Single carrier PHY

The LDPC code employs a Cyclic Shifted Identity (CSI) construction based on a submatrix size of 42 and was designed to permit very efficient encoding using back substitution, and decoding using either fully parallel or layered decoding techniques.

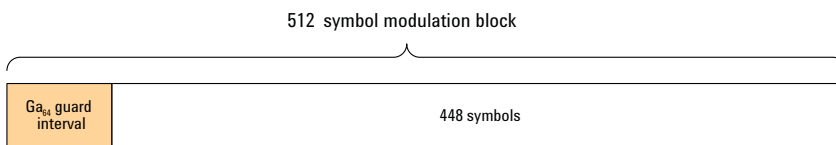


Figure 13. SC PHY payload modulation block

The data blocking and guard interval divides the modulation symbols into groups of 448 symbols interspersed with 64 symbol "Golay sequence guard intervals" (GI) that provide the receiver with a periodic known reference signal to assist with gain and phase tracking. The 64 symbol guard interval is a Ga₆₄ Golay sequence and its periodic occurrence can be confirmed by examining the output of the Ga₆₄ correlator.

The modulation is very conventional single-carrier modulation which is $\pi/2$ rotated to minimise the peak to average power ratio (PAPR) of the BPSK modulation (the GI's are always BPSK modulated) and to allow equivalent GMSK modulation.

Spectrum shaping is mandated but the details are not specified, to permit some design freedom.

OFDM PHY

Modulation and Coding Schemes 13 through 24 (MCS13 – MCS24) employ multi-carrier modulation; specifically Orthogonal Frequency Division Multiplex (OFDM) modulation, which can provide higher modulation densities and hence higher data throughput than the single carrier modes. As for the single carrier modes, all 12 OFDM modes have near identical encoding, varying only in choice of error protection ratio and the depth of modulation applied to the OFDM data carriers, again to provide operational control over the robustness/throughput trade-off. Support for OFDM modulation is not required by the specification, but if it is implemented, then MCS13 to MCS16 are mandatory to ensure some level of interoperability between OFDM-capable devices.

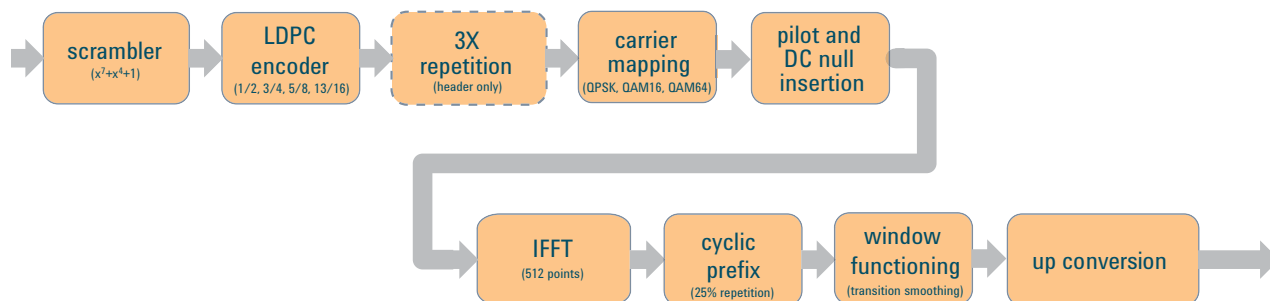


Figure 14. Summary block diagram of OFDM PHY encoding and modulation steps

Overview of IEEE 802.11ad-2012 PHY

Modulation and coding schemes

OFDM PHY

With regard to the choice of single carrier or OFDM modulation; the generally accepted reason for favouring one over the other is the relative importance, in a given application, of power consumption (i.e. maximizing battery life) compared with maximizing data throughput.

OFDM modulation has a large and often unpredictable peak to average power ratio (PAPR) which is challenging for a linear power amplifier to accommodate efficiently. On the other hand, single-carrier modulation typically has a low or even unity PAPR, which lends itself to very efficient and battery-friendly power amplification.

Conversely, OFDM has a significant advantage over single carrier modulation in terms of energy per bit and is particularly robust in the presence of multi-path distortion, both of which give it the edge in the data throughput achievable for a given channel.

That said, such distinctions are shifting and eroding all the time as the technologies develop.

The LDPC encoding is identical to that used in the single carrier modes.

The OFDM is based on a 512-point FFT with 336 active data carriers, and 16 fixed pilot tones. The carriers at DC and on either side of DC are nulled to avoid any issues with carrier feed-through and the cyclic prefix is fixed at 25% of the symbol period.

The individual OFDM carrier modulation may be SQPSK, QPSK, QAM16 or QAM64.

SQPSK is Spread QPSK, in this mode, the OFDM carriers are paired and the same data is modulated onto two carriers maximally separated in frequency to improve the modulation's robustness in the presence of selective frequency fading. The idea is that if one carrier is lost to a null the other is unlikely to be affected at the same time. The pairing of tones is normally static, but there is an option to pair them dynamically according to channel conditions, which has been shown to provide additional robustness.

MCS15, 16 and 17 are described as using QPSK but in fact use Dual Carrier Modulation, which is QPSK-like in its performance, but is, nonetheless, a different technique.

Dual carrier modulation also uses frequency diversity to mitigate selective fading, but it does so in a more subtle way than SQPSK.

In DCM, four bits of payload data are assigned to two subcarriers, which means that, in terms of "bits per subcarrier" it is similar to QPSK. However, in DCM the state of all four bits determines the amplitude and phase state of both subcarriers. Put another way, both subcarriers convey information about all four bits. At the receiver, information from both subcarriers can be combined to recover the original 4 bits.

The QAM16 and QAM64 modulations are very conventional.

Overview of IEEE 802.11ad-2012 PHY

Modulation and coding schemes

Low power single carrier PHY

Finally, consider Modulation and Coding Schemes 25 to 31 (MCS25 – MCS31). This distinctly different group of modes also employs single-carrier modulation, specifically to minimize power consumption, but goes beyond that to specify an alternative channel encoding scheme that replaces LDPC with a combination of Reed-Solomon and Hamming block codes.

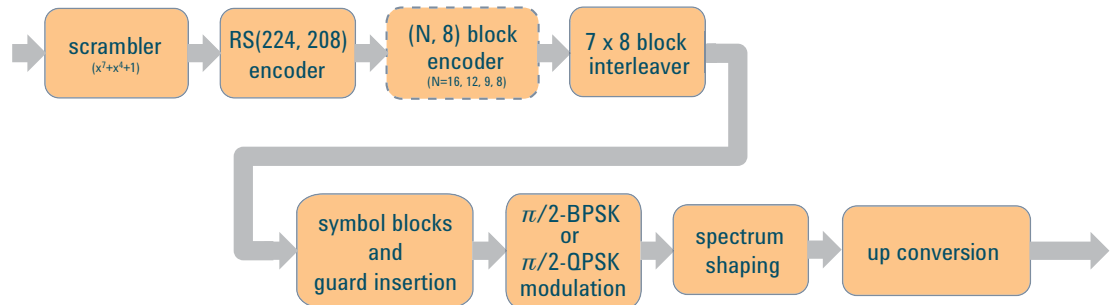


Figure 15. Summary block diagram of LPSCPHY encoding and modulation steps

Again the motivation is to minimize power consumption. In the current state of the art, LDPC encoding/decoding consumes significantly more IC real-estate and hence power than a Reed-Solomon based solution, but that power saving comes at the expense of less robust error correction.

Nonetheless, small battery-powered devices could benefit from the extra power savings and so these MCS have been included and collectively constitute the Low Power Single Carrier PHY (LPSC-PHY). Although the LPSC PHY payload encoding is significantly different from the other modes, the LPSC PHY packets use the common preamble to facilitate coexistence with devices that do not support these MCS. MCS25 to MCS31 are optional, but a device that implements the LPSC PHY modes will still have to implement at least MCS0 to MCS4.

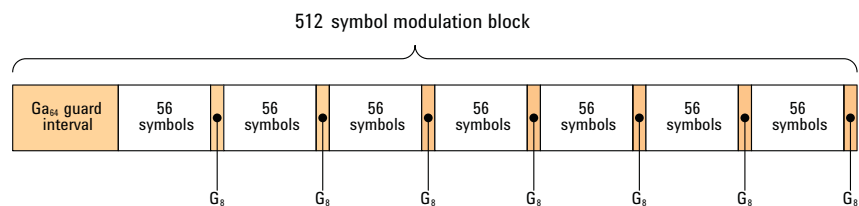


Figure 16. UPC PHY payload modulation block

The symbol blocking and guard interval divides the modulation symbols into groups of 448 symbols interspersed with 64 symbol GI in a manner compatible with the SCPHY. However the 448 symbols are further deconstructed into 7 sub-groups of 56 data symbols each postfixed with a “G₈” guard interval comprising the first 8 symbols of a G₆₄ sequence (7 x 64 = 448). Thus each LPSCPHY block carries 392 data symbols.

Beamform training

The optional optional beamforming training field is the same for all packet types. It, again, comprises a pattern of modulated repeating Golay sequences, the details being determined by the Training Length and Packet Type fields in the header.

Beam Management

The small physical size of an antenna at 60GHz, and the low-cost manufacturing techniques available, make phased array antenna systems commercially feasible. Beamforming allows a pair of devices to train their antenna systems to maximize transmission robustness.

Beamforming training is a bi-directional sequence of training frame transmissions that are appended to each transmission type as shown in the figures above, and are used to shape either or both transmit and receive antenna patterns in real time to account for local movement and interruptions to line-of-sight communication. Either of the pair of devices can initiate a "beam refinement transaction", which is a set of beam refinement frames consisting of beam refinement requests and responses. A beam refinement request can be either a transmit beam refinement request or a receive beam refinement request or both. A beam refinement transaction is complete when the device which initiated it determines that it does not need further training and it has received a beam refinement frame with no training requests from the other device of the pair (known as the responder).

60 GHz PHY Testing

Component and system design and test at 60 GHz is a well-understood and established science. Tools for mmWave circuit design and simulation, network analysis, signal analysis and power measurement have been available for a number of years for use in applications such as short-range radar and military communications. The major difference required by the new commercial 60 GHz applications is the much wider modulation bandwidth, and hence the different test solutions, required.

Agilent's design simulation and stimulus and analysis solutions are described below.

W1915 SystemVue mmWave WPAN baseband verification library

SystemVue is a system-level communications design environment that brings together physical layer baseband algorithmic modelling, accurate RF modelling, standards-based reference IP, and direct interaction with test equipment. It is used early in the R&D lifecycle by system architects, and follows both the RF and Baseband design paths into implementation, providing continuity for cross-domain verification.

W1915 mmWave WPAN Baseband Verification Library is a SystemVue add-on library that provides configurable IP references for 802.11ad and 802.15.3c wireless communications physical layers operating at 60 GHz. It is used by designers to verify baseband algorithms, system performance with faded and precisely impaired channels, and various RF components. Because of the difficulty in making 60 GHz components and measurements, SystemVue simulations are able to assist in these key ways:

- Validation of early RFIC and MMIC designs in Agilent GoldenGate and ADS, prior to taping out a wafer.
- Economical system-level validation and high-fidelity early pre-compliance using simulations, so that final hardware compliance testing can be performed more quickly, with greater confidence.
- Generation of consistent test vectors for simulation vs. hardware testing, using a direct download to the Agilent M8190A AWG and measurement using the 81199A WVC software. The W1915 library is interoperable with the 81199A and 89600 VSA applications.

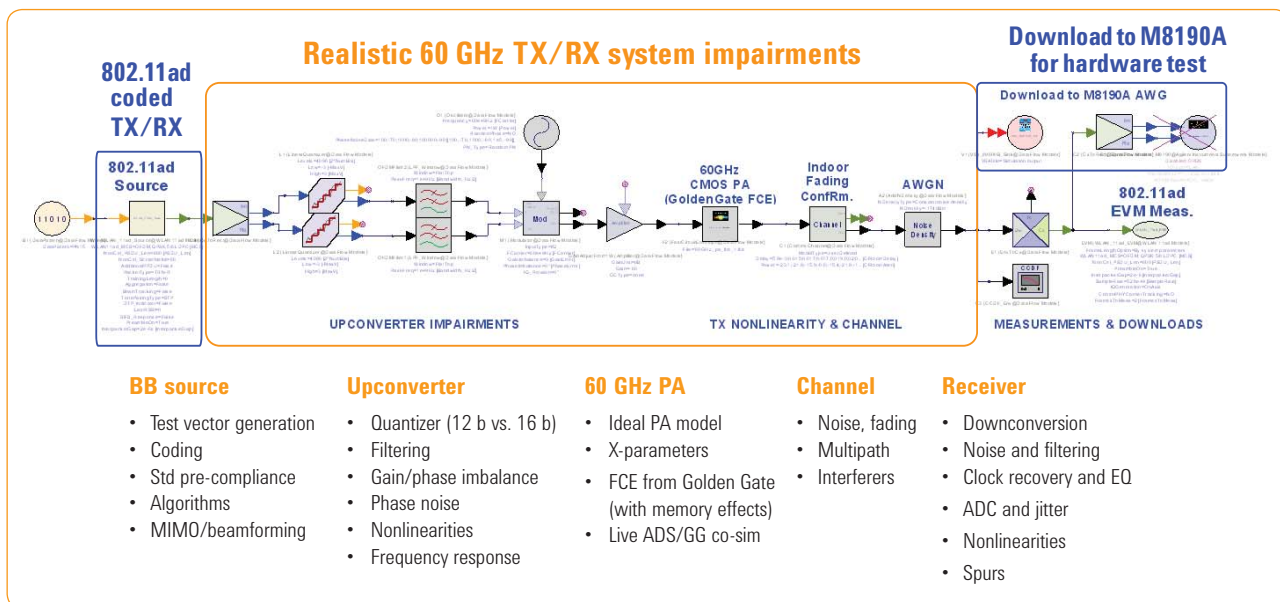


Figure 17. SystemVue's W1915 library provides simulation-based verification of baseband algorithms, difficult RF components, and system-level physical layer performance, such as EVM and closed-loop BER with fading.

60 GHz PHY Testing

60 GHz signal generation and analysis system

When testing 60 GHz wireless signals, one of the biggest challenges is creating and analyzing signals with 2 GHz modulation bandwidth, which is many times greater than other wireless communications systems.

The system shown in Figure 18 combines all the equipment needed for transmitter and receiver test in one package, controlled by Agilent's new wideband waveform center software – signal generation and analysis software tailored to applications running in the 60GHz band. It provides the full range of measurements required to validate components, subsystems and finished devices. Optional software capabilities cover the specific needs and PHY specifications of 802.11ad, WirelessHD and general purpose generation and analysis.

The signal generation and analysis control software is fully compatible with the SystemVue libraries described above. See the 81199A data sheet, publication number 5990-9141EN, for full details and configuration information.

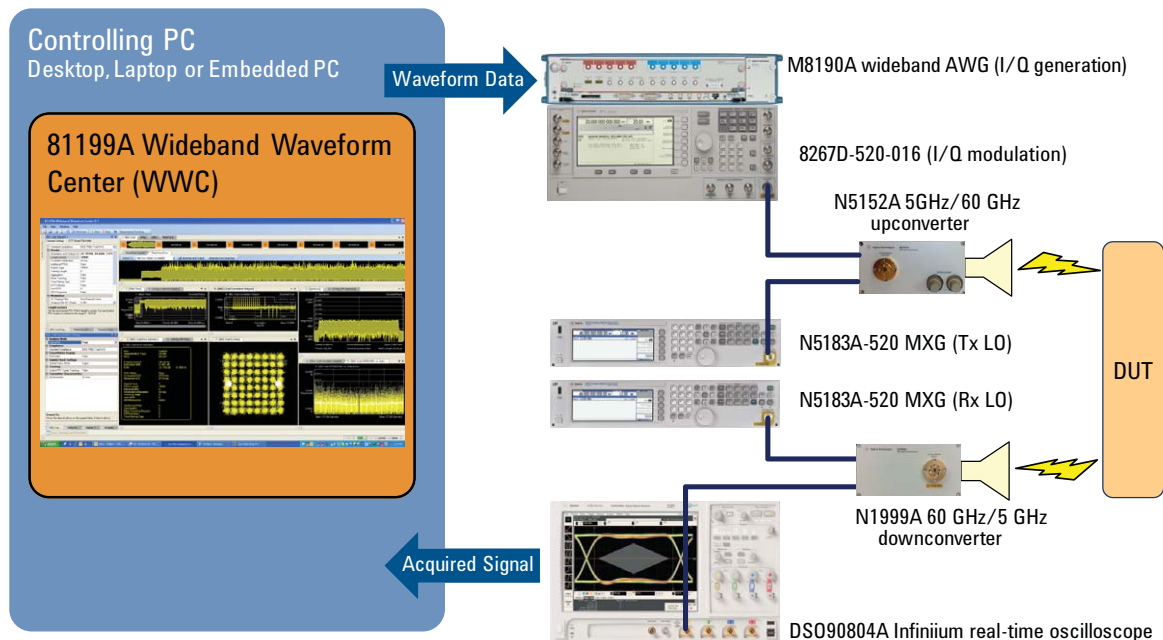


Figure 18. PHY signal generation and analysis system

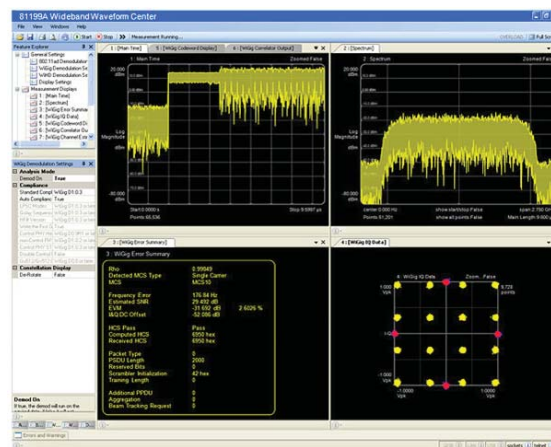
The signal generation and analysis system is controlled by the 81199A wideband waveform center software, which provides the fully coded and modulated PHY signal generation and analysis capability. An arbitrary waveform generator converts the digital waveform data into baseband I and Q signals which are passed to an RF vector signal generator to provide an IF signal to the mmWave upconverter which takes it to the channel of interest. Downconversion to a wideband IF and demodulation is the reverse process, providing the signal to vector signal analysis software to complete the measurement.

60 GHz PHY Testing

81199A wideband waveform center

For each standard, wideband waveform center provides a library of individually-configurable waveform segments. Assembling a desired signal is a simple matter of dragging and dropping waveform segments and then assigning essential attributes to them. Before downloading to an arbitrary waveform generator at an appropriate sample rate, you can also add noise and other impairments.

On the receiver side, wideband waveform center provides a software environment for modulation analysis of fully-coded signals using the power of Agilent's industry-leading 89600 VSA software. 89600 software supports over 30 hardware platforms, including the Infiniium 90000 X-series oscilloscope used to provide the analog bandwidth needed for wideband demodulation, EVM measurement and analysis of other important signal characteristics at 60 GHz. The combination of tabular and graphical results presentation makes at-a-glance analysis and problem detection simple.



M8190A arbitrary waveform generator

The Agilent M8190A arbitrary waveform generator provides 8.0 GSa/s, 2 GHz IQ modulation bandwidth and 14-bit vertical resolution for applications where waveform resolution is an issue. High-bandwidth setups require a reliable and precise modulation source. Any signal distortion gets multiplied by each of the test instruments, making it difficult to pinpoint a failure in the device under test. When the foundation for your signals is more precise, your test results are more meaningful.



60 GHz PHY Testing

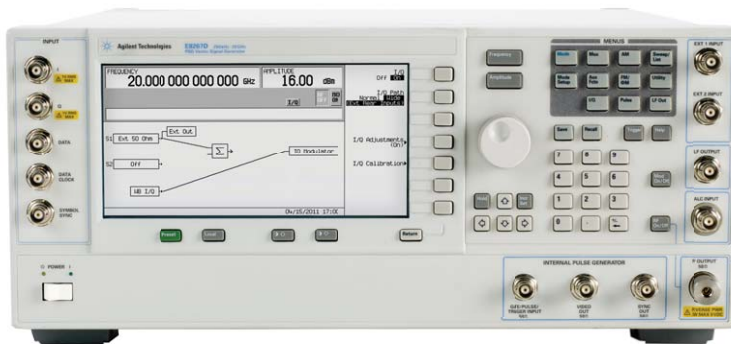
N5183A-520 MXG microwave signal generator (local oscillators)

Excellent power and level accuracy make the N5183A MXG microwave analog signal generator a reliable stimulus for driving high power devices, with all the performance needed for LO substitution.



8267D performance signal generator (vector signal generator)

With the PSG vector signal generator, it is easier to create realistic signal simulations to test broadband wireless communications systems. Whether performing parametric tests on components and devices, or functional tests on subsystems and systems, testing with realistic signal simulations allows you to identify and address issues early in the design process and gain confidence that, when deployed, your designs will be successful. Featuring support for external arbitrary waveform generators with RF modulation bandwidths up to 2 GHz, you now have convenient access to advanced signal simulation technology for generating real-world test signals. With integrated, calibrated, wideband vector signal generation at your fingertips, the signal simulation possibilities are endless. The PSG is the perfect complement to your RF and microwave signal simulation and analysis lab. With the PSG vector signal generator, you have the bandwidth and dynamic range to develop your high-performance radio designs, and the flexibility to ensure you've exercised all possible operating conditions.



N5152A 60GHz up converter and N1999A 60GHz down converter

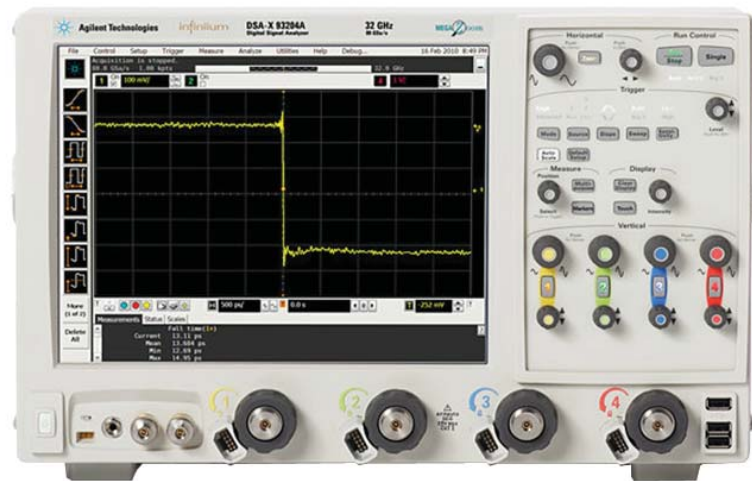
These modules convert an IF of approximately 5 GHz to and from the 60 GHz channel for the DUT tests. The 60 GHz connection in each case is V-band waveguide. Connection to the device can be via either a waveguide to coax adaptor (Agilent V281A) (if the device has a metallic connection) or a horn antenna with known gain.



60 GHz PHY Testing

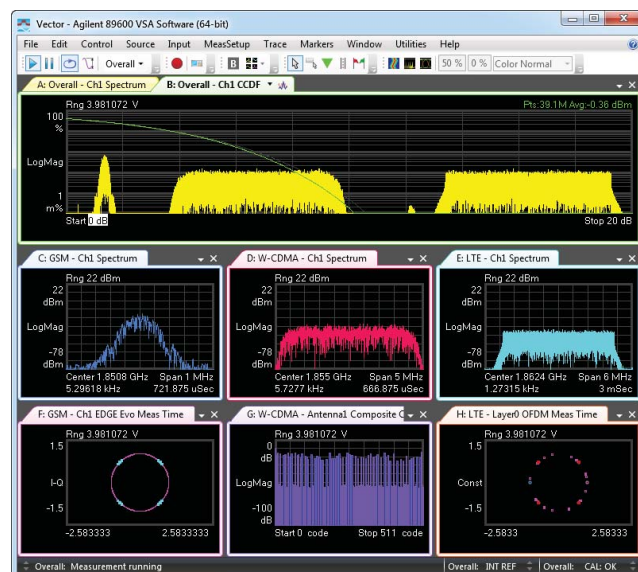
DSO-X91604A InfiniiMax digital signal oscilloscope and DSA-X91604A digital Signal analyzer

When you're identifying spectral content of wide-bandwidth RF signals, you need the truest representation of your signals under test. Agilent invested in leading edge technology to bring you the highest real-time oscilloscope measurement accuracy available today. New custom integrated circuits using a proprietary Indium Phosphide (InP) process and breakthrough packaging technology enable industry-leading performance.



89600 VSA software

The VSA software architecture provides DSP demodulation algorithms with user-controlled modulation parameters for flexible demodulation of a range of new and emerging formats. Data can come from several sources, including multiple supported hardware platforms, recorded files, and stream data from Agilent EEsosf's ADS simulation software. In RF/wireless communications applications, the 89600 VSA software lets you characterize complex, time-varying signals with detailed and simultaneous spectrum, modulation and time waveform analysis. Use these tools to uncover system problems—problems you really need to see and track down. The 89600 VSA software connects your measurement hardware to your PC environment, using familiar, PC-based tools, providing a tightly linked software/hardware test and measurement environment. Use these tools to track down problems at any stage of your design process: from simulation to final prototype.



Agilent's 60 GHz Product Portfolio

Other Agilent products for use in the 60 GHz frequency range are listed in Table 3 below. For the latest product details, see www.agilent.com

Table 3. Agilent's 60 GHz product portfolio

Task	Relevant Agilent Products
Design Simulation	W1461BP SystemVue Communications Architect W1915EP mm-Wave WPAN Baseband Verification Library
Signal Creation	81199A Wideband Waveform Center
Signal Generation	81180A Wideband Arbitrary Waveform Generator (2 channel, 64Msamples, 10 bit, 4.2Gsa/s) M8190A Wideband Arbitrary Waveform Generator (2 channel, 2Gsamples, 14 bit, 12Gsa/s) E8267D PSG Vector Signal Generator, up to 44 GHz + Opt 016 Wideband External I/Q Inputs E8257D-567 Frequency Range from 250 kHz to 67 GHz (CW) N5152A 5GHz / 57-66GHz Up-Converter N5183A-520 MXG Microwave Signal Generator (as U/C Local Oscillator)
Network Analysis	N5227A PNA Series Microwave Network Analyzer, 10 MHz to 67 GHz V11644A Mechanical Calibration Kit, 40 to 75 GHz, Waveguide, WR-15
Spectrum Analysis	E4448A PSA Series Spectrum Analyzer, 3 Hz - 50 GHz + Option AYZ (External Mixing) 11974V Preselected Millimeter Mixer, 50 GHz to 75 GHz + Option 001 (Cal accessory) N9030A PXA Series Spectrum Analyzer, 3 Hz - 50 GHz M1970V 50 – 75 GHz Waveguide Harmonic Mixer
RF Power Measurement	N1913/14A, EPM Series Power Meters V8486A, V-band Power Sensor -30dBm to +20dBm Option H02, V-band Power Sensor -60dBm to +20dBm N8488A, 10 MHz – 67GHz Power Sensor -35dBm to +20dBm
Signal Acquisition	N1999A 57-66GHz Down-Converter N5183A-520 MXG Microwave Signal Generator (as D/C Local Oscillator) DSO90000 Series Infiniium High Performance Oscilloscope: up to 13 GHz 1169A 12 GHz InfiniiMax II series probe amplifier + N5380A InfiniiMax II 12 GHz differential SMA adapter DSO90000X Series Infiniium High Performance Oscilloscope: up to 32 GHz
Vector Signal Analysis	89601B - 89600 Vector Signal Analysis Software 81199A - Wideband Waveform Cente
DC Power Measurement	66300 Mobile Communications DC Sources
Protocol Analysis	N5998A HDMI Protocol / Audio / Video Analyzer and Generator



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