Understanding IEEE 802.11ad Physical Layer and Measurement Challenges

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Microwave Communications Division

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Acknowledgements - Contributing Authors

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David retired, worked for Agilent Technologies Inc. and, before that, Hewlett-Packard Inc. in a variety of engineering and management roles for 34 years before retiring in 2013. For the last 19 years, he has represented the company internationally – contributing to definition and test - in a variety of technical specification and standards-defining organizations, such as DVB, ETSI, Bluetooth SIG, 3GPP, and more recently WirelessHD and Wireless Gigabit Alliance. He served from 2010 to 2013 as the WGA Interoperability Working Group Chair and as the 60 GHz Program Lead in Agilent’s Technology Leadership Organization.

Bob Cutler
Bob started with Hewlett-Packard/Agilent in 1985 and is now a Lead Technologist in Agilent’s Technology Leadership Organization and is also a Senior Member of the IEEE. Bob was the lead engineer in the development of the world’s first vector signal analyzer and has developed many of the RF calibration, modulation, and signal analysis algorithms used in them, including cellular, public safety, broadcast and WiFi, including the newest 60 GHz format, 802.11ad. As a measurement and technology expert, Bob has actively contributed to various IEEE and ETSI standards. More recently Bob served as interim chair of the Interoperability Working Group for the Wireless Gigabit Alliance. Bob holds a number of patents relating to signal detection, system synchronization and vector calibration. Bob now focuses on mmW and 5G technologies.

John Harmon
John is a Wireless Application Lead & has worked for Hewlett-Packard/Agilent since 1980. In that time, he has held various positions in R&D, Manufacturing, Marketing, Business Development and now Application Planning in Agilent Microwave Communications Division. John currently focuses on next generation WLAN technologies and is an Agilent representative to the Wi-Fi Alliance and IWPC Industry Consortium.
Overview
Market drivers, standards, challenges

Physical Layer Overview: Packet types and structure
Physical Layer Detail: Modulation, encoding, error correction
  - Preamble
  - Control PHY
  - Single Carrier PHY
  - OFDM PHY
  - Low Power Single Carrier PHY
  - Forward Error Correction and Scrambling

Design Challenges and Measurement examples

Summary / where to find more information
Agenda

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WLAN Market Growth Drivers

Integration of WLAN into more consumer products
- Smartphones, digital cameras, e-readers, media players, gaming consoles, Blu-ray players, HDTVs

Increasing adoption and use of WLAN in the Enterprise
- BYOD: Enterprise shift toward use of tablets and smartphones

Use of WLAN to offload data from cellular networks
- Up to 65% of mobile data traffic can be offloaded to Wi-Fi

Multi-media Sharing and Streaming
- Displays, TV, Upload/Downloads, Printing, Camera, Gaming

The Internet of Things - New applications keep coming
- Health/fitness, medical, smart meters, home automation, M2M
IEEE 802.11 Standards Evolution

- **802.11-1997**
  - 2 Mbps, DSSS, FHSS

- **802.11b**
  - 11 Mbps, CCK, DSSS

- **802.11a**
  - 54 Mbps, OFDM, 5 GHz

- **802.11g**
  - 54 Mbps, OFDM, 2.4 GHz

- **802.11n**
  - 600 Mbps with 4x4 MIMO, 20/40 MHz BW, 2.4 or 5 GHz

- **802.11p**
  - 27 Mbps, 10 MHz BW, 5.8 GHz
  - Wireless Access for Vehicular Environment (WAVE/DSRC)

- **802.11af**
  - TV White Spaces

- **802.11ac**
  - VHT, <6 GHz
  - Very High Throughput (VHT) Goal: > 1 Gbps

- **802.11ad**
  - VHT, 60 GHz

- **Wireless Gigabit (WiGig)**
Exploiting the Physical Layer
Enhancing and extending the mission of WLAN

- **Bandwidth**
  - More hertz

- **Spectrum**
  - Additional bands & channels

- **Modulation Order**
  - More bits per symbol

- **Error Correction**
  - Closer to Shannon Limit

- **MIMO**
  - More spatial streams

\[ C = B \times \log_2 \left[ 1 + \frac{S}{N} \right] \]

*Digital Communications, Sklar, B., 1988, Prentice Hall, p. 394*
**802.11ac Design Challenges**

**Bandwidth: increase to 80/160 MHz**

- 802.11a/b/g/n only required 40 MHz
- PA digital pre-distortion requires 3-5x system BW

**Higher order modulation: 256QAM**

- 256QAM modulation requires higher SNR, better phase noise
- Transmitter requires 4 dB better EVM for 256QAM than for 64QAM modulation

**MIMO (up to 8 spatial streams)**

- More antennas, more processing, more space required
- Prototyping a multi-antenna radio requires the use of multi-channel test systems
802.11ac Design Challenges

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Data rates: Best case: 6.93 Gbps (160 MHz, 8 Tx, MCS9, short GI)
Typical case: 1.56 Gbps (80 MHz, 4 Tx, MCS9)
802.11ac Channelization

• Operates in 5-6 GHz band only, not in 2.4 GHz band

• Mandatory support for 20, 40, and 80 MHz channels

• 40 MHz same as 802.11n. 80 MHz has more than 2x data subcarriers: 80 MHz has 234 data subcarriers + 8 pilots vs. 108 data subcarriers + 6 pilots for 40 MHz

• Optional support for contiguous 160 MHz and non-contiguous 80+80 MHz transmission and reception. 160 MHz tone allocation is the same as two 80 MHz channels.

• U.S. region frequency allocation (shown below) includes 5710-5835 MHz channels not available elsewhere. *(Need to avoid weather radars in some areas)*

Adapted from Specification Framework, IEEE 802.11-09/0992r15, Updated based on 802.11ac/D1.0
IEEE 802.11a/b/g/n/ac

PHY Data Rates

- 802.11ac Wave II
- 802.11ac Wave I
- 802.11n
- 802.11a/g
- 802.11b
- 802.11

PHY Data Rate (Mbps)

May 2014
IEEE 802.11a/b/g/n/ac/ad PHY Data Rates

- 802.11ad LPSC
- 802.11ad OFDM
- 802.11ad SC
- 802.11ac Wave II
- 802.11ac Wave I
- 802.11n
- 802.11a/g
- 802.11b
- 802.11

PHY Data Rate (Mbps)
IEEE 802.11ad Overview

- The 2.4 and 5 GHz wireless bands are congested and lack the capacity to deliver multi-gigabit data. 802.11ac scoped to address this, but may find it difficult to deliver to multiple users.

- The globally available 60 GHz unlicensed band is “green-field” and can meet the demand for short-range multi-gigabit links, both technically and commercially.

- A backwards-compatible extension to the IEEE 802.11-2012 specification that adds a new MAC/PHY to provide short range, high capacity links in the 60 GHz unlicensed band.

- A managed ad-hoc network of directional, short-range, point-to-point links
  - The PHY uses RF burst (packet) transmissions.
  - Packets contain a common sync preamble (single carrier) followed by header and payload data (SC or OFDM).
  - The PHY supports active antenna beam forming / steering (but not MIMO).
  - The MAC augments the standard IEEE 802.11 MAC with new, 60 GHz specific, capabilities.
60 GHz Unlicensed Band
Atmospheric Absorption of 60 GHz

60 GHz Channel Plan by Region

1. U.S. and Canada (57.05 GHz – 64.00 GHz)
2. European Union (57.00 GHz – 66.00 GHz)
3. South Korea (57.00 GHz – 64.00 GHz)
4. Japan (57.00 GHz – 66.00 GHz)

- **Channel 1**
  - 57.00 GHz
  - $F_c = 58.32$ GHz

- **Channel 2**
  - 59.40 GHz
  - $F_c = 60.48$ GHz

- **Channel 3**
  - 61.56 GHz
  - $F_c = 62.64$ GHz

- **Channel 4**
  - 63.72 GHz
  - $F_c = 64.80$ GHz

Australia (59.40 GHz – 62.90 GHz)
China (59.00 GHz – 64.00 GHz)
60 GHz Channel Plan by Region

CWPAN (China) also planning 43.5-47.0 GHz deployment TGaj (802.11aj)
802.11aj - 45 GHz Frequency Band

Frequency band: 42.3 to 47.0 GHz, 47.2 to 48.4 GHz

Bandwidth: 1080 MHz, 540 MHz

Frequency tolerance: $100 \times 10^{-6}$

Maximum transmit power at antenna port: 20dBm

Maximum EIRP: 36dBm
60GHz Specification Evolution

- WiGig
- WirelessHD
- IEEE802.11ad
- IEEE802.15.3c
- ECMA-387
- Wi-Fi CERTIFIED
- WiGig™
## Where is 802.11ad going to be used?

### High Rate Throughput

<table>
<thead>
<tr>
<th>Use Model</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless Display/Audio</td>
<td>Uncompressed transfer to computers, portable devices to one or more monitors/projectors</td>
</tr>
<tr>
<td>Distribution of HDTV</td>
<td>Games, DVD players to displays, projectors</td>
</tr>
<tr>
<td>Upload/Download</td>
<td>Docking</td>
</tr>
<tr>
<td>Networking/Backhaul</td>
<td>Mesh networks, Peer-to-Peer, Tri-band (2.4/5/60 GHz) Access Points.</td>
</tr>
<tr>
<td>Cordless Computing</td>
<td>Wireless IO docking</td>
</tr>
</tbody>
</table>
The Bigger Picture
A BIG wireless pipe

HD Computer Display
And HD Multimedia

Protocol Adaptation
Layer (WDE³ PAL)

MAC/PHY

Computer I/O, Peripherals,
and Mobile Devices

Protocol Adaptation
Layer (WSD⁴ PAL)
(WBE¹ PAL)
(WSE² PAL)

Wireless DisplayPort

Wireless HD™

Wireless Gigabit Alliance®
MAC/PHY v1.2
is word-for-word identical to...

IEEE 802.11ad

Approved IEEE 802.11ad final text
(published in Dec 2012).

Wireless Bus Extension
Wireless Serial Extension
Wireless Display Extension
Wireless Secure Digital

IEEE®

Wi-Fi® Alliance

Superspeed USB

Wireless Gigabit Alliance®/Wi-Fi Alliance®/VESA® are collaborating in development of Wireless DisplayPort.
The Bigger Picture

A BIG wireless pipe

HD Computer Display
And HD Multimedia

Protocol Adaptation Layer (WDE³ PAL)

MAC/PHY

Wireless Gigabit Alliance®

IEEE 802.11ad

Wireless Display Extension

Approved IEEE 802.11ad final text
(published in Dec 2012).

Computer I/O, Peripherals, and Mobile Devices

Protocol Adaptation Layer (WSD⁴ PAL)
(WBE¹ PAL)
(WSE² PAL)

Wi-Fi Alliance® is responsible for 60 GHz MAC/PHY Certification Test

Wireless Bus Extension

Wireless Serial Extension

Wireless Secure Digital
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Design Challenges and Measurement examples

Summary / where to find more information
PHY Modes (Packet Overview)

Control

Preamble

\(\pi/2\)-BPSK

STF

CEF

Header

Data

Beamforming Training

Single Carrier

Preamble

\(\pi/2\)-BPSK

STF

CEF

Header

Data

Beamforming Training

OFDM

Preamble

\(\pi/2\)-BPSK

QPSK-OFDM

SQPSK/QPSK/QAM16/QAM64-OFDM

Header

Data

Beamforming Training
The preamble always comprises two fields:

- **Short Training Field (STF)**
  - Timing estimation
  - AGC adjustment
- **Channel Estimation Field (CEF)**
  - Channel estimation
Golay Complementary Sequences — $G_{32}, G_{64}, G_{a128}, G_{b128}$

Used extensively in 802.11ad
- Synchronization and AGC
- Data Spreading
- Channel Estimation
- Gain and phase tracking
- Beamforming training

Important attributes of Golay sequences are:
- Low side lobes and low DC content under $\pi/2$ rotation.
- Sum of $G_a$ and $G_b$ autocorrelations is perfect.
- $G_a$ and $G_b$ autocorrelations can be performed in parallel using a single correlator.

At the receive side the correlator indicates which sequence was received by producing a correlation spike on the Ga output OR the Gb output (not both).
Preamble Variants
(showing basic construction)

CPHY Short Training Field (STF) \(5120\) \(T_c\)

SC Channel Estimation Field (CEF) \(1152\) \(T_c\)

Short Training Field (STF) \(2176\) \(T_c\)

SC Channel Estimation Field (CEF) \(1152\) \(T_c\)

Short Training Field (STF) \(2176\) \(T_c\)

OFDM Channel Estimation Field (CEF) \(1152\) \(T_c\)
Preamble Variants
(showing CEF grouping)

CPHY Short Training Field (STF) 5120 $T_c$

Short Training Field (STF) 2176 $T_c$

SC Channel Estimation Field (CEF) 1152 $T_c$

OFDM Channel Estimation Field (CEF) 1152 $T_c$

CAUTION:
Gu & Gv are NOT complementary pairs but a nomenclature convenience
The Channel Estimation Field (CEF)
PHY Header/Payload Modulation

Control

Preamble

\(\pi/2\)-BPSK

STF

CEF

\(\pi/2\)-DBPSK

Beamforming Training

Single Carrier

Preamble

\(\pi/2\)-BPSK

STF

CEF

\(\pi/2\)-BPSK/QPSK/QAM16

Beamforming Training

OFDM

Preamble

\(\pi/2\)-BPSK

QPSK-OFDM

SQPSK/QPSK/QAM16/QAM64-OFDM

Beamforming Training
Modulation and Coding Schemes (MCS)

• Very robust 27.5 Mbps Control Channel
• Variable Error Protection
• Variable Modulation Complexity
  - Therefore EVM specs. from -6dB to -25dB
• Variable Data Rates
  - from 385 Mbps (MCS1) to 6756.75 Mbps (MCS24)
• Mandatory modes ensure all 802.11ad devices capable of at least 1Gbps
  - MCS0-4 Mandatory
  - MCS13-16, if OFDM invoked

<table>
<thead>
<tr>
<th>Control (CPHY)</th>
<th></th>
<th></th>
<th>Raw Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Coding</td>
<td>Modulation</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1/2 LDPC, 32x Spreading</td>
<td>$\pi$/2-DBPSK</td>
<td>27.5 Mbps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single Carrier (SCPHY)</th>
<th></th>
<th></th>
<th>Raw Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Coding</td>
<td>Modulation</td>
<td></td>
</tr>
<tr>
<td>1-12</td>
<td>1/2 LDPC, 2x repetition 1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC</td>
<td>$\pi$/2-BPSK, $\pi$/2-QPSK, $\pi$/2-16QAM</td>
<td>385 Mbps to 4620 Mbps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orthogonal Frequency Division Multiplex (OFDMPHY)</th>
<th></th>
<th></th>
<th>Raw Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Coding</td>
<td>Modulation</td>
<td></td>
</tr>
<tr>
<td>13-24</td>
<td>1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC</td>
<td>OFDM-SQPSK OFDM-QPSK OFDM-16QAM OFDM-64QAM</td>
<td>693 Mbps to 6756.75 Mbps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low-Power Single Carrier (LPSCPHY)</th>
<th></th>
<th></th>
<th>Raw Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Coding</td>
<td>Modulation</td>
<td></td>
</tr>
<tr>
<td>25-31</td>
<td>RS(224,208) + Block Code(16/12/9/8,8)</td>
<td>$\pi$/2-BPSK, $\pi$/2-QPSK</td>
<td>625.6 Mbps to 2503 Mbps</td>
</tr>
</tbody>
</table>
Control PHY (MCS 0) *(Header & Payload Encoding)*

- $\pi/2$-DBPSK modulation
- Data Throughput = 27.5 Mbps  $= 1.76 \frac{GSa}{sec} \div 32 \times \frac{1}{2}$
- Compatible preamble with other PHY for timing and channel estimation
- Baseband filtering is not defined, however EVM is specified with a RRC filter

*Ga32 correlator output showing the results of 32x despreading.*
Low SNR Control PHY (MCS0) Demodulation
Low SNR Control PHY (MCS0) Demodulation
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Low SNR Control PHY (MCS0) Demodulation
The CPHY uses:
- differential encoding
- code spreading
- DBPSK modulation and
- an effective rate of 1/2 LDPC FEC
to ensure reliable communication at very high path loss.

Low SNR Control PHY (MCS0) Demodulation

A weak, but 100% decodable MCS0 signal

De-spread Constellation
-4 dB SNR
45° pk PM

Carrier Tracked

De-rotated
SC PHY (MCS 1 to 12) *(Header & Payload Encoding)*

- Variable modulation depth
- Symbol Rate = 1.76 GSym/sec
- Date rates up to 4.62 Gbps
- Baseband filtering is not defined, however EVM is specified with a RRC filter
- Shares common preamble with OFDM PHY for timing and channel estimation
- Mandatory modes MCS1 to MCS4
SC PHY (MCS 1 to 12) *(Header & Payload Encoding)*

- Variable modulation depth
- Symbol Rate = 1.76 GSym/sec
- Date rates up to 4.62 Gbps
- Baseband filtering is not defined, however EVM is specified with a RRC filter
- Shares common preamble with OFDM PHY for timing and channel estimation
- Mandatory modes MCS1 to MCS4
OFDM PHY (MCS13 to 24) (Header & Payload Encoding)

- Variable modulation depth
- Date rates up to 6.75 Gbps
- Occupied BW = 1.825 GHz
- 16 Static pilots
- 512 subcarriers total
  - 336 Data subcarriers
  - 157 Null subcarriers
  - 3 DC subcarriers nulled: $F_c$ and $F_c \pm 1$
- 3 DC subcarriers nulled: $F_c$ and $F_c \pm 1$
- Shares common preamble with SCPHY for timing and channel estimation
- Different sample rate to SC. Preamble is up-sampled from SC definition by a specified interpolation filter.
- If OFDM implemented, Mandatory Modes MCS13 to MCS16
Special OFDM Modulation Types—SQPSK and DCM

Spread QPSK (SQPSK)

- QPSK modulates the same data onto two, well separated OFDM carriers to mitigate against frequency selective fades.
- Robust, but inefficient in its use of OFDM data carriers.

Dual Carrier Modulation (DCM)

- Modulates four bits of payload data onto two subcarriers in such a way that both subcarriers convey information about all four bits.
- Carrier pairing mitigates against frequency selective fades.
- More efficient use of OFDM data carriers.

Tone Pairing

- Static Tone Pairing assumes simple maximum separation rule. Does not require feedback path.
- Dynamic Tone Pairing assigns pairs more intelligently based on dynamic channel state information to achieve better performance. Does require a feedback path. Optional.
Low Density Parity Check (LDPC)

“Even better than turbo codes” performance has since stimulated a lot of research.

LDPC codes are systematic block codes that use parity check as the error detection/correction mechanism.

A large, sparse, randomly populated parity matrix, coupled with a soft-decision iterative decoding algorithm can produce error correcting codes with performance within 0.05dB of the Shannon Limit.

The 802.11ad parity matrix is optimized for simple codeword generation by back-substitution on the parity matrix and efficient hardware implementation of the iterative soft decoding algorithm.

m = r x 672 where r = 1/2, 5/8, 3/4, or 13/16
PHY Beamforming Training

Ga_{64}

Ga_{128}

Gb_{128}
• Beamforming is optional

• However, the Receiver must support BFT protocol – i.e. it must report which packet was received with the best quality. The Transmitter can then determine best beam direction.
• Beamforming is optional

• However, the Receiver must support BFT protocol – i.e. it must report which packet was received with the best quality. The Transmitter can then determine best beam direction.

• If Transmitter Beamforming is supported, then the peer device uses the same beam direction (assumes reciprocity of the channel)
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802.11ad Design Challenges

**mm Technology**
- Performance taken for granted at lower frequencies, not so easy to achieve at mm frequencies
- Mismatch, skew, cable lengths matter

**Wide Bandwidth**
- ~2 GHz Modulation BW
  - Data rates up to 6.75 Gbps
  - **100x wider modulation** bandwidth than 802.11n.
    11x wider than 802.11ac
  - Complex frequency response (flatness) difficult

**No Connectors at 60 GHz**
- Built-in multi-element antennas lack test connection
- Path losses significant
- Over-the-air (OTA) testing required jeopardizes measurement plane
- Multi-path intrinsic in performance and in measurement environment
PHY Measurement Challenges

**Practical Problems**
- Connectivity!
- Modulation Bandwidth

**PHY Challenges**
- Phase stability / frequency accuracy
- Quadrature errors
- DC/LO feedthrough
- I / Q Mismatch
- Transmit power

![Diagram of RF ASIC with antenna array bonded directly on top of RFIC.]

*Baseband ASIC*

*RF ASIC with antenna array bonded directly on top of RFIC.*
Have I got a signal?

**Time Domain**
- SNR?
- Clipping?
- Transients?
- Structure?
- Etc...

**Frequency Domain**
- Shape?
- Flatness?
- Bandwidth?
- Spurs?
- Etc...
Spectrum, Time, Power Statistics, Spectrogram

Spectrogram display

Gated Spectrum

Power vs Time

CCDF

Gated Power Measurement
802.11ad Tx Mask

Per specification IEEE 802.11-2012
Paragraph 21.3.2

IEEE 802.11ad Tx Mask
802.11ad Tx Mask
Golay Correlator Outputs

SCPHY with -7 dB SNR, 20° phase jitter and 50ps IQ skew

Preamble jitter in the IQ plane

Ga64 Real
Gb64 Imaginary
Ga64 I-Q

Agilent Technologies
Channel Impulse Response
(estimated from CEF field)

3x multipath:
Main path +
-10ns @ -10dB
+4ns @ -15dB
Channel Frequency Response

Derived from the channel impulse response
Step 4... Error Vector Magnitude (EVM)

\[ EVM = \sqrt{\frac{1}{N} \sum_{n=1}^{N} |e_n|^2} \]

- Ideal MCS10 constellation
- More typical MCS10 constellation
- 25 dB Gaussian noise
- 5° jitter at 4 MHz
- 50 ps IQ skew
- 1.93 dB gain mismatch
- 5° quadrature error
Phase Error and Carrier Tracking

Phase Error
20° pk PM
at 20 MHz

Carrier Tracking
20° pk PM
at 1 MHz
EVM versus Time and Frequency

5 ppm symbol clock error

in-band spur at +450 MHz
OFDM EVM by Symbol and by Carrier

EVM spread per OFDM symbol

EVM spread per OFDM carrier

WiHD LRP co-channel interferer
Constellation Display and Error Summary

MCS10 SC PHY constellation

Error Summary for SC PHY

MCS24 OFDM PHY constellation

Agilent Technologies
Step 5... FEC Codewords and Data

MCS12
LDPC 13/16 at FEC failure threshold.
Binary display

Error corrected, descrambled, payload data.
Octet display

MCS27
RS(224,208)
no uncorrectable errors.
Octet display
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Summary / where to find more information
Summary

- 802.11ad extends the highly successful 802.11 WLAN family.

- 802.11ad mixes single carrier and OFDM modulation techniques to support a wide range of price/performance points up to 6.75 Gbps.

- Golay Complementary Sequences are a foundation of the 802.11ad specification.

- The IEEE has specified 11ad technology. The Wi-Fi Alliance® is certifying and promoting this technology.

- 802.11ad-capable devices are already announced and more will emerge in 2014 and 2015.
All of the signals and impairments were generated and analyzed using this 60 GHz PHY Test Solution

Controlling PC
(Could be Desktop, Laptop or Embedded)

81199A Wideband Waveform Center (WWC)

89601B VSA SW

WARNING: Exit 89600 VSA Software before changing instrument setup
For more information

Solution Information: www.agilent.com/find/WLAN
(including a six-part tutorial series) www.agilent.com/find/802.11ad

Web Form: www.agilent.com/find/wlan-insight

IEEE: www.ieee.org

Wi-Fi Alliance®: www.wi-fi.org

Wireless Gigabit Alliance®: www.wigig.org