IEEE 802.11ad PHY Layer Testing

Presented by: David Grieve, Agilent Technologies
Agenda

- Overview of IEEE 802.11ad
- Tutorial introduction to the PHY layer
- PHY Measurement challenges
- PHY Measurements
  - Have I got a signal?
  - Basic diagnostics
  - Demodulating the CPHY
  - Modulation quality
  - Decoding the data
- Conclusions
IEEE 802.11ad Overview

What? A backwards-compatible extension to the IEEE 802.11-2007 specification that adds a new MAC/PHY to provide short range, high capacity links in the 60 GHz unlicensed band.

Where? The 60 GHz MAC/PHY specification was initially developed privately by the Wireless Gigabit Alliance. It was contributed to the IEEE TGad in May 2010 and has subsequently been developed to a final draft standard in IEEE.

When? The specification will be signed off by TGad in June 2012 and formally released for publication in Dec 2012. We expect first commercial silicon in 2H 2012, and anticipate first certified product announcements in Jan 2013.
IEEE 802.11ad Overview

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

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

How? A managed ad-hoc network of directional, short-range, point-to-point links at 60 GHz.

- The PHY uses RF burst (packet) transmissions.
- Packets start with a common sync preamble followed by header and payload data. The common preamble always uses single-carrier (SC) modulation, the header and data may use SC or OFDM modulation depending on the selected mode.
- 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 Spectrum Mask

Frequency (GHz)
60GHz Channel Plan by Region

- U.S. and Canada (57.05 GHz – 64.00 GHz)
- European Union (57.00 GHz – 66.00 GHz)
- South Korea (57.00 GHz – 64.00 GHz)
- Japan (59.00 GHz – 66.00 GHz)
- Australia (59.40 GHz – 62.90 GHz)
- China (59.00 GHz – 64.00 GHz)

Channel 1
- $F_c = 58.32$ GHz

Channel 2
- $F_c = 60.48$ GHz

Channel 3
- $F_c = 62.64$ GHz

Channel 4
- $F_c = 64.80$ GHz
PHY Modes (Packet Overview)

Control

- **Preamble**
- **STF**
- **CEF**
- **Header**
- **Data**
- **Beamforming Training**

**Modes:**
- **π/2-BPSK**
- **π/2-DBPSK**

Single Carrier

- **Preamble**
- **STF**
- **CEF**
- **Header**
- **Data**
- **Beamforming Training**

**Modes:**
- **π/2-BPSK**
- **π/2-BPSK/QPSK/QAM16**

OFDM

- **Preamble**
- **STF**
- **CEF**
- **Header**
- **Data**
- **Beamforming Training**

**Modes:**
- **π/2-BPSK**
- **QPSK-OFDM**
- **SQPSK/QPSK/QAM16/QAM64-OFDM**
The preamble always comprises two fields;

- Short Training Field (STF)
  - Timing estimation
  - AGC adjustment
- Channel Estimation Field (CEF)
  - Channel estimation

Table 21-24 – The sequence Ga_{128}(n)

<table>
<thead>
<tr>
<th>The Sequence Ga_{128}(n), to be transmitted from left to right, up to down</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1 +1 -1 -1 -1 -1 -1 -1 +1 +1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
<tr>
<td>-1 -1 +1 +1 +1 +1 +1 -1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
<tr>
<td>+1 +1 -1 -1 -1 -1 -1 -1 +1 +1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
<tr>
<td>+1 +1 -1 -1 -1 -1 -1 -1 +1 +1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
</tbody>
</table>

Table 21-25 – The sequence Gb_{128}(n)

<table>
<thead>
<tr>
<th>The Sequence Gb_{128}(n), to be transmitted from left to right, up to down</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 -1 +1 +1 +1 +1 +1 -1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
<tr>
<td>+1 +1 -1 -1 -1 -1 -1 -1 +1 +1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
<tr>
<td>+1 +1 -1 -1 -1 -1 -1 -1 +1 +1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
<tr>
<td>+1 +1 -1 -1 -1 -1 -1 -1 +1 +1 -1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1 -1</td>
</tr>
</tbody>
</table>
Preamble Variants (showing basic construction)

| \( G_b_{128} \) | \( G_b_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( -G_a_{128} \) | \( -G_b_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|

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

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

| \( G_b_{128} \) | \( G_a_{128} \) | \( G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( -G_b_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|

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

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

| \( G_b_{128} \) | \( G_a_{128} \) | \( G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( -G_b_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) | \( -G_b_{128} \) | \( G_a_{128} \) | \( -G_a_{128} \) | \( G_b_{128} \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|

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

OFDM Channel Estimation Field (CEF) 1152 \( T_c \)
Complementary Golay Codes

Used extensively in 802.11ad;

- Synchronization and AGC
- Data Spreading
- Channel Estimation
- Gain and phase tracking

Important attributes of Golay codes are;

- Low side lobes and low DC content under $\pi/2$ rotation.
- Sum of Ga and Gb autocorrelations is perfect.
- Ga and Gb autocorrelations can be performed in parallel using a single correlator.
Golay Correlator Output

Ga_{128} Ga_{128} Ga_{128} Ga_{128} -Ga_{128} -Gb_{128} -Gb_{128} -Gb_{128} Ga_{128} -Gb_{128} -Gb_{128} -Gb_{128} Gu_{512} Gu_{512} Gu_{512} Gu_{512} Gv_{512} Gv_{512} Gv_{512} Gv_{512} -Gb_{128} -Gb_{128} -Gb_{128} -Gb_{128}
Preamble Variants
(showing CEF grouping)

CPHY Short Training Field (STF) 5120 $T_c$

Short Training Field (STF) 2176 $T_c$

Short Training Field (STF) 2176 $T_c$

SC Channel Estimation Field (CEF) 1152 $T_c$

SC Channel Estimation Field (CEF) 1152 $T_c$

OFDM Channel Estimation Field (CEF) 1152 $T_c$
Channel Estimation Opportunity

Can also use the 128-length sequences for improved SNR

Greater insight. Greater confidence. 
Accelerate next-generation wireless
Principle of Channel Estimation
(application of Golay codes)

\[ R_a = a \cdot a \cdot h(t) \]
\[ R_b = b \cdot b \cdot h(t) \]
\[ \text{output} = R_a + R_b \]
\[ = a \cdot a \cdot h(t) + b \cdot b \cdot h(t) \]
\[ = a \cdot a + b \cdot b \cdot h(t) \]
\[ = \delta \cdot t \cdot h(t) \]
\[ = h(t) \]
### Header Variants

#### Single Carrier

<table>
<thead>
<tr>
<th>7 bits</th>
<th>5 bits</th>
<th>18 bits</th>
<th>1</th>
<th>1</th>
<th>5 bits</th>
<th>1</th>
<th>1</th>
<th>4 bits</th>
<th>1</th>
<th>4 bits</th>
<th>16 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrambler Initialization</td>
<td>MCS</td>
<td>Length</td>
<td>Packet Type</td>
<td>Additional PDU</td>
<td>Training Length</td>
<td>Beam Tracking Request</td>
<td>Aggregation</td>
<td>Last RSSI</td>
<td>SIFS response</td>
<td>Reserved</td>
<td>HCS</td>
</tr>
</tbody>
</table>

#### OFDM

<table>
<thead>
<tr>
<th>7 bits</th>
<th>5 bits</th>
<th>18 bits</th>
<th>1</th>
<th>1</th>
<th>5 bits</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>4 bits</th>
<th>1</th>
<th>2</th>
<th>16 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrambler Initialization</td>
<td>MCS</td>
<td>Length</td>
<td>Packet Type</td>
<td>Additional PDU</td>
<td>Training Length</td>
<td>Beam Tracking Request</td>
<td>Aggregation</td>
<td>Last RSSI</td>
<td>SIFS response</td>
<td>Reserved</td>
<td>HCS</td>
<td></td>
</tr>
</tbody>
</table>

### Control

<table>
<thead>
<tr>
<th>10 bits</th>
<th>5 bits</th>
<th>2</th>
<th>16 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserved</td>
<td>Scrambler Initialization Length</td>
<td>Packet Type</td>
<td>Training Length</td>
</tr>
</tbody>
</table>

**Single Carrier**:
- Preamble
- Header
- Data
- BFT

**OFDM**:
- Preamble
- Header
- Data
- BFT
PHY Header/Payload Modulation

Control

Preamble

STF

CEF

Header

Data

Beamforming Training

Single Carrier

Preamble

STF

CEF

Header

Data

Beamforming Training

OFDM

Preamble

STF

CEF

Header

Data

Beamforming Training

QPSK-OFDM

SQPSK/QPSK/QAM16/QAM64-OFDM

© 2012 Agilent Technologies
Modulation and Coding Schemes (MCS)

Key Points

- Very robust 27.5 Mbps Control Channel
- Variable Error Protection
- Variable Modulation Complexity
  - Hence 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

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

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

<table>
<thead>
<tr>
<th>Orthogonal Frequency Division Multiplex (OFDMPHY)</th>
<th>Coding</th>
<th>Modulation</th>
<th>Raw Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Coding</td>
<td>Modulation</td>
<td>Raw Bit Rate</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>Coding</th>
<th>Modulation</th>
<th>Raw Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS</td>
<td>Coding</td>
<td>Modulation</td>
<td>Raw Bit Rate</td>
</tr>
<tr>
<td>25-31</td>
<td>RS(224,208) + Block Code(16/12/9/8,8)</td>
<td>π/2-BPSK, π/2-QPSK</td>
<td>625.6 Mbps to 2503 Mbps</td>
</tr>
</tbody>
</table>
Single Carrier (SC) Modulation

- Variable modulation depth
- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupied BW</td>
<td>1.76 GHz (3dB)</td>
</tr>
<tr>
<td>Modulation chip rate</td>
<td>1.76 Gsamples/s</td>
</tr>
<tr>
<td>Block length</td>
<td>512 symbols, ~ 291 ns</td>
</tr>
<tr>
<td>Guard Interval</td>
<td>64 symbols, ~ 36.4 ns</td>
</tr>
<tr>
<td>Data symbols per block</td>
<td>448 symbols</td>
</tr>
<tr>
<td>Modulation</td>
<td>π/2-BPSK, π/2-QPSK, π/2-16QAM</td>
</tr>
<tr>
<td>Error Protection</td>
<td>LDPC 1/2, 5/8, 3/4 or 13/16</td>
</tr>
</tbody>
</table>
OFDM Modulation

- Variable modulation depth
- Data rates up to 6.76 Gbps
- 16 Static pilots
- Fc and Fc±1 nulled
- 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupied BW</td>
<td>1.825 GHz</td>
</tr>
<tr>
<td>Ref. sampling rate</td>
<td>2.640 Gsamples/s</td>
</tr>
<tr>
<td>No. of subcarriers</td>
<td>512</td>
</tr>
<tr>
<td>FFT period</td>
<td>~ 194 ns</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>5.15625 MHz</td>
</tr>
<tr>
<td>Cyclic prefix</td>
<td>128 symbols, ~ 48.4 ns</td>
</tr>
<tr>
<td>Symbol duration</td>
<td>~242 ns</td>
</tr>
<tr>
<td>Data subcarriers</td>
<td>336</td>
</tr>
<tr>
<td>DC subcarriers</td>
<td>3</td>
</tr>
<tr>
<td>Pilots</td>
<td>16</td>
</tr>
<tr>
<td>Null subcarriers</td>
<td>157</td>
</tr>
<tr>
<td>Modulation</td>
<td>SQPSK, QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Error Protection</td>
<td>LDPC 1/2, 5/8, 3/4 or 13/16</td>
</tr>
</tbody>
</table>
Control PHY (MCS 0) (Header & Payload Encoding)

- Scrambler ($x^7 + x^4 + 1$)
- LDPC Encoder (Shortened 3/4)
- Differential Encoding
- 32x Spreading
- $\pi/2$-BPSK Modulation
- Spectrum Shaping
- Up Conversion

Ga32 correlator output showing the results of 32x despreading.
SC PHY (MCS 1 to 12) (Header & Payload Encoding)

Scrambler
\((x^7 + x^4 + 1)\)

LDPC Encoder
\((1/2, 3/4, 5/8, 13/16)\)

2x Repetition
(header only)

Data Blocking and Guard Interval
(448 block + 64 Gi = 512)

\(\pi/2\)-BPSK
\(\pi/2\)-QPSK
\(\pi/2\)-16QAM
Modulation

Spectrum Shaping

Up Conversion

512 symbol modulation block

Ga64 correlator output showing the regular guard interval.
OFDM PHY (MCS13 to 24) (Header & Payload Encoding)

- **Scrambler**
  \((x^7 + x^4 + 1)\)

- **LDPC Encoder**
  \((1/2, 3/4, 5/8, 13/16)\)

- **3x Repetition**
  (header only)

- **Carrier Mapping**
  (QPSK, QAM16, QAM64)

- **Pilot and DC Null Insertion**

- **IFFT**
  (512 points)

- **Cyclic Prefix**
  (25% repetition)

- **Windowing Function**
  (Transition smoothing)

- **Up Conversion**

SQPSK, QPSK, 16QAM, 64QAM
LPSC PHY (MCS 25 to 31) (Header & Payload Encoding)

Scrambler
\((x^7+x^4+1)\)

RS(224,208) Encoder

\((N,8)\) Block Encoder
\((N = 16, 12, 9, 8)\)

7 x 8 Block Interleaver

Symbol Blocks and Guard Insertion

\(\pi/2\)-BPSK or \(\pi/2\)-QPSK Modulation

Spectrum Shaping

Up Conversion

512 symbol modulation block
Low Density Parity Check (LDPC)

First proposed by Gallager in 1960, but ignored
Re-discovered by McKay and others in the mid 1990’s
“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.

\[ m = r \times 672 \text{ where } r = 1/2, 5/8, 3/4, \text{ or } 13/16 \]
PHY Measurement Challenges

Practical Problems
- Connectivity!
- Modulation Bandwidth

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

Baseband ASIC
RF ASIC with antenna array bonded directly on top of RFIC.
Step 1… Have I got a signal?

Time Domain
- SNR?
- Clipping?
- Transients?
- Structure?
- Etc…

Frequency Domain
- Shape?
- Flatness?
- Bandwidth?
- Spurs?
- Etc…
Step 2… Golay Correlator Outputs

- SCPHY with -7 dB SNR, 20° phase jitter and 50ps IQ skew
- Preamble jitter in the IQ plane
Step 3… Control PHY Demodulation

The CPHY uses differential encoding, code spreading, BPSK modulation and a rate 1/2 LDPC FEC to ensure reliable communication at very high path loss.
Phase Error and Carrier Tracking

Phase Error 20° pk PM at 20 MHz

Carrier Tracking 20° pk PM at 1 MHz
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
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 SCPHY constellation

Error Summary for SCPHY

MCS24 OFDM PHY constellation
Step 5... FEC Codewords and Data

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

MCS27 RS(224,208) no uncorrectable errors. Octet display

Error corrected, descrambled, payload data. Octet display
Agilent 60 GHz PHY Test Solution

Controlling PC
(Could be Desktop, Laptop or Embedded)

81199A Wideband Waveform Center (WWC)

89601B Vector Signal Analyzer

M8190A Wideband AWG (I/Q Generation)

8267D-520-016 (I/Q Modulation)

N5152A 5GHz/60GHz U.C.

N5183A-520 MXG (Tx LO)

N5183A-520 MXG (Rx LO)

N1999A 60GHz/5GHz D.C.

DSO90404A Infiniium Real-time Oscilloscope
Conclusions

802.11ad capable devices will start to appear late 2012, early 2013.

802.11ad extends the highly successful 802.11 WLAN family.

Wireless Gigabit Alliance, IEEE and Wi-Fi Alliance are working in close collaboration to specify, certify and promote this technology.

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

Golay codes are a foundation of the WiGig/802.11ad specification that also enable significant measurement insight.

There are many design challenges for PHY development at 60 GHz, think in terms of 10x to 100x 802.11a, compounded by the need to do RF testing over-the-air.

Agilent has unique solutions for developing and verifying PHY designs.
QUESTIONS?