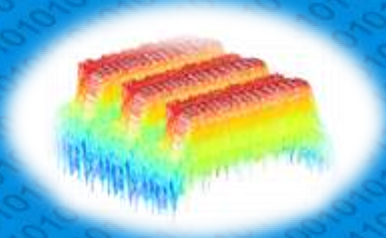
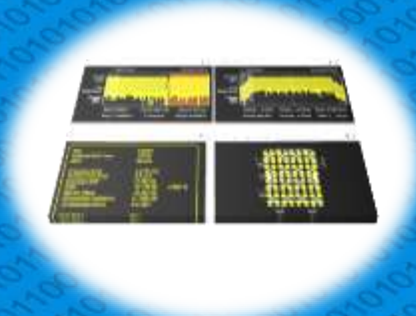
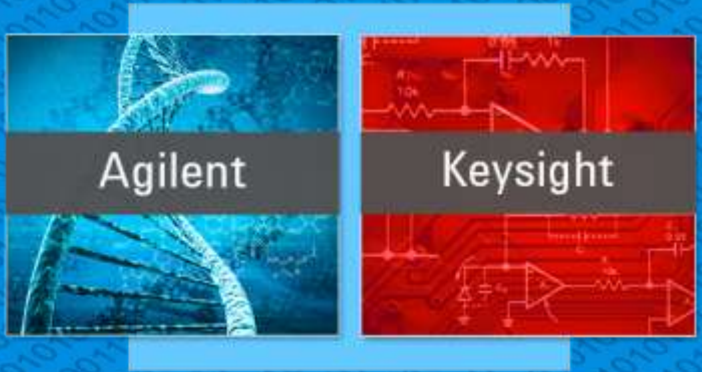




Understanding IEEE 802.11ad Physical Layer and Measurement Challenges

IEEE



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Wireless Application Marketing
Microwave Communications Division

May 2014

Acknowledgements - Contributing Authors

David Grieve

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.

Agenda

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

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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

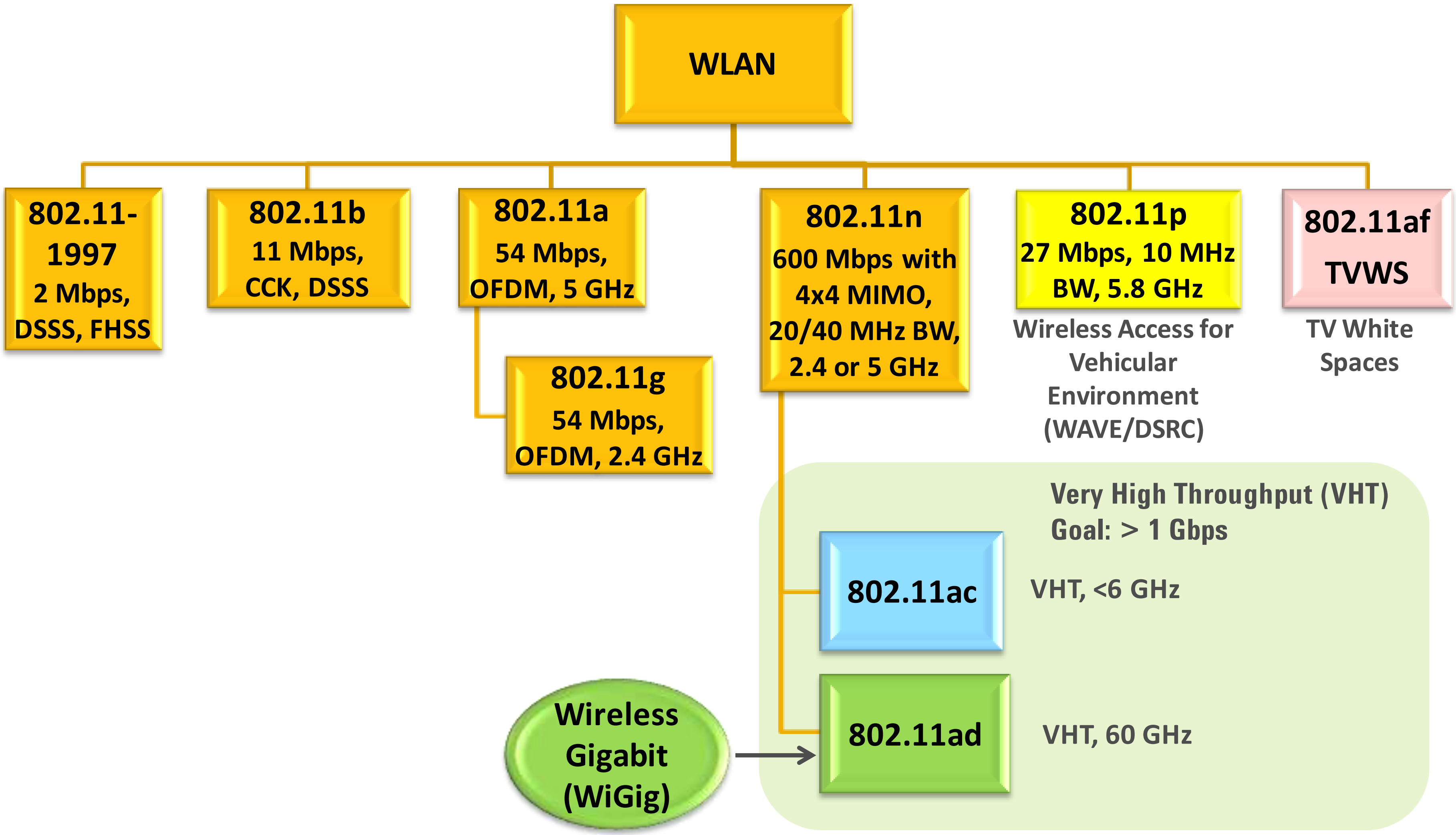
Multi-media Sharing and Streaming

- Displays, TV, Upload/Downloads, Printing, Camera, Gaming

The Internet of Things - New applications keep coming

- Health/fitness, medical, smart meters, home automation, M2M

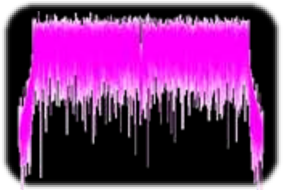
IEEE 802.11 Standards Evolution



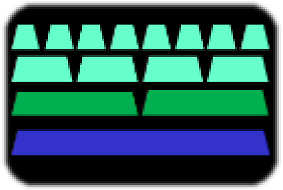
Exploiting the Physical Layer

Enhancing and extending the mission of WLAN

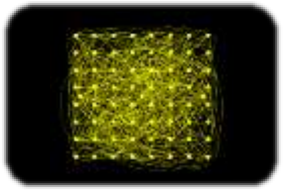
Bandwidth
More hertz



Spectrum
Additional bands & channels

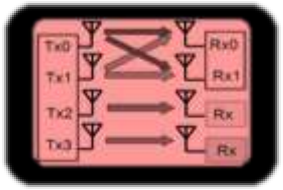


Modulation Order
More bits per symbol

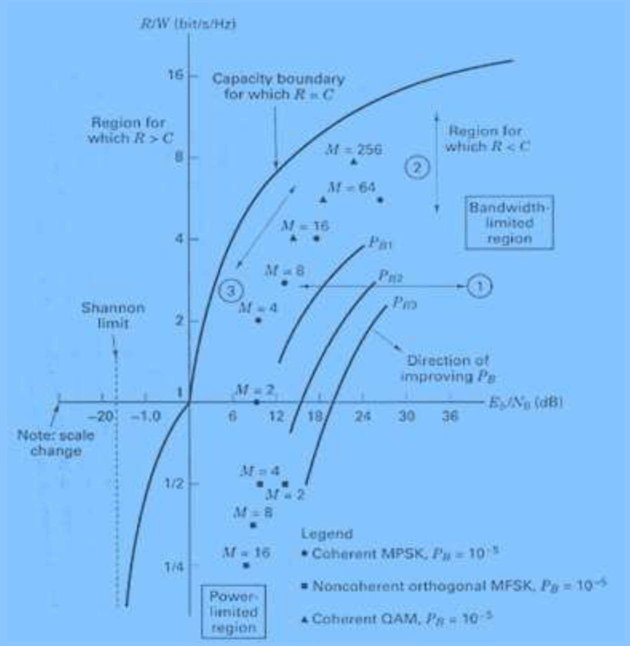


Error Correction
Closer to Shannon Limit

MIMO
More spatial streams



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



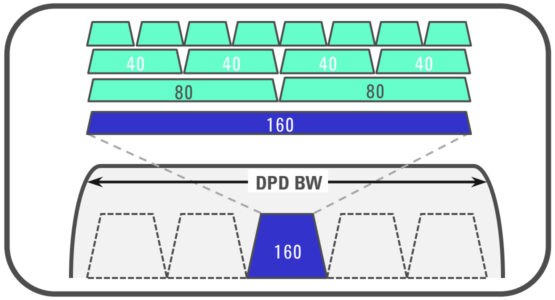
Digital Communications, Sklar, B., 1988, Prentice Hall, p. 394

Beamforming

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

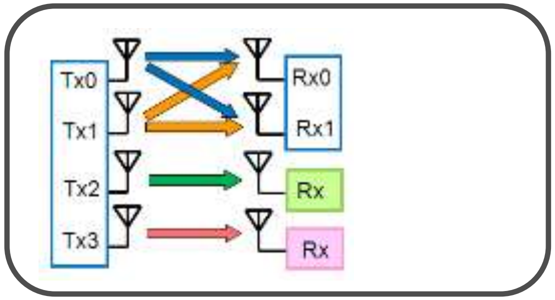


Higher order modulation: 256QAM

- 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

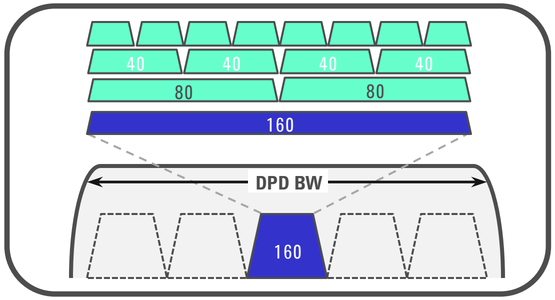


802.11ac Design Challenges

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

Bandwidth: increase to 80/160 MHz

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



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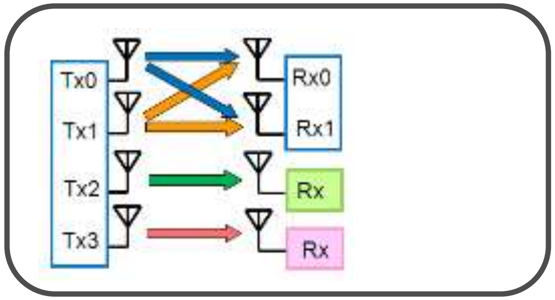
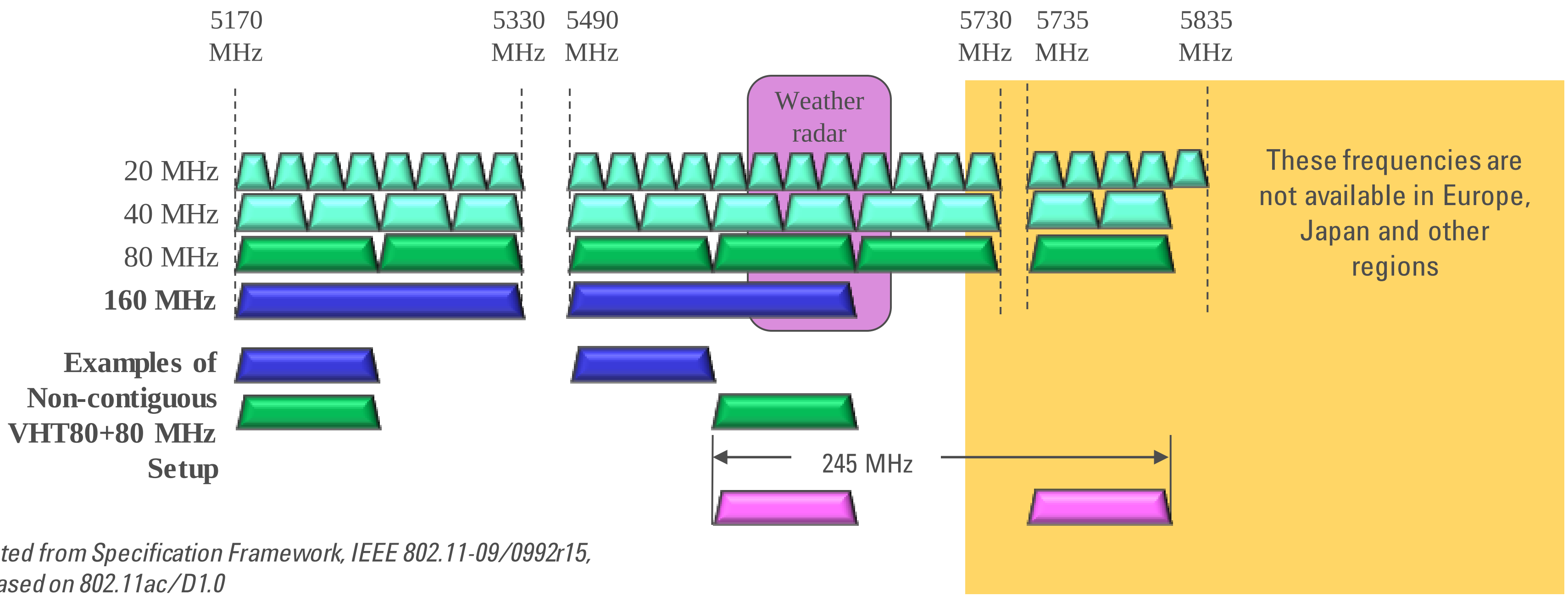


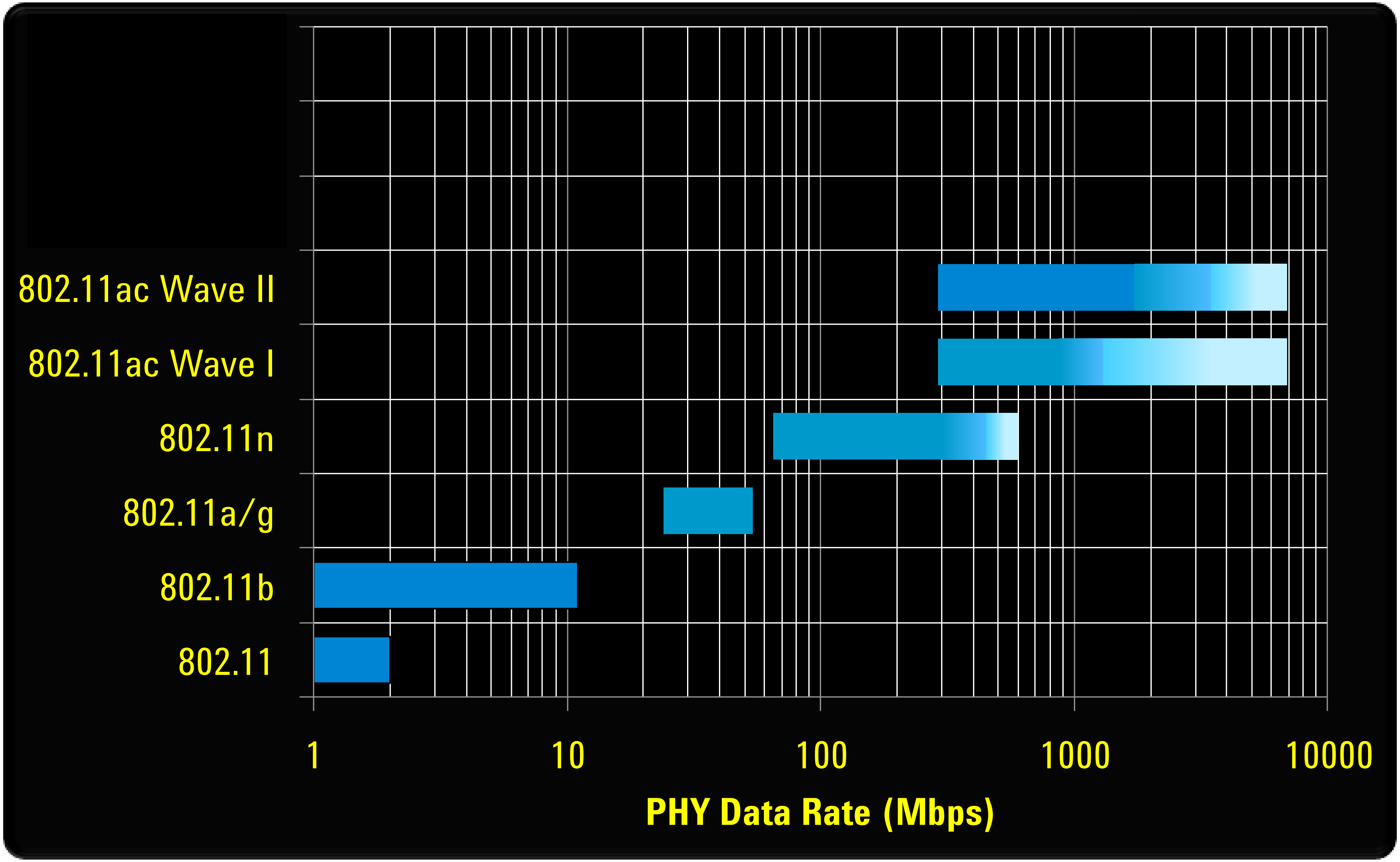
802.11ac Channelization

- 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)*

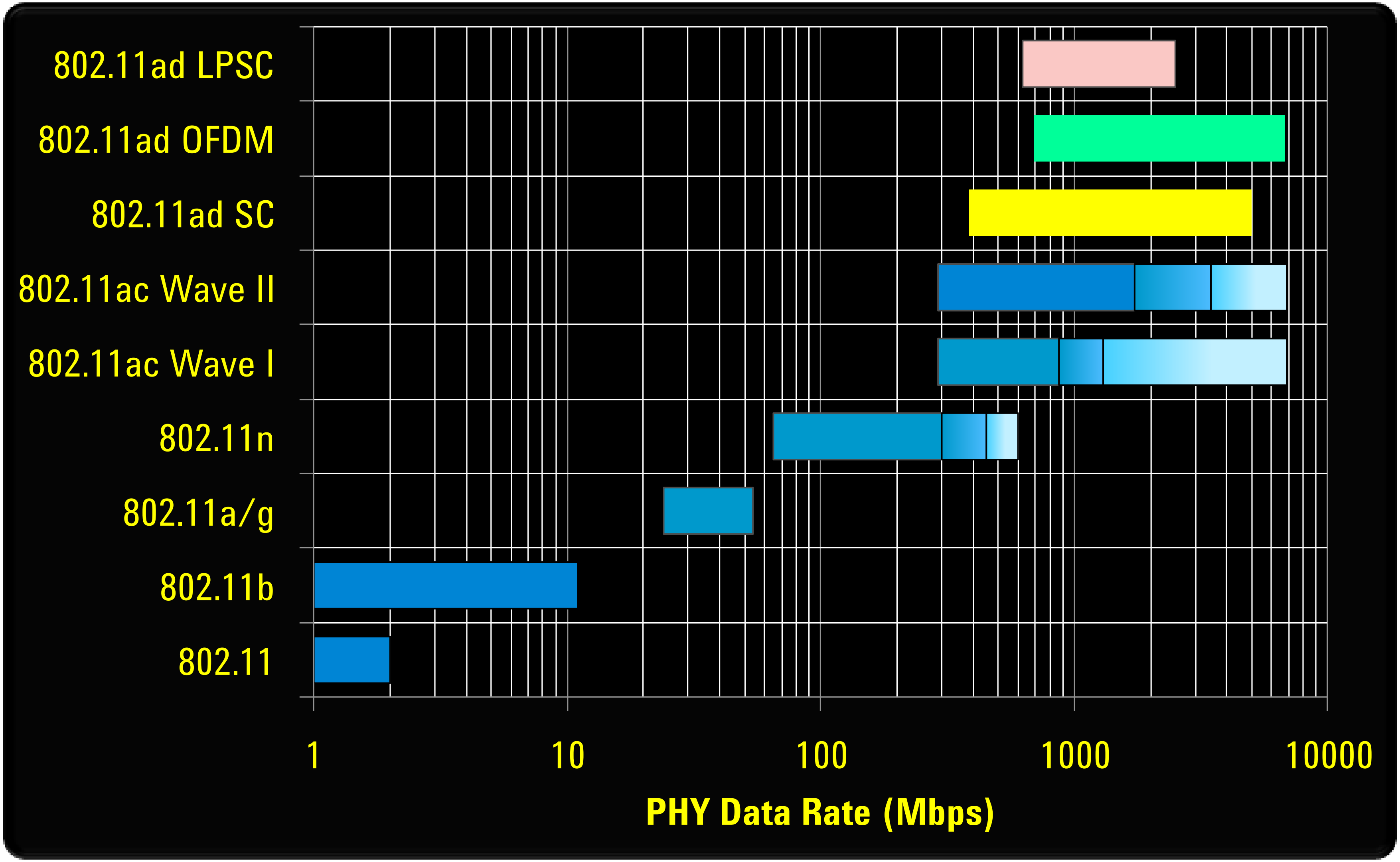


Adapted from Specification Framework, IEEE 802.11-09/0992r15, Updated based on 802.11ac/D1.0

IEEE 802.11a/b/g/n/ac PHY Data Rates



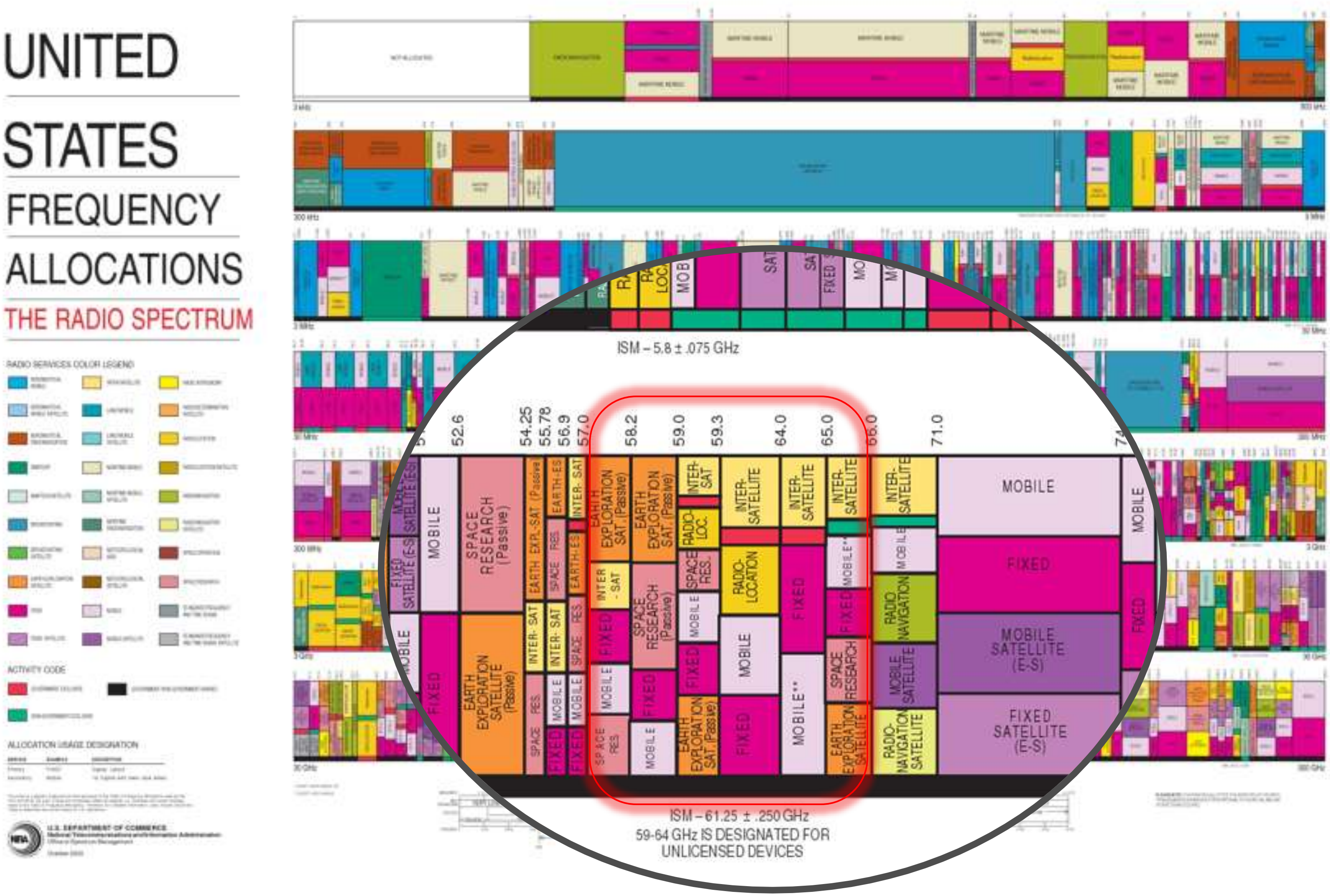
IEEE 802.11a/b/g/n/ac/ad PHY Data Rates



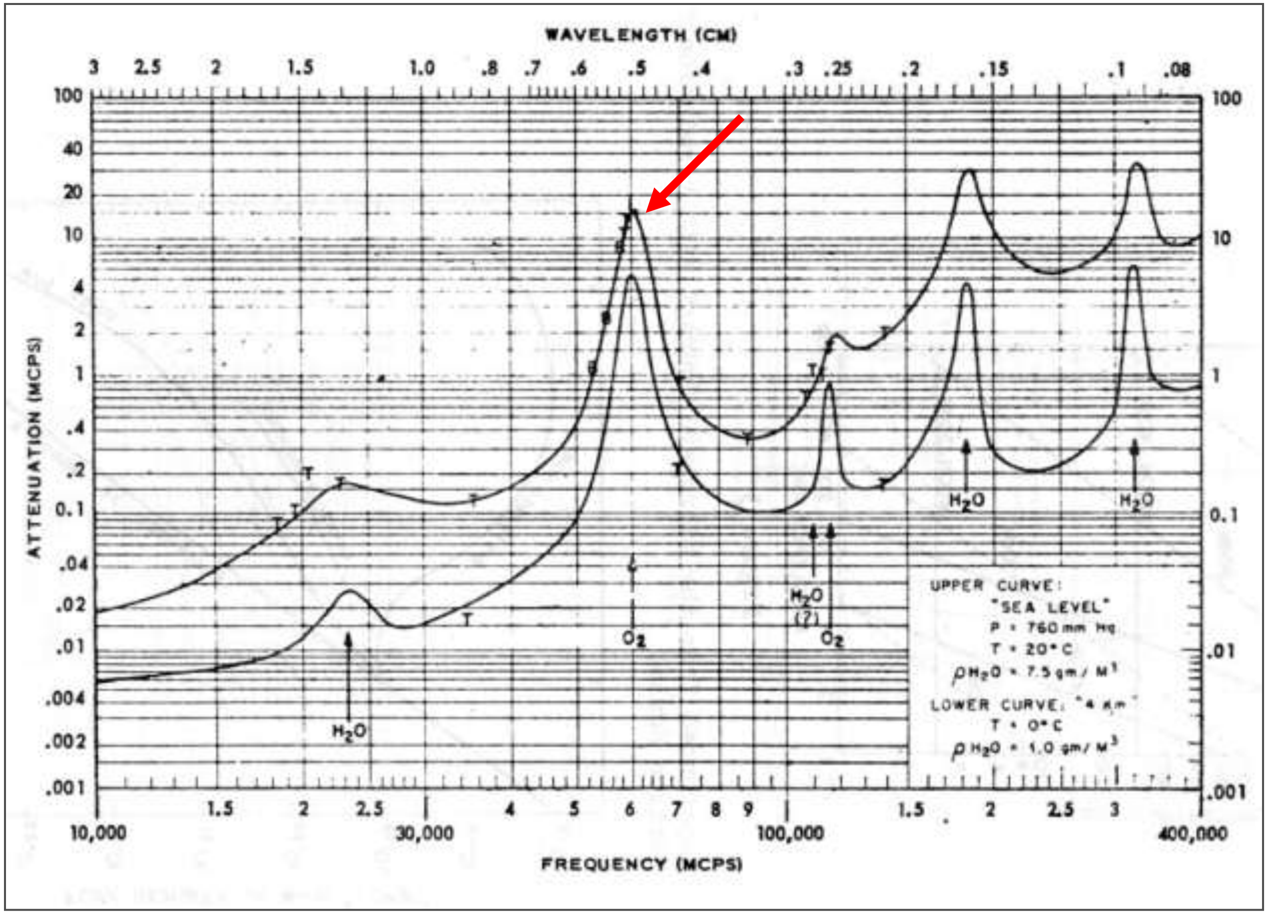
IEEE 802.11ad Overview

- 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

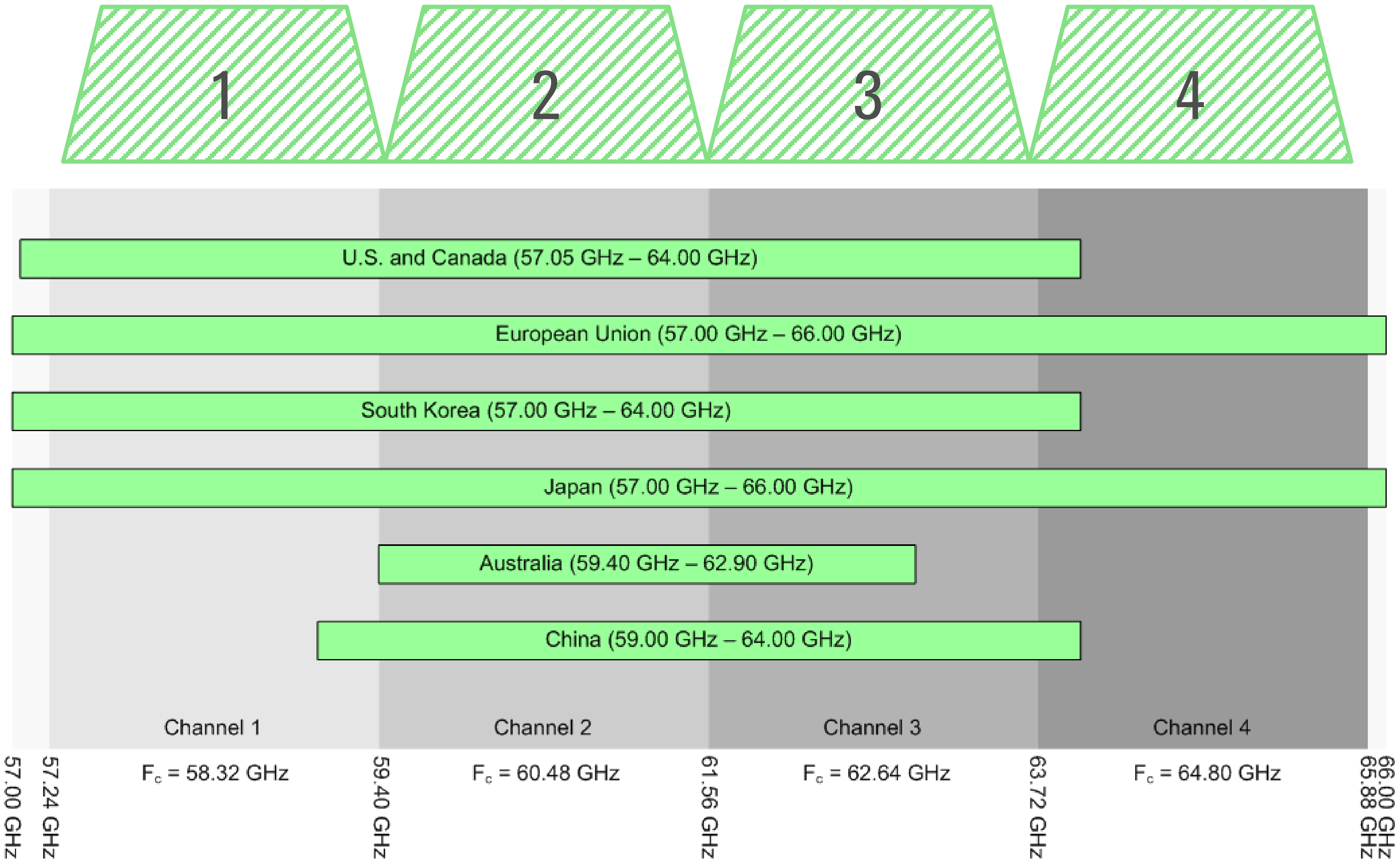


Atmospheric Absorption of 60 GHz

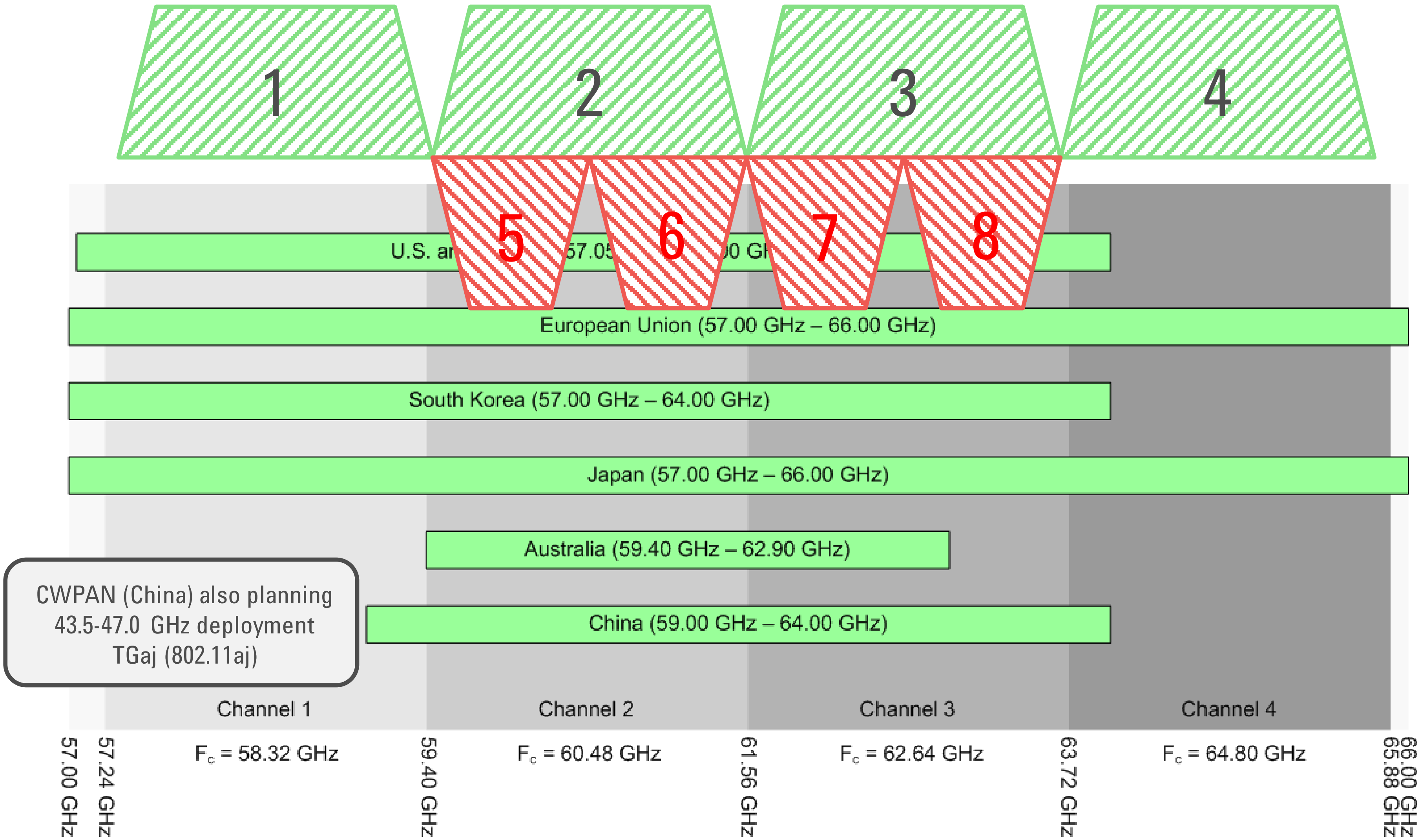


From: E.S. Rosenblum, "Atmospheric Absorption of 10-400 kMCPS Radiation: Summary and Bibliography to 1961," Microwave Journal, March, 1961

60 GHz Channel Plan by Region



60 GHz Channel Plan by Region



802.11aj - 45 GHz Frequency Band

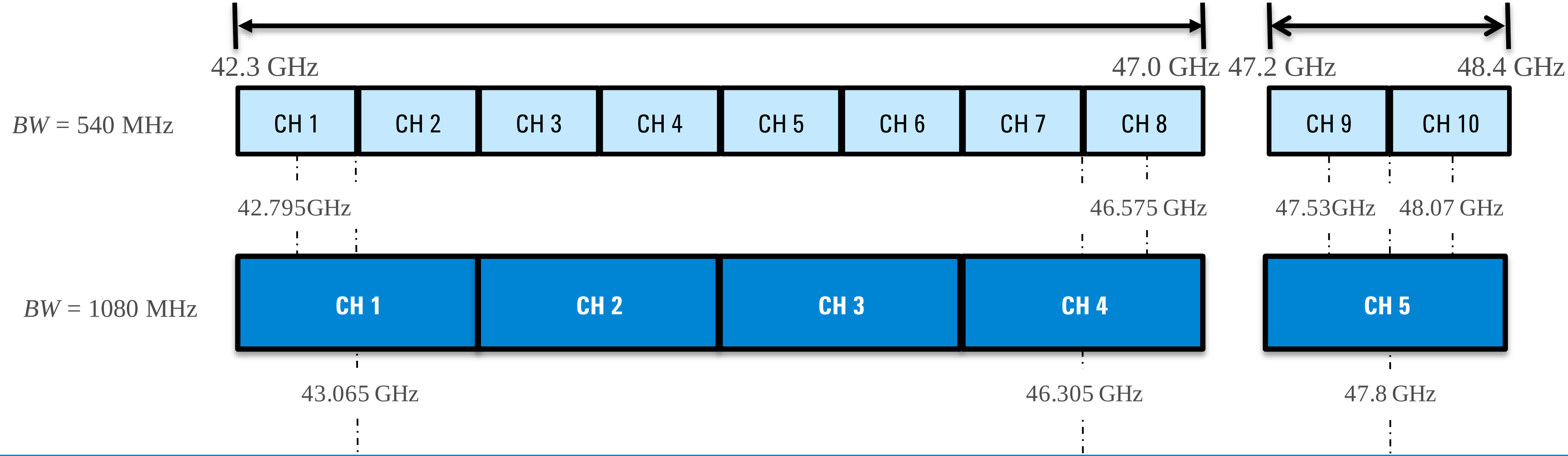
Frequency band: 42.3 to 47.0 GHz, 47.2 to 48.4 GHz

Bandwidth: 1080 MHz, 540 MHz

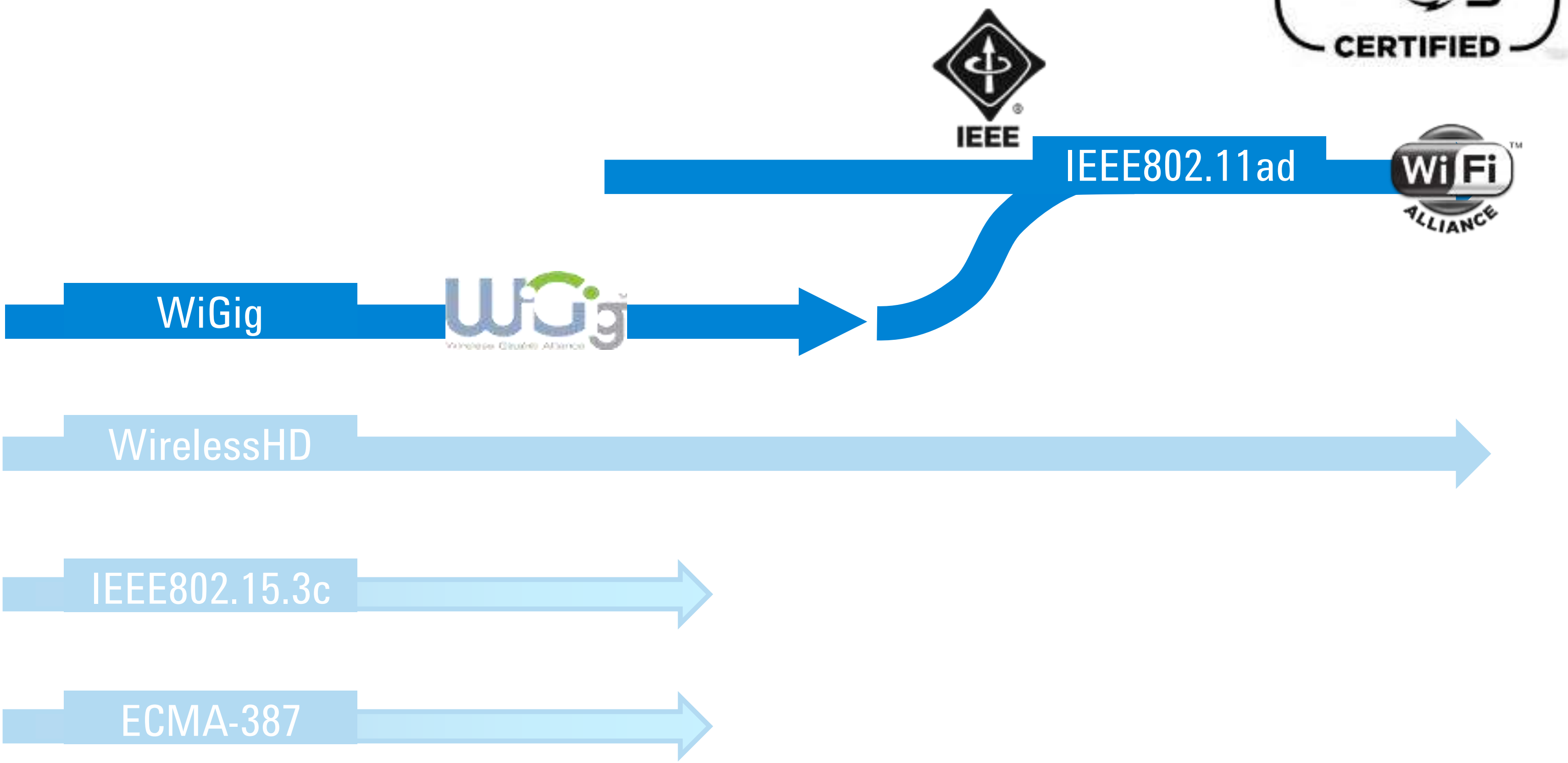
Frequency tolerance: 100×10-6

Maximum transmit power at antenna port: 20dBm

Maximum EIRP: 36dBm

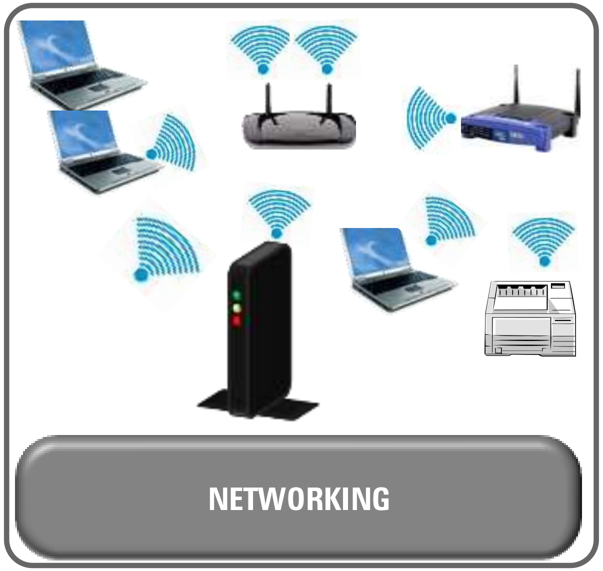


60GHz Specification Evolution



Where is 802.11ad going to be used?

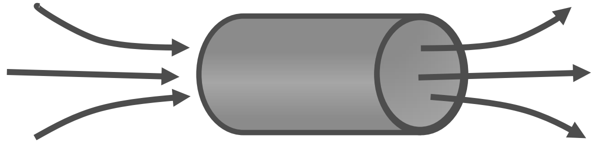
High Rate Throughput

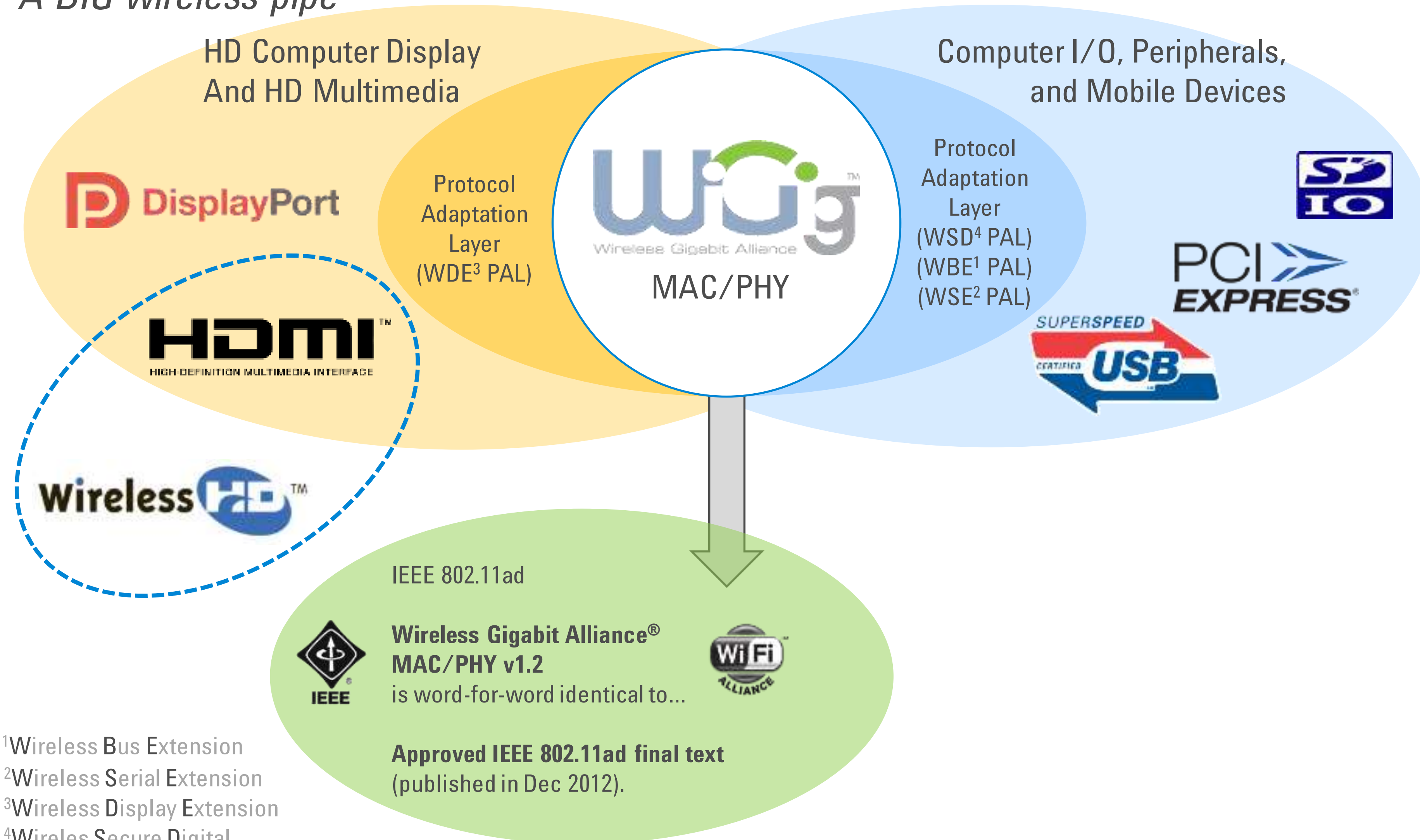


Use Model	Example
Wireless Display/Audio	Uncompressed transfer to computers, portable devices to one or more monitors/projectors
Distribution of HDTV	Games, DVD players to displays, projectors
Upload/Download | Docking	Kiosk Download, Movies to computer for editing, library sharing
Networking/Backhaul	Mesh networks, Peer-to-Peer, Tri-band *(2.4/5/60 GHz)* Access Points.
Cordless Computing	Wireless IO docking

The Bigger Picture

A BIG wireless pipe

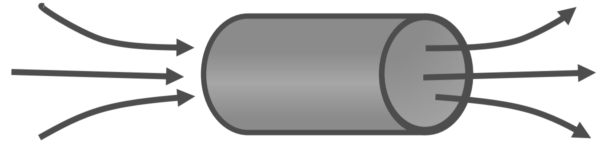




[1]Wireless Bus Extension
[2]Wireless Serial Extension
[3]Wireless Display Extension
[4]Wireles Secure Digital

The Bigger Picture

A BIG wireless pipe



HD Computer Display
And HD Multimedia

Protocol
Adaptation
Layer
(WDE[3] PAL)

MAC/PHY

Computer I/O, Peripherals,
and Mobile Devices

Protocol
Adaptation
Layer
(WSD[4] PAL)
(WBE[1] PAL)
(WSE[2] PAL)

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

IEEE 802.11ad

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

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

[1]Wireless Bus Extension
[2]Wireless Serial Extension
[3]Wireless Display Extension
[4]Wireles Secure Digital

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Control PHY

Single Carrier PHY

OFDM PHY

Low Power Single Carrier PHY

Forward Error Correction and Scrambling

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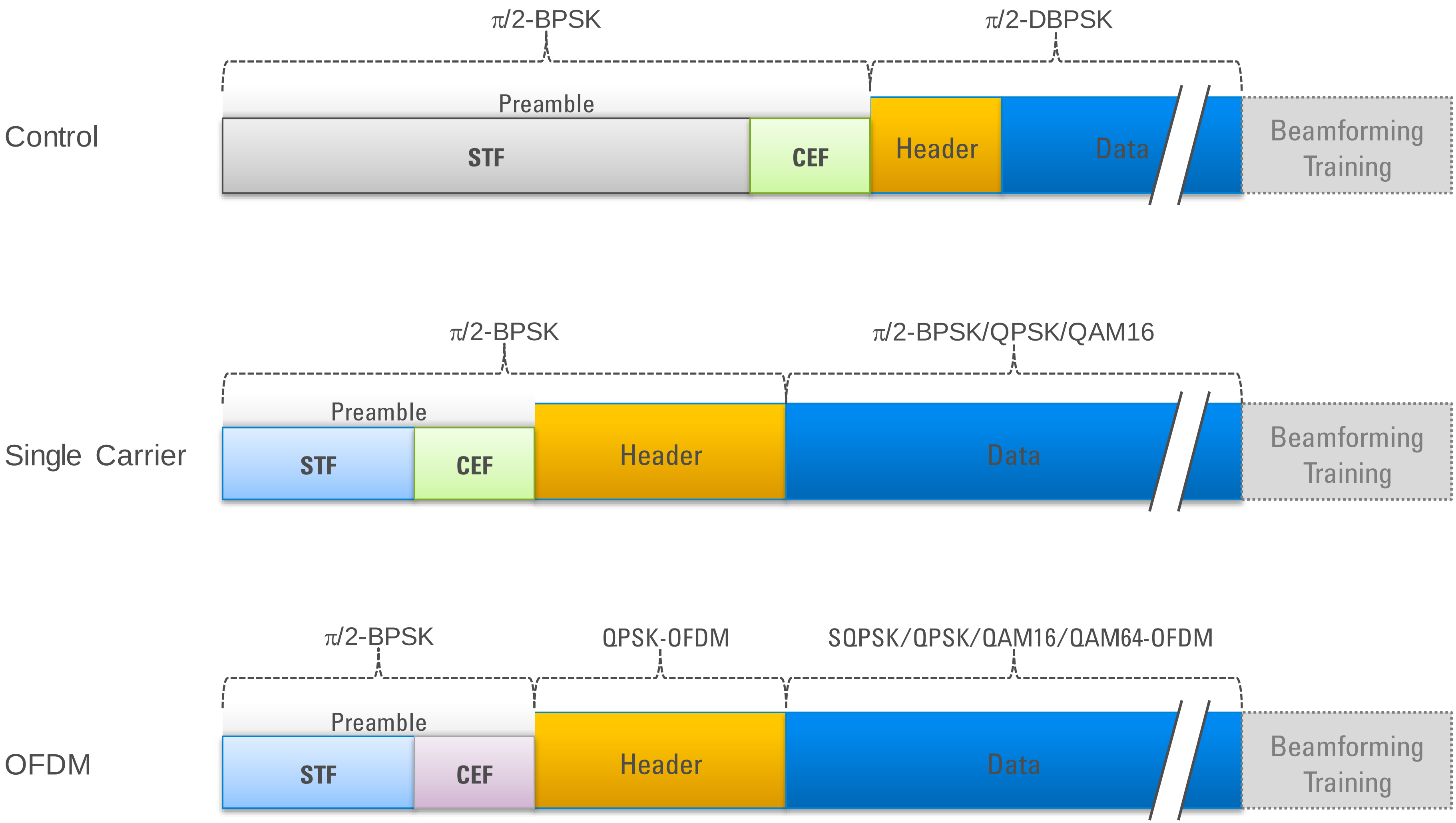
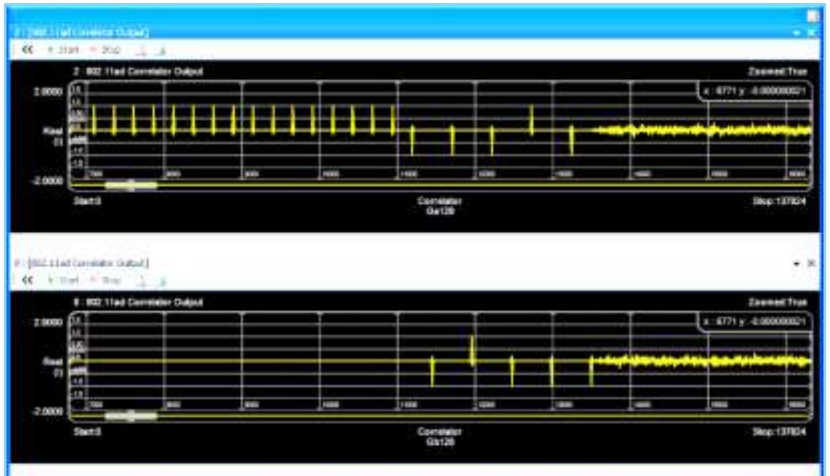
PHY Modes (Packet Overview)



Preambles

The preamble always comprises two fields:

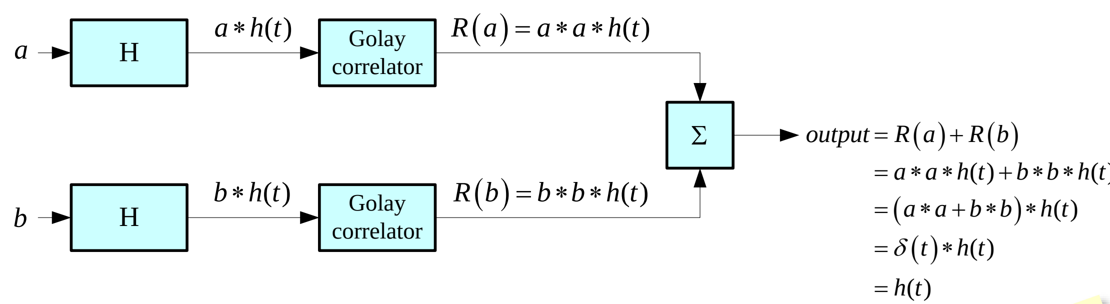
- Short Training Field (STF)
  - Timing estimation
  - AGC adjustment
- Channel Estimation Field (CEF)
  - Channel estimation



Golay Complementary Sequences – G_{32}, G_{64}, Ga_{128}, Gb_{128}

Used extensively in 802.11ad

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



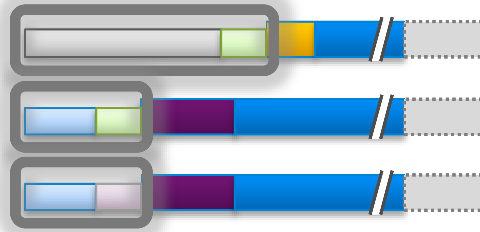
Important attributes of Golay sequences are:

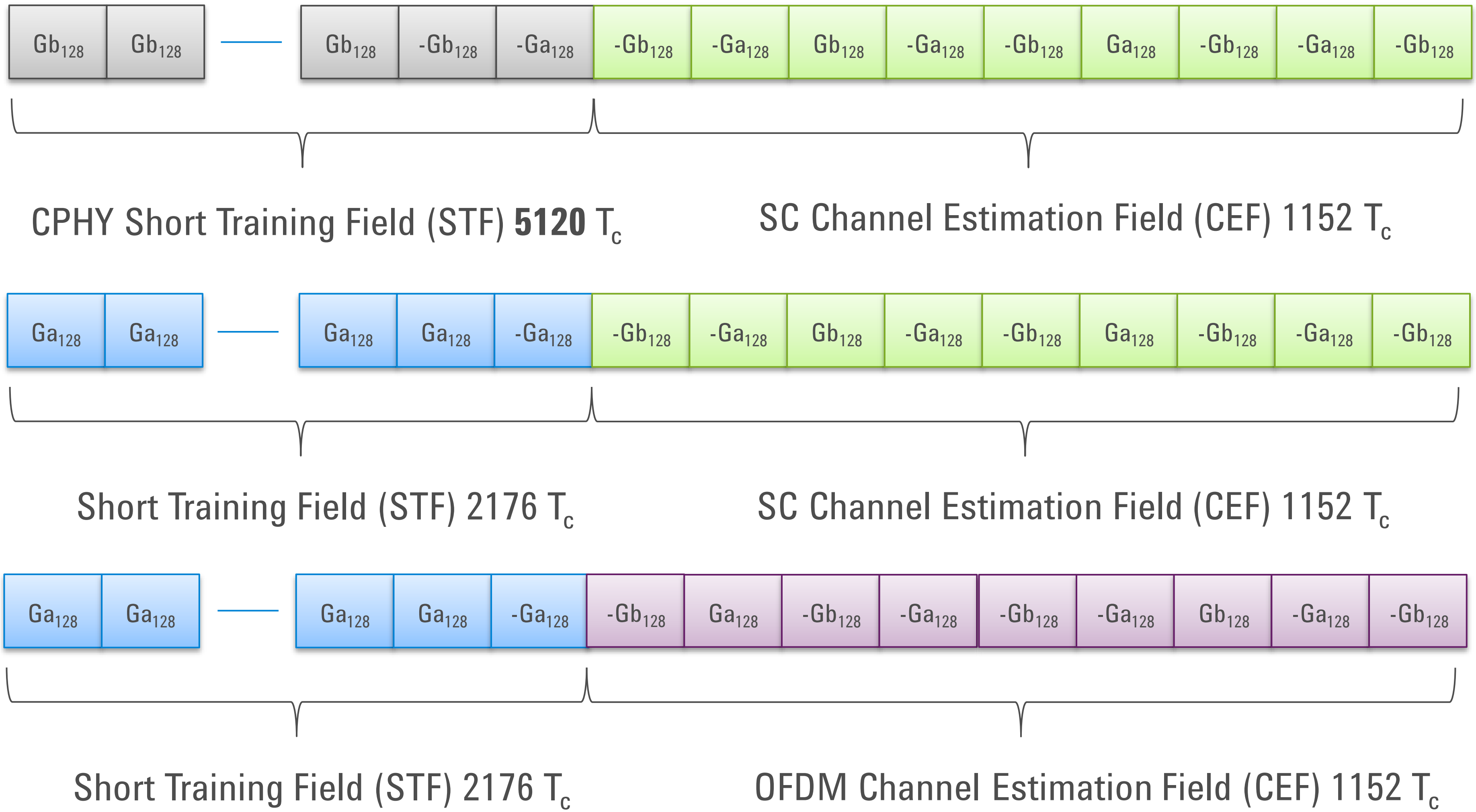
- Low side lobes and low DC content under $\pi/2$ rotation.
- Sum of G_a and G_b autocorrelations is perfect.
- G_a and G_b autocorrelations can be performed in parallel using a single correlator.

*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

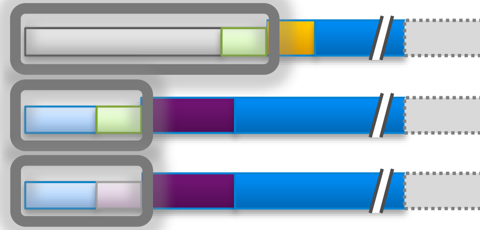
(showing basic construction)





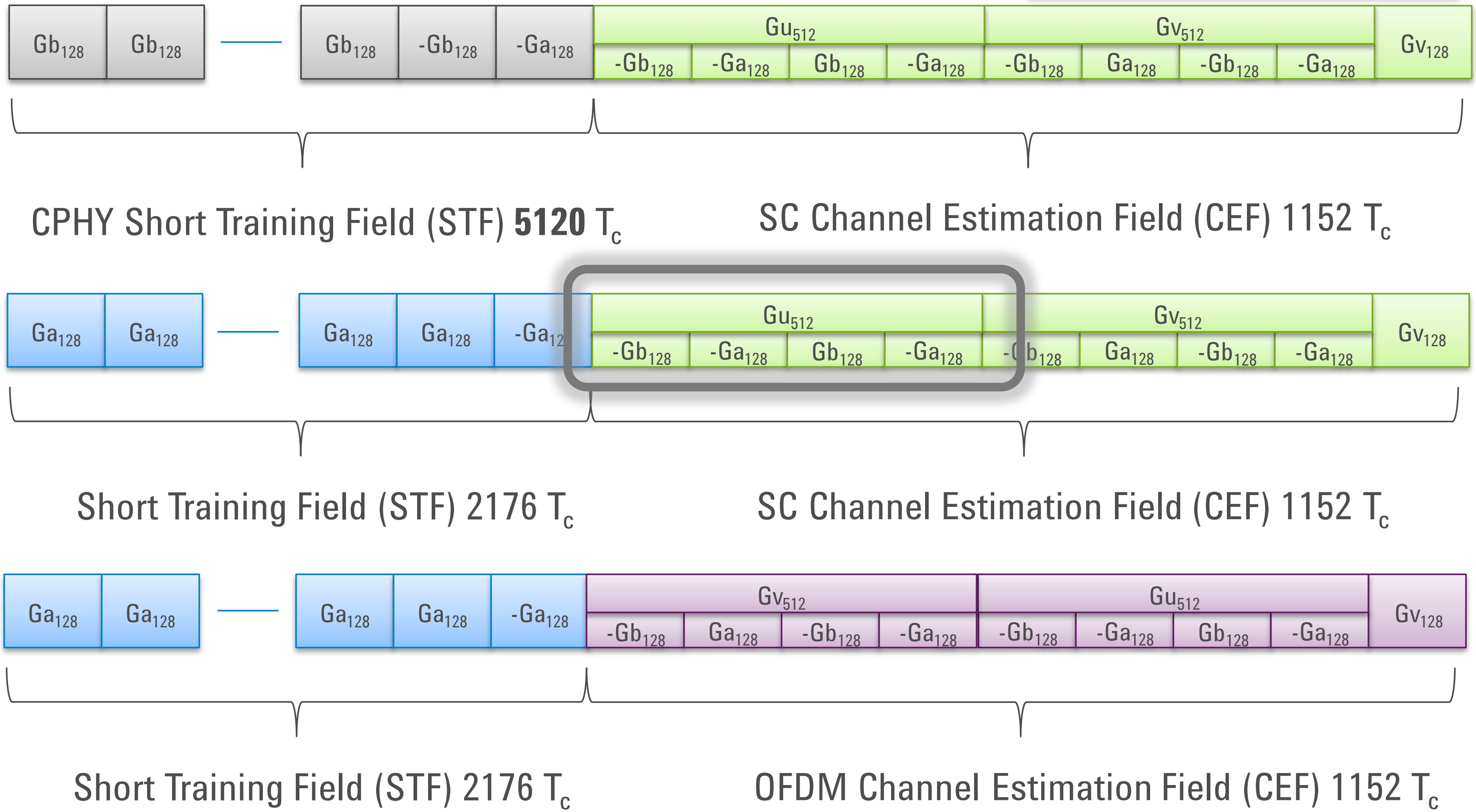
Preamble Variants

(showing CEF grouping)

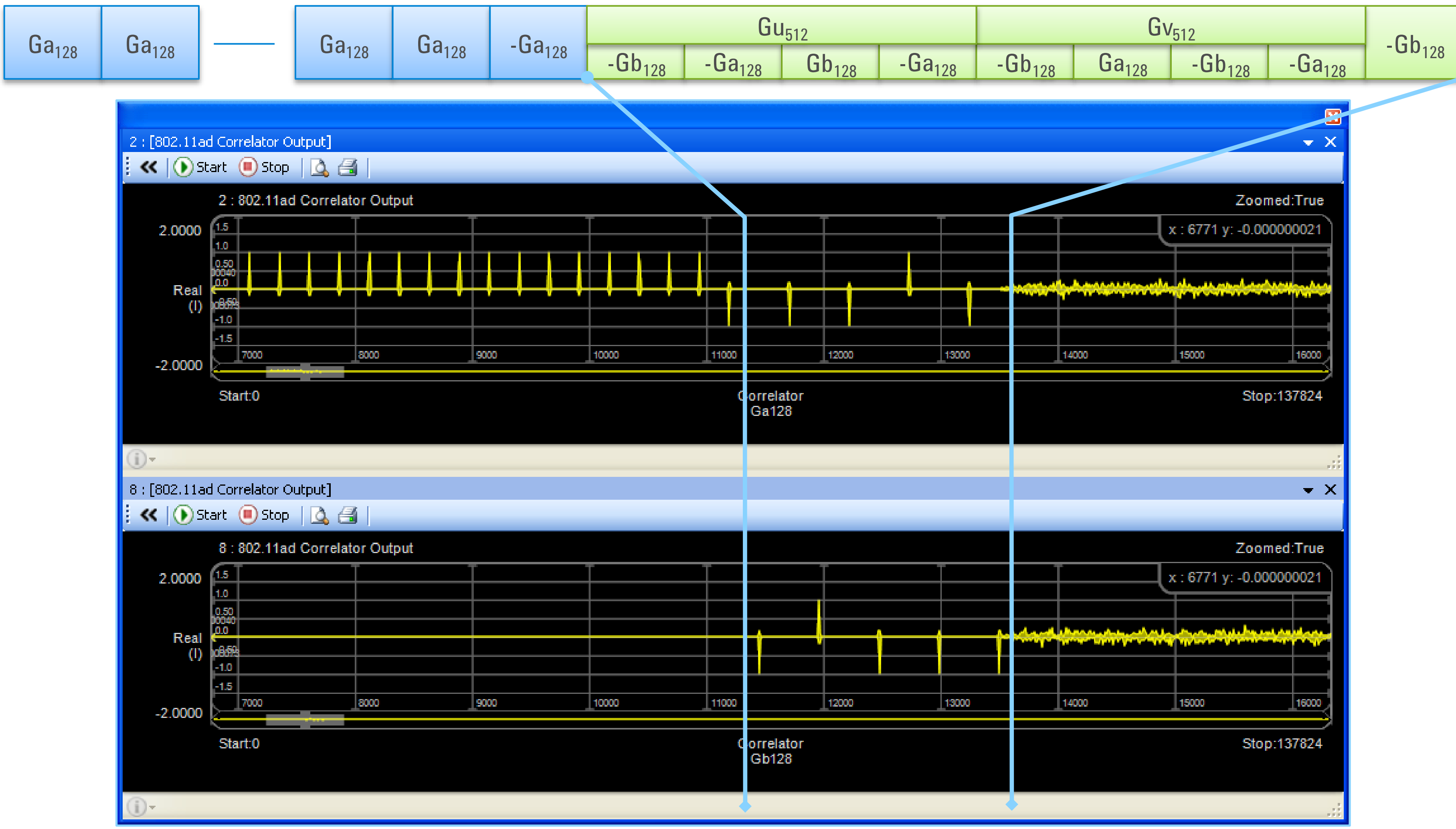


CAUTION:

Gu & Gv are NOT complementary pairs but a nomenclature convenience



The Channel Estimation Field (CEF)



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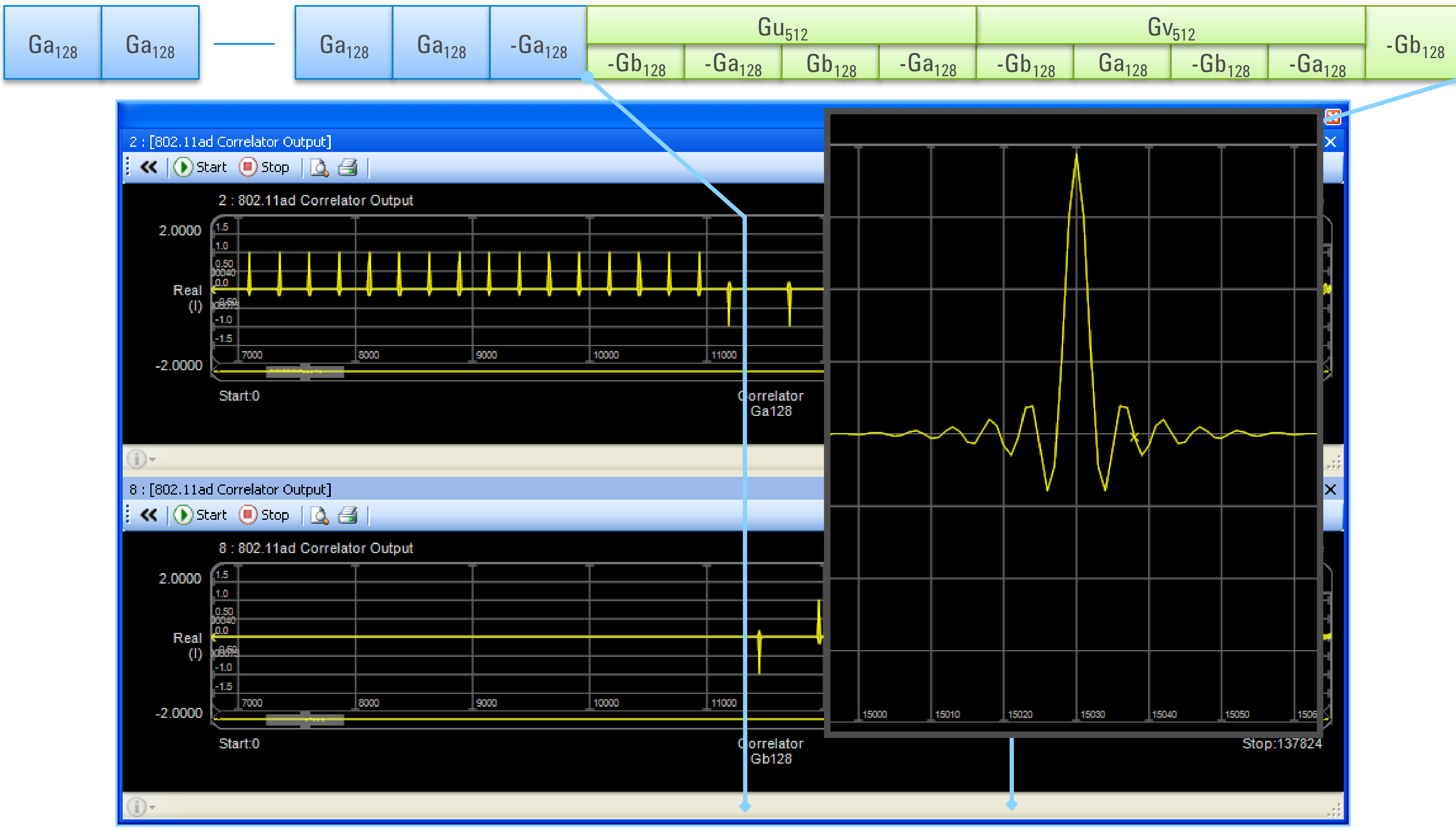
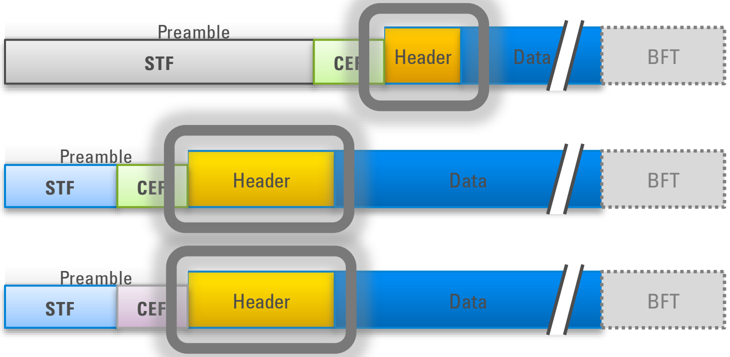


Header Variants



Control

1	4	10 bits	1	5 bits	1	2	16 bits
Reserved (diff detector init)	Scrambler Initialization	Length	Packet type	Training Length	SIFS response	Reserved bits	HCS

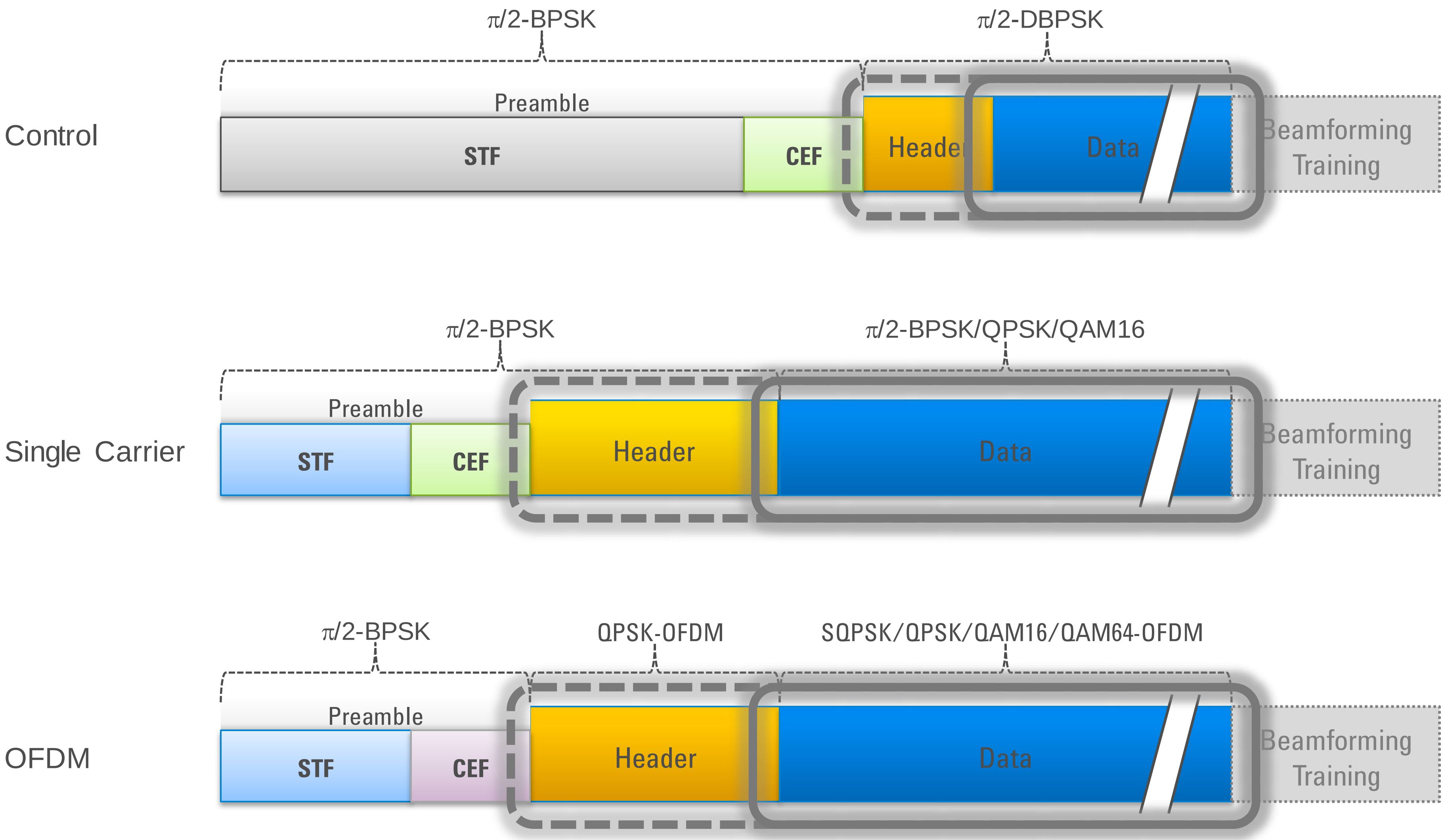
Single Carrier

7 bits	5 bits	18 bits	1	1	5 bits	1	1	4 bits	1	4 bits	16 bits
Scrambler Initialization	MCS	Length	Additional PPDU	Packet type	Training Length	Aggregation	Beam Tracking Request	Last RSSI	SIFS response	Reserved	HCS

OFDM

7 bits	5 bits	18 bits	1	1	5 bits	1	1	1	1	4 bits	1	2	16 bits
Scrambler Initialization	MCS	Length	Additional PPDU	Packet type	Training Length	Aggregation	Beam Tracking Request	Tone Pairing Type	DTP Indicator	Last RSSI	SIFS response	Reserved	HCS

PHY Header/Payload Modulation

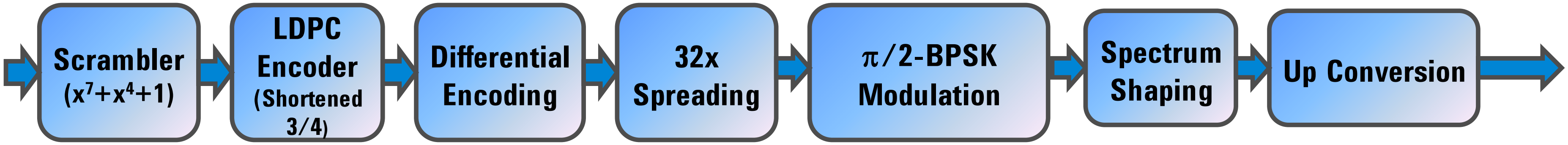


Modulation and Coding Schemes (MCS)

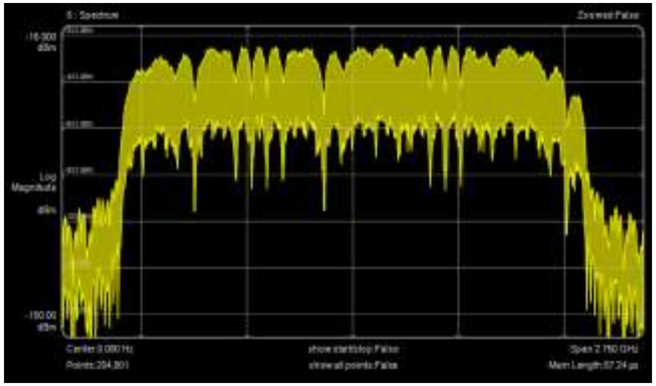
- Very robust 27.5 Mbps Control Channel
- Variable Error Protection
- Variable Modulation Complexity
  - Therefore EVM specs. from -6dB to -25dB
- Variable Data Rates
  - from 385 Mbps (MCS1) to 6756.75 Mbps (MCS24)
- Mandatory modes ensure all 802.11ad devices capable of at least 1Gbps
  - MCS0-4 Mandatory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

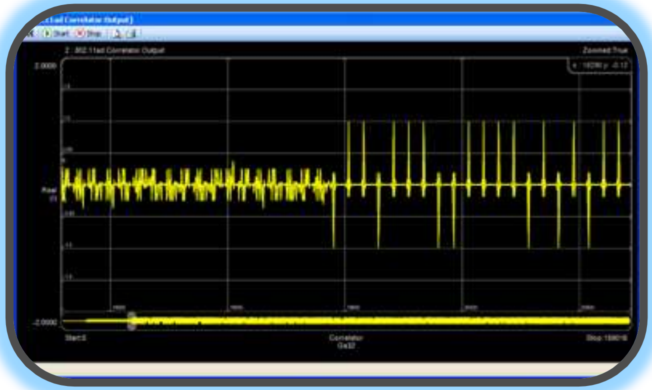
Control (CPHY)			
MCS	Coding	Modulation	Raw Bit Rate
0	1/2 LDPC, 32x Spreading	π/2-DBPSK	27.5 Mbps
Single Carrier (SCPHY)			
MCS	Coding	Modulation	Raw Bit Rate
1-12	1/2 LDPC, 2x repetition 1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC	π/2-BPSK, π/2-QPSK, π/2-16QAM	385 Mbps to 4620 Mbps
Orthogonal Frequency Division Multiplex (OFDMPHY)			
MCS	Coding	Modulation	Raw Bit Rate
13-24	1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC	OFDM-SQPSK OFDM-QPSK OFDM-16QAM OFDM-64QAM	693 Mbps to 6756.75 Mbps
Low-Power Single Carrier (LPSCPHY)			
MCS	Coding	Modulation	Raw Bit Rate
25-31	RS(224,208) + Block Code(16/12/9/8,8)	π/2-BPSK, π/2-QPSK	625.6 Mbps to 2503 Mbps

Control PHY (MCS 0) *(Header & Payload Encoding)*



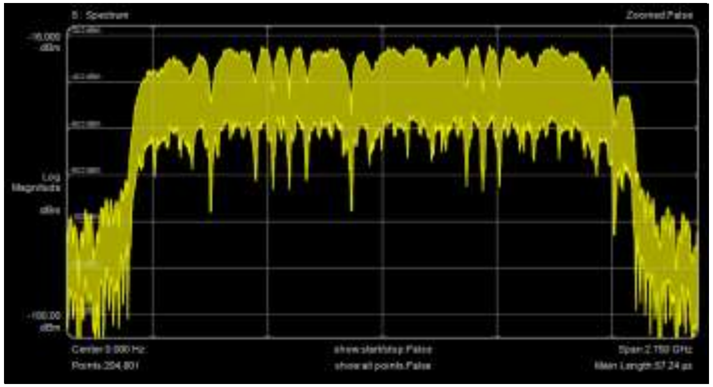
- π/2-DBPSK modulation
- Data Throughput = 27.5 Mbps $= 1.76\,\frac{GSa}{sec} \div 32 \times \frac{1}{2}$
- Compatible preamble with other PHY for timing and channel estimation
- Baseband filtering is not defined, however EVM is specified with a RRC filter

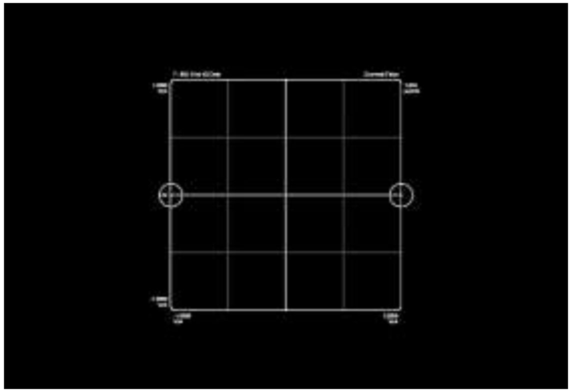




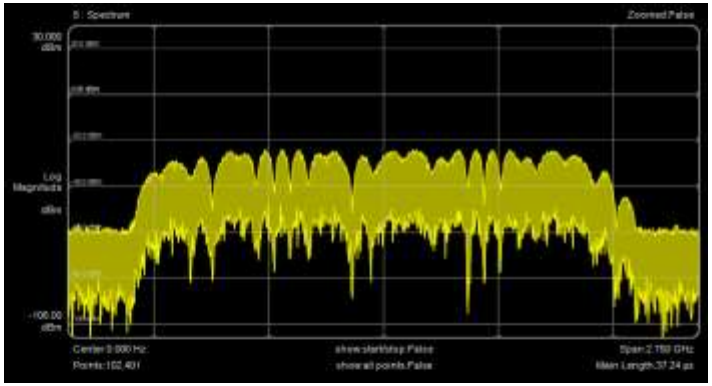
Ga32 correlator output showing the results of 32x despreading.

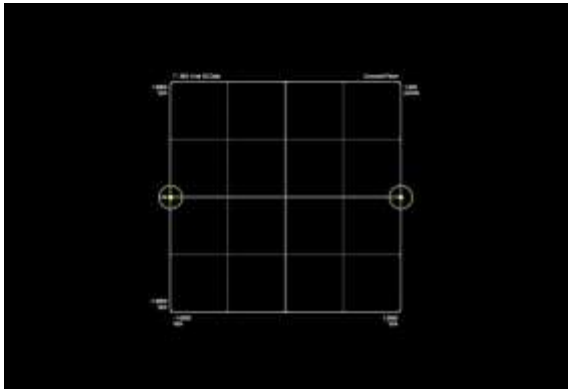
Low SNR Control PHY (MCS0) Demodulation



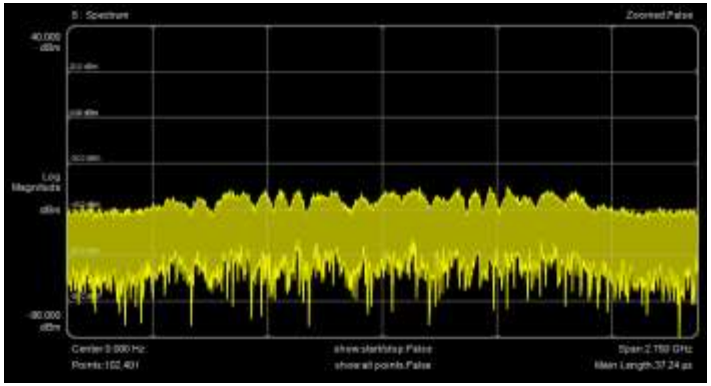


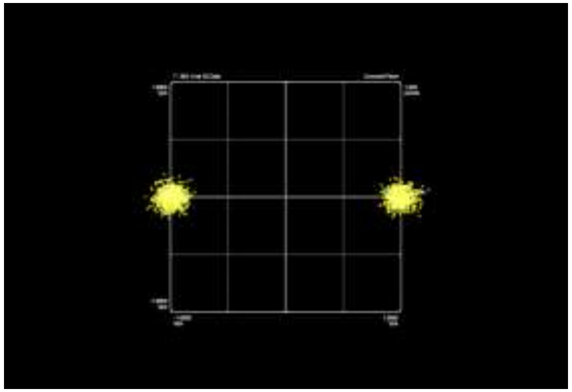
Low SNR Control PHY (MCS0) Demodulation



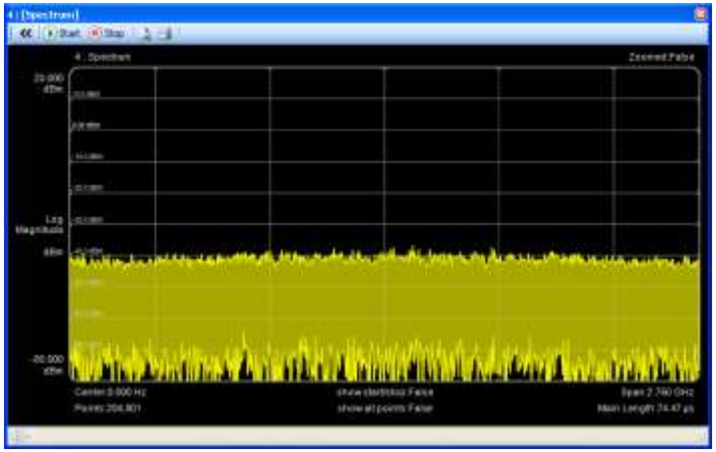


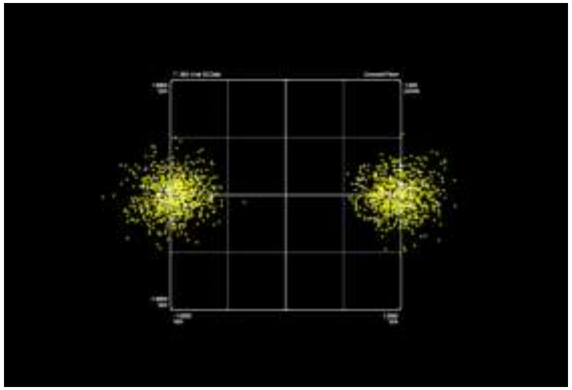
Low SNR Control PHY (MCS0) Demodulation



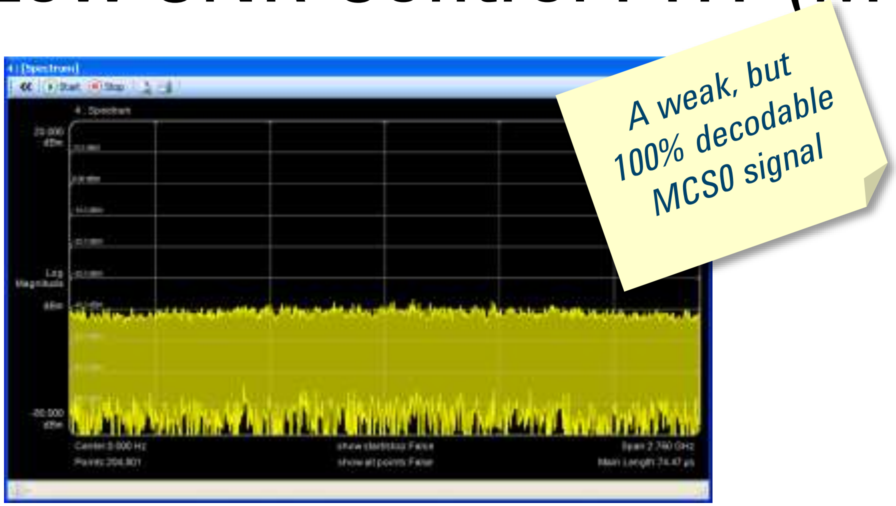


Low SNR Control PHY (MCS0) Demodulation





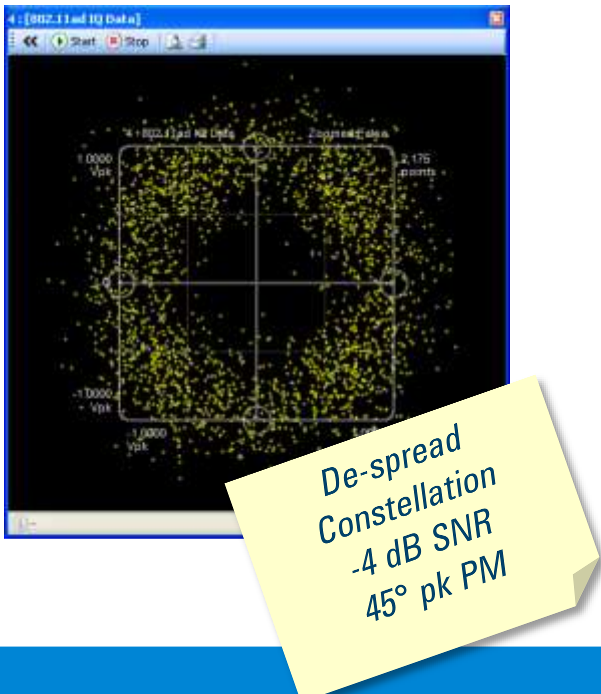
Low SNR Control PHY (MCS0) Demodulation

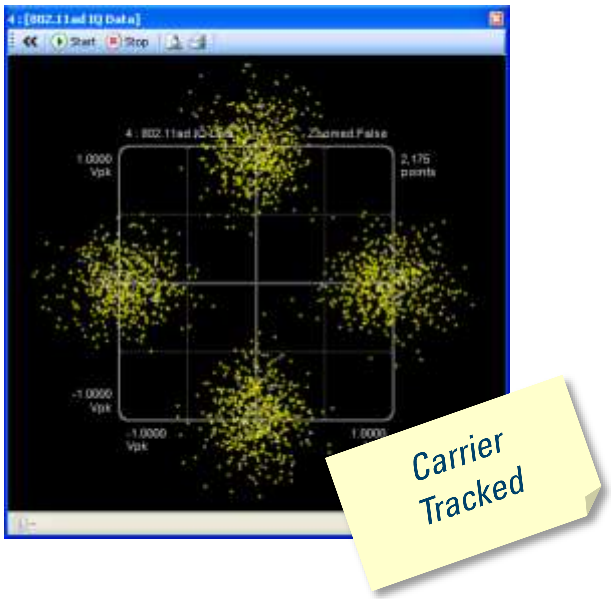


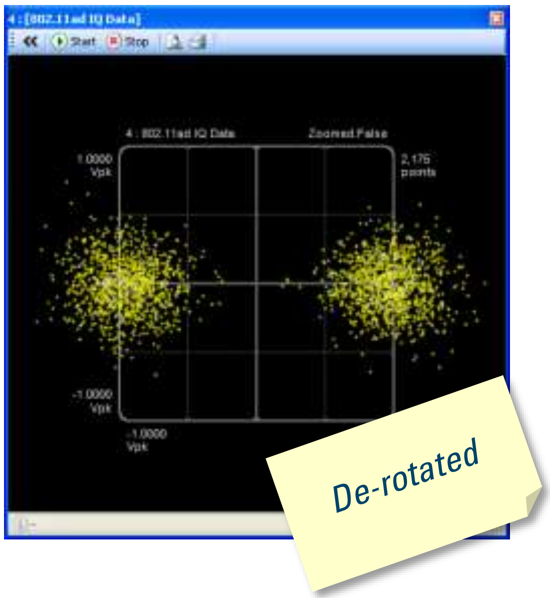
The CPHY uses:

- differential encoding
- code spreading
- DBPSK modulation and
- an effective rate of 1/2 LDPC FEC

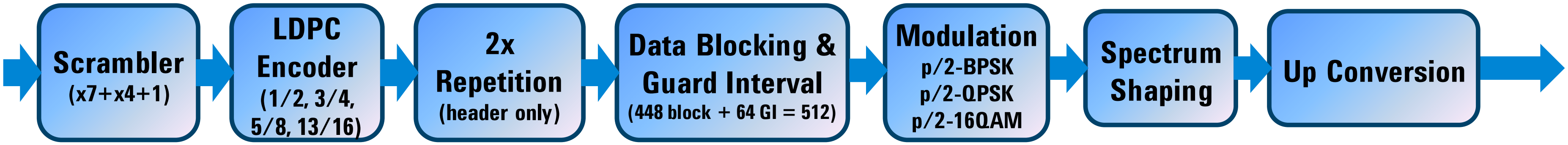
to ensure reliable communication at very high path loss.

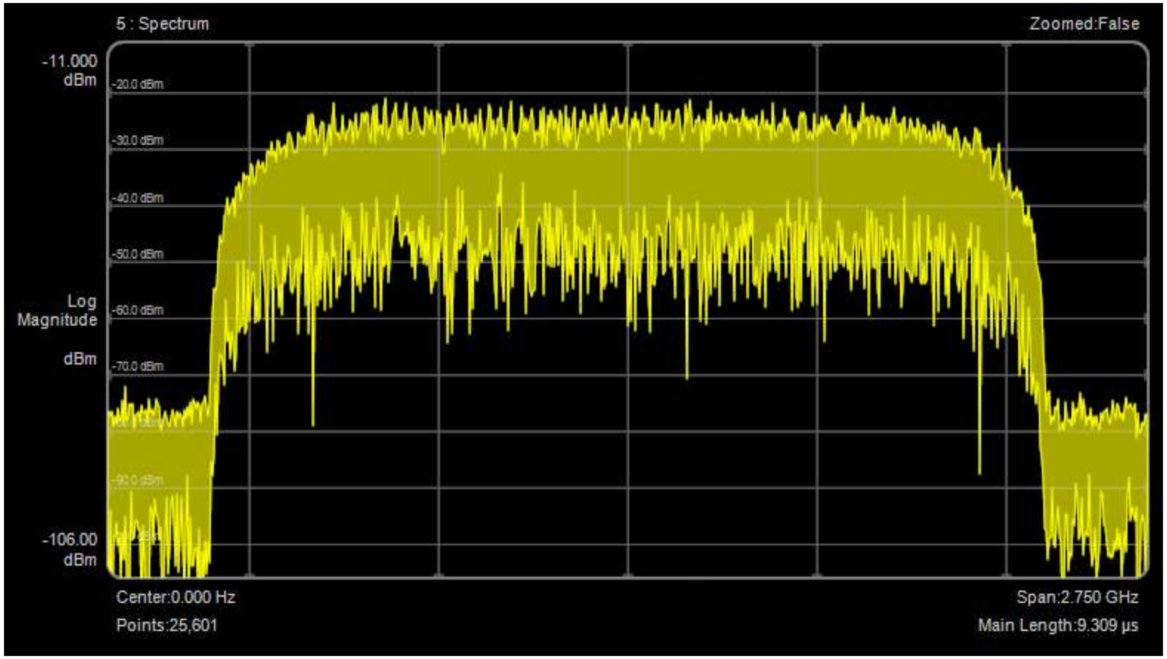






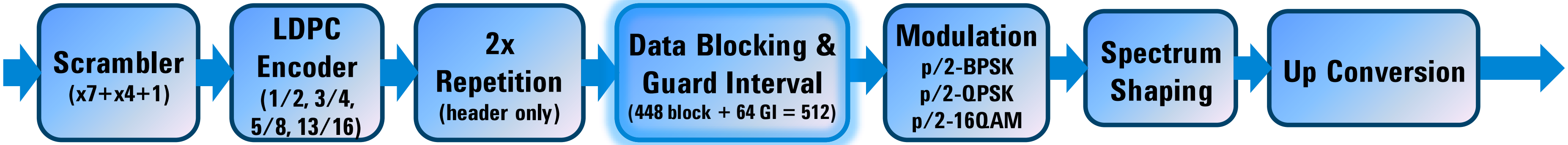
SC PHY (MCS 1 to 12) *(Header & Payload Encoding)*

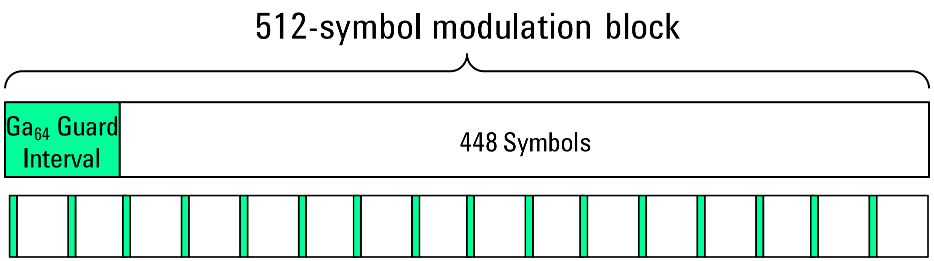


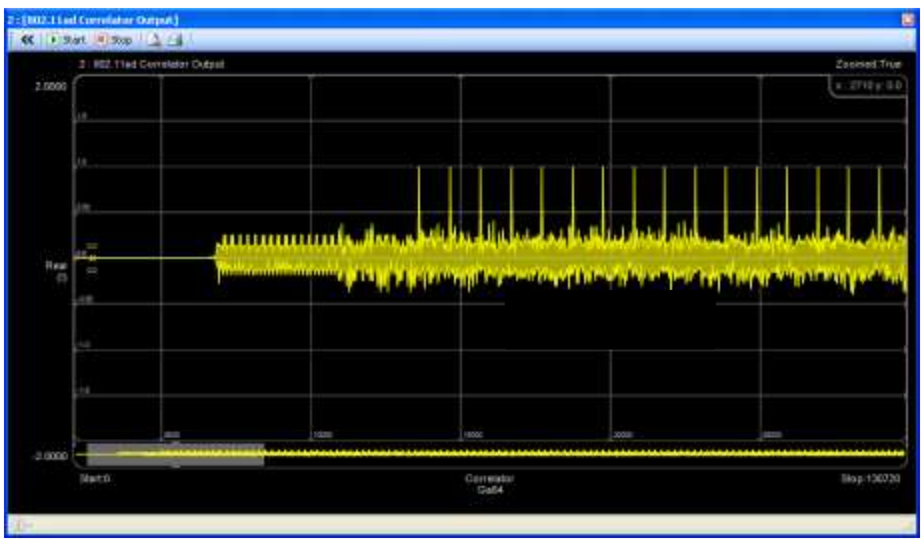


- Variable modulation depth
- Symbol Rate = 1.76 GSym/sec
- Date rates up to 4.62 Gbps
- Baseband filtering is not defined, however EVM is specified with a RRC filter
- Shares common preamble with OFDMPHY for timing and channel estimation
- Mandatory modes MCS1 to MCS4

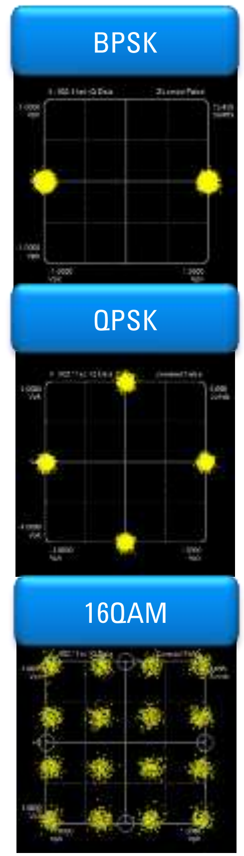
SC PHY (MCS 1 to 12) *(Header & Payload Encoding)*





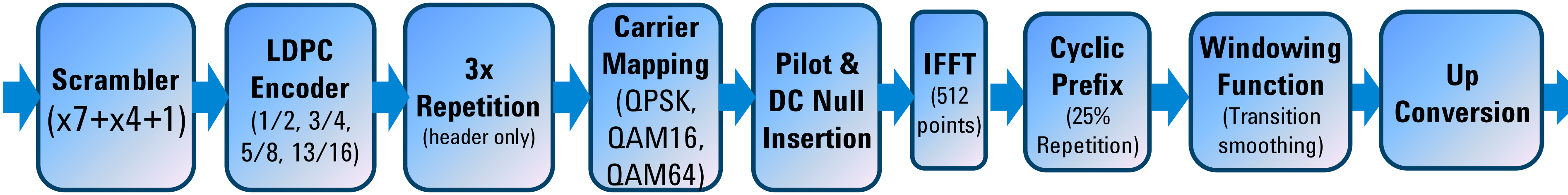


Ga64 correlator output showing the regular guard interval



- 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 OFDMPHY for timing and channel estimation
- Mandatory modes MCS1 to MCS4

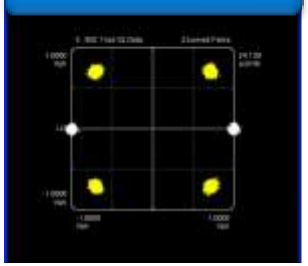
OFDM PHY (MCS13 to 24) *(Header & Payload Encoding)*



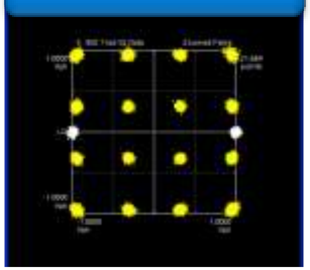
- Variable modulation depth
- Date rates up to 6.75 Gbps
- Occupied BW = 1.825 GHz
- 16 Static pilots
- 512 subcarriers total
  - 336 Data subcarriers
  - 157 Null subcarriers
  - 3 DC subcarriers nulled: Fc and Fc±1

- 3 DC subcarriers nulled: Fc and Fc±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

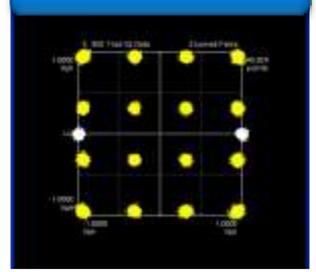
SQPSK



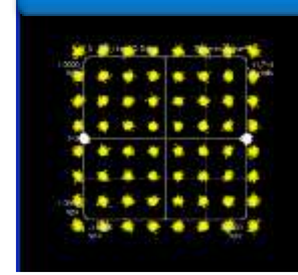
QPSK



16QAM



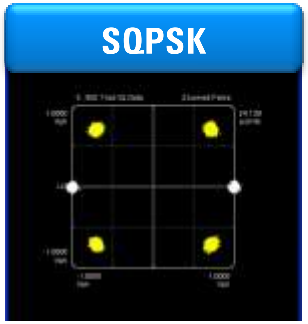
64QAM



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.

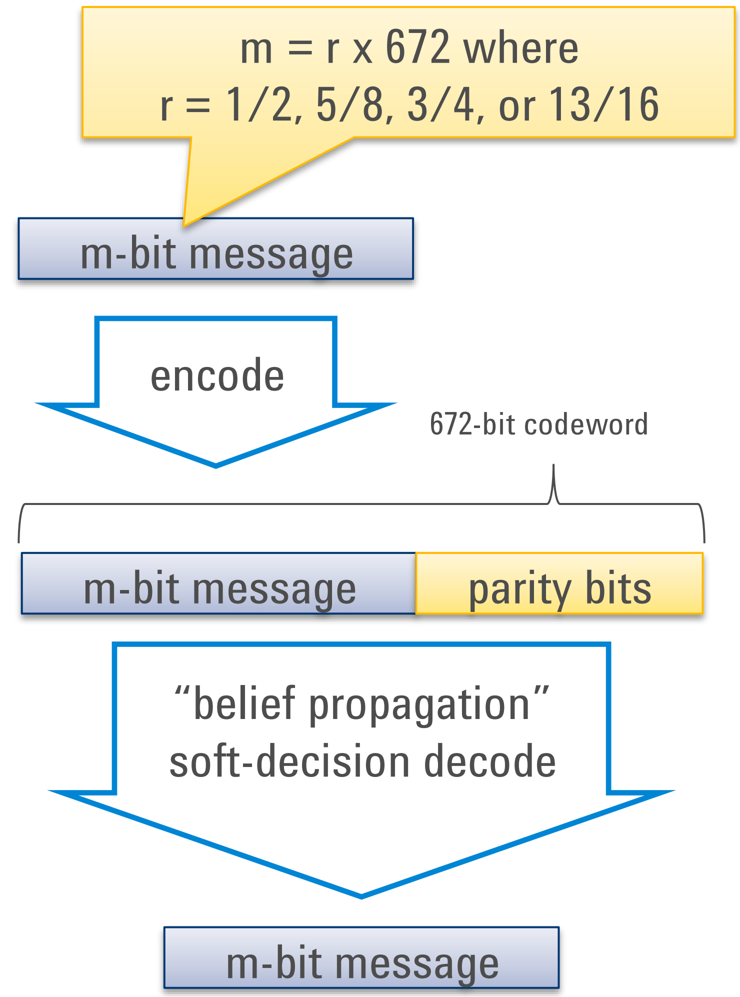
Low Density Parity Check (LDPC)

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

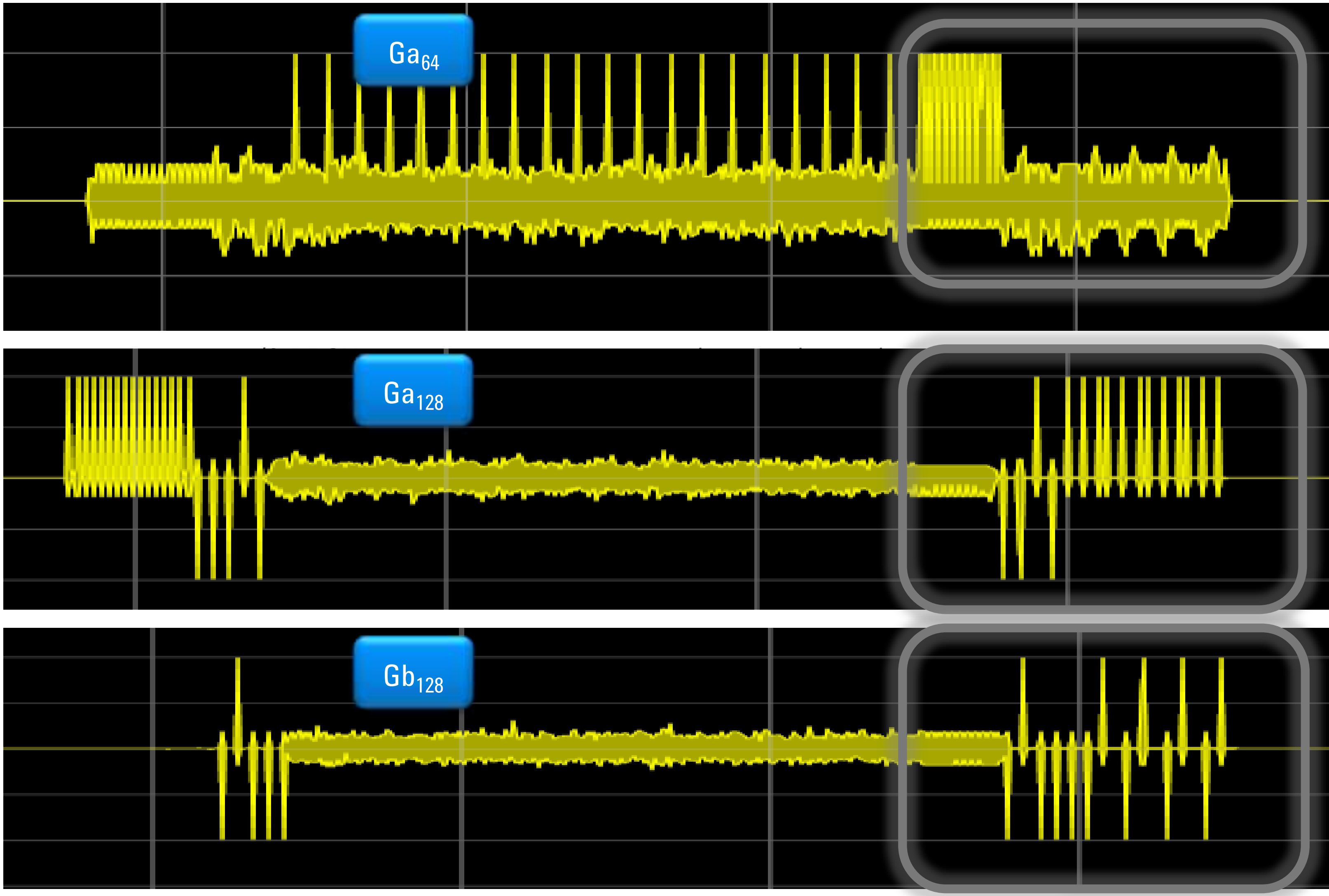
LDPC codes are systematic block codes that use parity check as the error detection /correction mechanism.

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.

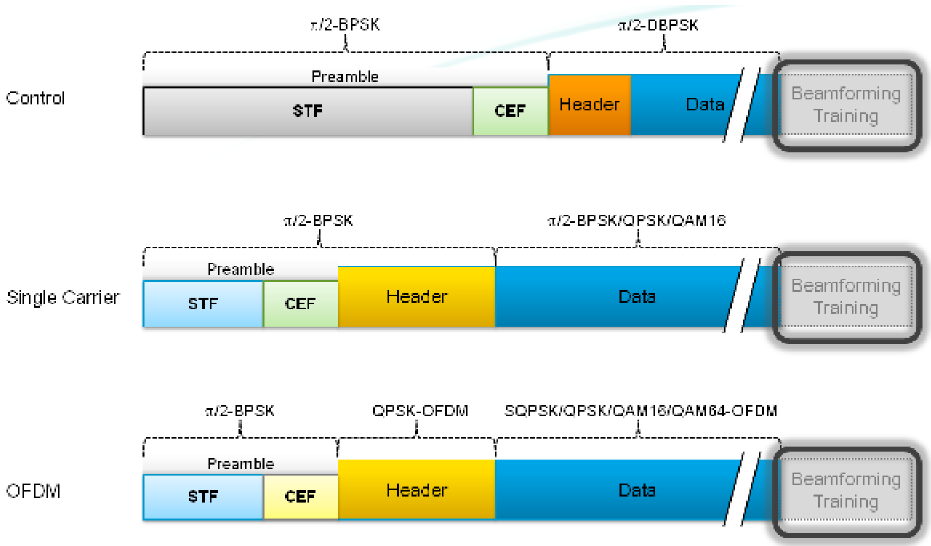
The 802.11ad parity matrix is optimized for simple codeword generation by back-substitution on the parity matrix and efficient hardware implementation of the iterative soft decoding algorithm.

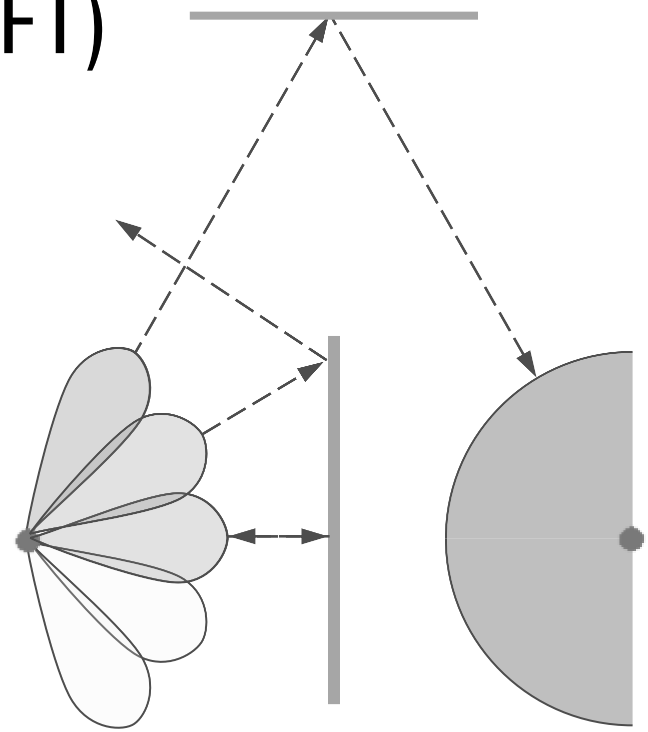


PHY Beamforming Training



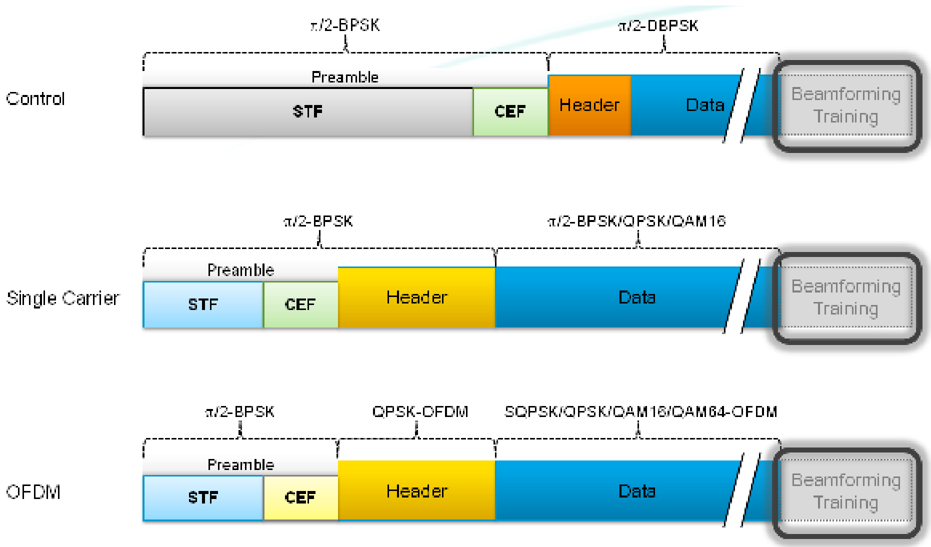
PHY Beamforming Training (BFT)

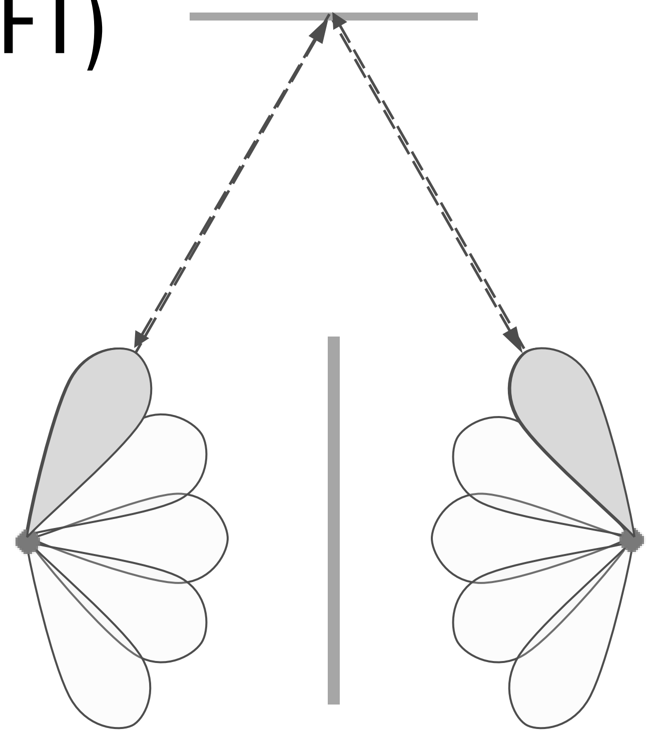




- Beamforming is optional
- However, the Receiver must support BFT protocol – i.e. it must report which packet was received with the best quality. The Transmitter can then determine best beam direction.

PHY Beamforming Training (BFT)





- 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)

Agenda

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

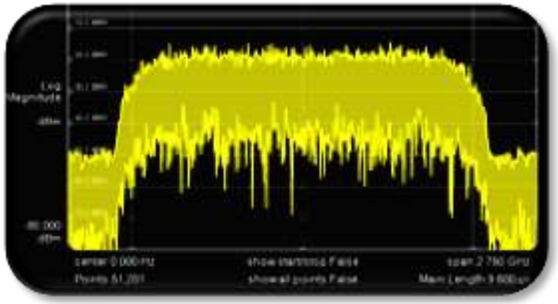
802.11ad Design Challenges

mm Technology

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

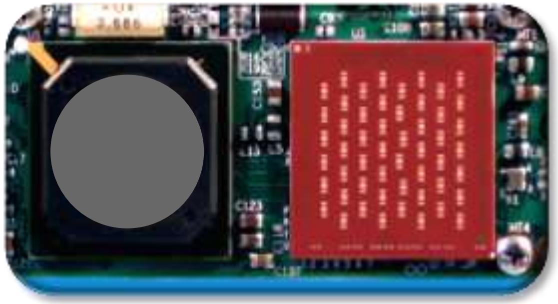
Wide Bandwidth

- ~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 anntenas lack test connection
- Path losses significant
- Over-the-air (OTA) testing required jeapodizes measurement plane
- Multi-path intrinsic in performance and in measurement environment



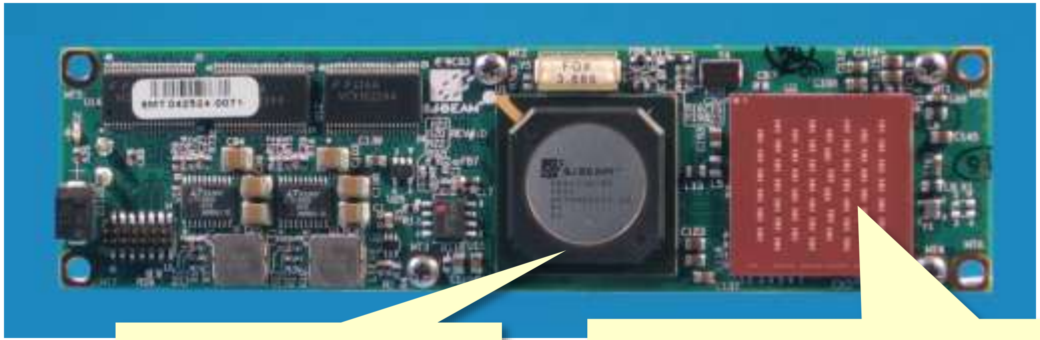
PHY Measurement Challenges

Practical Problems

- Connectivity!
- Modulation Bandwidth

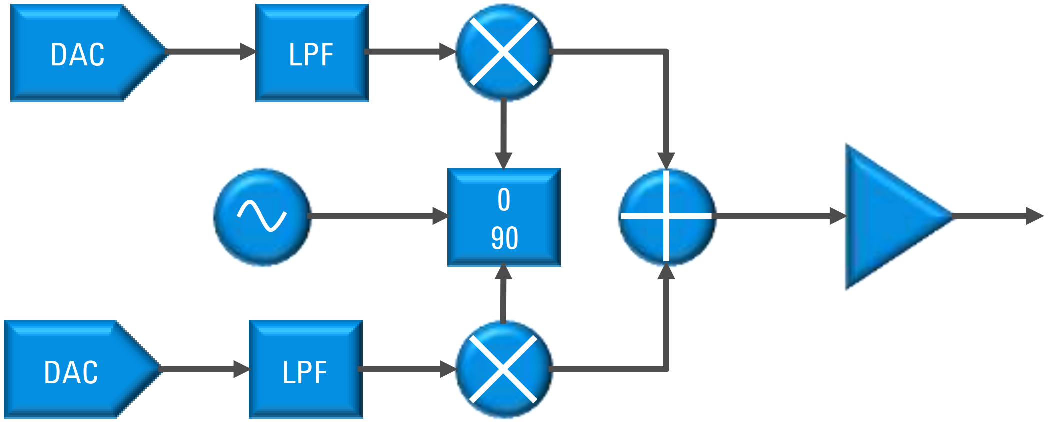
PHY Challenges

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

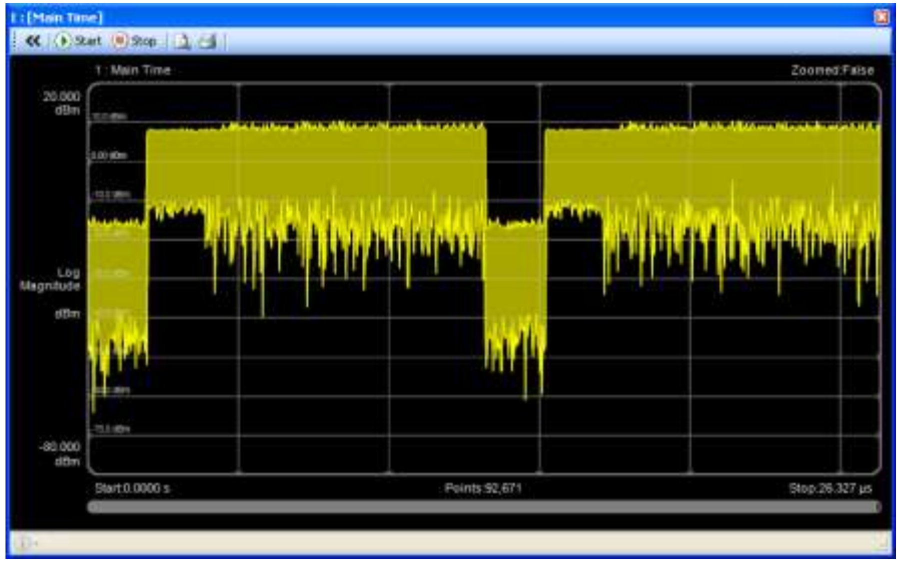


Baseband ASIC

RF ASIC with antenna array bonded directly on top of RFIC.

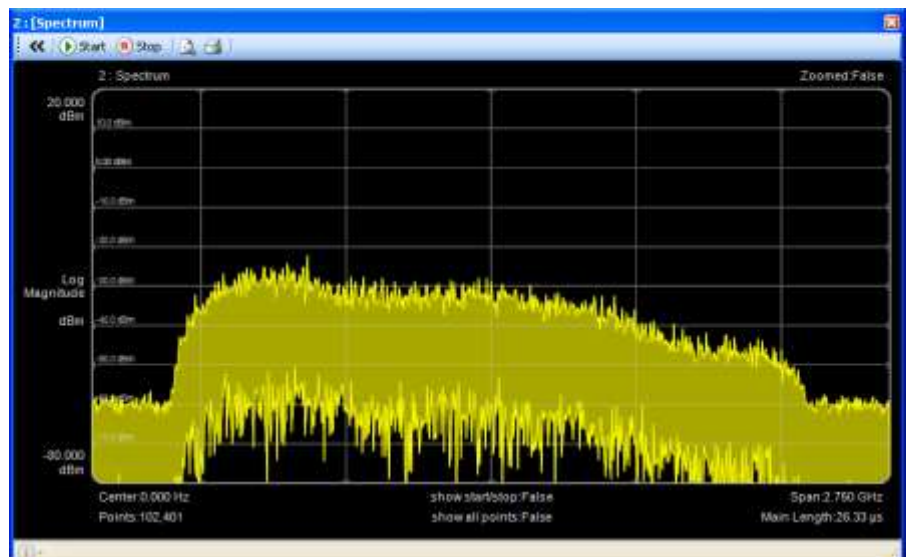


Have I got a signal?



Time Domain

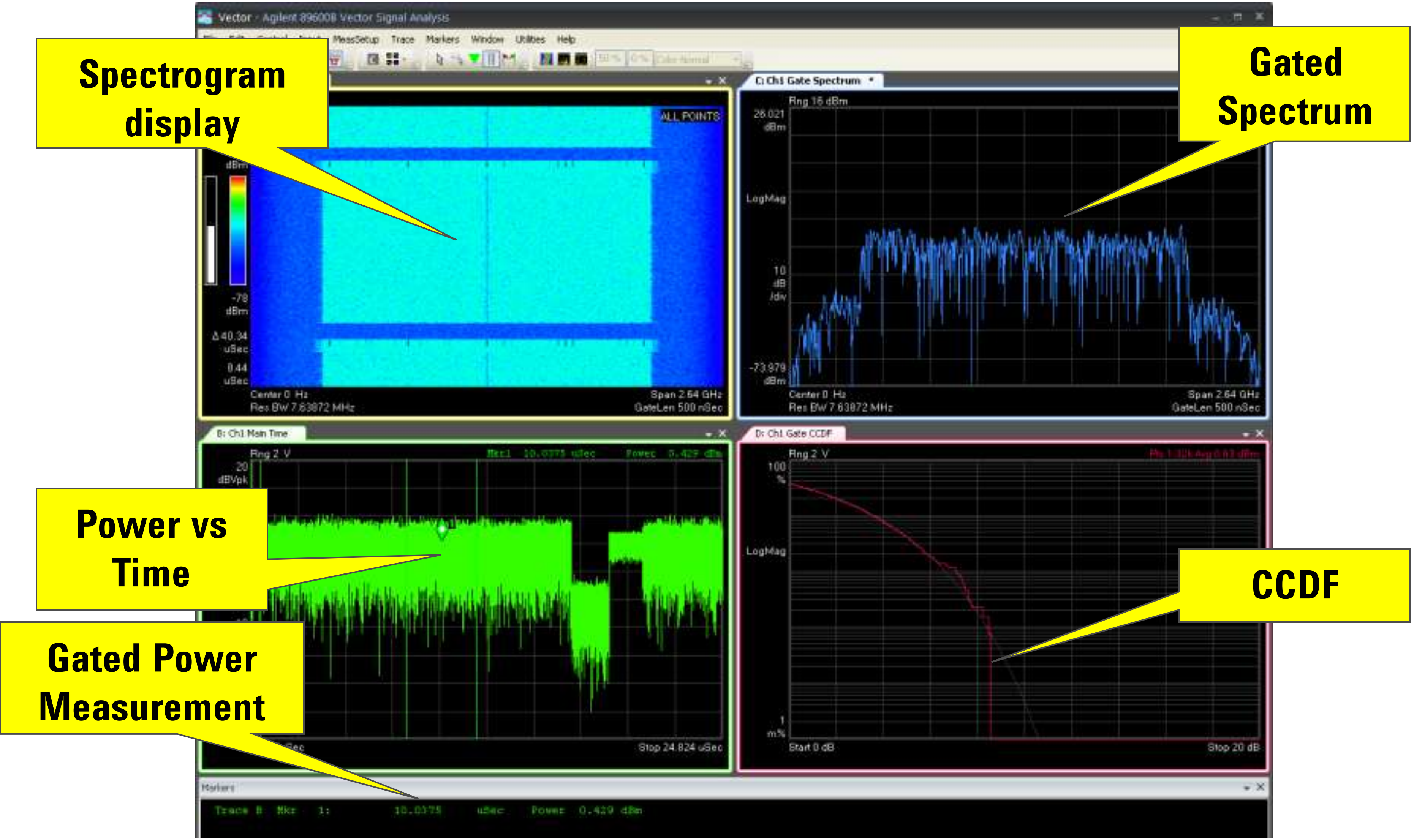
- SNR?
- Clipping?
- Transients?
- Structure?
- Etc...



Frequency Domain

- Shape?
- Flatness?
- Bandwidth?
- Spurs?
- Etc...

Spectrum, Time, Power Statistics, Spectrogram



802.11ad Tx Mask

Per specification IEEE 802.11-2012
Paragraph 21.3.2

The transmit mask shall be measured on data packets longer than 10 μs without training fields.

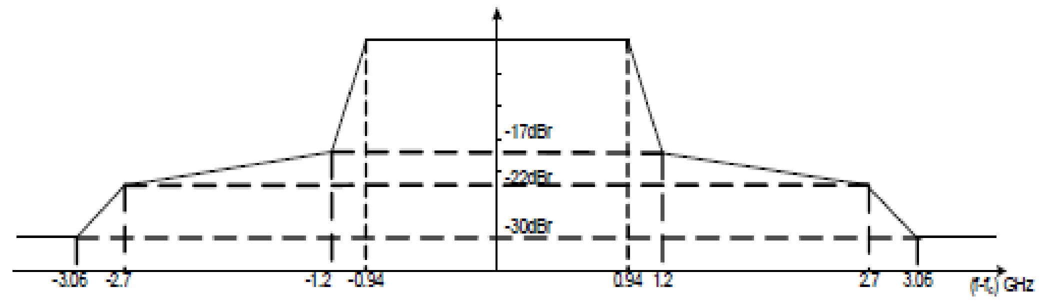
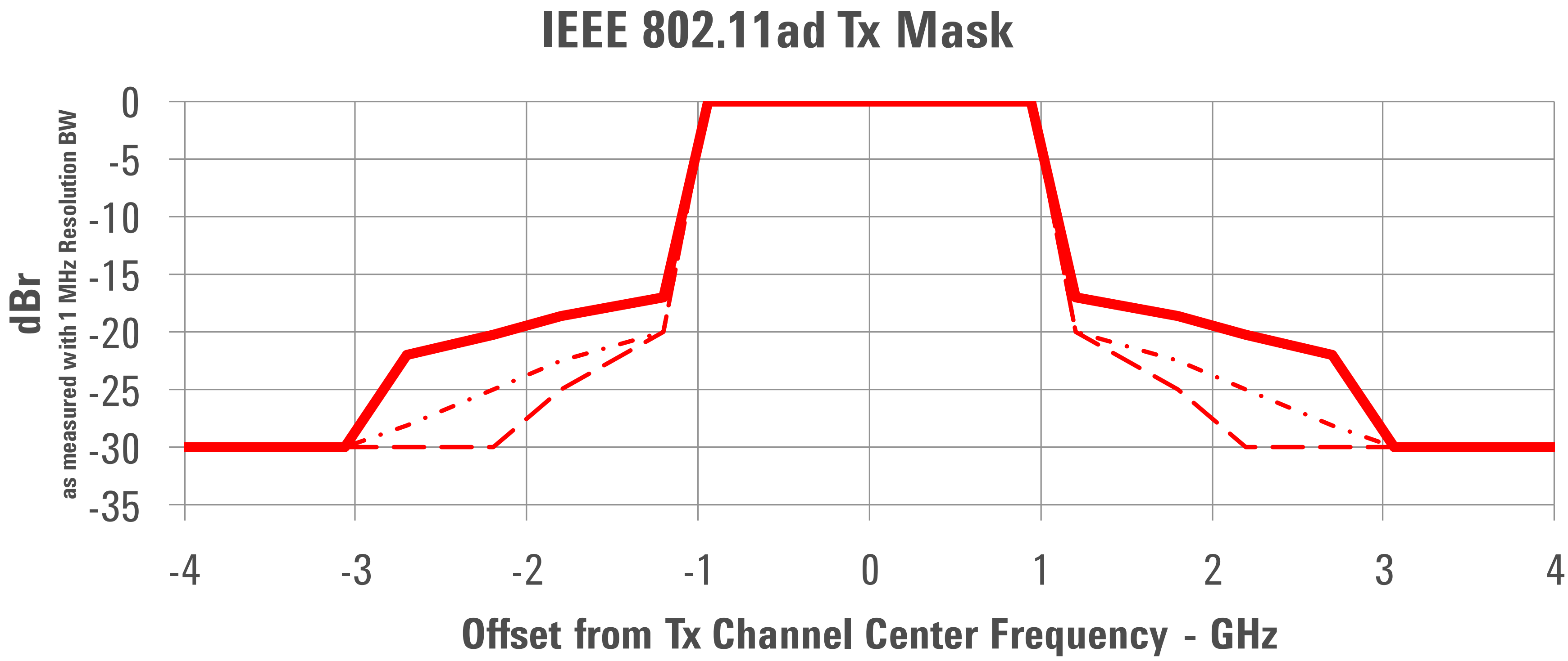
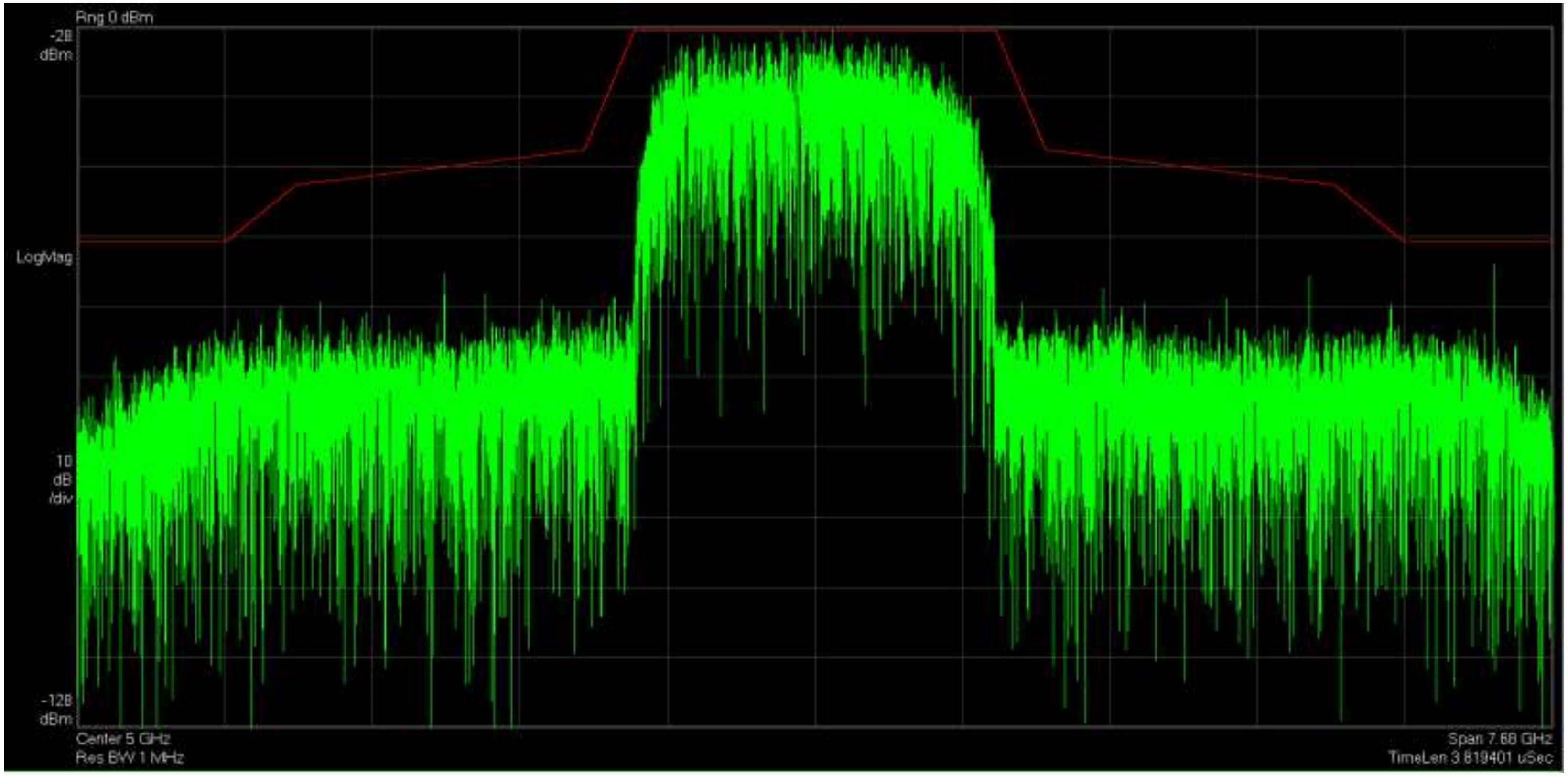


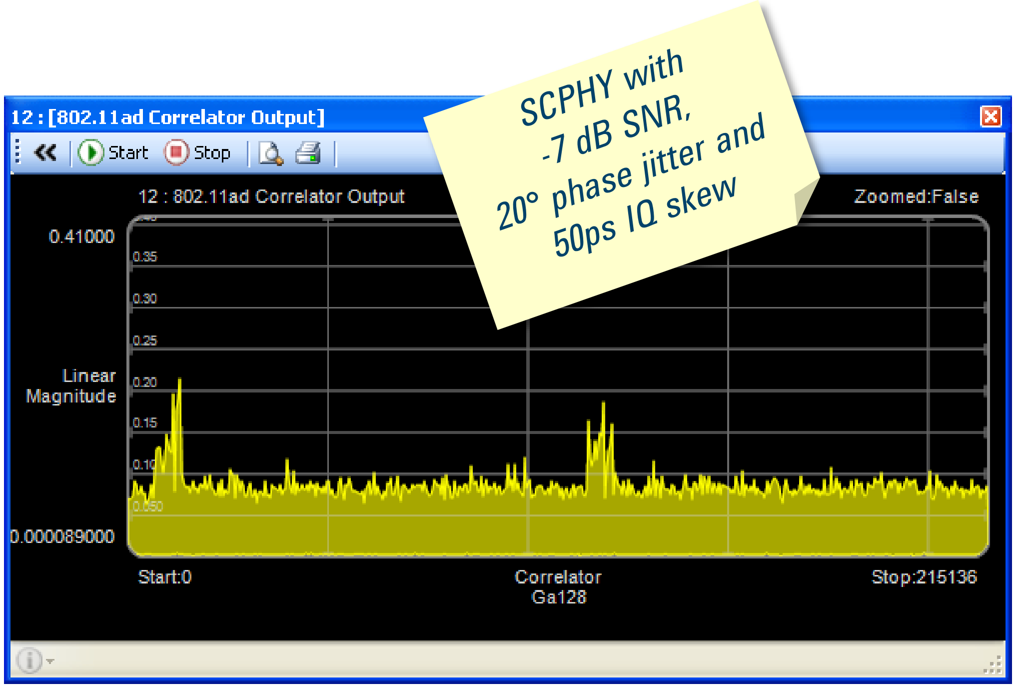
Figure 21-1—Transmit mask

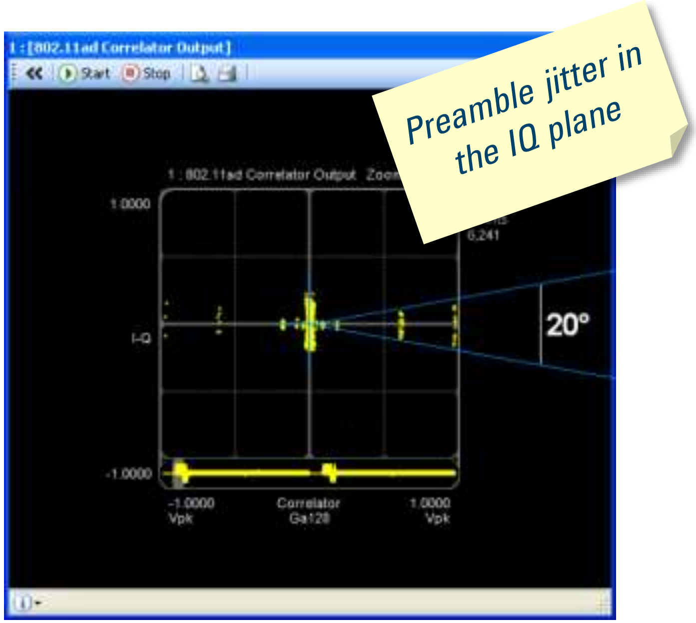


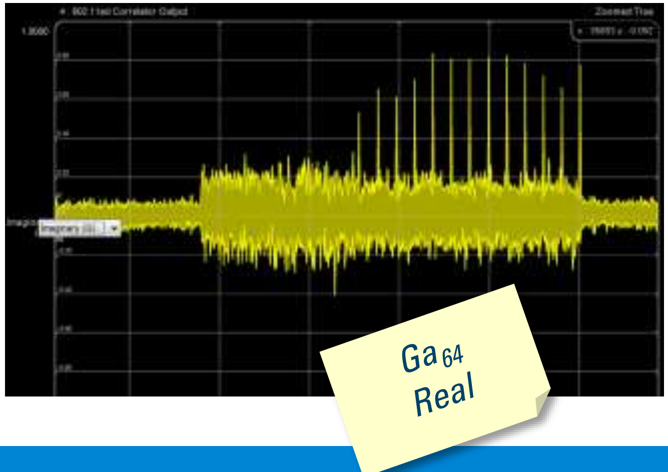
802.11ad Tx Mask

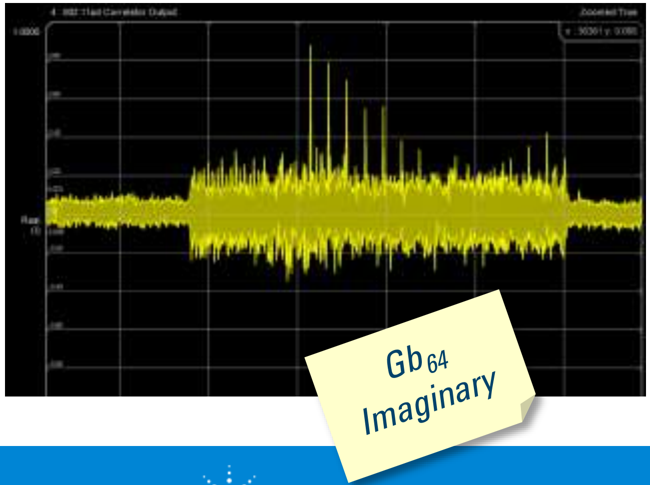


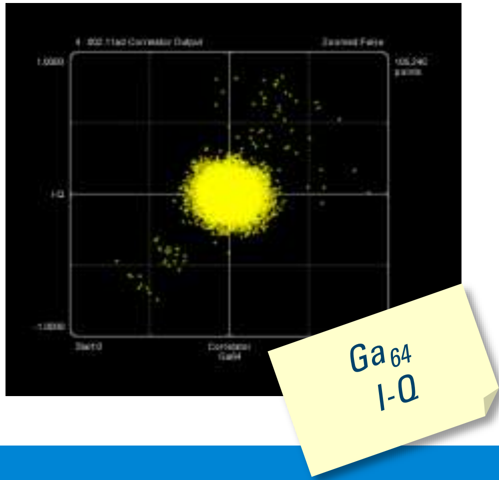
Golay Correlator Outputs



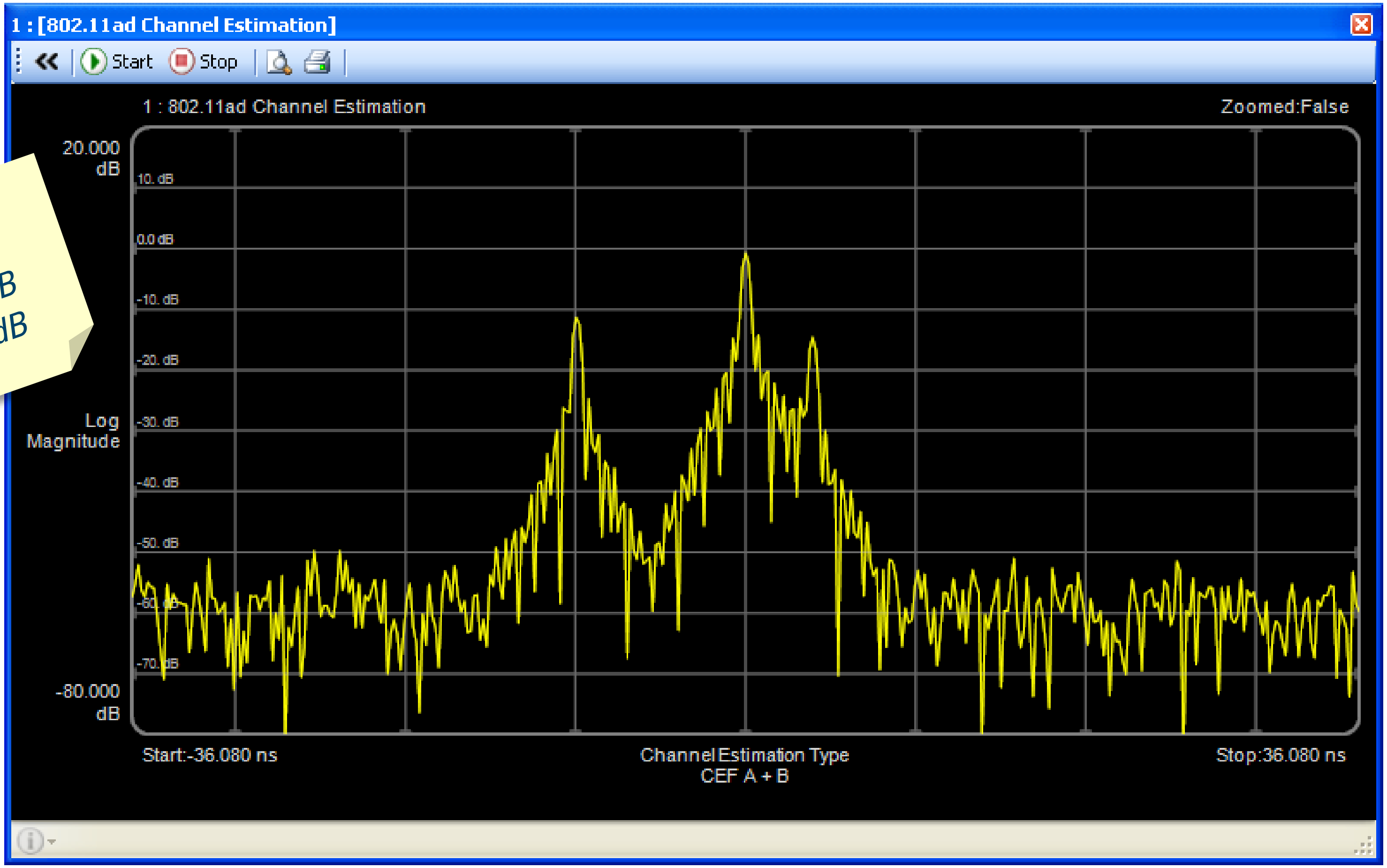


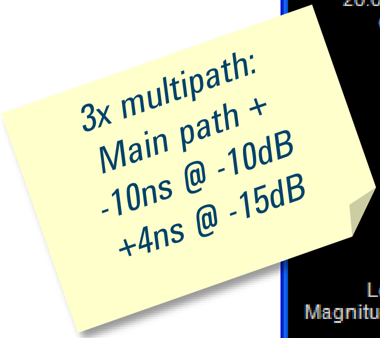






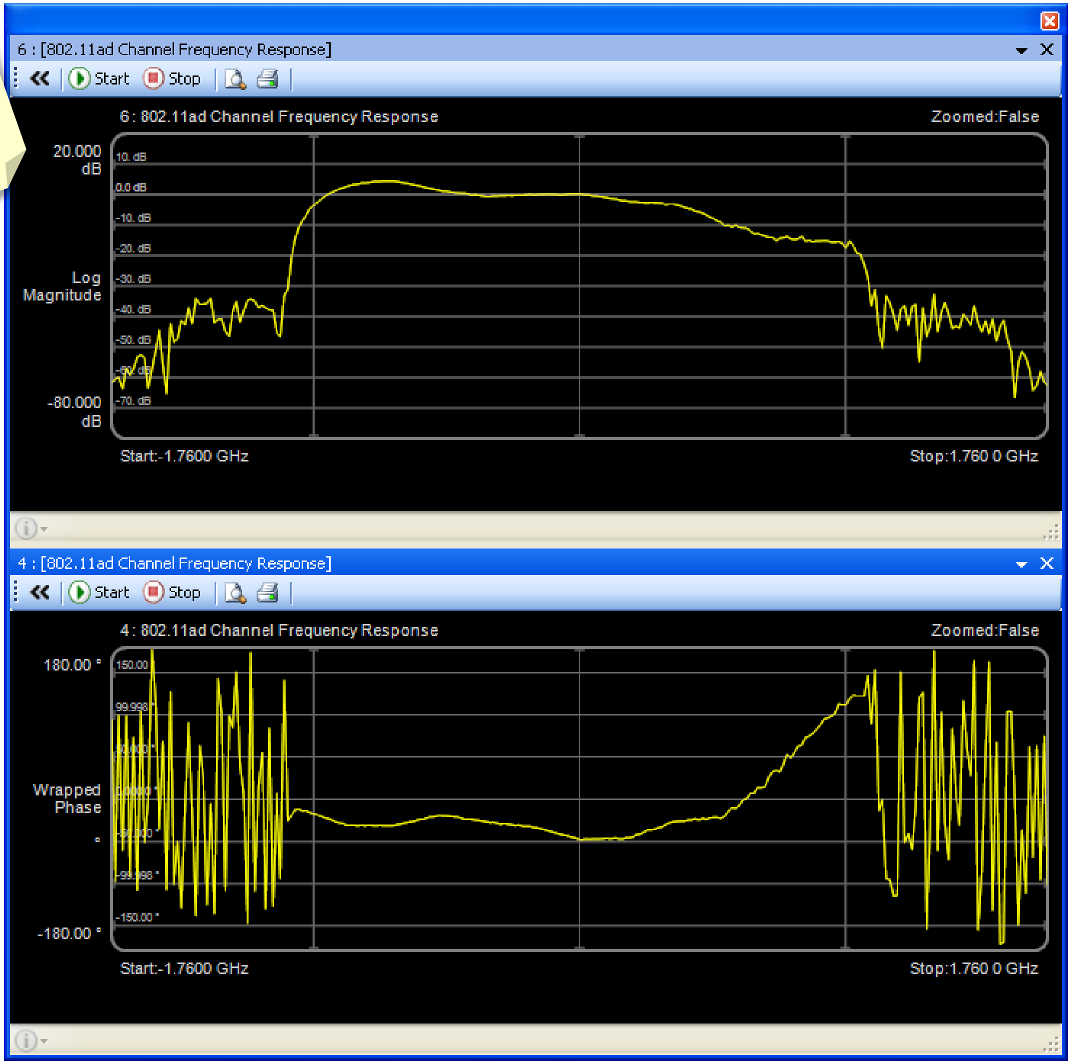
Channel Impulse Response
(estimated from CEF field)



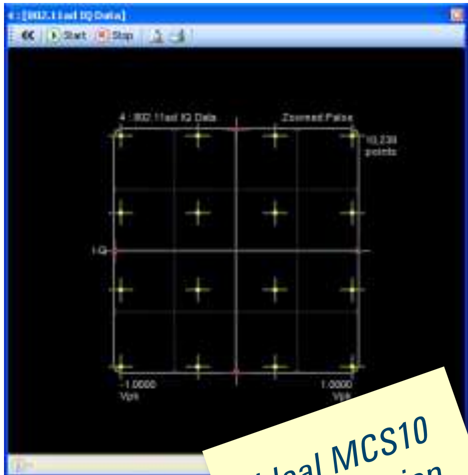


Channel Frequency Response

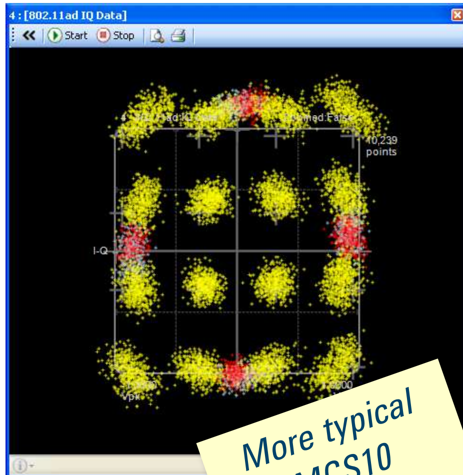
Derived from the channel impulse response



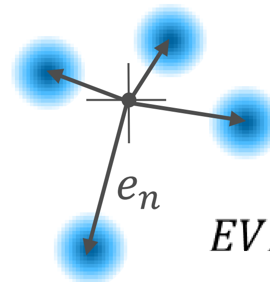
Step 4... Error Vector Magnitude (EVM)



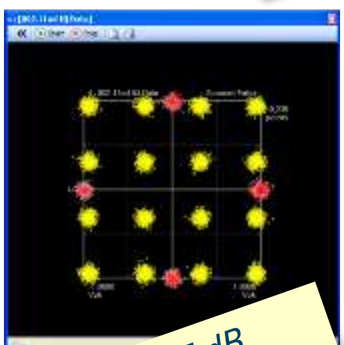
Ideal MCS10 constellation



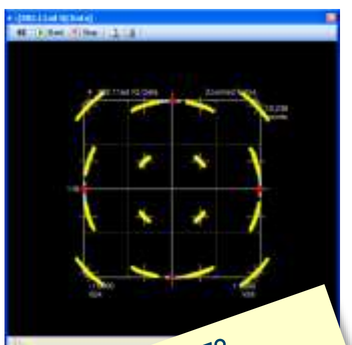
More typical MCS10 constellation



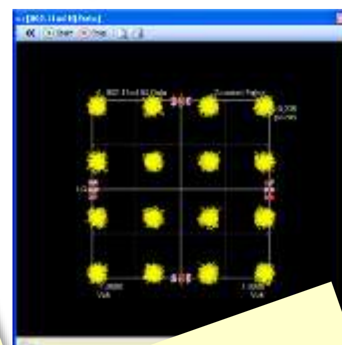
$$EVM = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|e_n|^2}$$



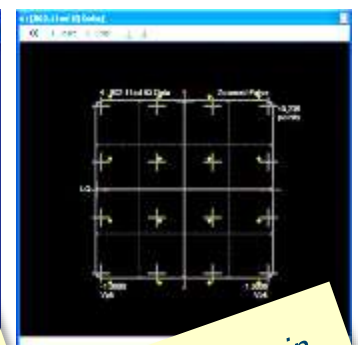
25 dB Gaussian noise



5° jitter at 4 MHz



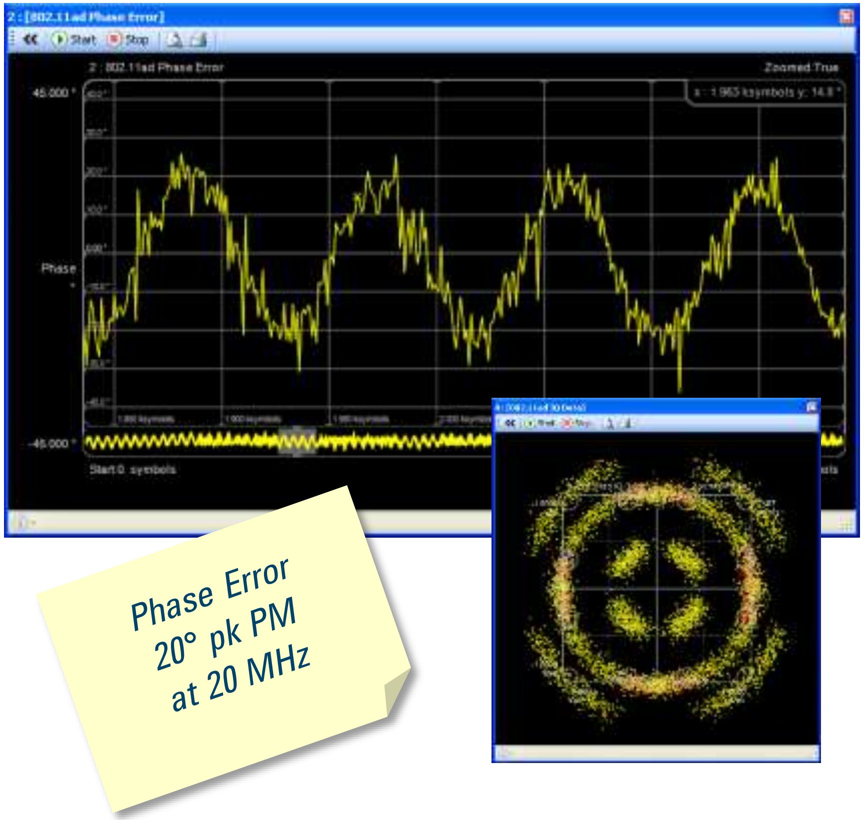
50 ps IQ skew

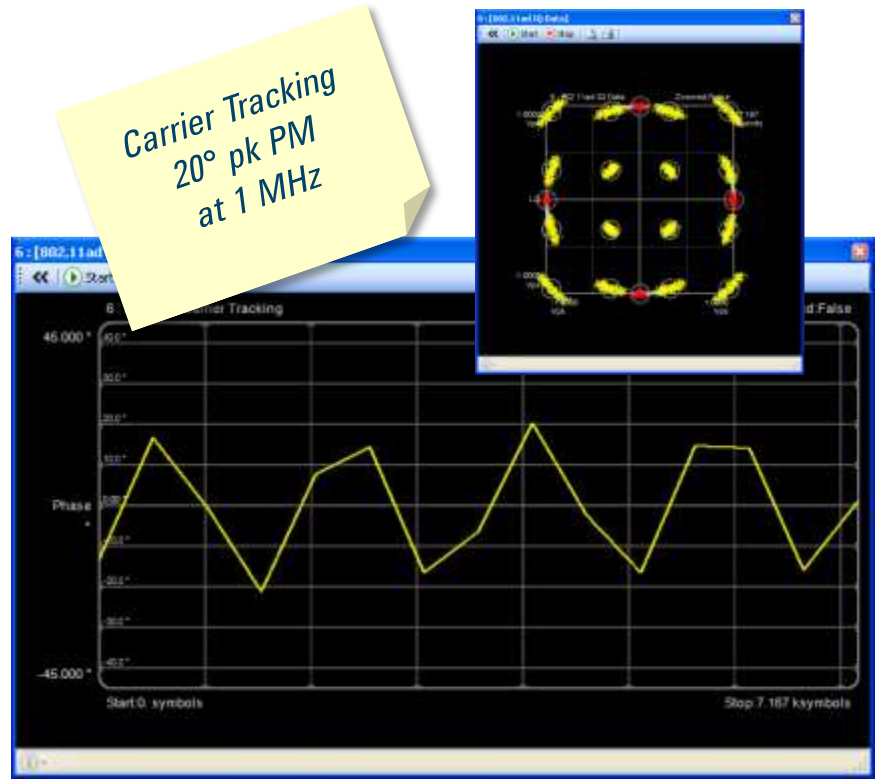


1.93 dB gain mismatch

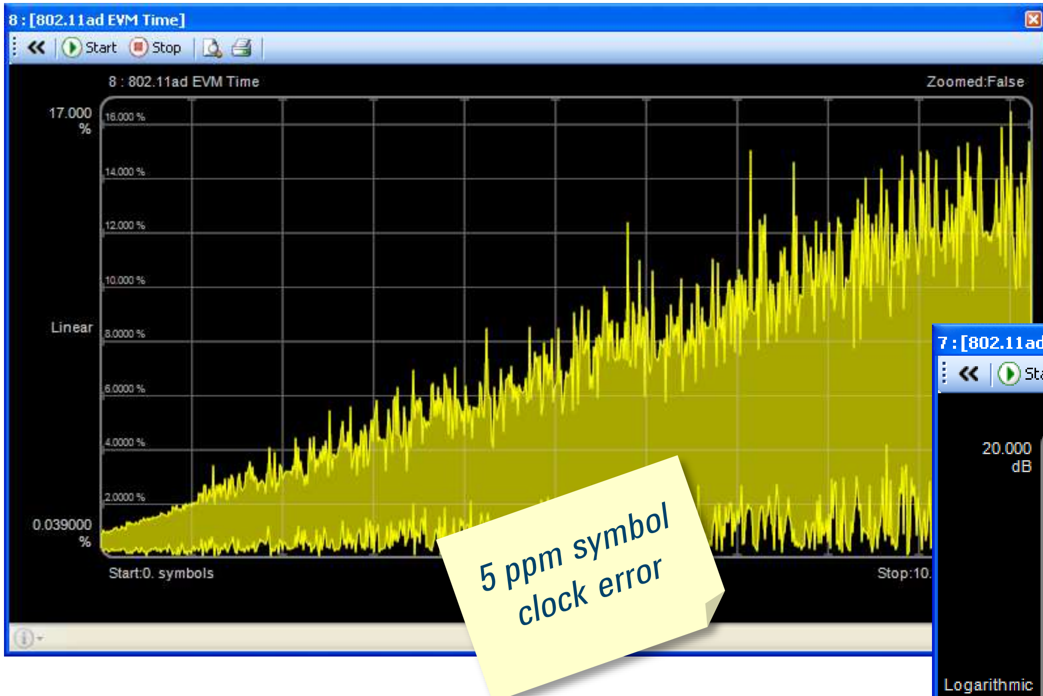
5° quadrature error

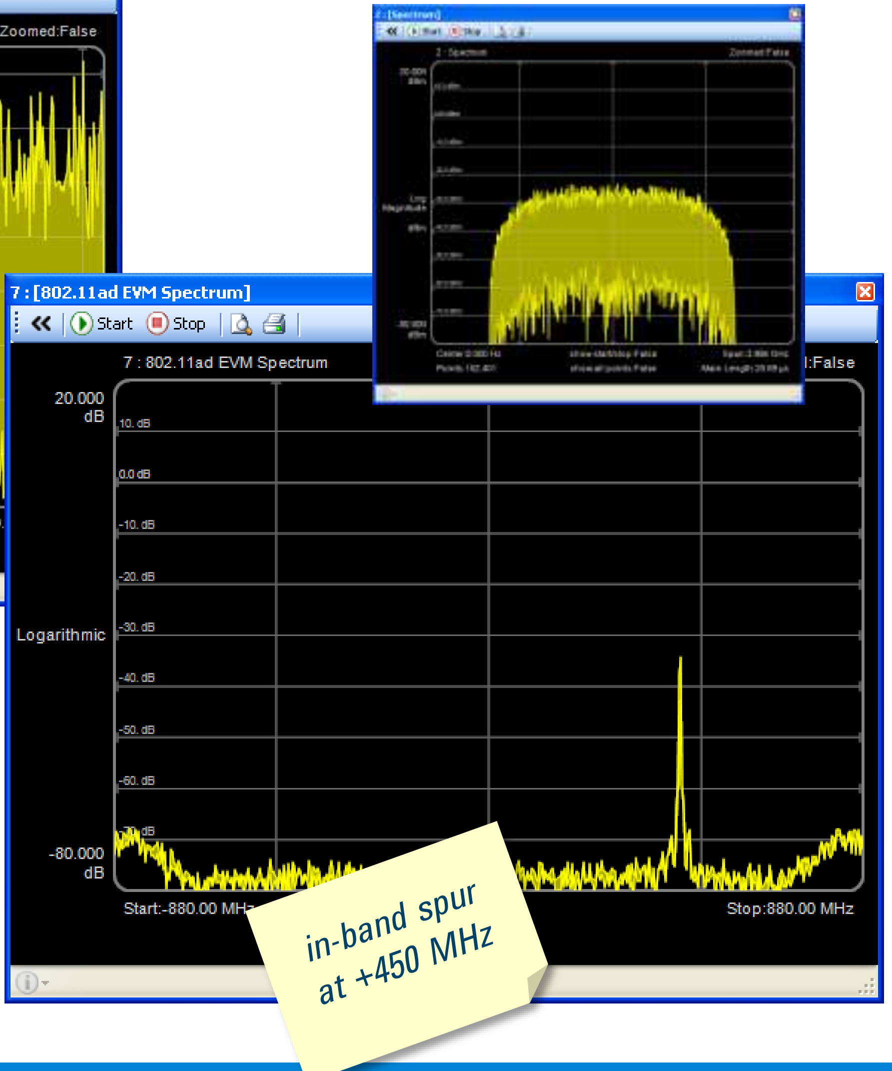
Phase Error and Carrier Tracking



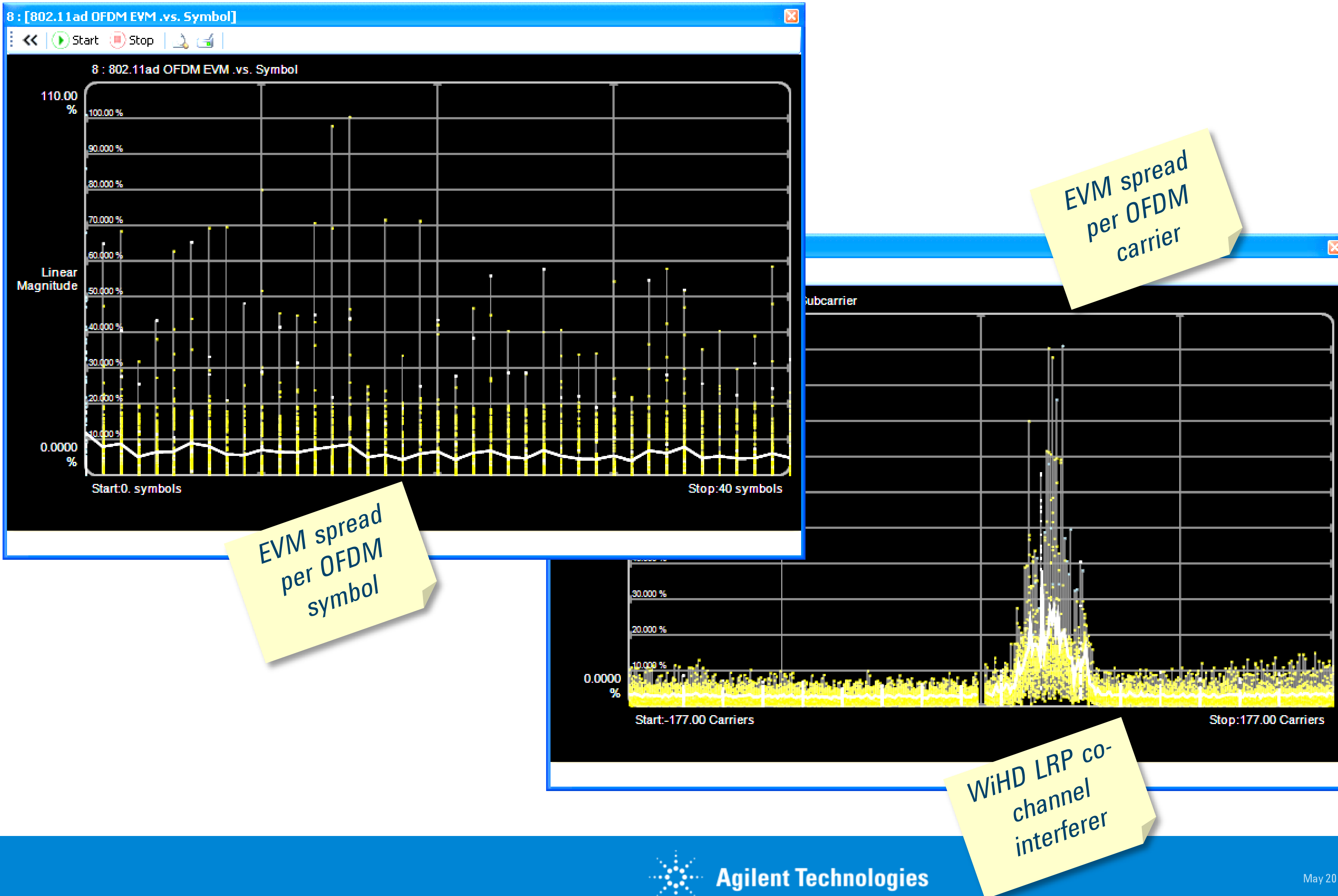


EVM versus Time and Frequency

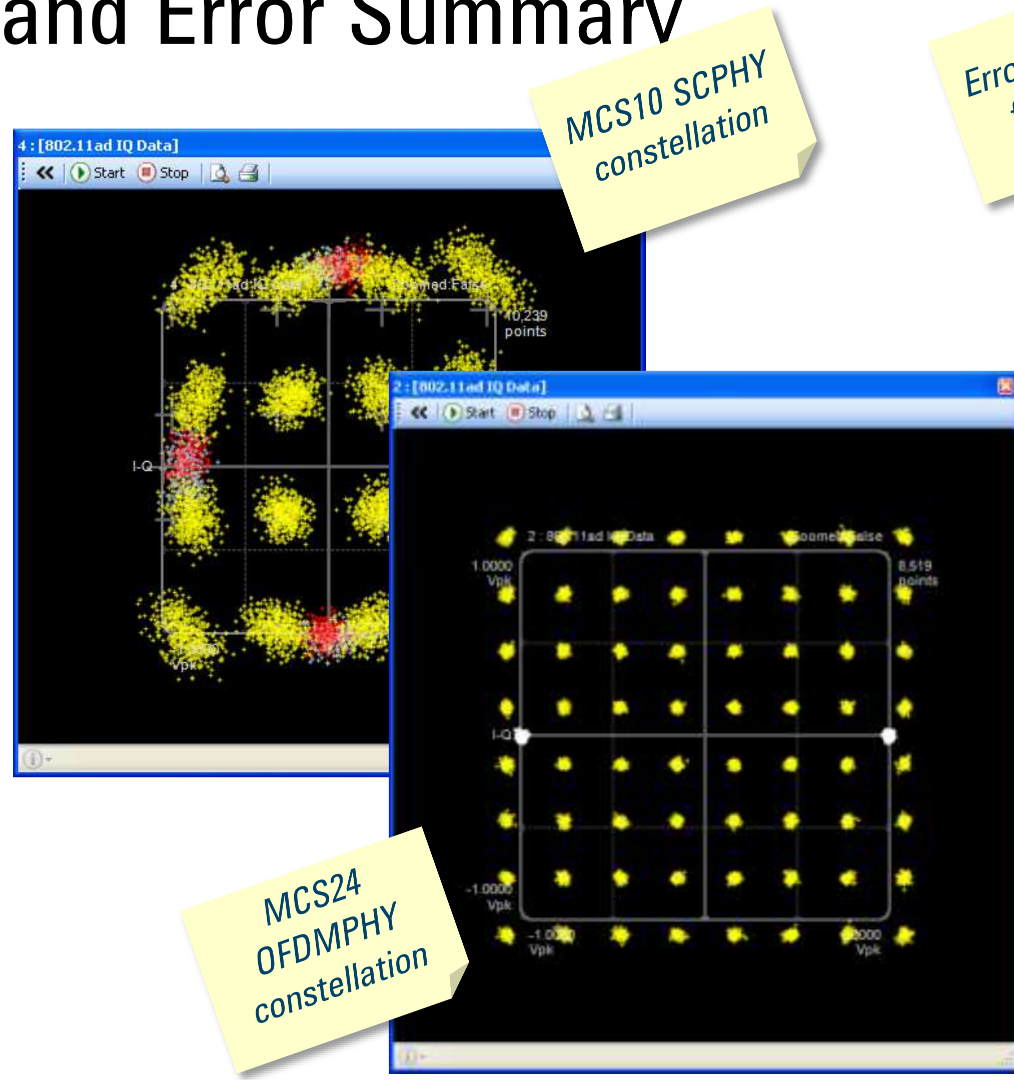


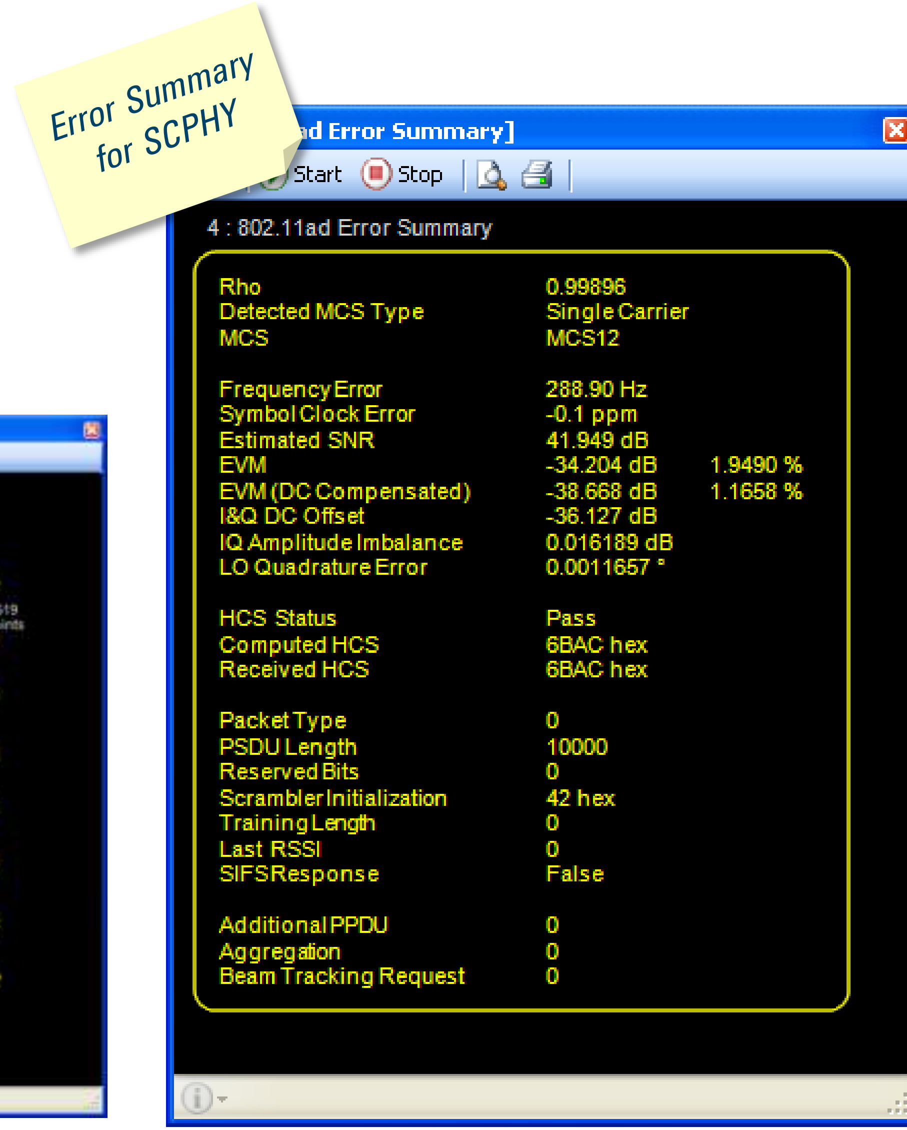


OFDM EVM by Symbol and by Carrier

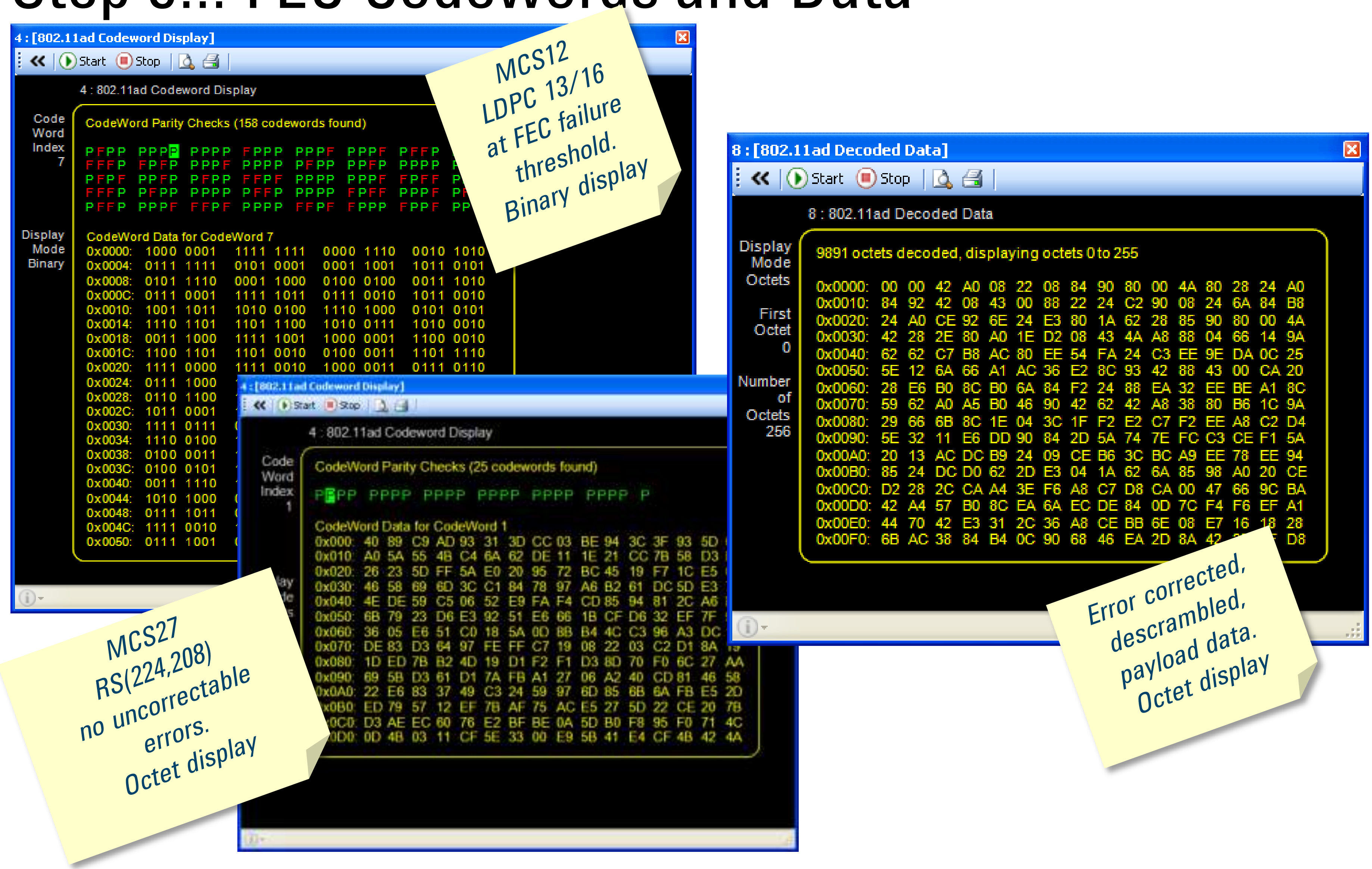


Constellation Display and Error Summary





Step 5... FEC Codewords and Data



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- Preamble
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- Single Carrier PHY
- OFDM PHY
- Low Power Single Carrier PHY
- Forward Error Correction and Scrambling

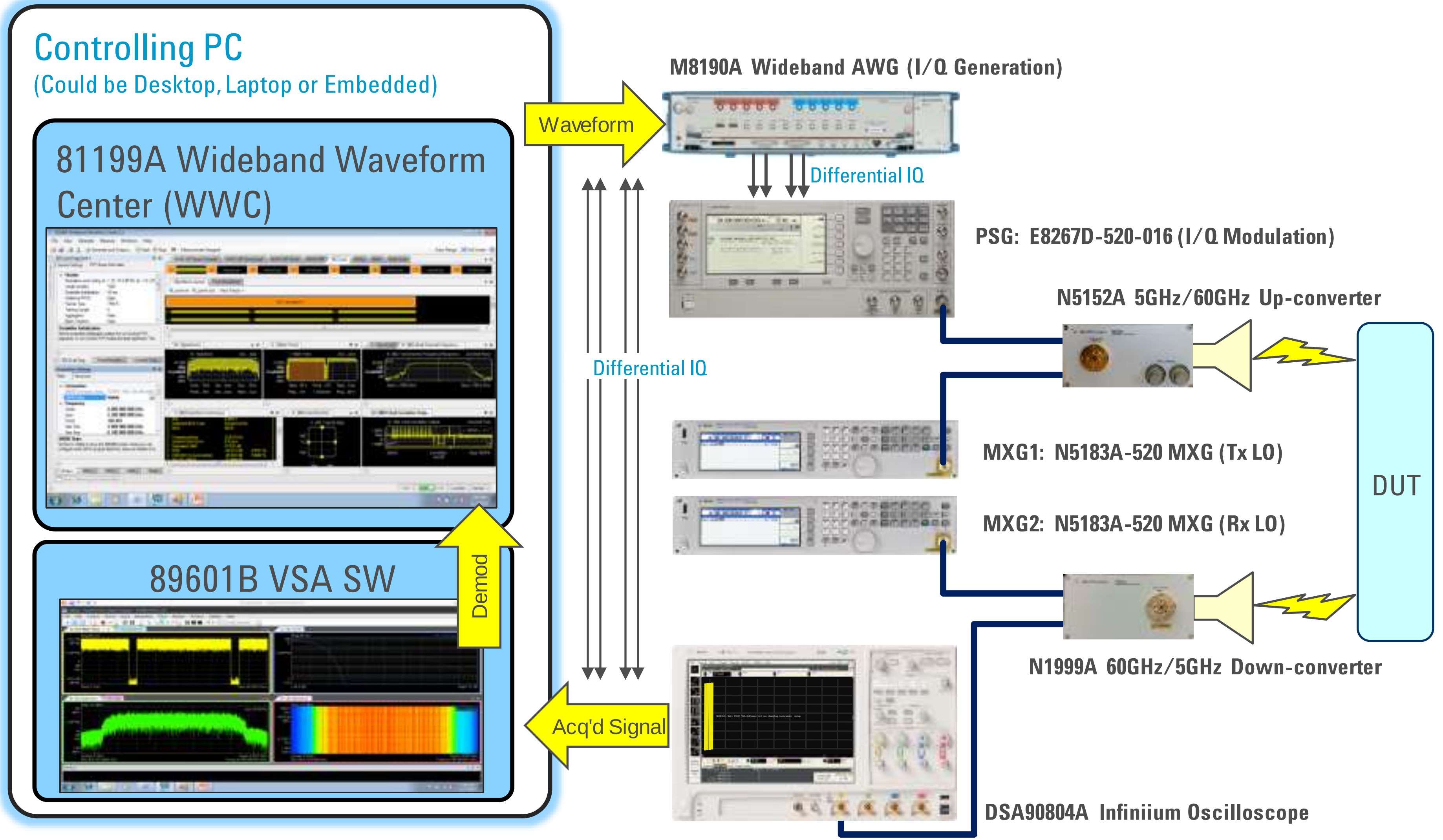
Design Challenges and Measurement examples

Summary / where to find more information

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



For more information

Solution Information:
(including a six-part tutorial series)

www.agilent.com/find/WLAN
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

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