Equalization algorithms in Millimeter wave Communication Systems

30 APRIL 2017

Srevats Laxman
Tektronix (India) Pvt. Ltd.
Bangalore
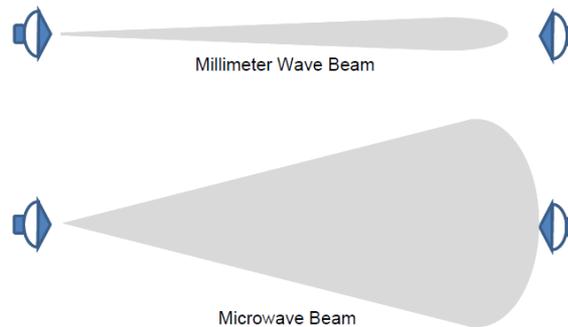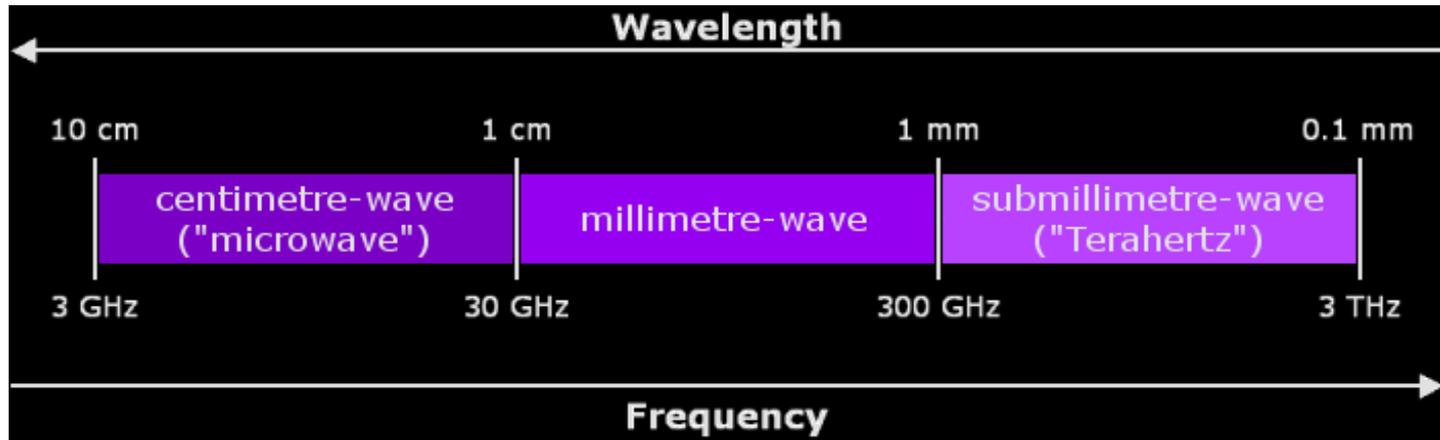
Equalization algorithms for Millimeter wave Communication Systems

AGENDA

- Millimeter wave Communication and 5G

- 802.11ad – A standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

Millimeter wave Communication
BANDS

Source: Loea Corporation

KEY
ADVANTAGES

Millimeter wave Communication- Applications

In-home/store/flight media distribution and miracast
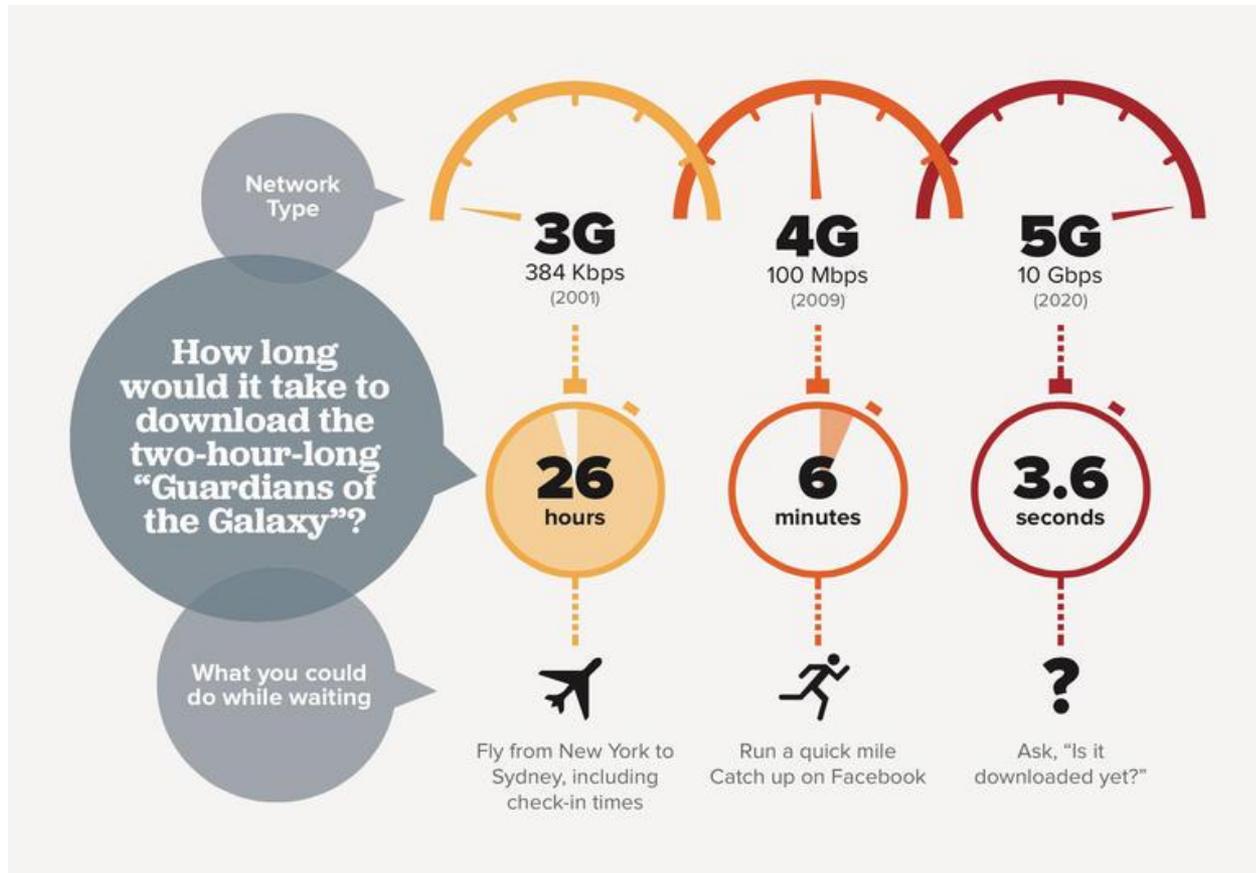
Virtual reality

Kiosk to mobile file sync

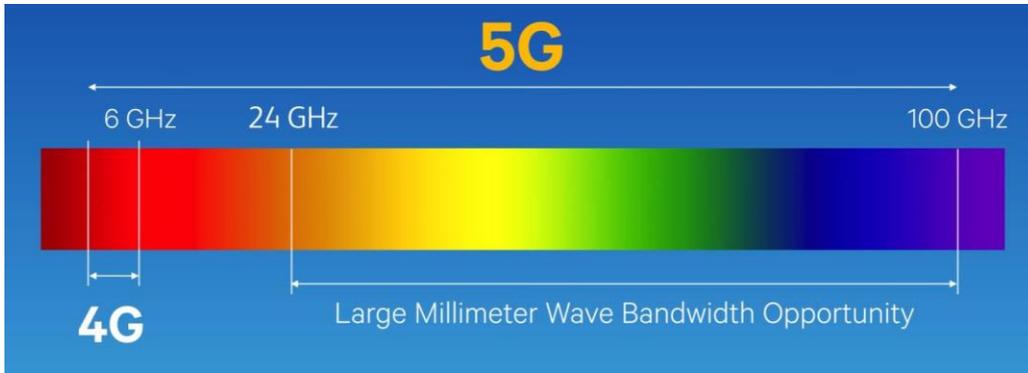*Source: Microsoft*

5G

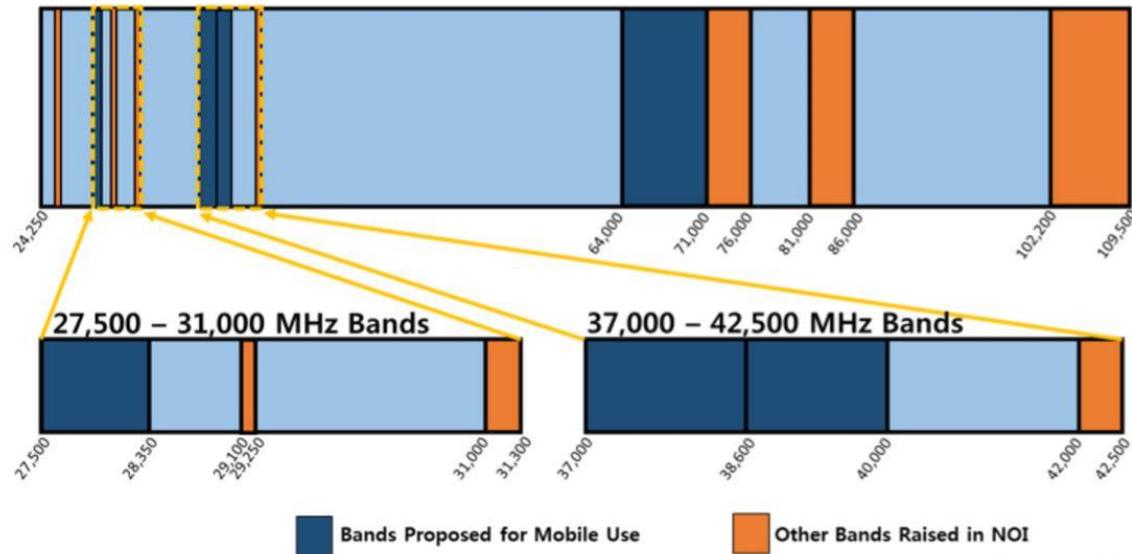Source: RCR Wireless News

Source: CNET

5G

Source: RCR Wireless News

5G

6 GHz 24 GHz 100 GHz

4G

Large Millimeter Wave Bandwidth Opportunity

Source: National Instruments

Bands Above 24 GHz for Possible Mobile Use

24,250   64,000   71,000   76,000   81,000   86,000   102,200   109,500

27,500 – 31,000 MHz Bands

27,500   28,350   29,100   29,250   31,000   31,300

37,000 – 42,500 MHz Bands

37,000   38,600   40,000   42,000   42,500

■ Bands Proposed for Mobile Use   ■ Other Bands Raised in NOI

Source: National Instruments

Equalization algorithms for Millimeter wave Communication Systems

AGENDA

- Millimeter wave Communication and 5G

- 802.11ad – A standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

IEEE 802.11ad Applications & Products
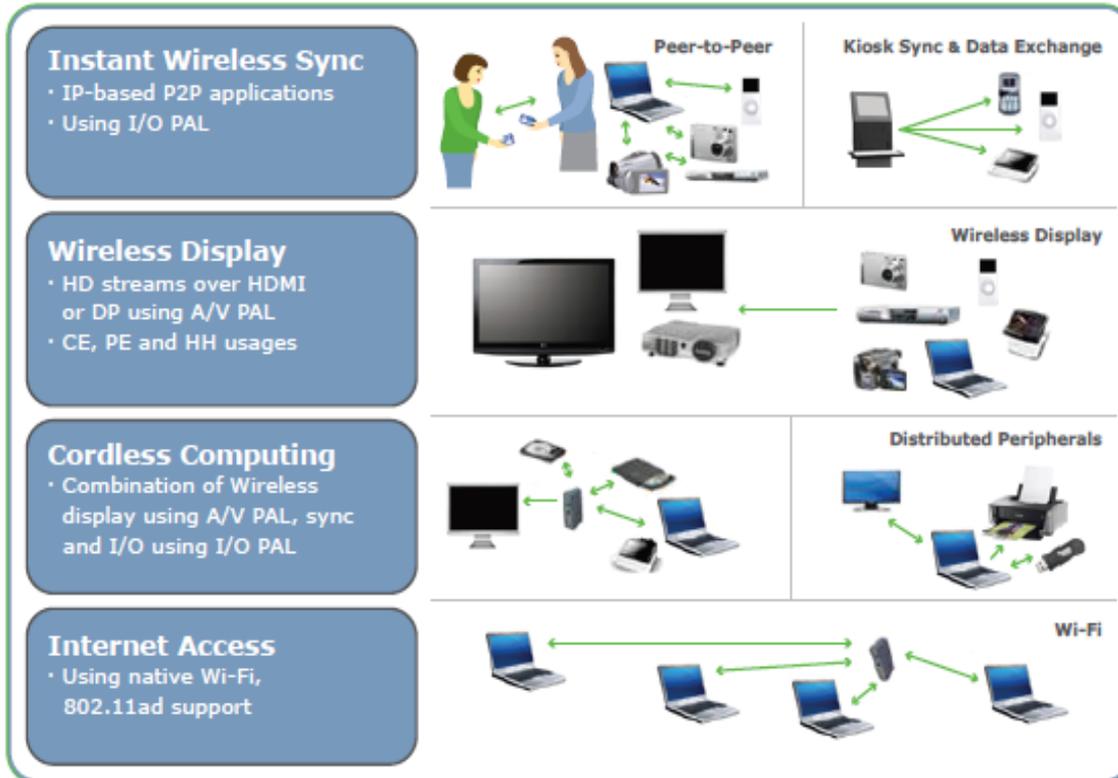
DELL Mobile PC Docking Stations

Le Max Pro will be the first phone with Snapdragon 820, ultrasonic sensor, and WiFi 802.11ad

TP-Link has unveiled the world's first 802.11ad (aka WiGig) router: the rather *unique* looking Talon AD7200.

The main purpose of WiGig is cable replacement for uncompressed video transmission and very fast data file transmission – within the same room
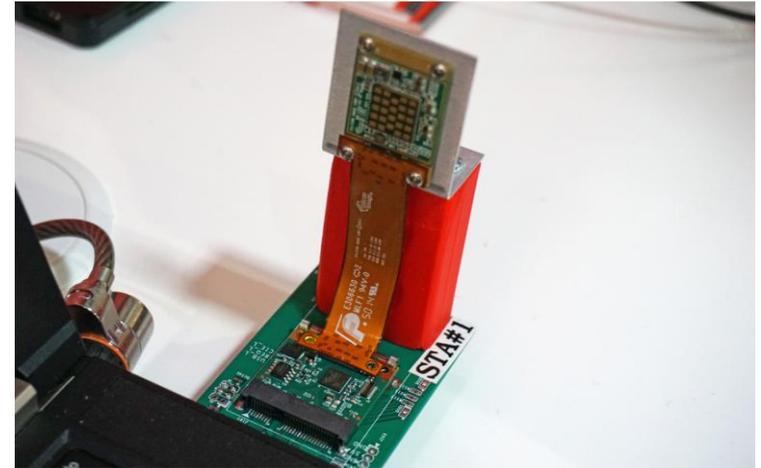***Augmented/ Virtual Reality***

802.11ad PRODUCTS
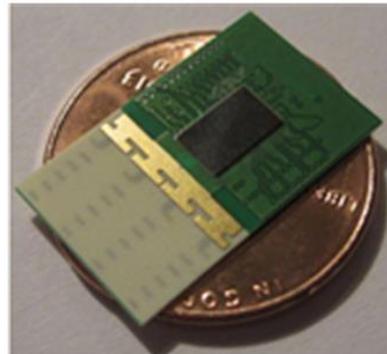
IC, MODULES AND BOARDS

Qualcomm module integrated into DELL products

SiBeam WiGig Antenna Module

Peraso WiGig Chipset

Tensorcom Green SoC

Intel® Tri-Band Wireless Card delivers WiGig 802.11ad

802.11ad

KEY FEATURES

- Support for data rates of up to 8.08 Gbit/s
  - Control PHY: (Mandatory) MCS0, BPSK
  - Single Carrier (SC): MCS (1 to 12.6) BPSK, QPSK,16-QAM and 64 QAM
  - OFDM mode MCS 13-24

- Use of the 60 GHz unlicensed band (globally available)
  - avoids the overcrowded 2.4 GHz and 5 GHz bands
  - uses short wavelengths (5 mm) so compact, affordable antennas or arrays

- Next Generation is 802.11ay
  - 4GHz bandwidth- double **symbol rate** 3.52Gsym/s

802.11ad
WORLDWIDE CHANNEL ALLOCATION
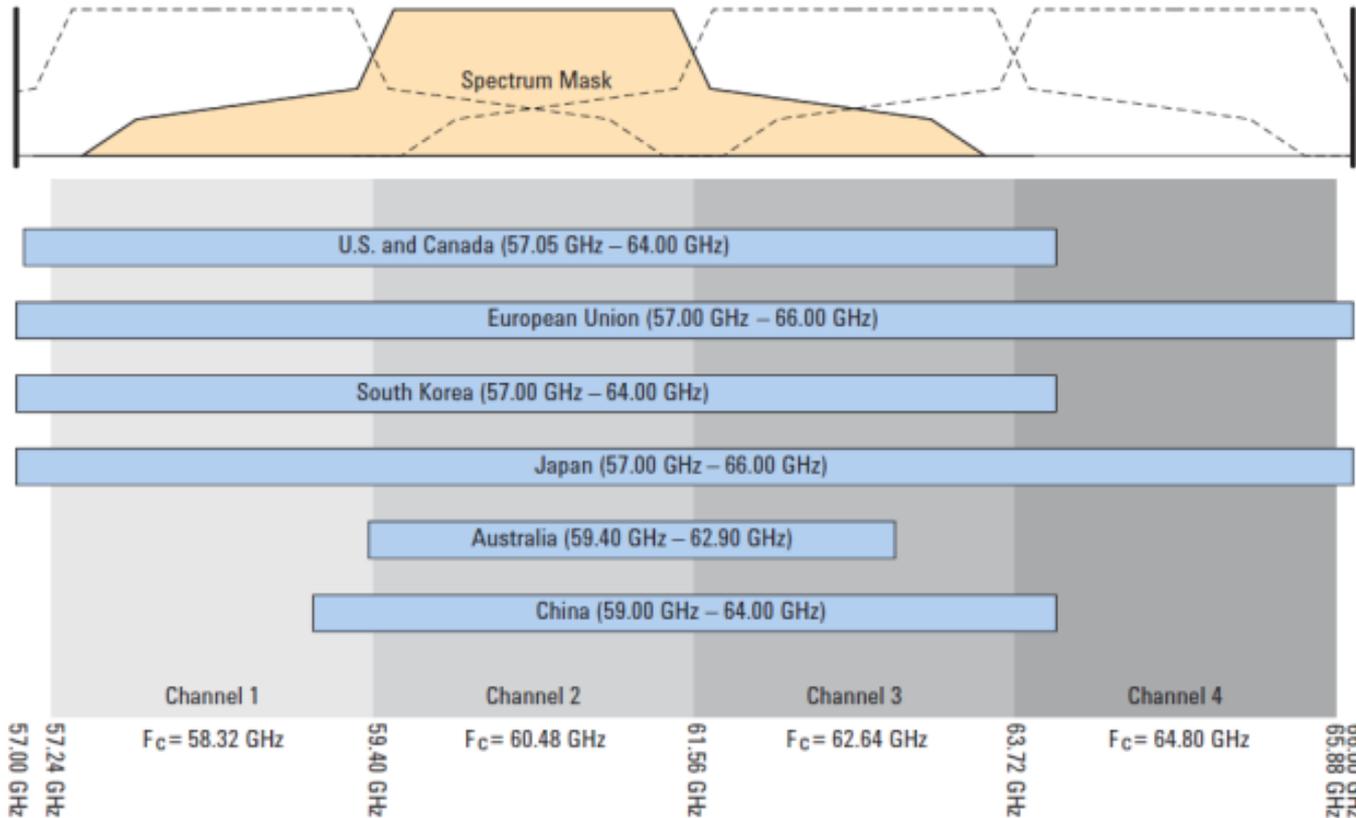
New FCC recommendation to extend the 802.11AD Band up to 72.6 GHz (early 2018) – adding 3 new channels: Channel 5 centered at 66.96 GHz & Channel 6 centered at 69.12 GHz Channel 7 centered at 71.28 GHz

Spectrum Mask

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 (57.00 GHz – 66.00 GHz)

Australia (59.40 GHz – 62.90 GHz)

China (59.00 GHz – 64.00 GHz)

Channel 1	Channel 2	Channel 3	Channel 4
F_C = 58.32 GHz	F_C = 60.48 GHz	F_C = 62.64 GHz	F_C = 64.80 GHz

57.00 GHz / 57.24 GHz · 59.40 GHz · 61.56 GHz · 63.72 GHz · 66.00 GHz / 65.88 GHz

- 4 channels in the 57 GHz to 66 GHz ISM band

- Channel bandwidth is 2.16 GHz

802.11ad

STRUCTURE OF THE SINGLE CARRIER PACKET
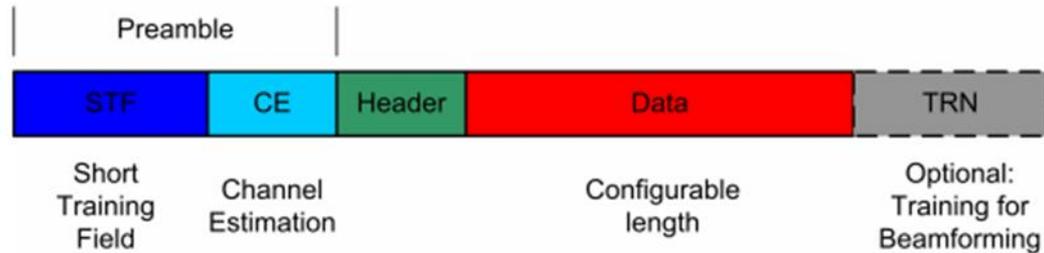
- Training Field made of Golay Code

- The data are transmitted block wise at 448 symbols per block. Another 64 symbols are inserted between the individual blocks as guard intervals (GI) in order to provide a known reference signal to the receiver in the case of long data packets.
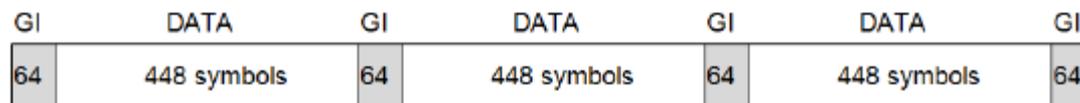

Figure 21-16—Block transmission

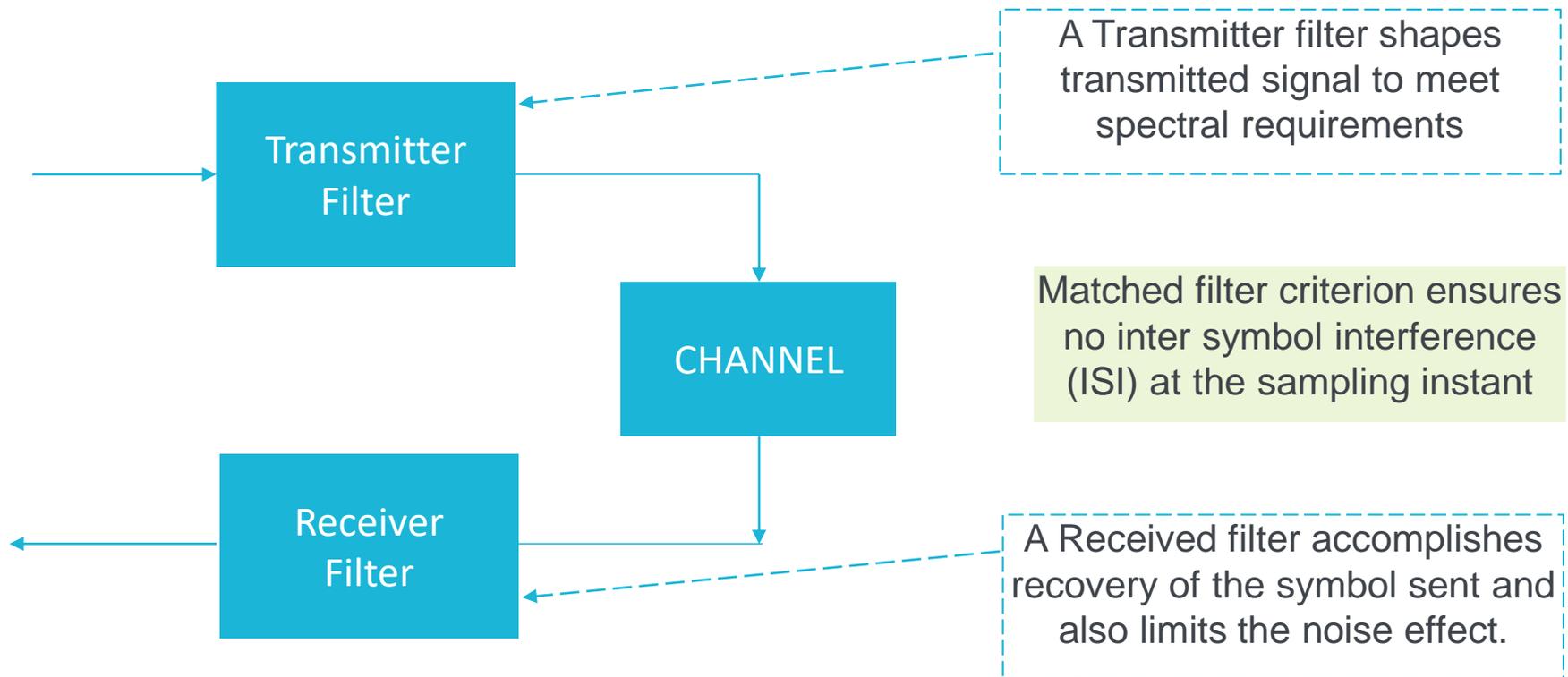# Equalization algorithms for Millimeter wave Communication Systems

- Millimeter wave Communication and 5G

- 802.11ad – A standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

Why is Equalization required?
## INTER SYMBOL INTERFERENCE

- A digital communication system requires transmit and receive filters (matched filter pair)

A Transmitter filter shapes transmitted signal to meet spectral requirements

Matched filter criterion ensures no inter symbol interference (ISI) at the sampling instant

A Received filter accomplishes recovery of the symbol sent and also limits the noise effect.

Transmitter Filter

CHANNEL

Receiver Filter

Why is Equalization required?
## INTER SYMBOL INTERFERENCE (ISI)

- Practical problems
  - The channel is band limited
  - Channel can be time varying too

- This could lead to ISI
  - Overlap at sampling intervals
  - Digital communication system requires transmit and receive filters (matched filter pair)

- Eye diagram gives an idea
  - Synchronization and
  - Noise resistance
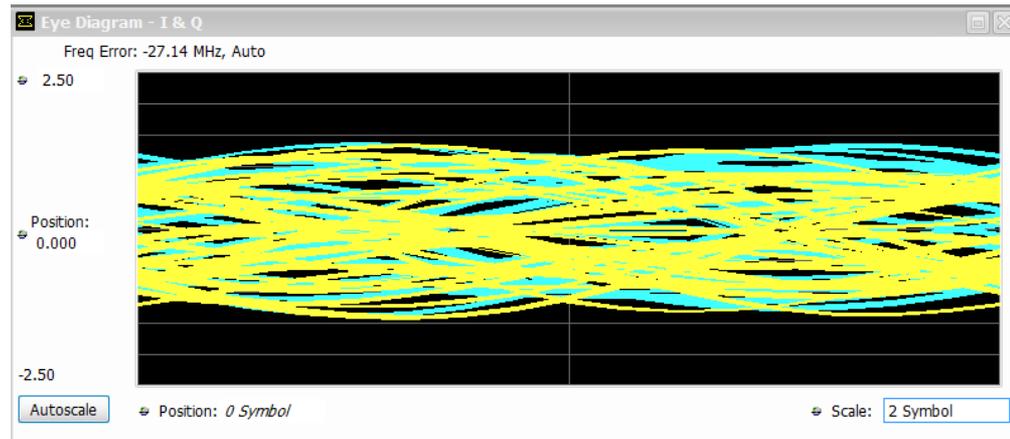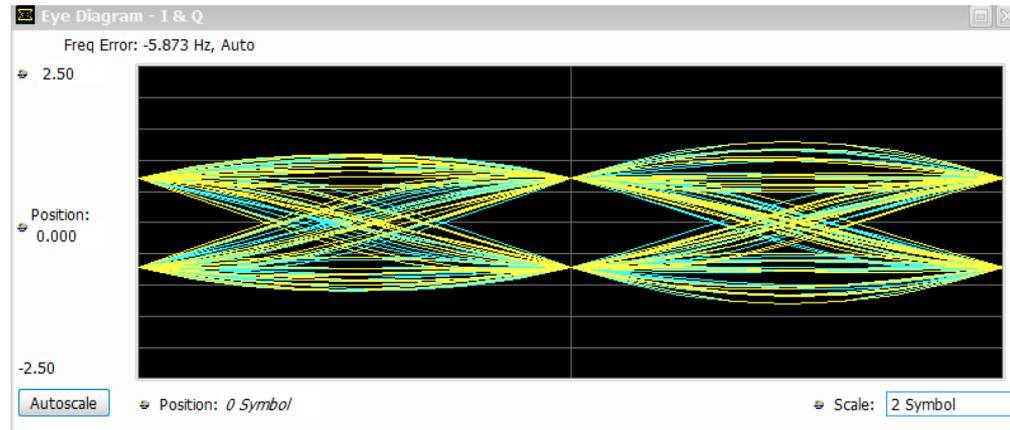
Why is Equalization required?

CHANNEL IMPACT

- In channels where ISI cannot be avoided, the transmitter and receiver filters are matched pairs (usually root raised cosine filters)

- And yet the effect of the channel c(t) effects have to be compensated and this is done by means of an Equalizer.

- Equalization is also about compensating other effects that distort the received data constellation
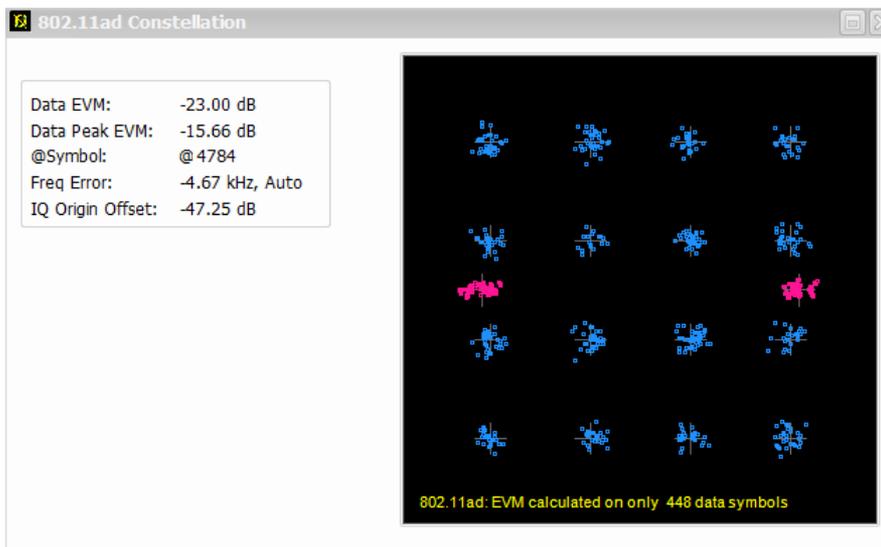

An example of un-equalized constellation caused by simple delay in channel
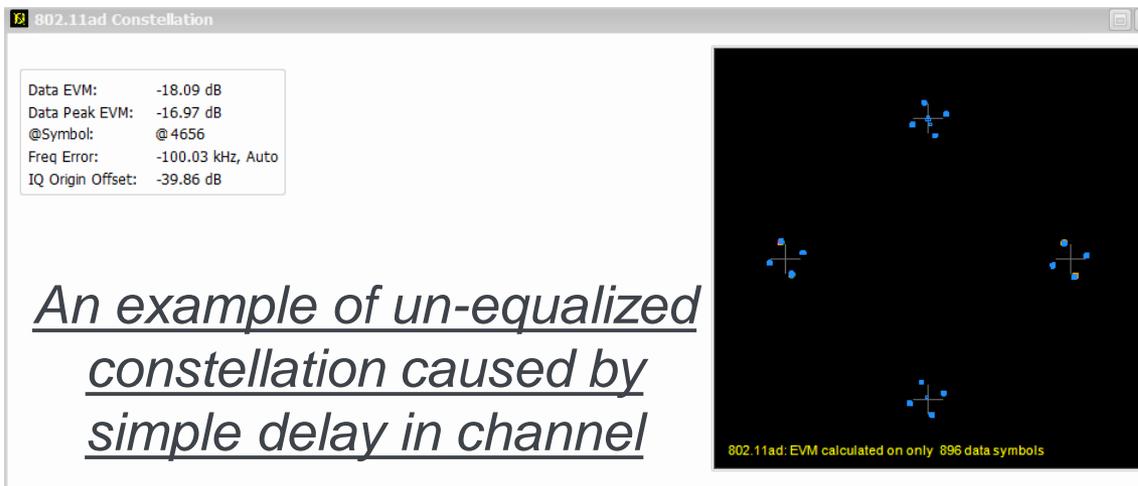
Why is Equalization required?

CHANNEL IMPACT

Compensating linear and non-linear effects with some knowledge about channel

Compensates other effects that distort received constellation
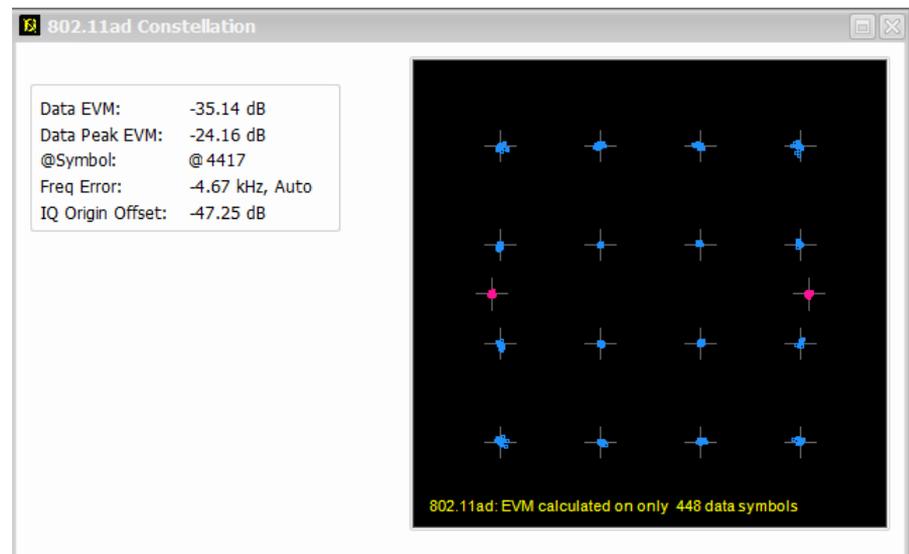
Equalization algorithms for Millimeter wave Communication Systems

AGENDA

- Millimeter wave Communication and 5G

- 802.11ad – A standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

Types of Equalizers
CLASSIFICATION

- **Blind vs Non Blind Equalizer**
  - Non- Blind - Estimating channel properties or Channel identification
  - Blind – Equalization without training sequence based on statistical properties.

- **Linear vs Non-Linear**
  - Linear (Zero forcing Equalizer (ZFE), Minimum Mean Square Error (MMSE)
  - Non-Linear (Decision Feedback (DFE), Max Likelihood Sequence estimation (MLSE))

- **Treatment of received symbols**
  - Symbol by Symbol (Linear, DFE)
  - Sequence estimator (MLSE)

- **Time Varying Characteristics**
  - Adaptive (Performs tracking) (DFE, Modified versions of Linear Equalizers)
 - Non Adaptive (very good when channel is static; does not follow previous acquisition)

Equalization algorithms for Millimeter wave Communication Systems

AGENDA

- Millimeter wave Communication and 5G

- 802.11ad – Standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

Linear Equalizer

- Tries to invert H(f) which is the channel response

- Cancels ISI at the cost of enhancing noise and yet provide a tradeoff between noise enhancement and ISI removal (MMSE)

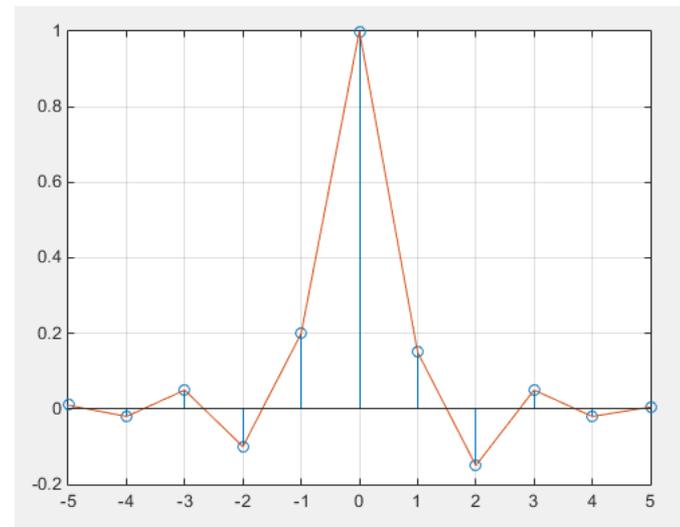- Equalizer implemented as FIR filter
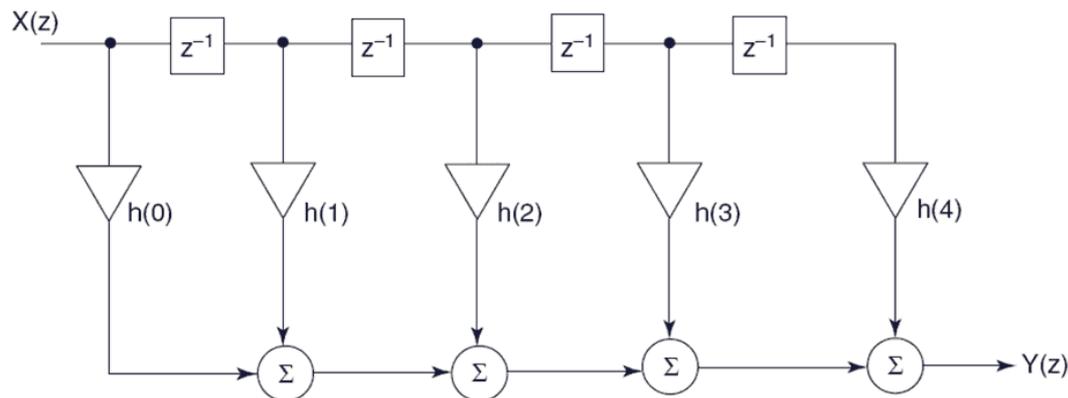
Zero Forcing equalizer

EXAMPLE

- An example of ZFE with 5 taps

- h(n) = [0.01 -0.02 0.05 -0.1 0.2 1 0.15 -0.15 0.05 -0.02 0.005]

- H^{-1} matrix -> Center column heq(n)


```
 1.0774    -0.2682     0.1932    -0.1314     0.0806
-0.2266     1.1272    -0.2983     0.2034    -0.1314
 0.2326    -0.2737     1.1517    -0.2983     0.1932
-0.1405     0.2516    -0.2737     1.1272    -0.2682
 0.0888    -0.1405     0.2326    -0.2266     1.0774
```
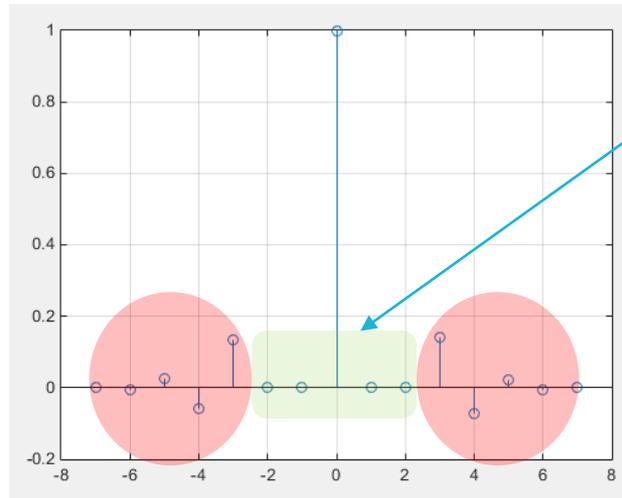
- Now if we convolve h(n) * h_{eq}(n)

Zero Forcing equalizer

EXAMPLE – IMPACT AFTER EQUALIZATION

- Now if we convolve $h(n) * h_{eq}(n)$

Impact of 5 tap equalizer

Linear Equalizer

MMSE CRITERION

- MMSE gives the filter coefficients to keep a minimum mean square error between the equalizer and the desired signal
  - Requires a training sequence d(t)

- Error sequence between the output and desired signal should be statistically orthogonal

- All random process are considered WSS (wide sense stationary) and jointly WSS

- Calculates coefficients from the autocorrelation of the input sequence and the cross correlation of the input sequence with the desired sequence

Equalization algorithms for Millimeter wave Communication Systems

AGENDA

- Millimeter wave Communication and 5G

- 802.11ad – Standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

Non Linear Equalizer

DECISION FEEDBACK

- Linear equalizers not good for compensating for the appearance of spectral zeros

- First estimates ISI directly and result is subtracted from the output of the feedforward part of the equalizer

- Estimated error is used to calculate the forward filter and the feedback filter coefficients(MMSE strategy can be used)

- Drawbacks
  - When a symbol is incorrectly decoded, the error could propagate.
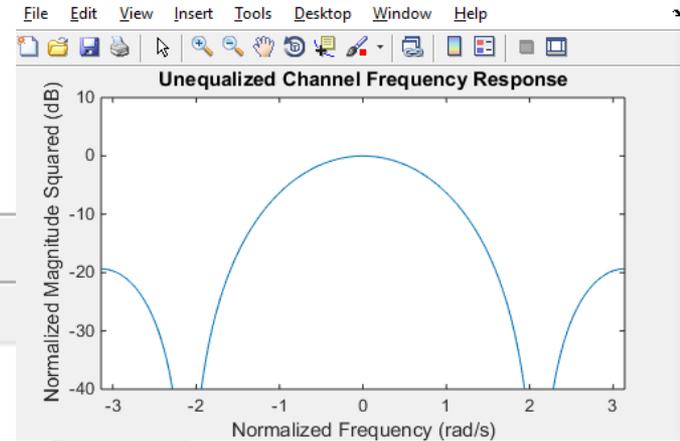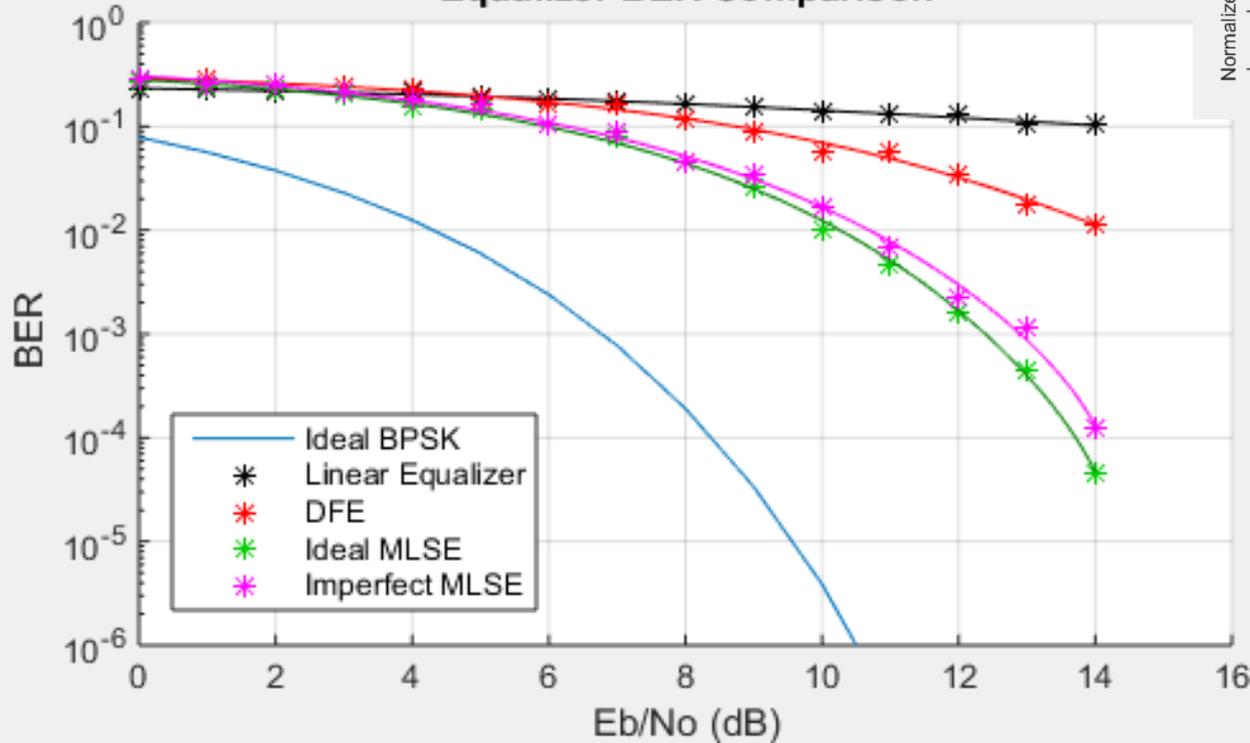
Comparison of performance

CHANNEL WITH SPECTRAL NULLS

FOR BPSK DATA

Equalization algorithms for Millimeter wave Communication Systems

- Millimeter wave Communication and 5G

- 802.11ad – Standard that operates in mm wave

- Equalization – Why is it required?

- Types of Equalizers

- Linear Equalizers

- Non Linear equalizers

- Golay Code based equalizers for 802.11 ad (and other equalizers)

GOLAY CODES
UNDERSTANDING COMPLIMENTARY GOLAY CODE

- As the simplest example we have sequences of length 2: (+1, +1) and (+1, −1). Autocorrelation results - (2, 1) and (2, −1), which add up to (4, 0).

- Sequences of length 4, we have (+1, +1, +1, −1) and (+1, +1, −1, +1). Autocorrelation results (4, 1, 0, −1) and (4, −1, 0, 1), which add up to (8, 0, 0, 0).

- Length 8 is (+1, +1, +1, −1, +1, +1, −1, +1) and (+1, +1, +1, −1, −1, −1, +1, −1). Autocorrelation- (8, −1, 0, 3, 0, 1, 0, 1) and (8, 1, 0, −3, 0, −1, 0, −1).

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

The Sequence $Ga_{128}(n)$, to be transmitted from left to right, up to down

+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	+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	-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	+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	-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	-1	-1	+1

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

The Sequence $Gb_{128}(n)$, to be transmitted from left to right, up to down

|																															
-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	-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	+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	+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	-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	-1	-1	+1

Equalizer for 802.11ad

GOLAY CODE USED FOR CHANNEL ESTIMATION
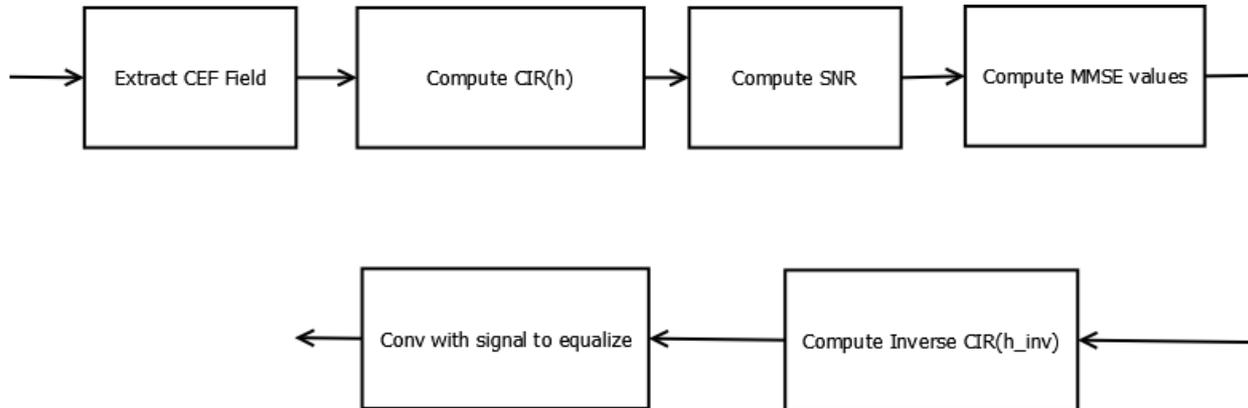
- Channel estimation is done using the property of Golay Codes

- The channel will leave its footprint on the Sum of Auto-correlated Complimentary Golay Codes which otherwise would have given a perfect impulse.

- 8 correlations in CEF which is 1152 symbols (1024+128) $[-Gb_{128} -Ga_{128} \, Gb_{128} -Ga_{128} \, -Gb_{128} \, Ga_{128} -Gb_{128} -Ga_{128} - Gb_{128}]$

802.11ad - Equalizer

MMSE METHOD
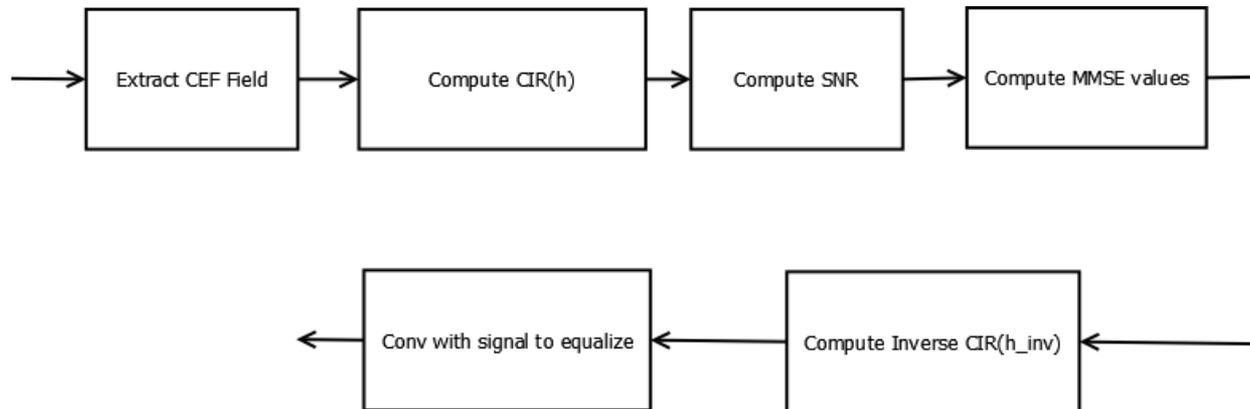
- SNR Estimation

- MMSE based equalizer coefficient calculation

- And final convolution to get Equalized signal
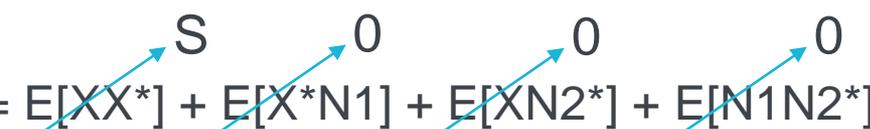
802.11ad Measurements
ESTIMATED SNR

- Signal is S=X+N, where X is the data and N is the noise.

- STF divides into two equal halves having the same X.

$$S1=X+N1 \text{ and } S2=X+N2.$$

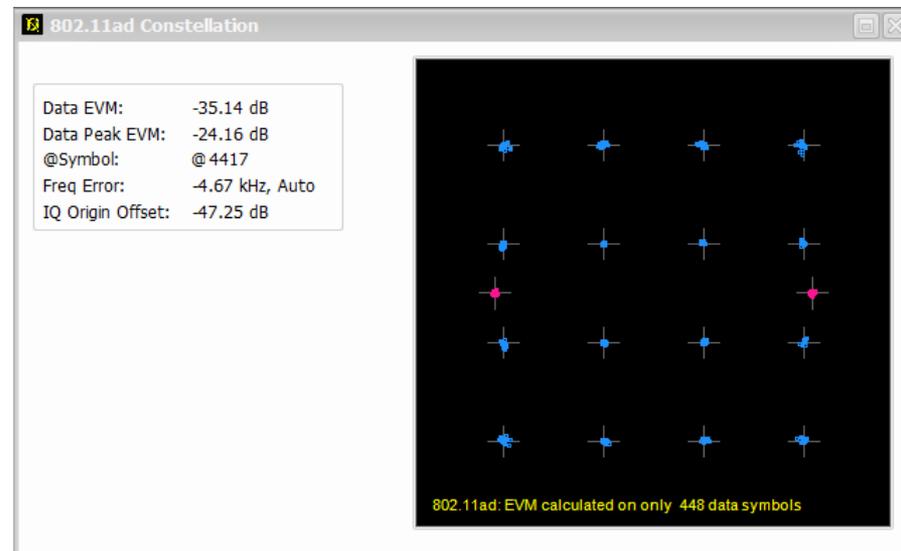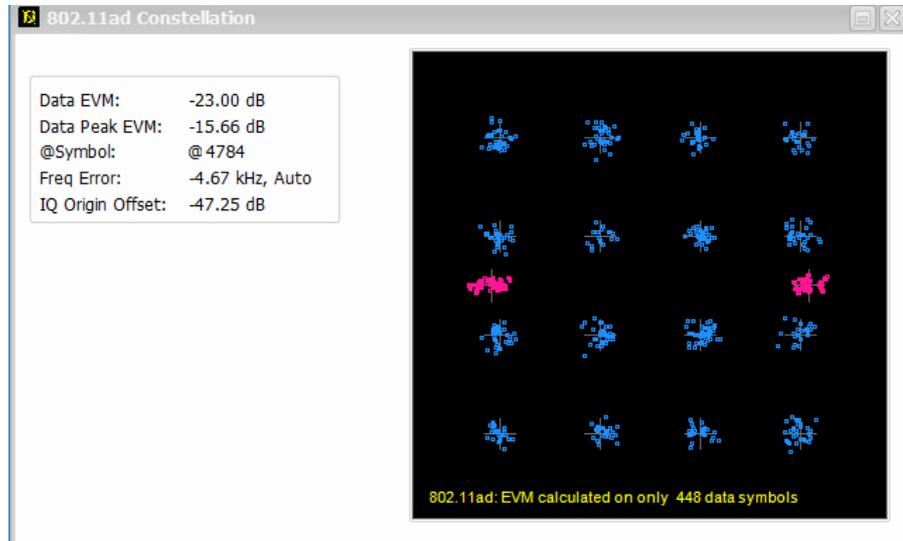- $E[S1S1^*]= E[\ (X+N1)\ (X+N1)^*\ ] = E[XX^*] + E[X^*N1] + E[XN1^*] + E[N1N1^*]$

  (labels above terms: S, 0, 0, N)

- $E[S1S2^*] = E[\ (X+N1)\ (X+N2)^*\ ] = E[XX^*] + E[X^*N1] + E[XN2^*] + E[N1N2^*]$

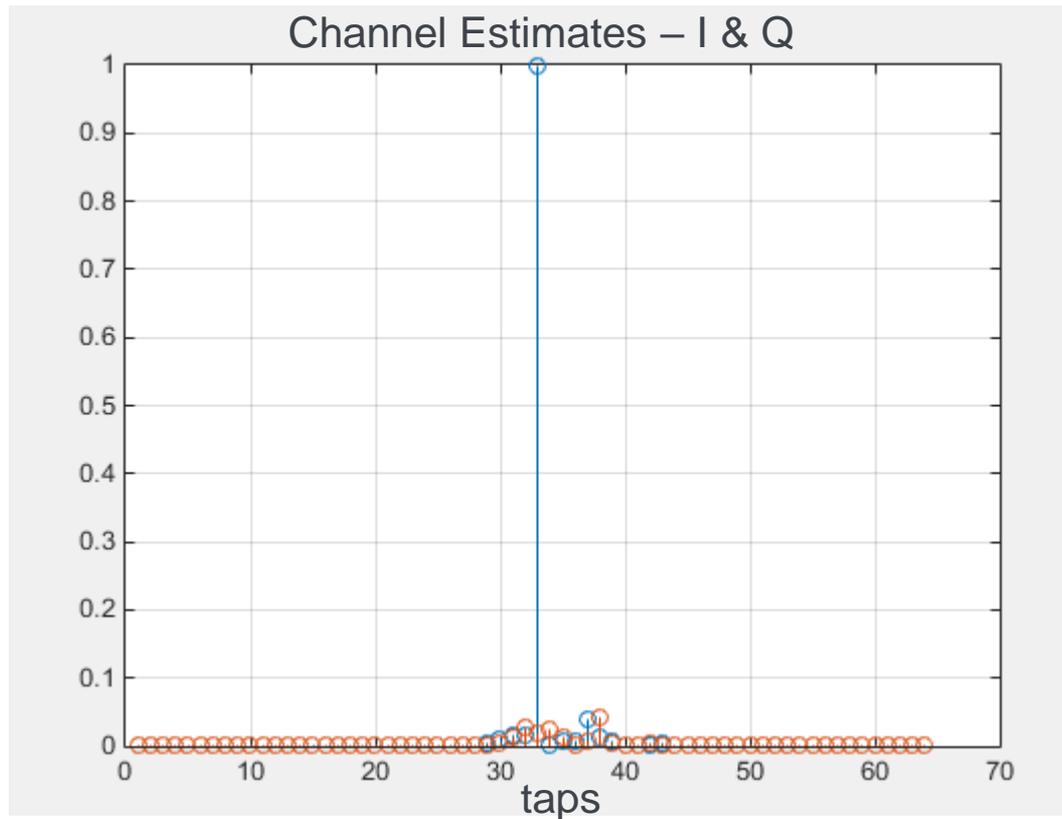 (labels above terms: S, 0, 0, 0)

$$SNR = S/N$$

MMSE based Linear Equalizer
SAMPLE RESULT

# MMSE based Linear Equalizer

CHANNEL RESPONSE

802.11ad - Equalizer

TRAINING EQUALIZER

- Decision Directed, Feed forward type

- FIR equalizing filter to correct only linear distortion

- Modes: Training and Hold

- Adjustable tap spacing (1, 2, 4, 8 points/symbol)

- Adjustable tap length

- Adjustable convergence speed (or update rate)

- Pre-defined impulse position

802.11ad - Equalizer
TRAINING EQUALIZER
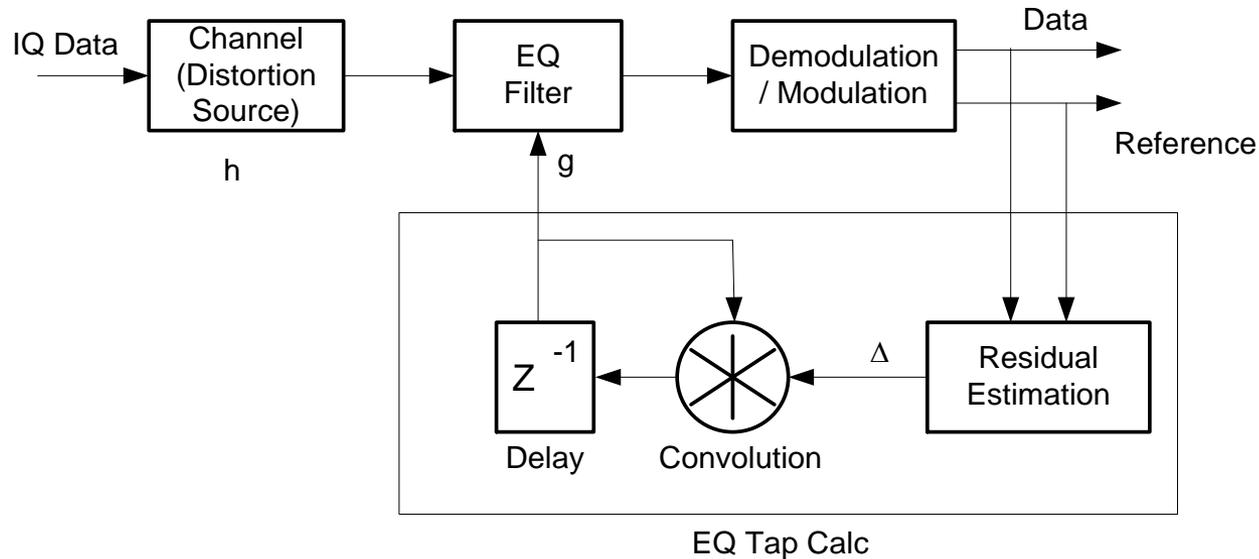
CONCLUSION

TAKE - AWAY

- A quick look at mm wave communication and 802.11 ad standard

- A peek at need of Equalization and types of Equalizer (with comparative performance)

- Understanding Golay Codes used in 802.11 ad

- An idea about MMSE based Equalizer and a Decision directed equalizer for 802.11 ad

References

- http://www.rcrwireless.com/20160815/fundamentals/mmwave-5g-tag31-tag99 - What is mm wave and how does it fit into 5G? – Phillip Tracy

- Equalization techniques – Franciso J Escribano

- Mathworks - Equalization