Satellite Communications: Part 4
Signal Distortions & Errors and their Relation to Communication Channel Specifications

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Satellite Communications: Part 4
Signal Distortions & Errors
and their Relation to Communication
Channel Specifications

- Communications Problem
- Signals Formats & Distortions
- Signal Errors
- Phase Noise
- Group Delay Distortion
- Amplitude Distortion
- Combined Signal Distortions
- Adjacent Channel Interference
- Time Domain Effects
- Summary -

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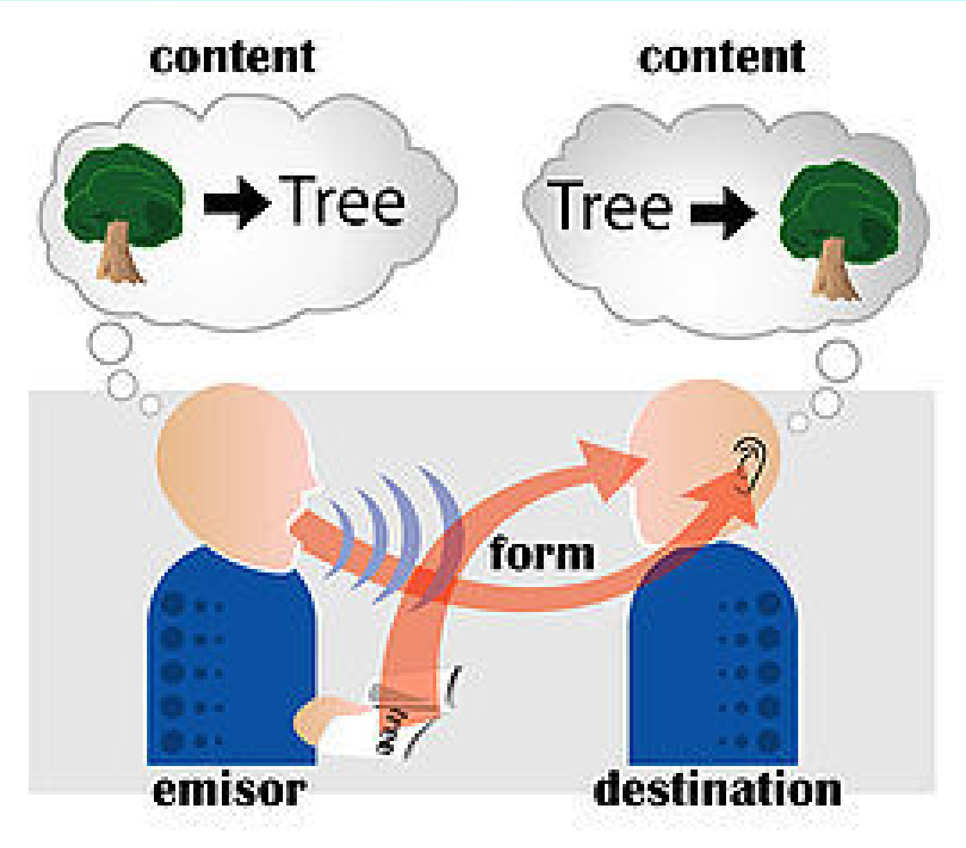
Communications Problem

- "Communication is the process of transfer of information from a sender to a receiver who understands the message from the sender." -

Process

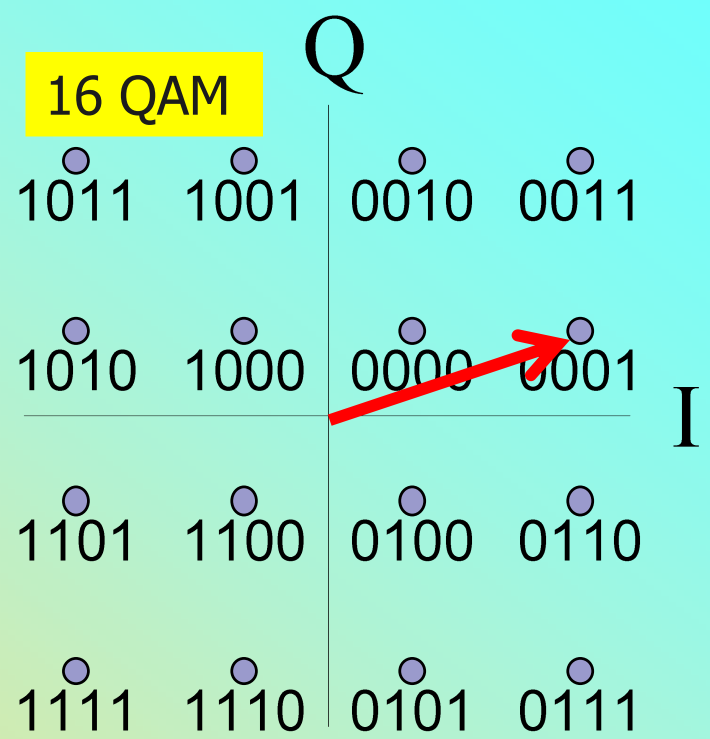
- Transmit an idea
- Receiver the signal
- Receive the idea



- Each step is a point of error
- Added medium or device will increase the likelihood of errors
- Specifications are designed to bring the error to acceptable level
  -

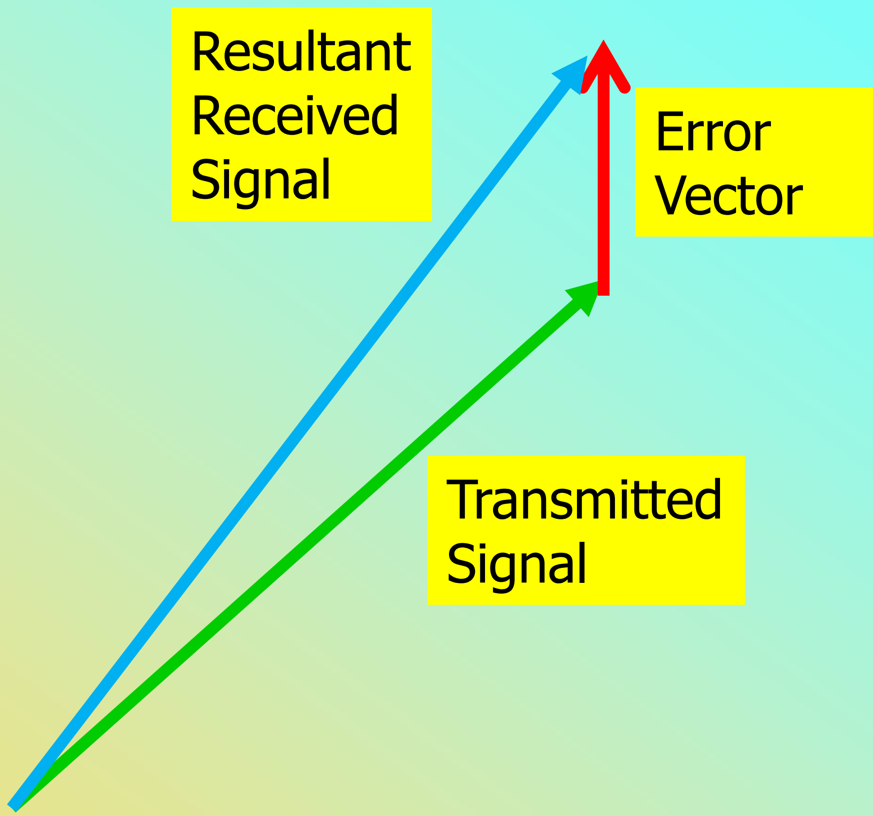
Vectors Modulation

- Digital Communications has almost universally replaced Analog Communications
  - Analog required higher S/N than digital
- Digital Transmission Efficiency
  - Maximized using amplitude and phase information - Vector
  - Vector location defines a symbol
- A Symbol is a collection of Bits (1's & 0's) -



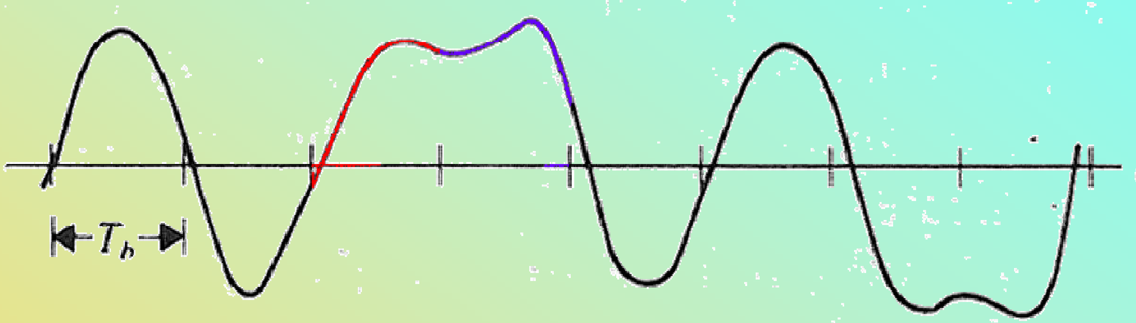
Error Vectors

- Vector Errors (EV) distort the original signal
- EVM, (Error Vector Measurements) common term for defining vector distortion
- Can cause the resultant vector to point to the wrong symbol -

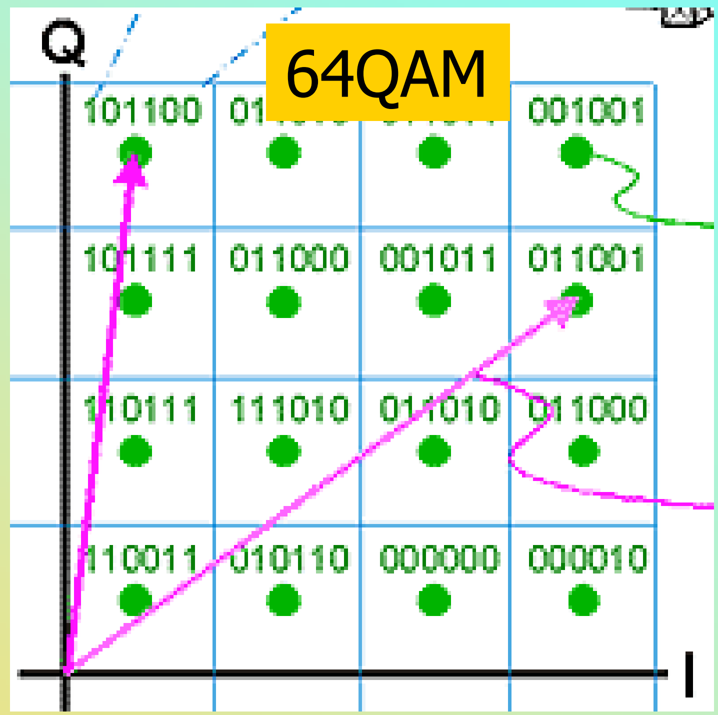


Decoded Vectors

- Vectors are decoded into bits in the time domain



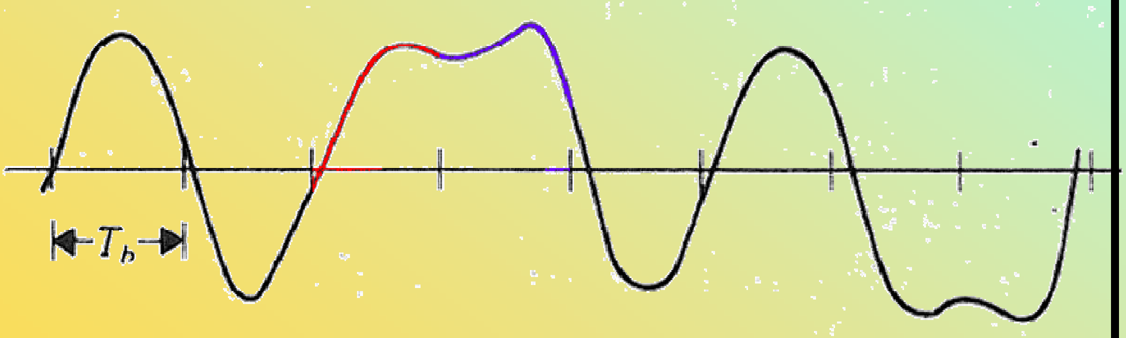
64 QAM - One Symbol location defines 6 bits
1 0 1 101

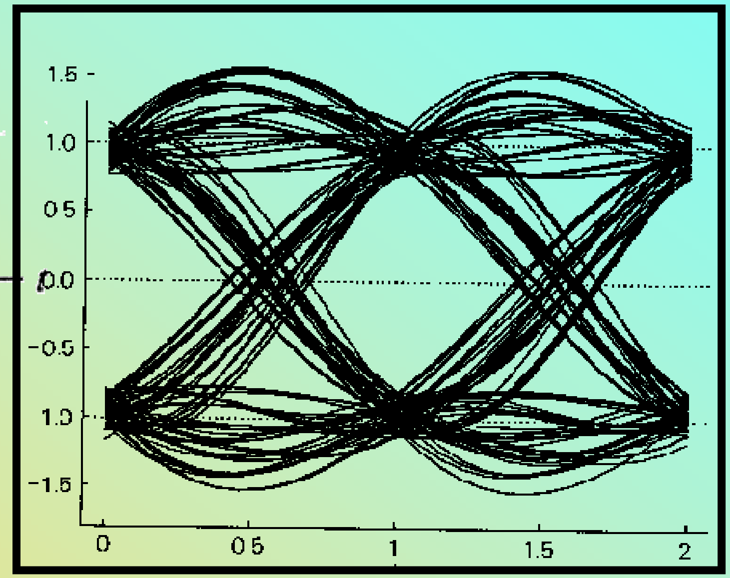


- Bit rate is 6 times symbol rate (64QAM)
- Base band is 6 times the IF bandwidth -

Time Domain Measurements

- Time domain symbols are superimposed on each other
- Time domain errors are identified using “Eye Diagrams” -





Eye Diagram

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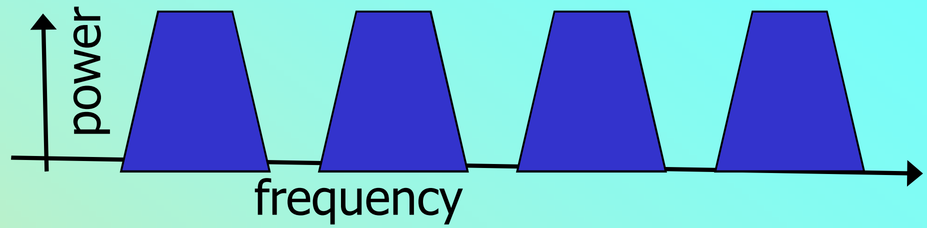
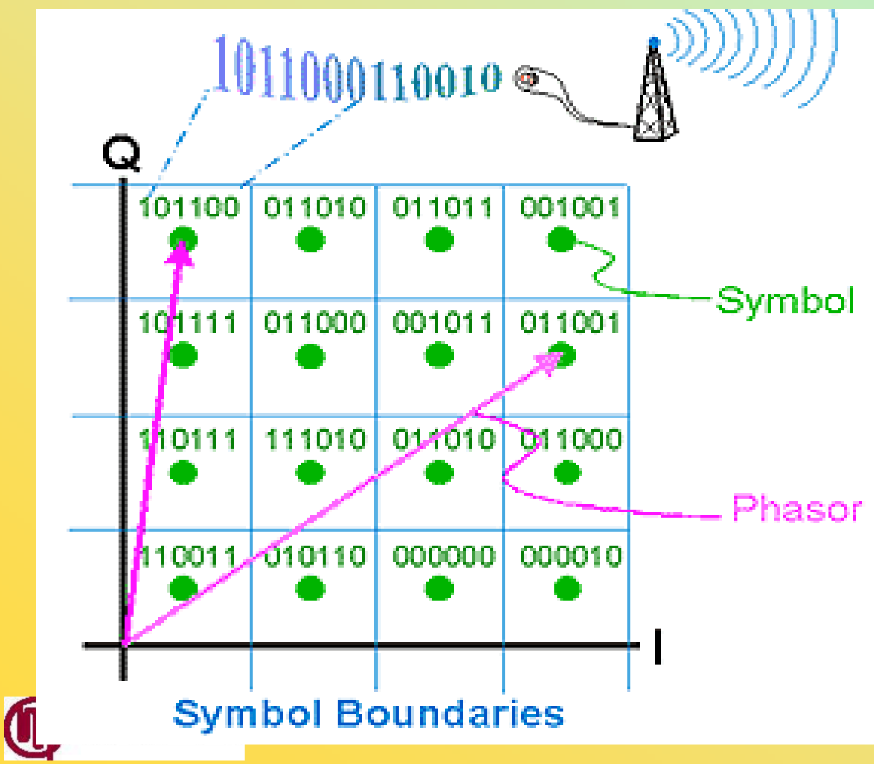
Equipment Specifications
Three Areas of Concern

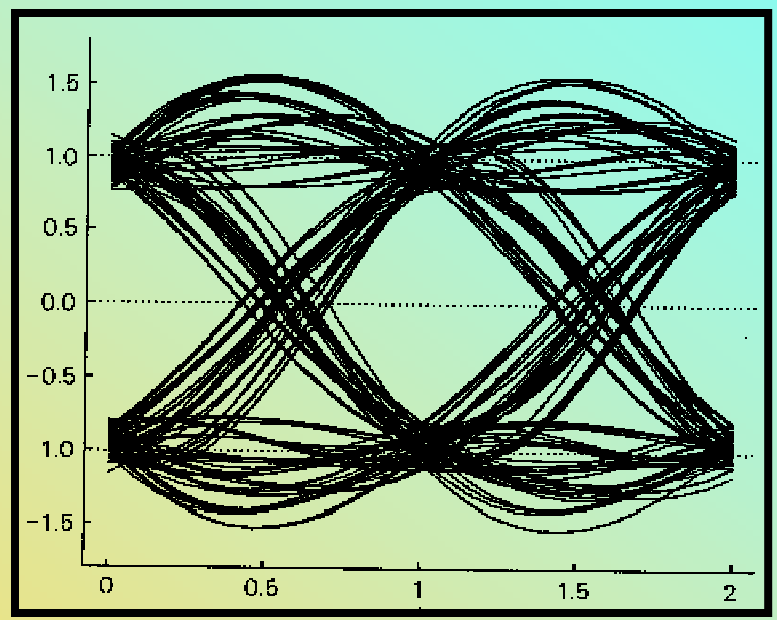
1. Don't interfere with your neighbor – Frequency Domain



2. Recover the correct symbol – Vector Measurements

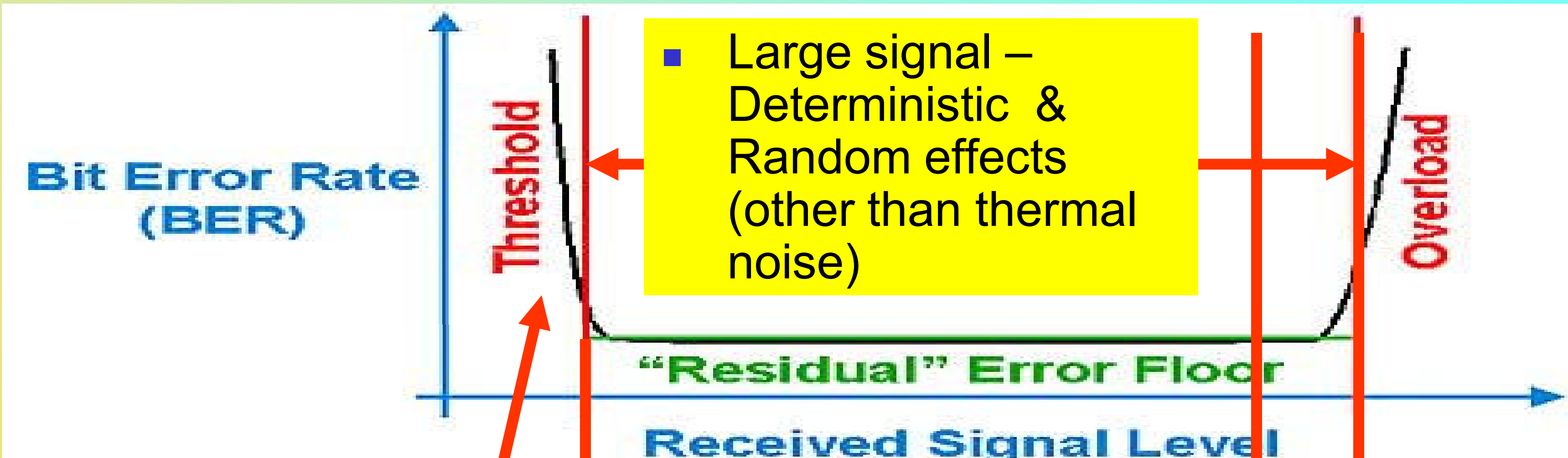


3. Recovery the bit information – Time Domain -



Signals Formats & Distortions

Signal Areas of Concern



- Large signal – Deterministic & Random effects (other than thermal noise)

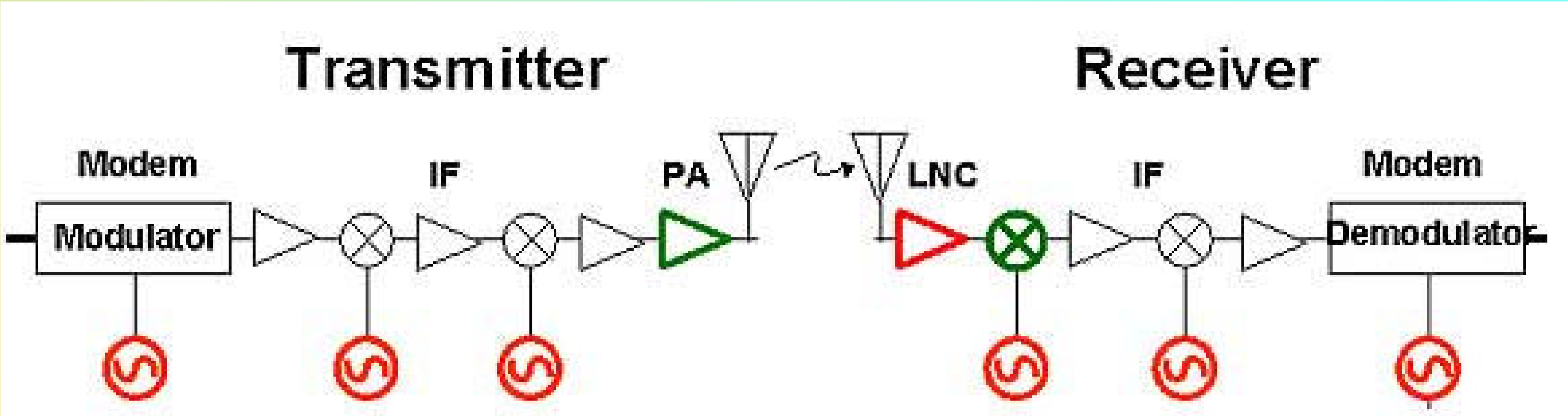
- Small Signal - Thermal noise

Average Power Operating Region

Peak Power Distortion

- Linear operating region must allow for the signal peaks (AM) -

Primary Noise & Distortion Elements



Noise Sources
- Local Oscillators
- Low Noise Amplifier

Distortion Sources
- Power Amplifier
- Filters
- Mixers, etc. -

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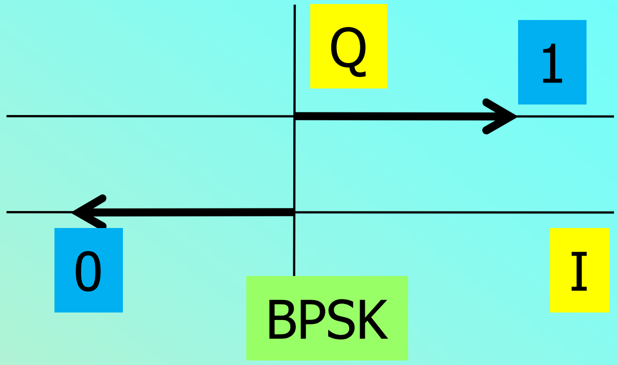
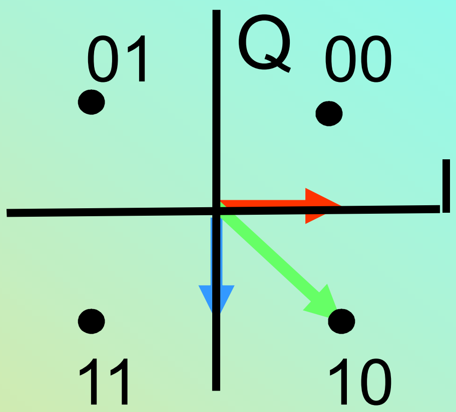
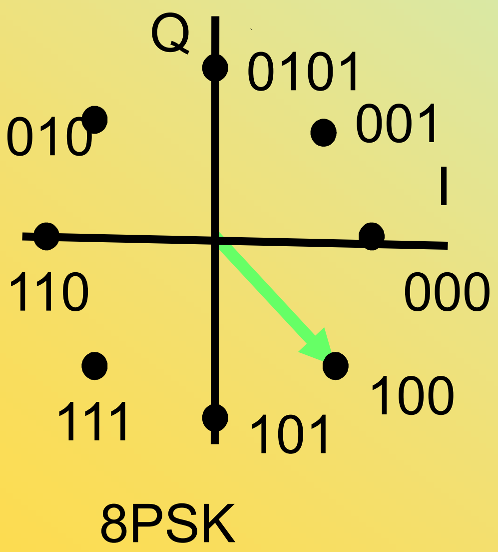
Constant Amplitude (CW) Transmission Formats

- Binary Phase-Shift Keying BPSK (2-QAM)
  - *Used for low speed communications*
- QPSK & 8PSK are used for higher speed communications



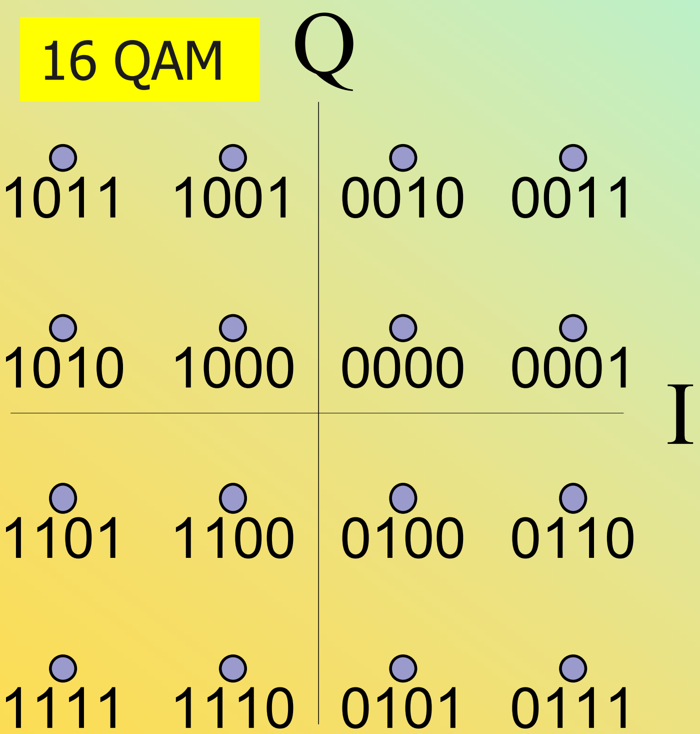


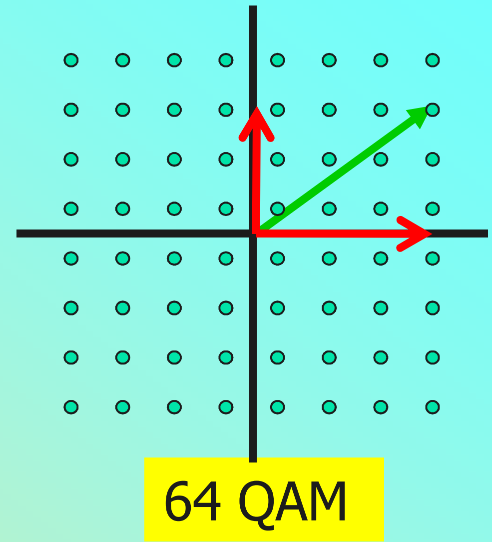


- Note: Vector phase is the only information needed to recover data -

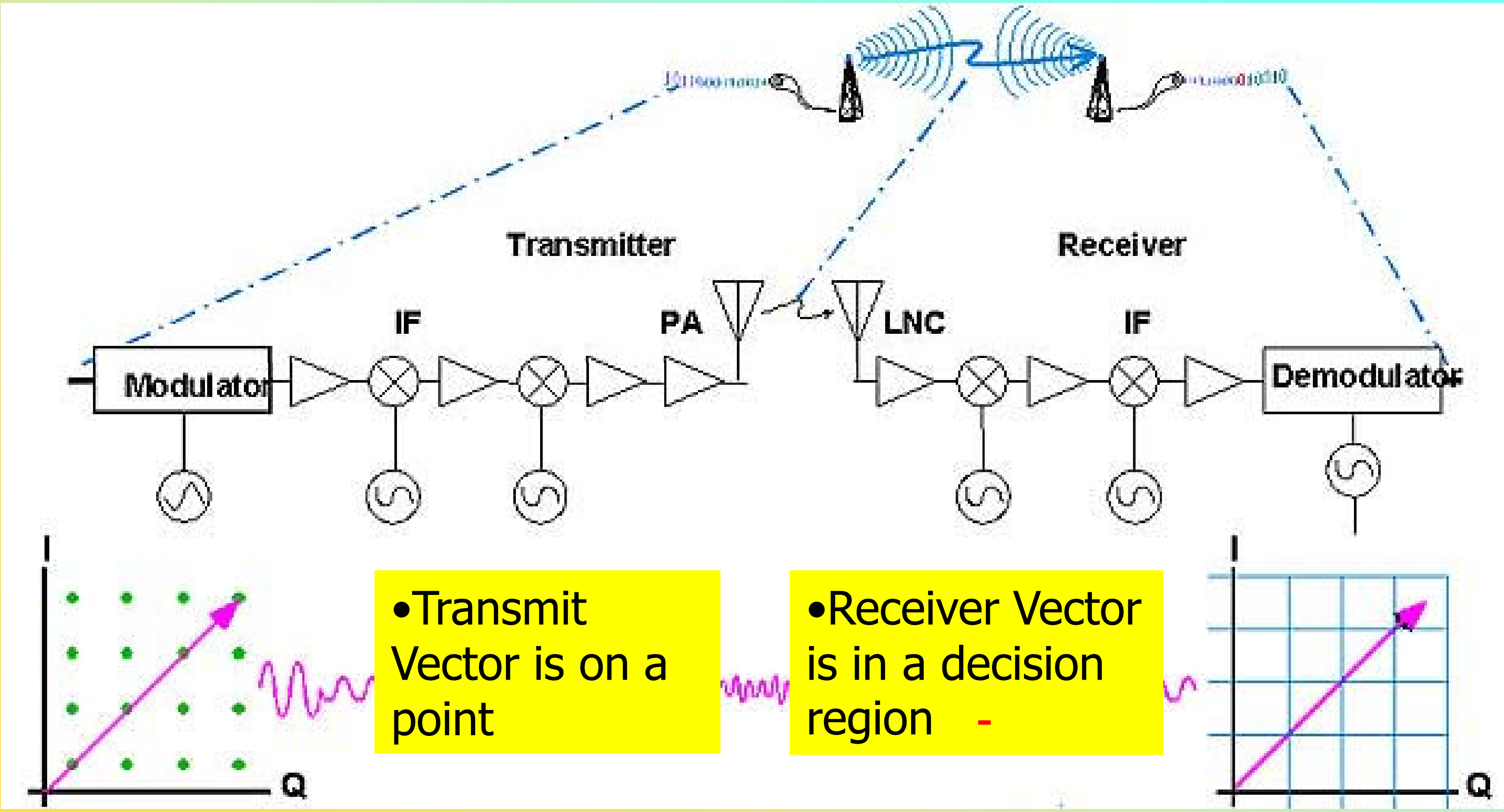
Quadrature Amplitude Modulation (QAM)

- Signal amplitude and phase must be resolved
- Used for much higher speed communication where bandwidth is severely limited





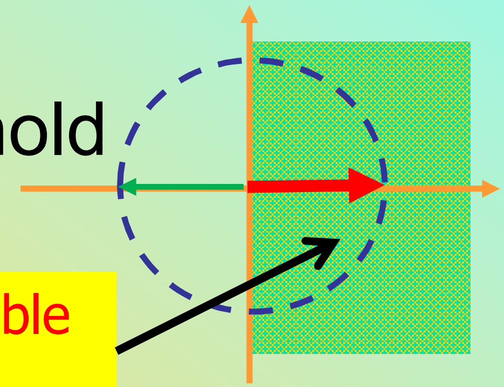
Decision Regions - System Diagram



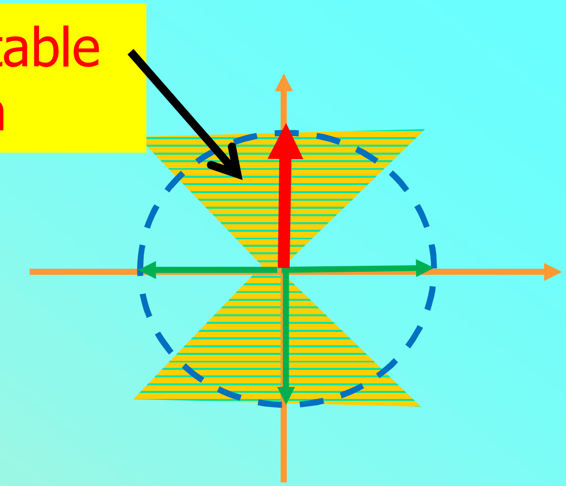
- Transmit Vector is on a point
- Receiver Vector is in a decision region -

CW Decision Regions

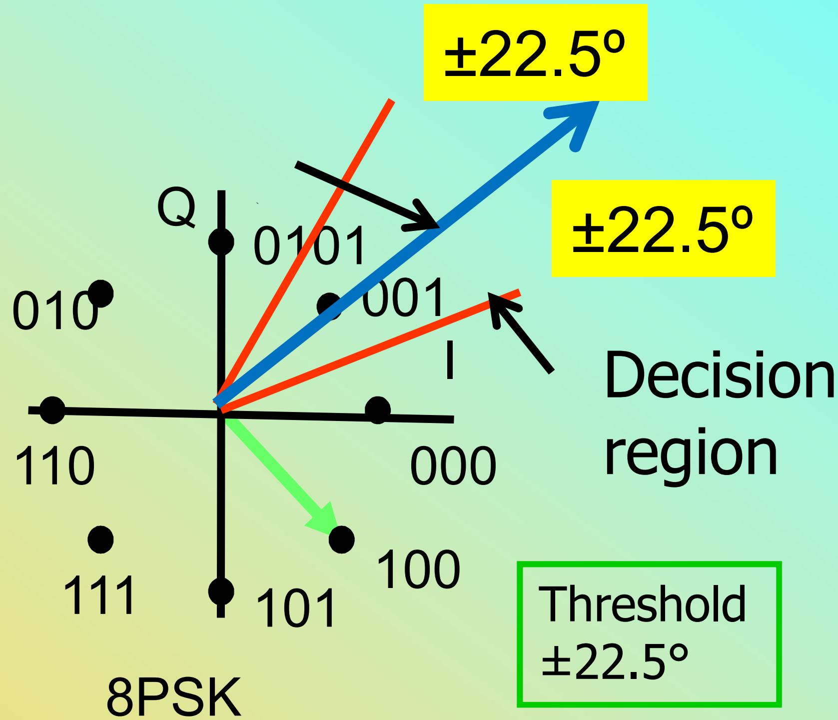
- BPSK
- Threshold ±90º



- QPSK
- Threshold ±45º

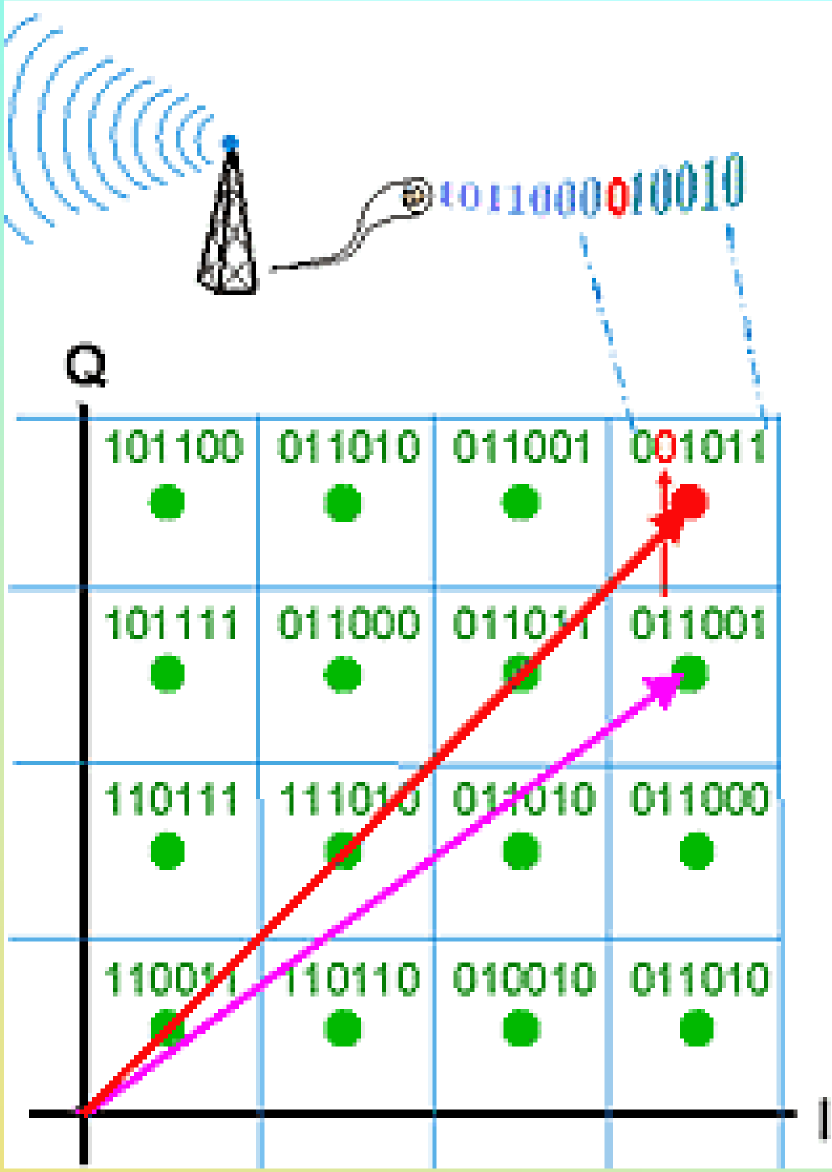


- **Vector Phase Only**
- Phase Thresholds
  - BPSK: ±90º
  - QPSK: ±45º
  - 8PSK: ±22.5º



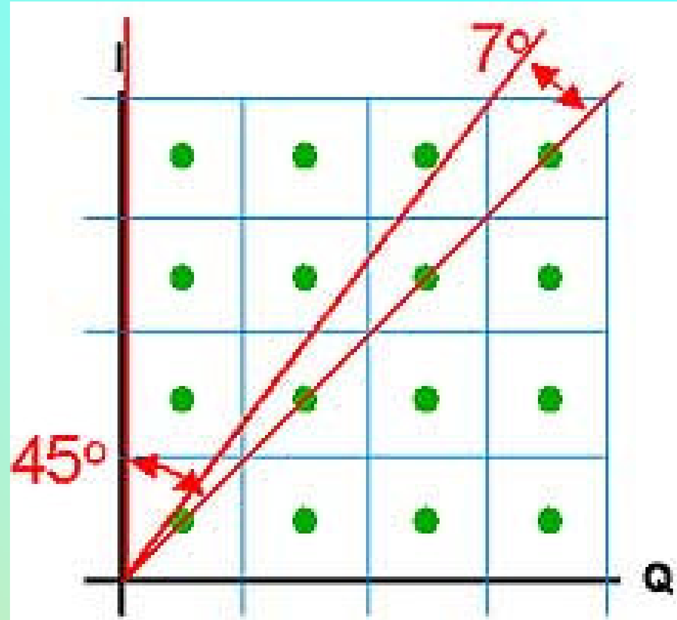
QAM Decision Region

- ❑ Lines between the constellation points are the threshold levels
- ❑ Signals residing in the square are assume to reside at the discrete vector location.
- ❑Note vector outside the square - Wrong Code
- ❑Codes are set such that all surrounding codes have a 1 bit error -



QAM Geometric Effects

- ❑ Maximum angle error is dependent on Symbol Location
- ❑ Outer Symbols Tolerate the least angle error
- ❑ Allowable Error Window is smaller for More Complex Modulations -



Modulation	Error
•2QAM	90.0°
•4QAM	45.0°
•16QAM	16.9°
•32AM	10.9°
•64QAM	7.7°
•128QAM	5.1°

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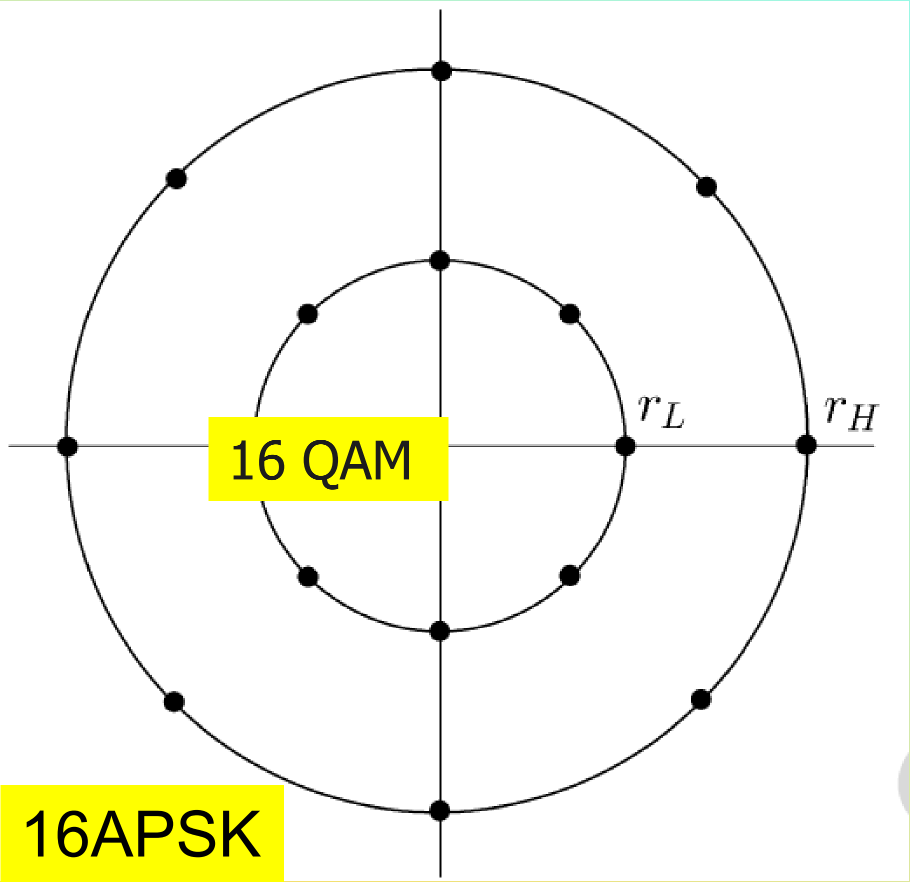
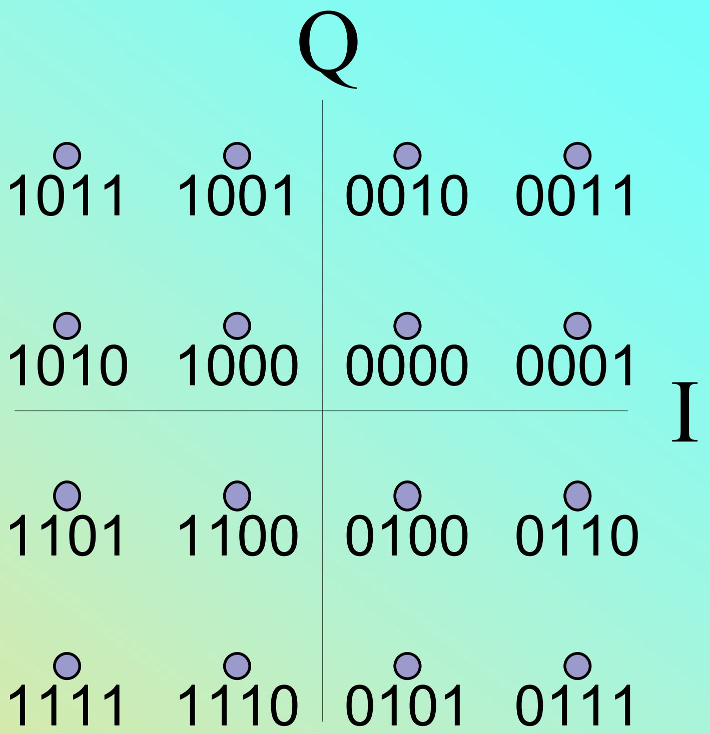
16APSK & 16 QAM





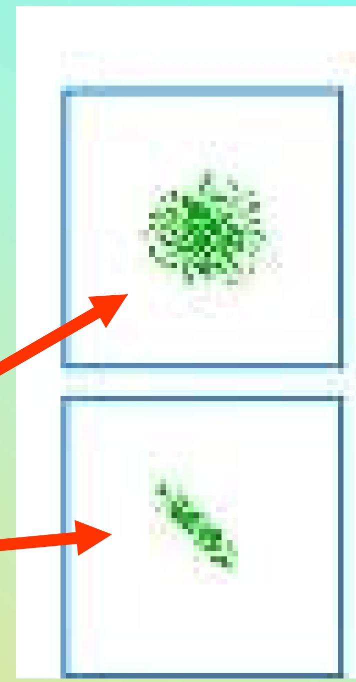
- 16 APSK Smaller peak to average ratio than 16QAM
- 16APSK more immune to Phase Noise than 16QAM ~

•16QAM ± 16.9°
•16APSK ± 22.5°

Signal Errors

Random Errors

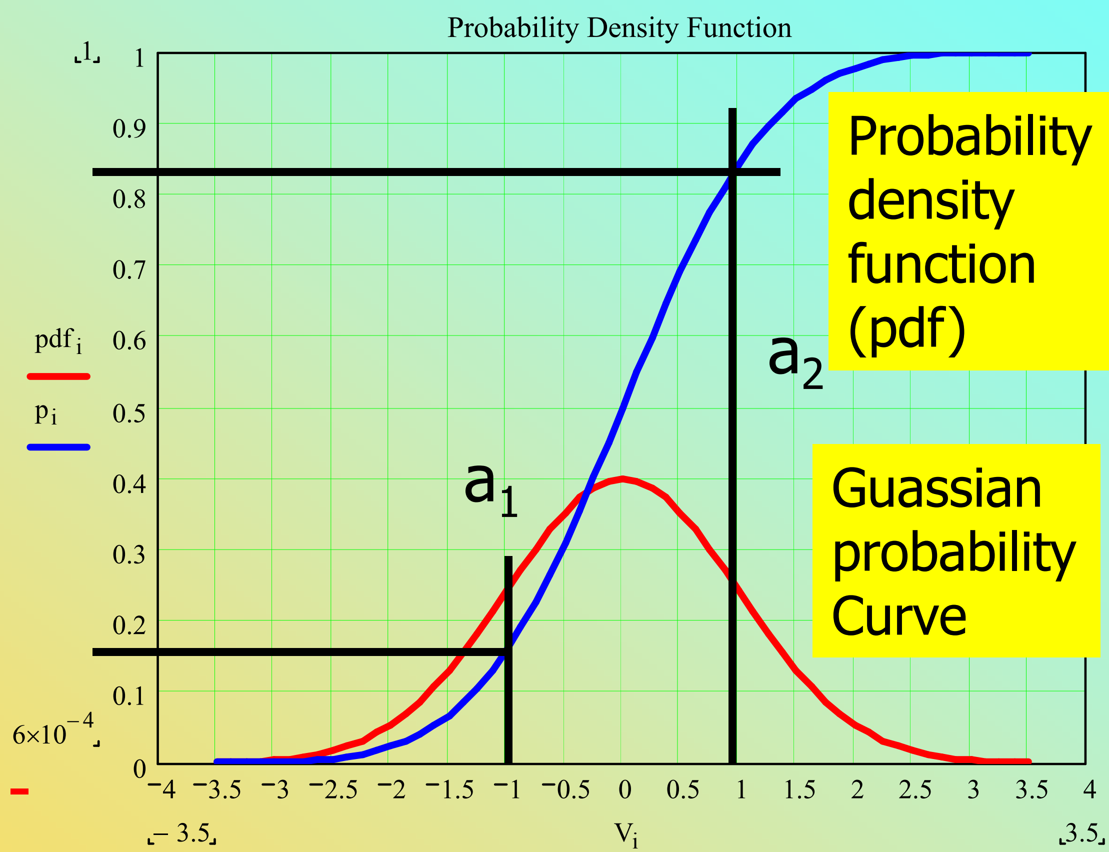
- Highly uncertain
- Characterized by a probability distribution
- Characterized by their standard deviation
- Errors are statistical
- Function of the number of standard deviations to the threshold (Multiples of σ)
- Thermal Noise – Low Noise Amplifier
- Phase Noise-Local Oscillators -



Standard Deviation & RMS Noise

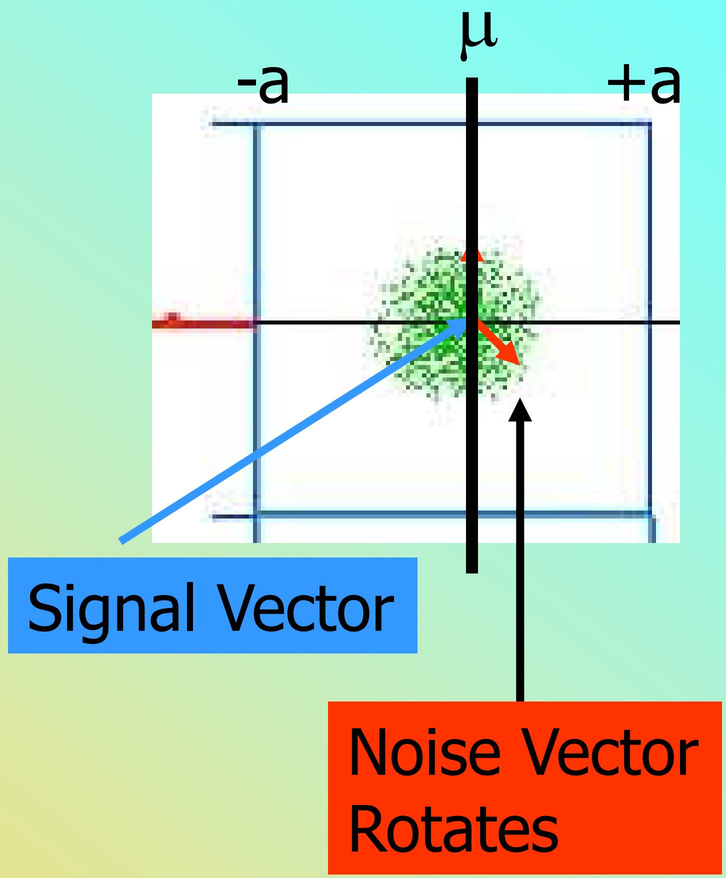
- pdf is area under Guassian curve from -□to a_1
- $P(a_1<-1\sigma)=.159$
- $P(a_2>1\sigma)=1-.841=.159$
- $P(V<-1\sigma \& V>+1\sigma)=.682$
- $P(>|1\sigma|) = .318$
- $P(>|2\sigma|) = .046$
- $P(>|3\sigma|) = 2.7x10^{-3}$
- $P(>|4\sigma|) = 6.3x10^{-5}$
- $P(>|5\sigma|) = 5.7x10^{-7}$

❑μ is Average (Mean)
❑σ=standard deviation: Relates to the function spreading



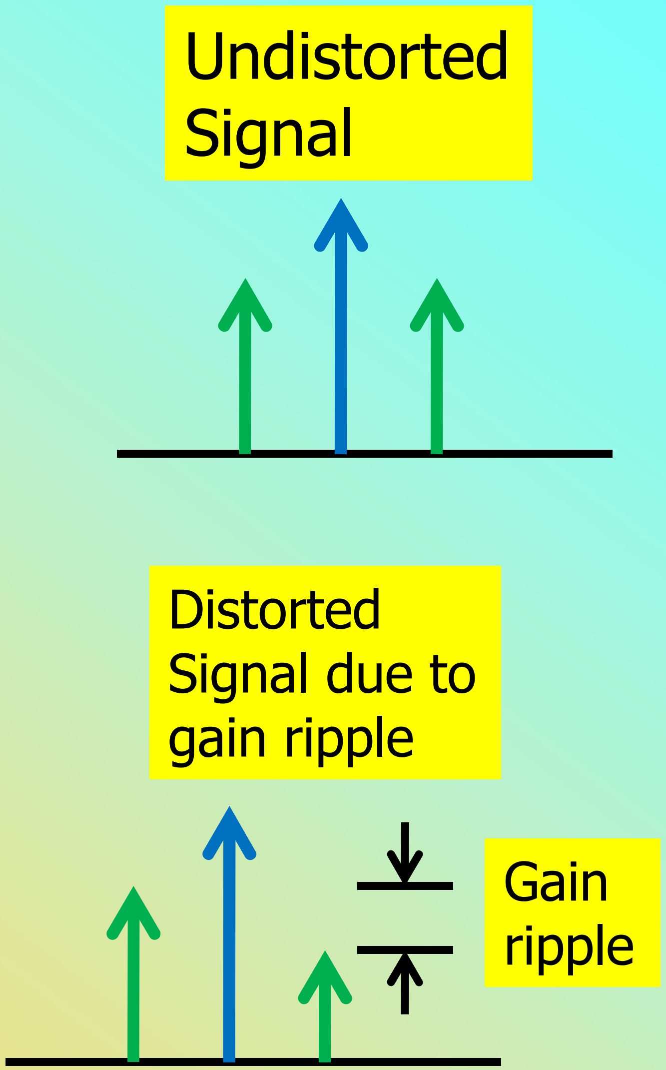
Standard Deviation & RMS Noise

- $\sigma=1$ ← → RMS Noise
- μ is the ideal signal point
- Error Probability = number of σ from μ to "a" (>0)
- Example
  - P(a=|4σ|) Bit Error = 6.3×10^{-5} -



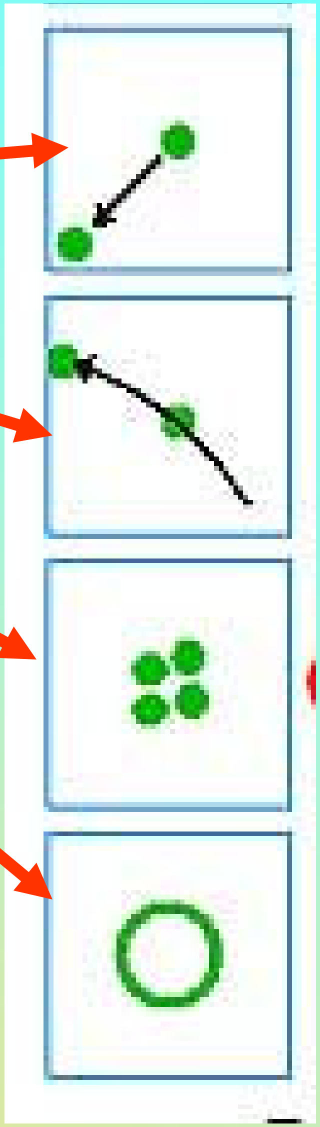
Deterministic Errors

- Deterministic – know everything with complete certainty
- Examples: Filter ripple
  - Causes Side Band amplitude errors
  - May change with frequency & Temperature
  - Characteristics are completely known
- Knowing the signal spectrum transmitted
  - Possible to correct the distortion



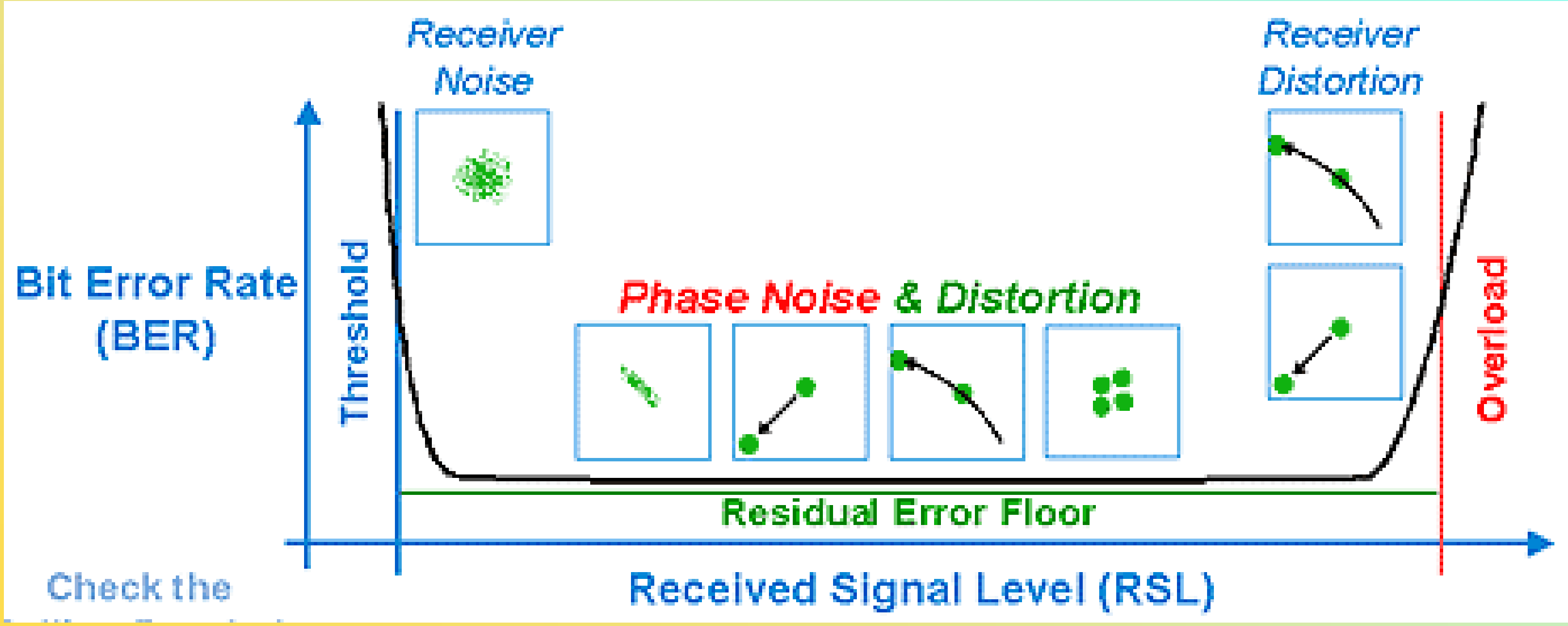
Examples of Deterministic Errors

- ❑Deterministic Effects:
  - ❑ Predictable & Correctable
- ❑AM/AM Distortion-Power Amplifier, ADC Quantization
- ❑AM/PM Distortion-Power Amplifier
- ❑Group Delay Distortion-Filters
- ❑Interference-Spurious, Power Supply, 3rd Order Interference
  - At set-up & periodically thereafter Learning codes are sent
  - Distortion is compensated the improve BER



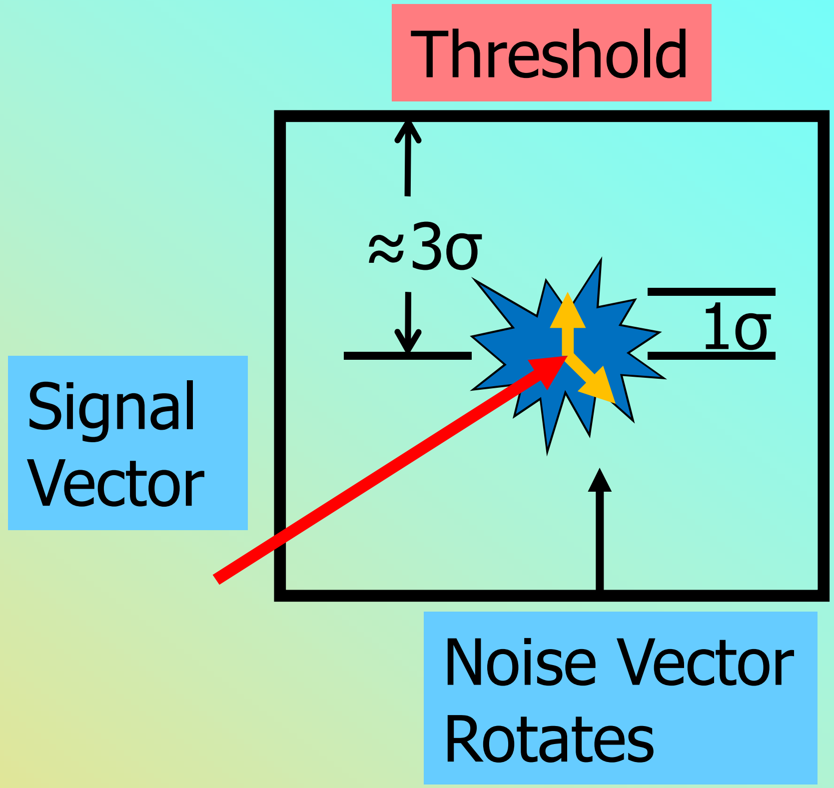
Random & Deterministic Effects

- Deterministic effects add directly: A + B = C
- Probabilistic (Noise) effects add RMS: $SQRT(A^2 + B^2) = C$
  - A, B, & C are standard deviations
- Large number of deterministic effects add as noise
  - Gaussian Theorem -



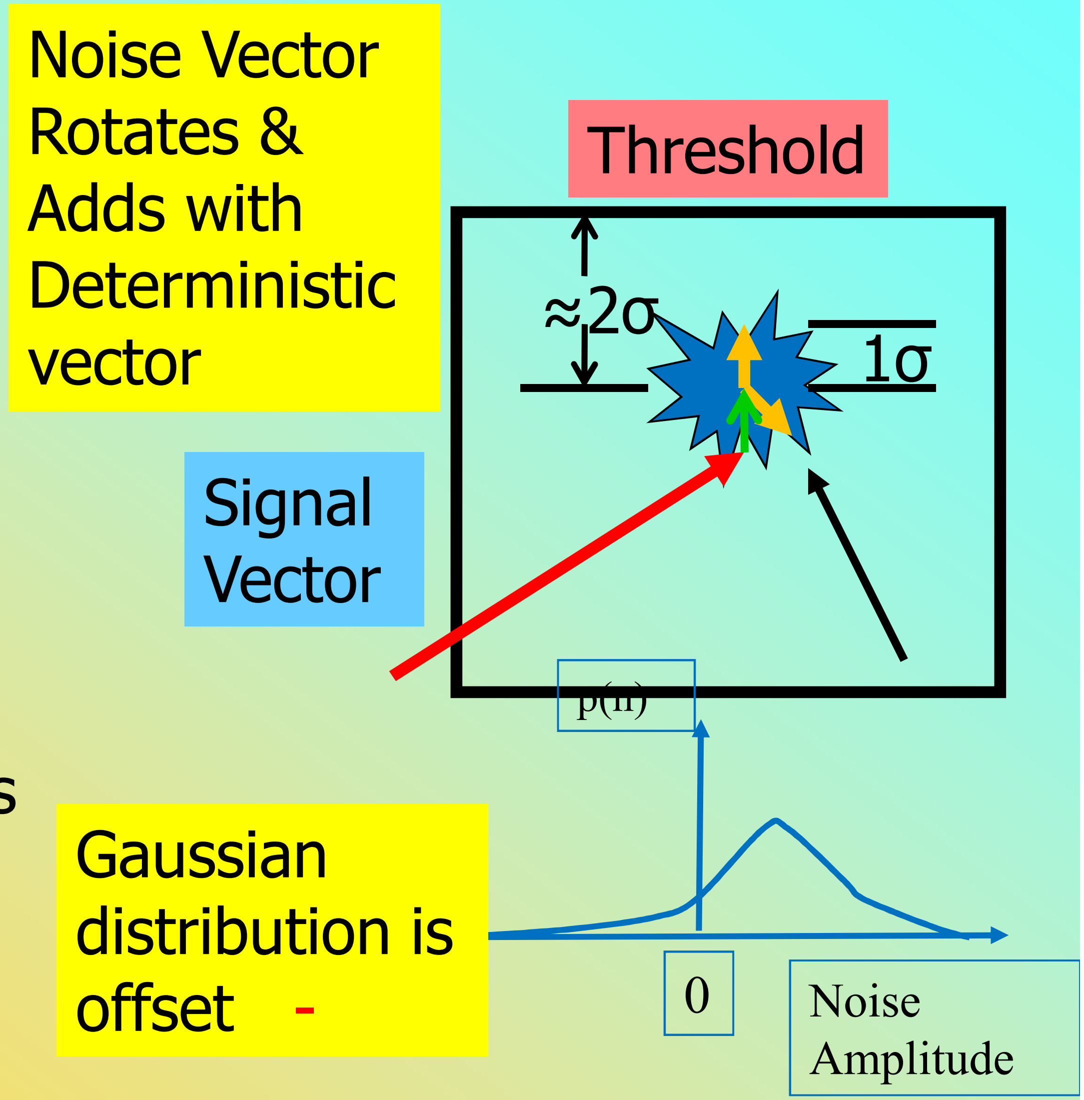
Random Noise in a Boundary

- ❑ Bit Error: Received Vector Falls Outside Boundary
- ❑ Signal Vector (Red)
- ❑ Random Noise (Yellow)
    - ❑ Rotates around signal vector (360°)
    - ❑ Gaussian Amplitude Distribution
- ❑BER is related to the number of σ's to the threshold -



Random Noise + Deterministic Errors in a Boundary

- ❑ Bit Error: Received Vector Falls Outside Boundary
- ❑ Signal Vector (Red)
- ❑ Random Noise (Yellow)
  - ❑ Rotates around signal vector (360°)
- ❑ Deterministic vector (Green) adds an error to the signal vector
- ❑ BER is the number of σ's to the threshold
- ❑ Number of σ's went from 3 to 2



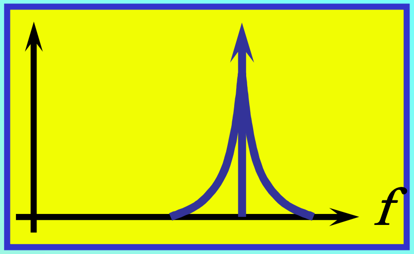
Phase Noise

Oscillator Stability

- Long Term Frequency Stability
  - Time frame: Typically hours to years
  - Temperature variations are long term
  - Data: ΔF / Fo Parts Per Million (PPM)
- Short Term Frequency Stability
  - Residual FM – ΔF Large: Change in frequency ΔF is much greater than the rate of frequency change, fm ($\Delta F/fm = \beta >> 1$)
  - Allen Variance - ΔF small: Rate of change : Δt >1 Second
  - Phase Noise: ΔF small: Rate of Change: $\Delta t < 0.1$ sec.-

Phase Noise - Short Term Stability

- Measures oscillator Stability over short periods of time
  - Typically 0.1 Second to 0.1 microsecond
- Noise varies the oscillator phase/frequency
  - **Not amplitude related**
- Noise level increases close to the carrier
  - Typical offset frequencies of interest: 10Hz to 10MHz
  - Stability closer to the carrier is measured using Allen Variance
  - Noise further from the carrier is usually masked by AM thermal noise

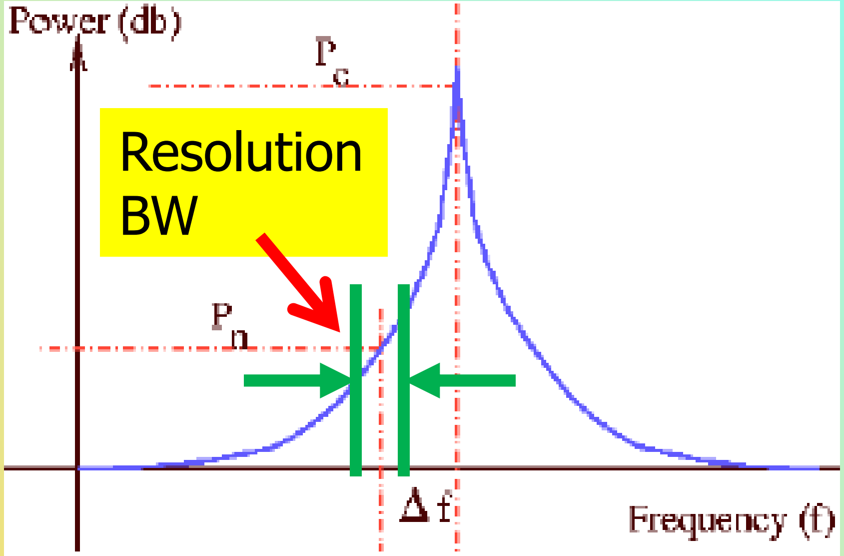


- Phase Noise cannot be eliminated or affected by filtering
- Phase & Frequency are related:
  - Frequency is the change in phase with respect to time
  - $\Delta\varphi / \Delta t \rightarrow d\varphi/dt$ as $t \rightarrow 0$ -

Phase (Frequency) Noise

- Specified and measured as a spectral density function in a 1 Hz bandwidth
- dBc/Hz at a given offset from the carrier
  - Level in dBc = 20 Log (β/2) where β is in radians
  - Modulation index (β) of noise in a 1 Hz bandwidth
- Measurement at Frequency offset from the carrier is the time interval of phase variation
  - 1 kHz offset is a 1 millisecond measurement time

➢ Measurement bandwidth or Resolution Bandwidth is the dwell time of the measurement
➢1Hz resolution bandwidth is a 1 second measurement time -



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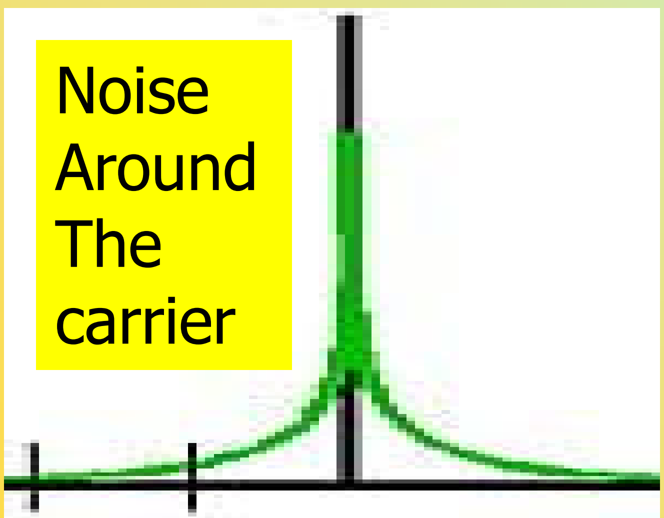
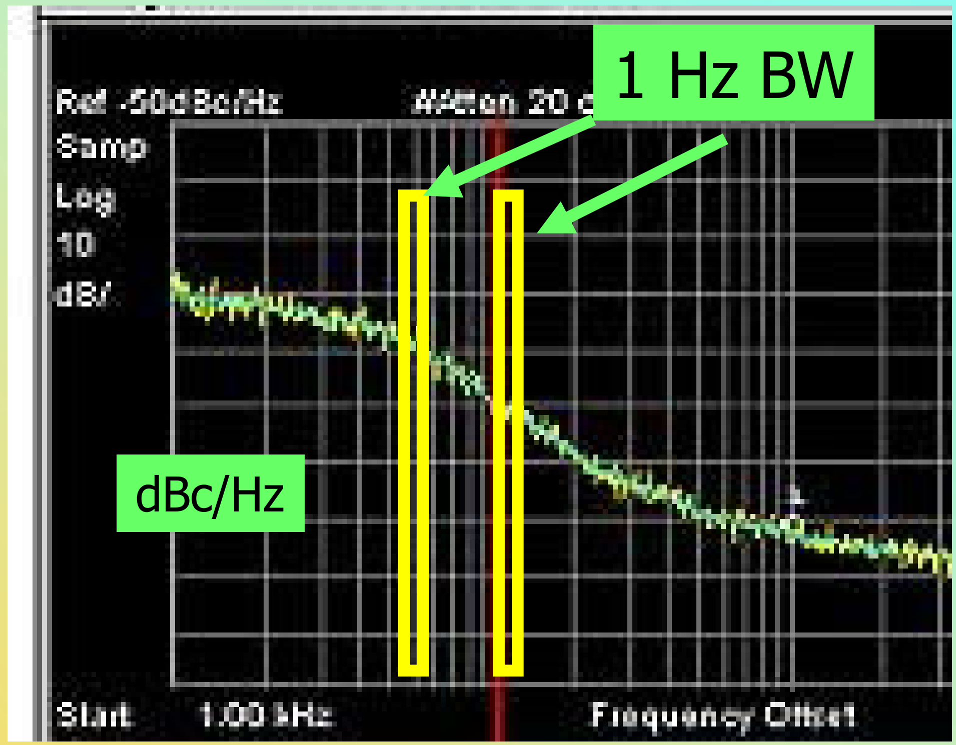
Total RMS Phase Noise

- Each 1 Hz bandwidth (dBc/Hz) is the result of narrow band modulation ($\beta \ll 1$)
- Convert SSB (dBc/Hz) to Degrees RMS ($\Delta\Phi_{RMS}$)
- Total Phase Noise (β_{Total})

-

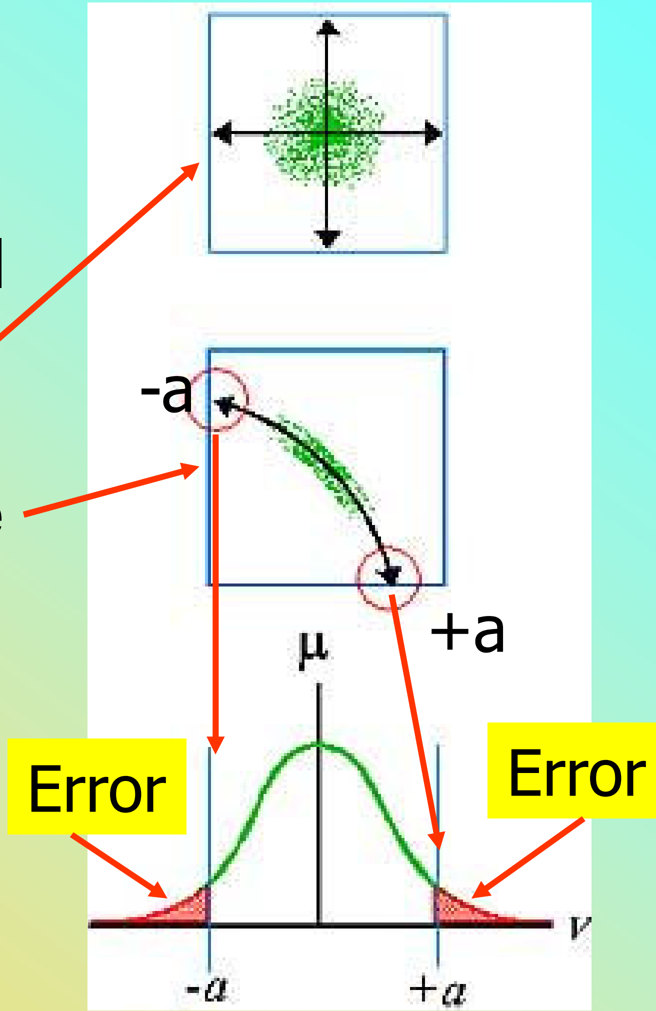
$$\beta_{Total} := \sqrt{(\beta_1)^2 + (\beta_2)^2 + (\beta_3)^2} \quad -$$





Phase Noise vs Thermal Noise

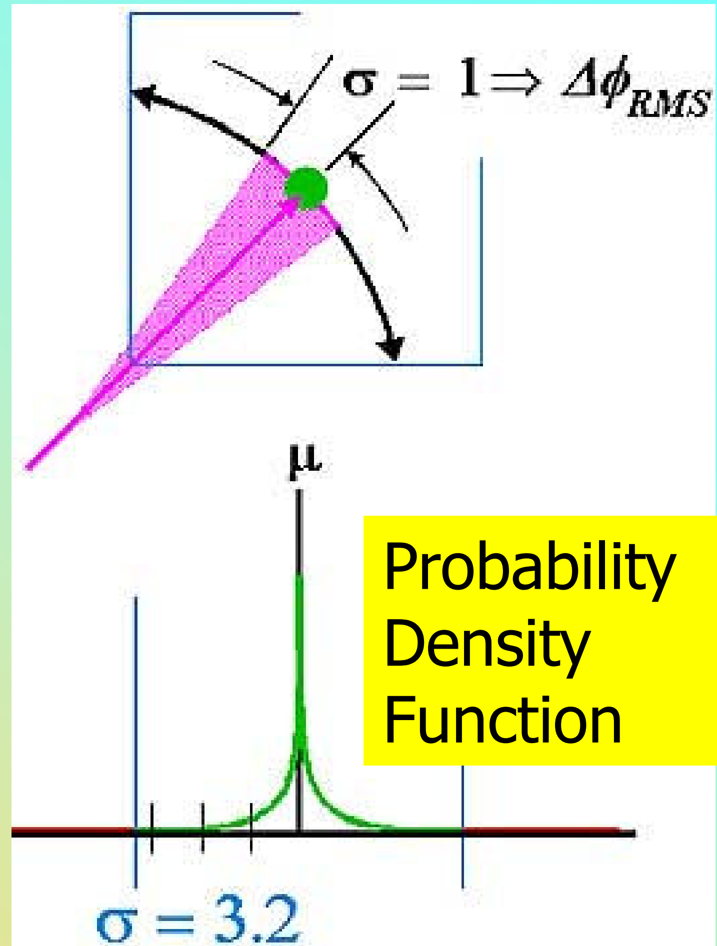
- Thermal Noise: Random in all directions
  - Relevant at Low Power
- Phase Noise: Random on the Angular Axis
  - •Independent of Signal Power
- Errors occur on Both Symbol Boundaries -



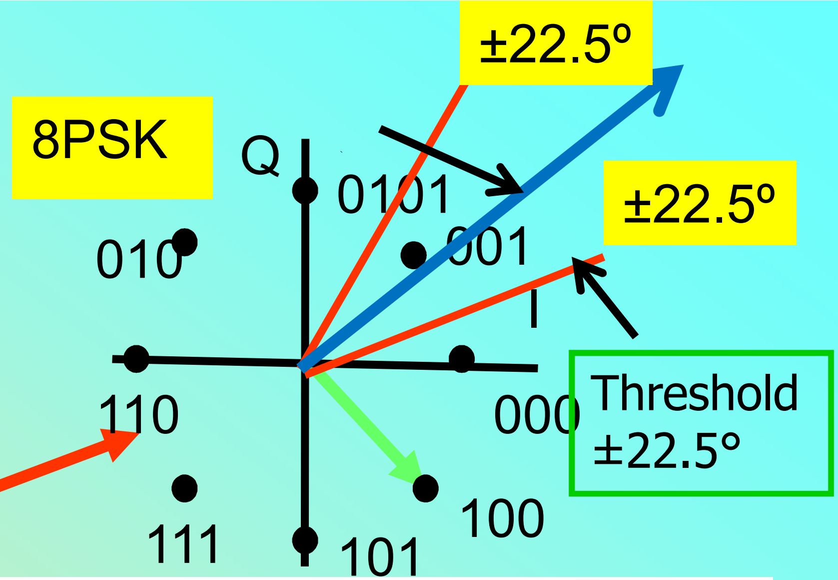
Phase Noise & Error Probability

- Gaussian Function
  - μ = Average angle
  - σ Standard Deviation
  - $\Delta\Phi_{RMS} = 1\sigma$ (Standard Deviation)
- Probability of Error (BER) is related to the number of σ's to the boundary
- σ's are in degrees RMS

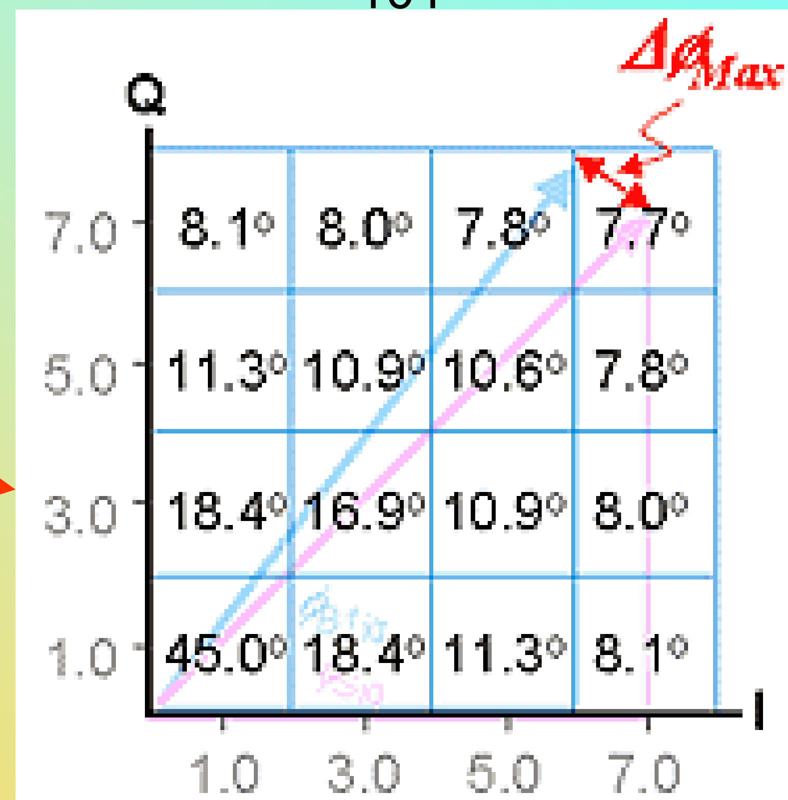
- $P(>|1\sigma|) = .318$
- $P(>|2\sigma|) = .046$
- $P(>|3\sigma|) = 2.7\text{x}10^{-3}$
- $P(>|4\sigma|) = 6.3\text{x}10^{-5}$
- $P(>|5\sigma|) = 5.7\text{x}10^{-7}$ -



System Phase Noise

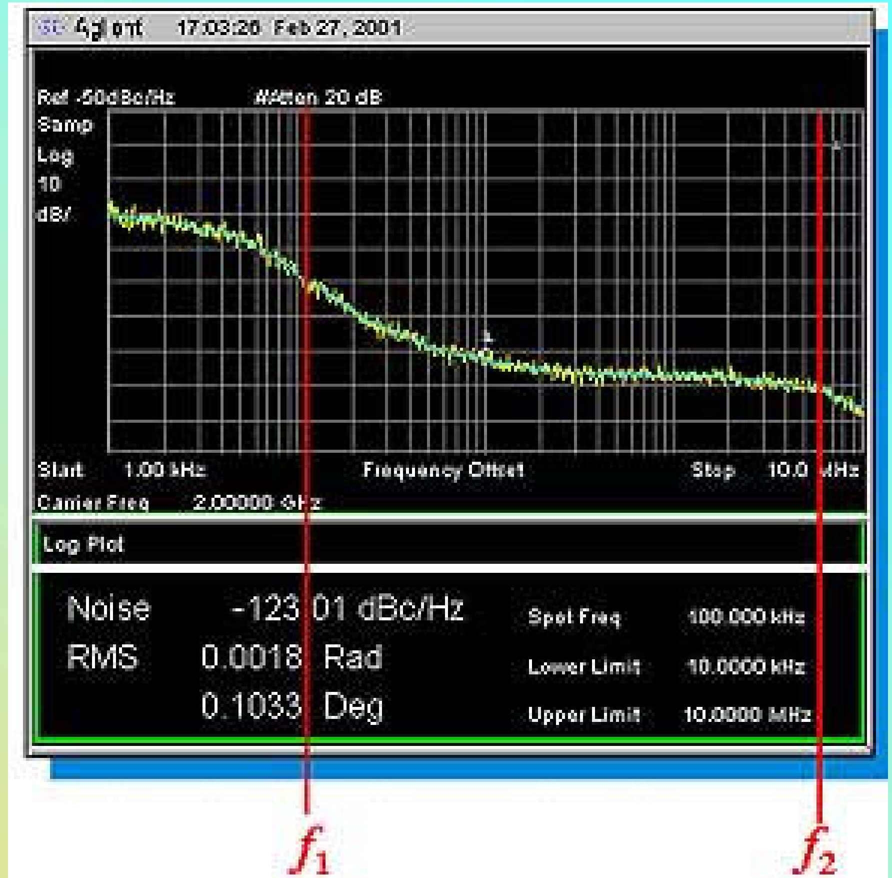


- Constant Amplitude Modulation (e.g. 8PSK)
  - Phase Noise threshold is constant (±22.5°)
- QAM Modulation
  - Allowable Phase Noise is a function of Bit Position
- Figure shows allowable phase error for 64QAM -



RMS Phase Noise Integration Limits

- Sum ONLY over Applicable Frequencies
- Typically 1/50 Symbol Rate to 1 Symbol Rate (f_1 to f_2)
- Ex: For 5Msymbols/sec
  - Typical integrated BW 100kHz to 5 MHz
- Integrate in segments <= 1 decade



$$\left(\Delta\phi_{RMS}\right)_{Total} := \sqrt{\left[\left(\Delta\phi_{RMS}\right)_1\right]^2 + \left[\left(\Delta\phi_{RMS}\right)_2\right]^2 + \left[\left(\Delta\phi_{RMS}\right)_3\right]^2}$$

- $\Delta\Phi_{RMS}$ is the Root Mean Square (1 Standard Deviation, 1 σ) -

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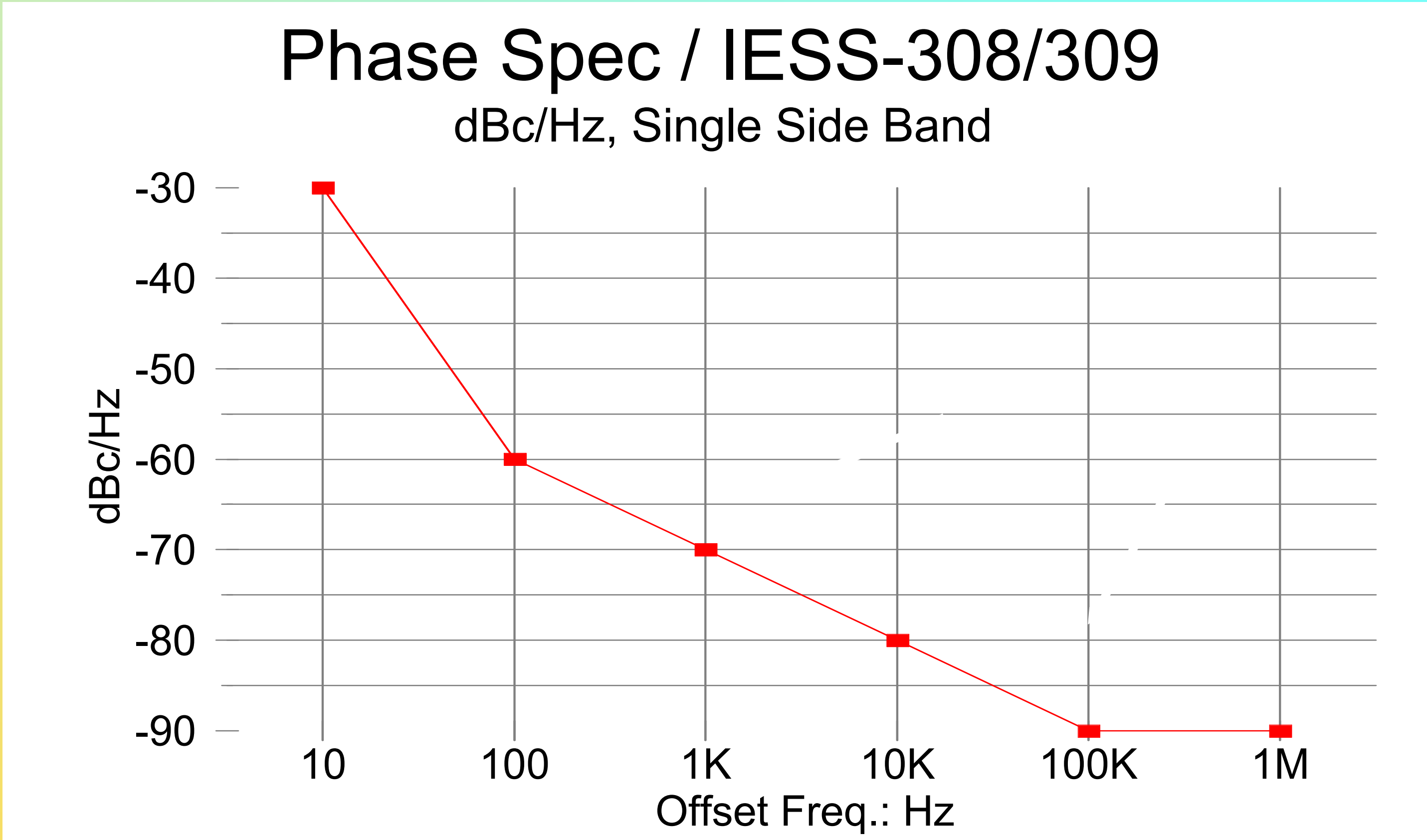
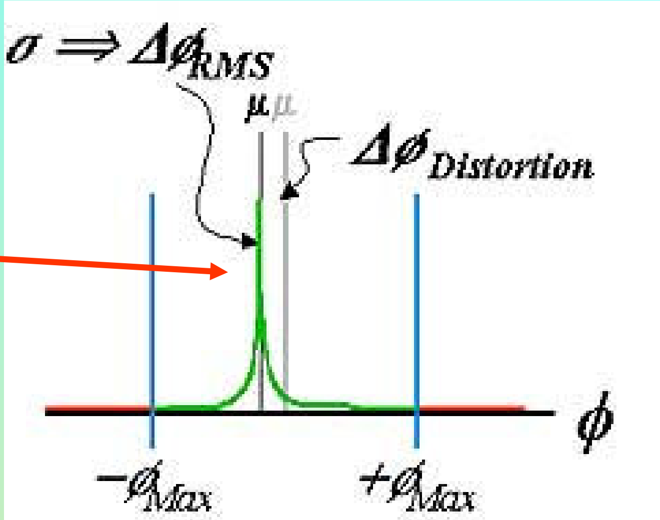
Intelsat Phase Noise Specification



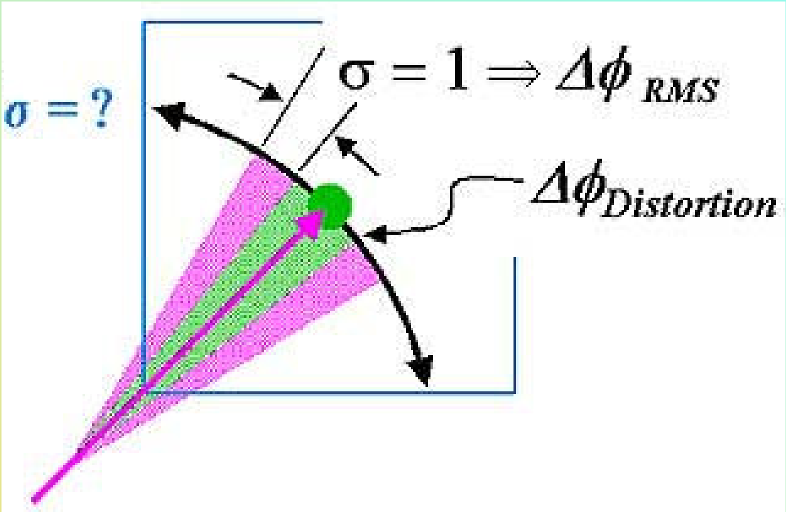
- Don't make symbol rate too low
- Phase Noise close to the carrier is higher
- See why low data rate modulators use BPSK -

Random + Deterministic Phase Distortion

- Phase errors reduces the number of standard deviations to threshold
- Maximum Angular error $\Delta\Phi_{MAX}$



$$\Delta\phi_{Max} = \sigma \cdot \Delta\phi_{RMS_{Total}} + \Delta\phi_{Distortion}$$



- Distortion Error 3°= $\Delta\Phi_{Distortion}$
- $\Delta\Phi_{RMS}$ =1.0°
- $\Delta\Phi_{MAX}$ = 5°
- $\Delta\Phi_{MAX}$ = 2 σ [P(>|2σ|) = .046]
- Should be 5 σ [P(>|5σ|) = 5.7x10^{-7}]

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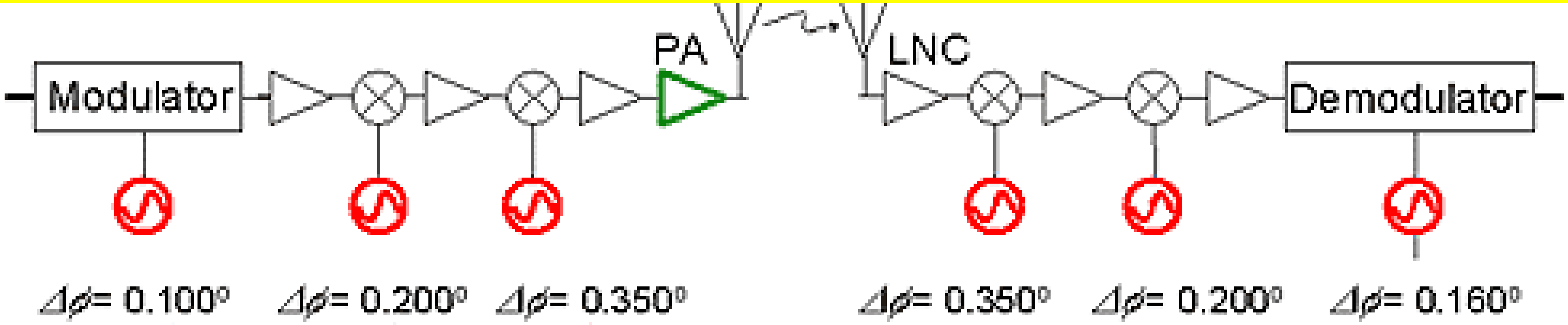
Phase Noise Allocation Budget

- Total Phase noise budget is the RMS sum of all the components
- Oscillators have the highest phase noise



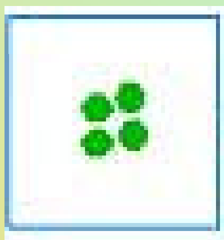
$$\Delta\phi_{RMS_{Total}} = \sqrt{(0.100)^2 + (0.200)^2 + (0.350)^2 + (0.350)^2 + (0.200)^2 + (0.160)^2} = 0.600^\circ$$

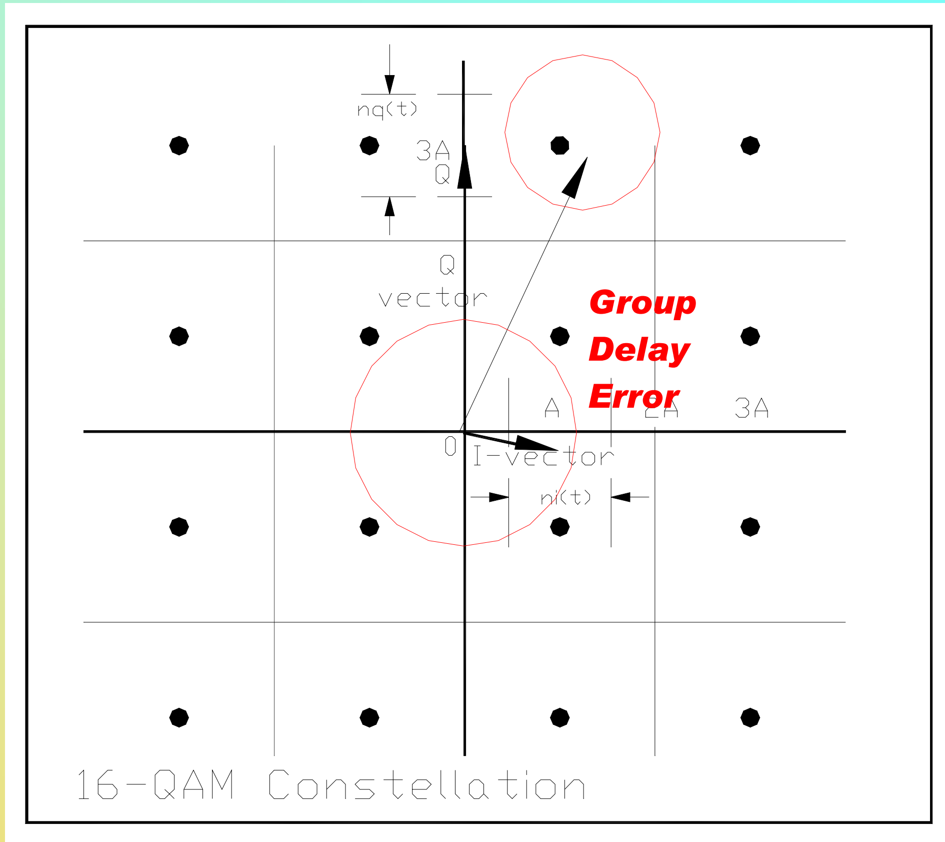
$$\Delta\phi_{Distortion_{Total}} = \Delta\phi_{Distortion_{PA}} + \Delta\phi_{Distortion\ Other}$$

Power Amplifier phase errors are caused when signal peaks -

Group Delay Distortion

- ❑ Quadrature of the initial vectors are effected
- ❑ Fixed Offset of Vectors
- ❑Group Delay Distortion is deterministic
- ❑Distortion is a function of frequency -





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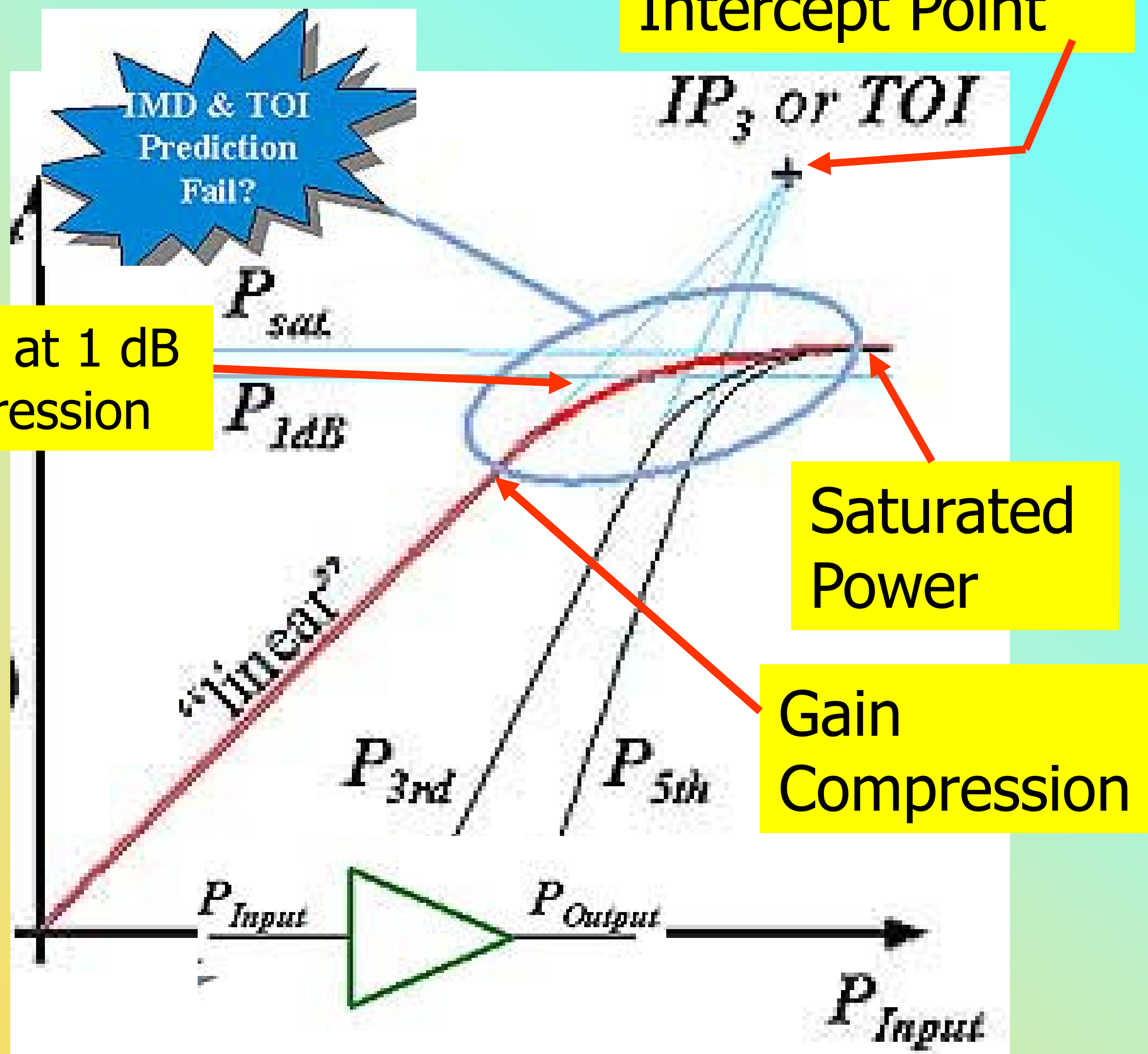
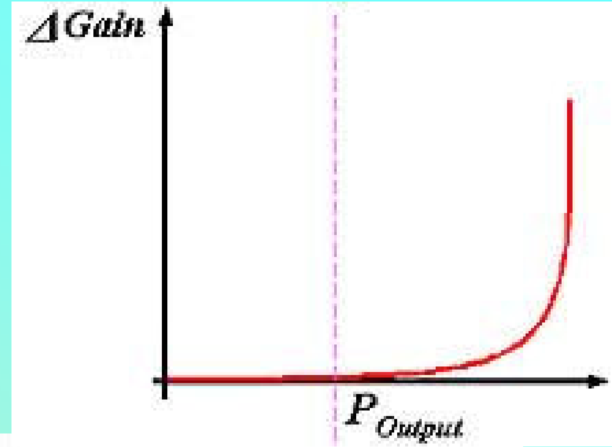
Amplitude Distortion

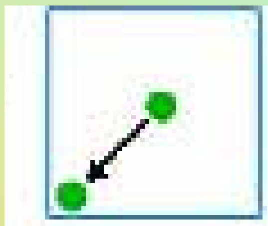
- Signal increases
  - Amplitude compresses: AM/AM Distortion
  - Phase changes: AM/PM Distortion
- Create Two Tone Intermodulation (IMD) distortion
  - 3rd and 5th Order Products



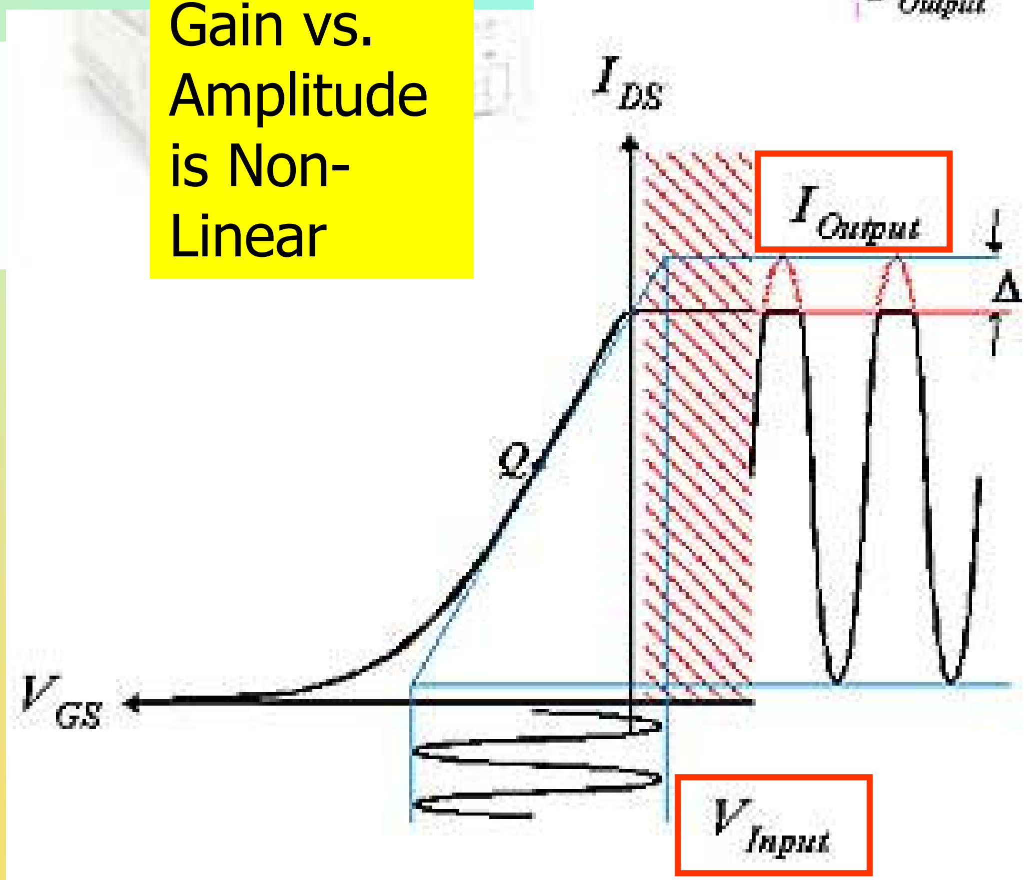
AM/AM Mechanism
(Non-Random Effect)



- Clipping Reduces Amplitude



Gain vs. Amplitude is Non-Linear



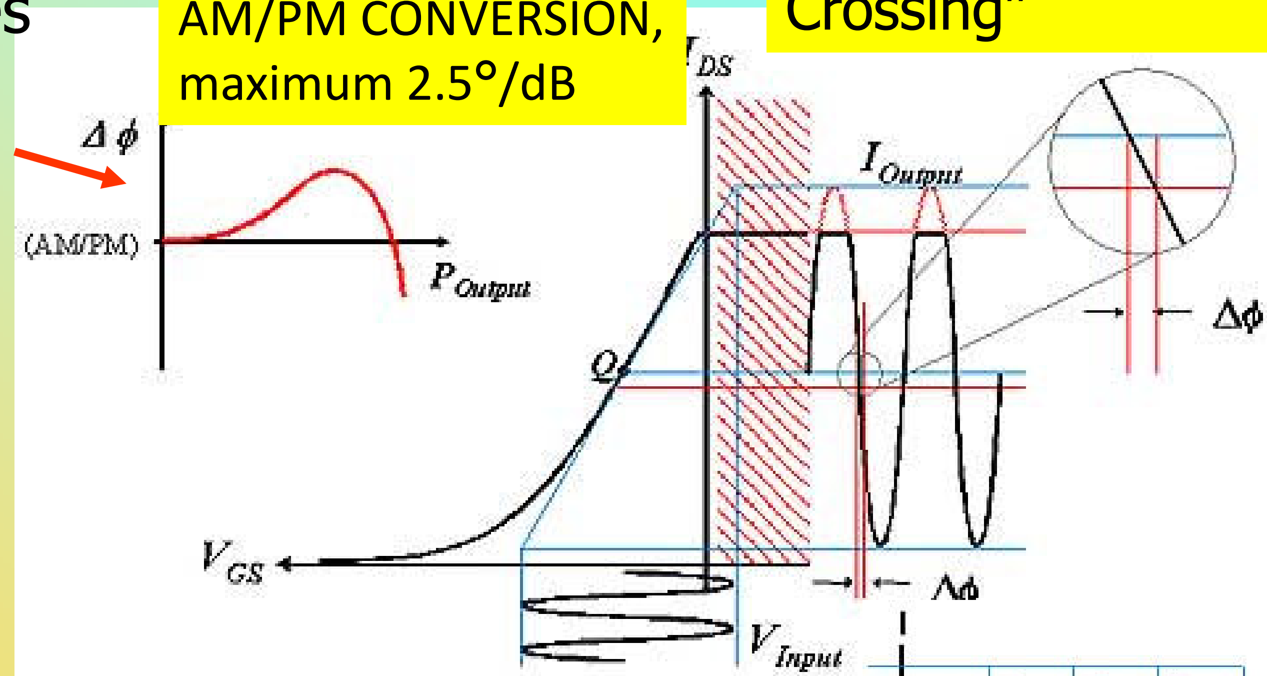
- Gain Compression results in AM/AM Distortion
- Amplitude variation is Non-Linear -

AM/PM Mechanism
(Non-Random Effect)

Clipping Amplitude Changes "Zero Crossing"

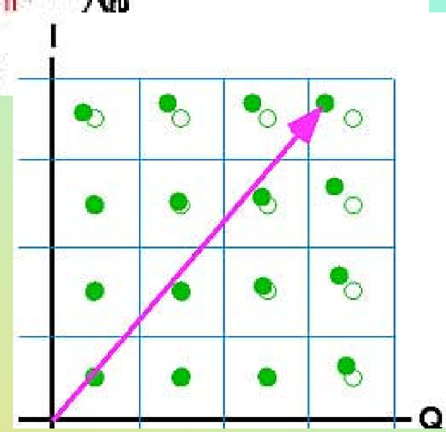
Typical Spec
AM/PM CONVERSION, maximum 2.5°/dB

❑ Offset Creates AM/PM (Phase changes with amplitude)



❑ AM/PM occurs before AM/AM

➢ AM/PM Distortion is more pronounced at the outer symbols
➢Peak to Average ratio has a pronounced effect on phase distortion -



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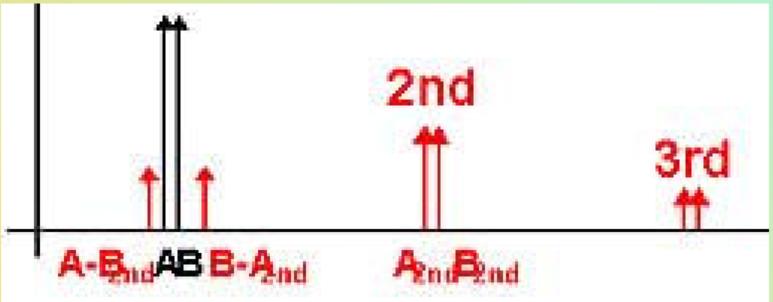
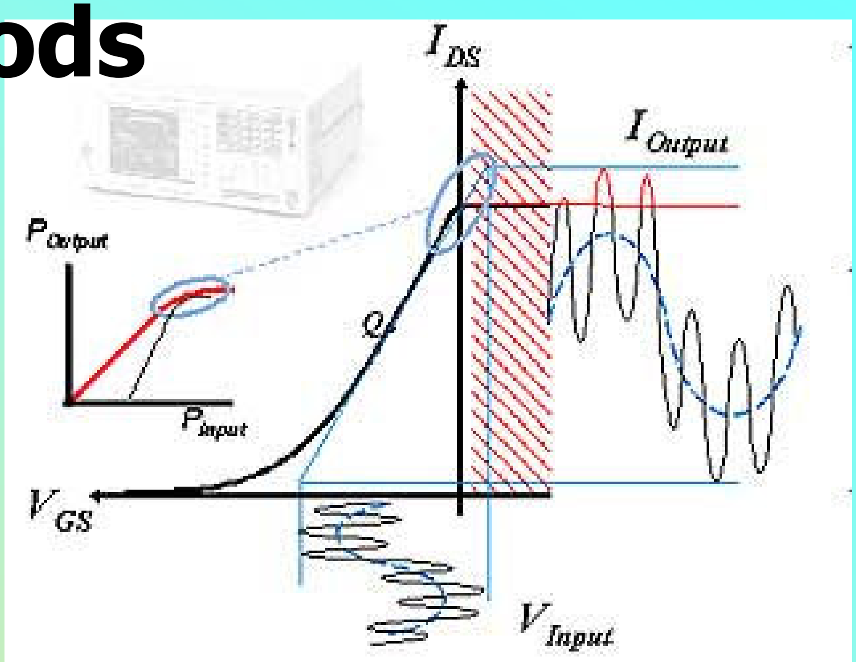
Two Tone Intermods

Typical Spec

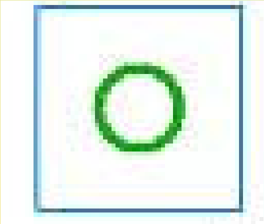
INTERMODULATION	-22 dBc maximum
with two equal signals	at 6 dB total output

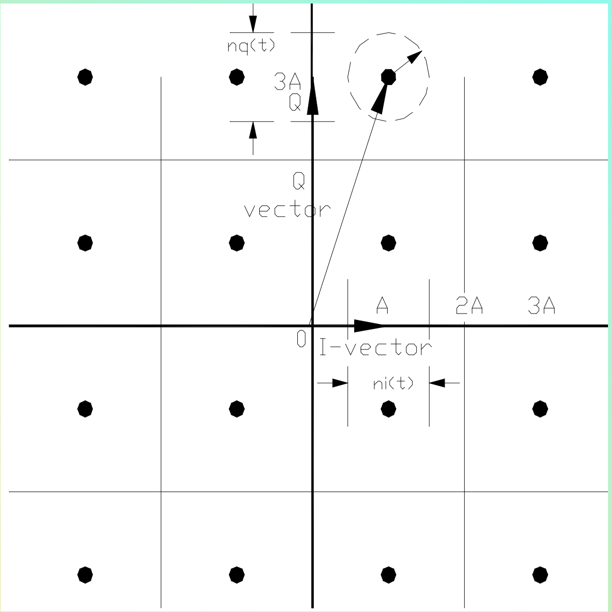




o 1^{st}, 2^{nd} , & 3^{rd} Harmonics Mix Together Forming IMD
o Level of Compression Determines Harmonics Amplitudes & IMD Tones

❑ IMD is a Rotating Spurious at the end of the signal vector -





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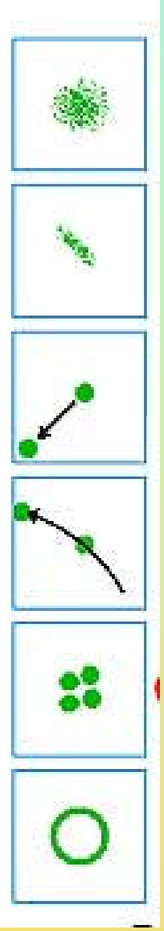
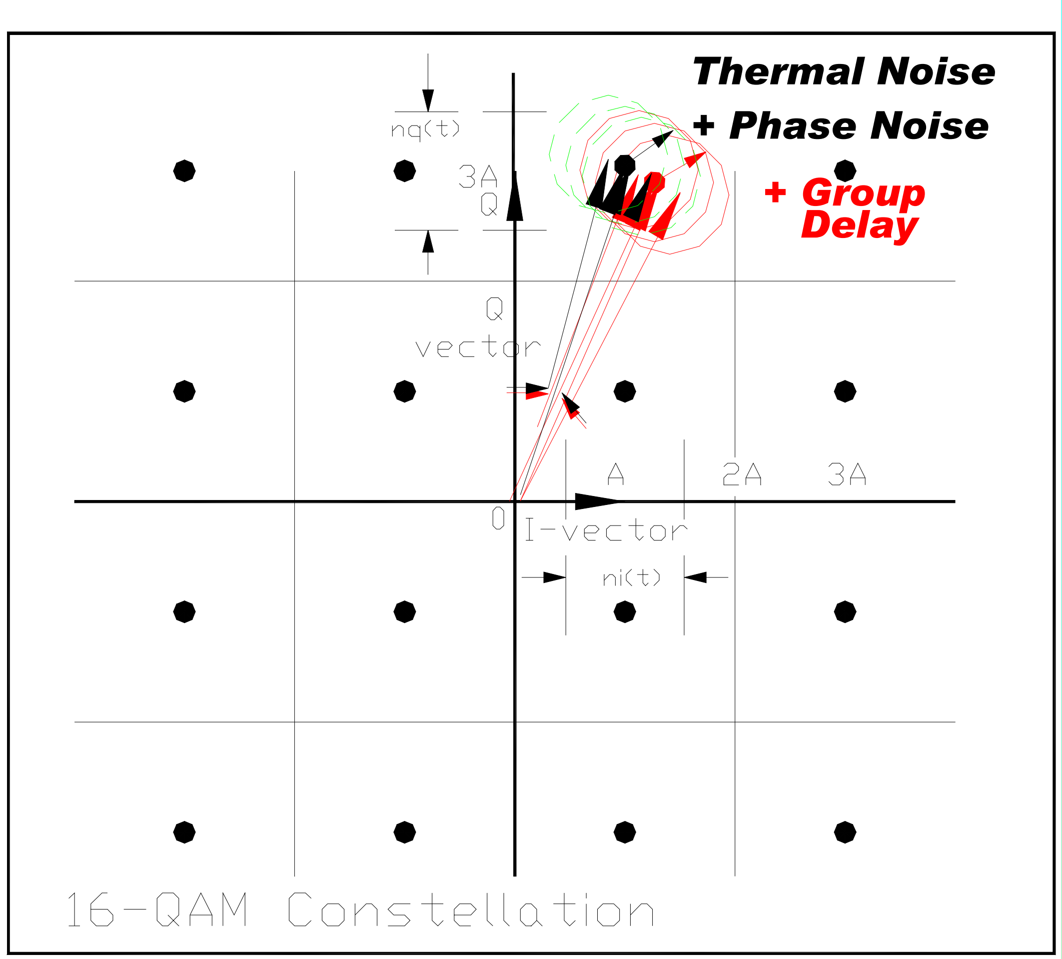
Combined Signal Distortions

- Thermal Noise
- Phase Noise
- AM/PM
- AM/AM
- Group Delay
- Intermodulation





Symbol Error Probability

$$P_{iq}\left(\Phi > \Delta\phi_{Max}\right) \approx 2 \cdot \int_{\Delta\phi_{Max}-\Delta\phi_{Distortion}}^{-\infty} \frac{1}{\sqrt{2\pi\sigma_{iq}^{2}}} \exp\left[-\frac{(\phi-\mu)^{2}}{2\sigma_{iq}^{2}}\right] d\phi$$

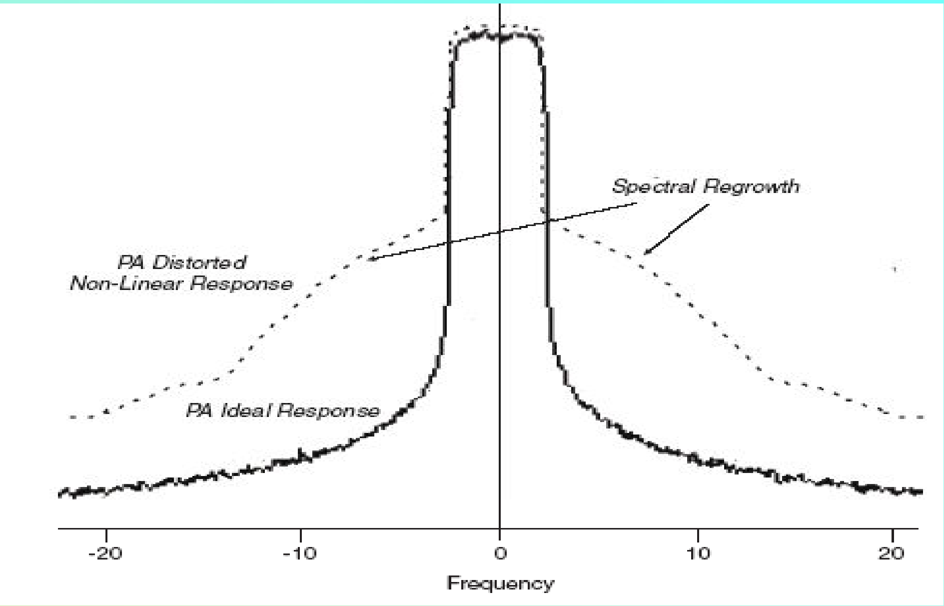
- ❑ Each Symbol has a different probability of Error (P_{iq})
- ❑ Assume all symbols are equally likely
- ❑ Calculate Expected Symbol Error Probability
- ❑ σ is the Random (RMS) variation
- ❑ μ is the deterministic offset -

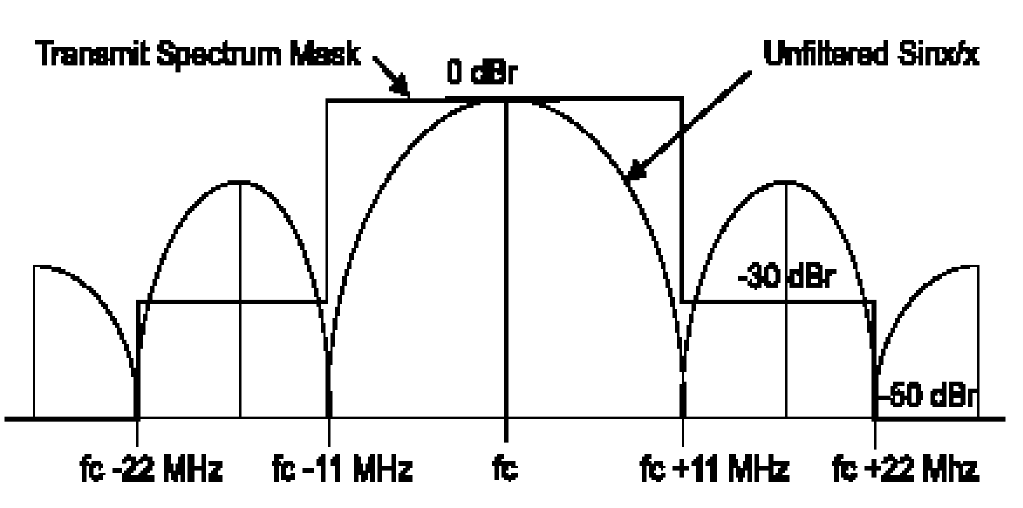
I \ Q	1.0	3.0	5.0	7.0
7.0	7E-15	5E-14	3E-13	2E-12
5.0	2E-39	1E-35	2E-32	3E-13
3.0	5E-139	6E-112	1E-35	5E-14
1.0	0E+00	5E-139	2E-39	7E-15

Adjacent Channel Interference

Spectral Re-Growth

- Modulated Spectrum is pre filtered to provided less than -40dBc of side band interference
- Non-linearities increase the side lobe level
- Typical maximum allowable spectral re-growth is –30dBc -





Spurious Signal

- Spurious signals are discrete non-signal related interference
- Individual spurious signals occur from multiple sources
- Add non-coherently
- Typical Specification is –60dBc for the entire Transmitter chain
- In band interference is controlled: -20 dBc interference effects C/N < 0.04dB
- -60dBc protects small carriers
  - Carrier power is a function of Bandwidth -

Out of Band Noise Power Output

- Transmitters have high C/N
  - Noise Figure is usually not an issue
- Output noise power can interfere with adjacent carriers
- Maximum output noise is given in dBm/Hz
- Noise Power output = Noise Figure (dB) + Gain from signal generator (primary oscillator) to final output (dB) -174dBm/Hz (thermal noise)
- Low Noise Figure and High Gain ➔ High output noise power -

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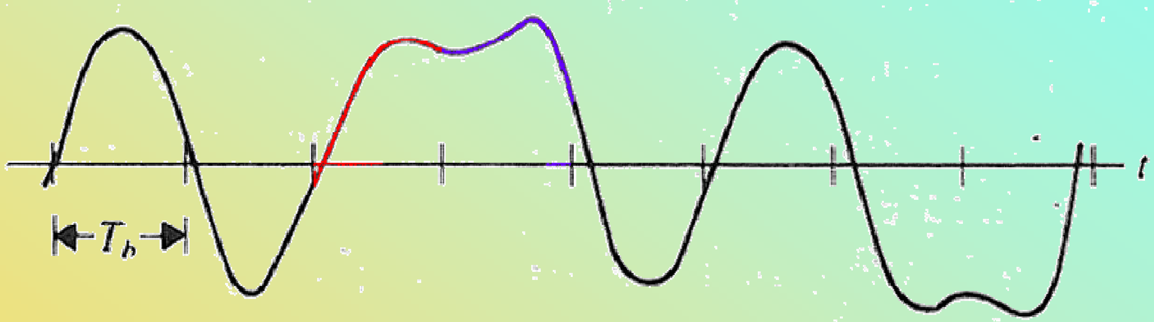
Time Domain Effects

Eye Diagrams

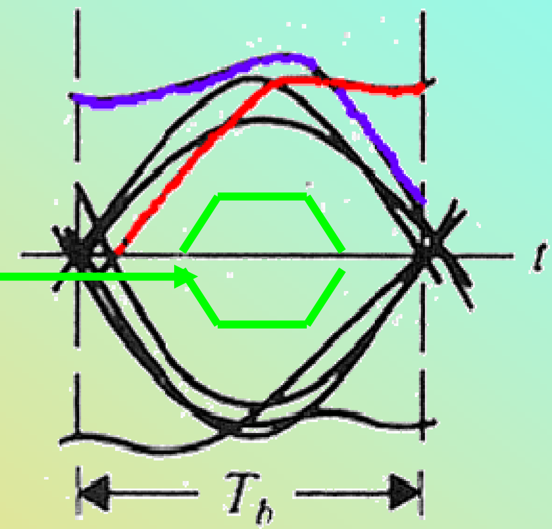
A means of assessing Received signal quality



Recovered Data

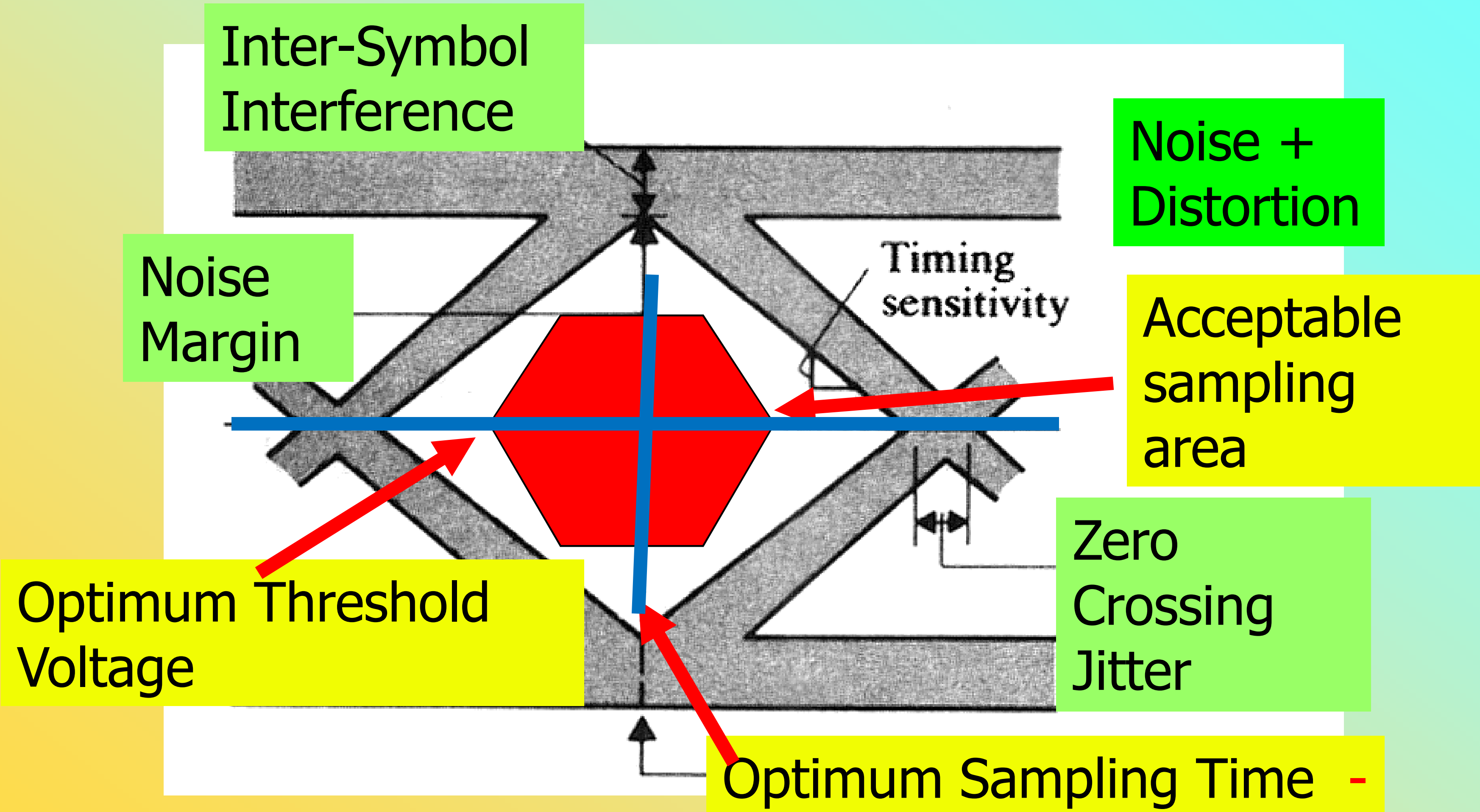
Fold Data "1"s & "0"s Overlap

- Establish an Area of Known Good Data in Time and Voltage
- Larger the "EYE" less errors



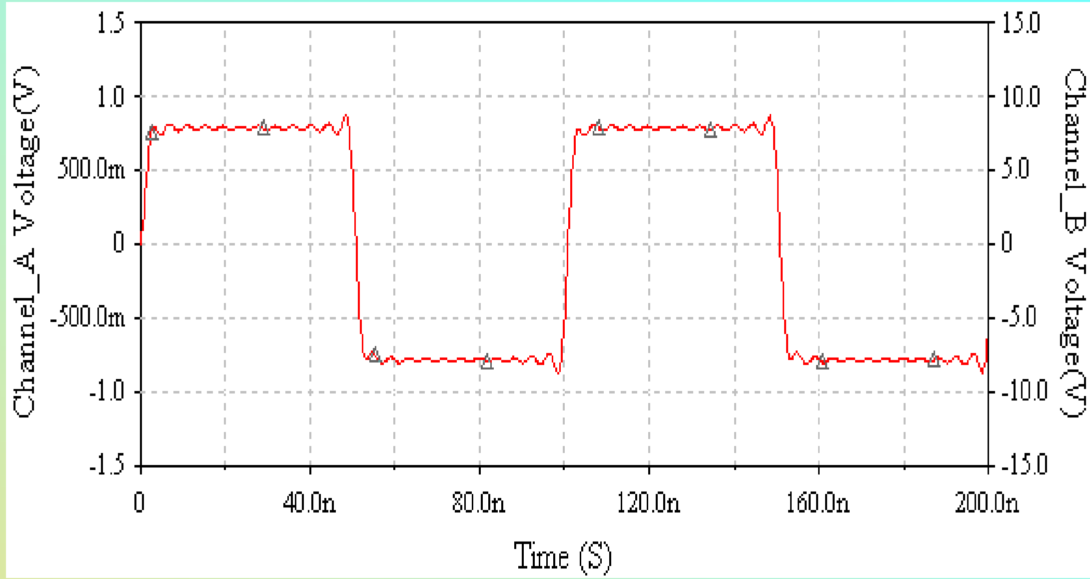
Eye Diagram Specifications

- ➢Recovered Pulse must avoid the **RED** area
- ➢ **RED** area is an error in the amplitude or time

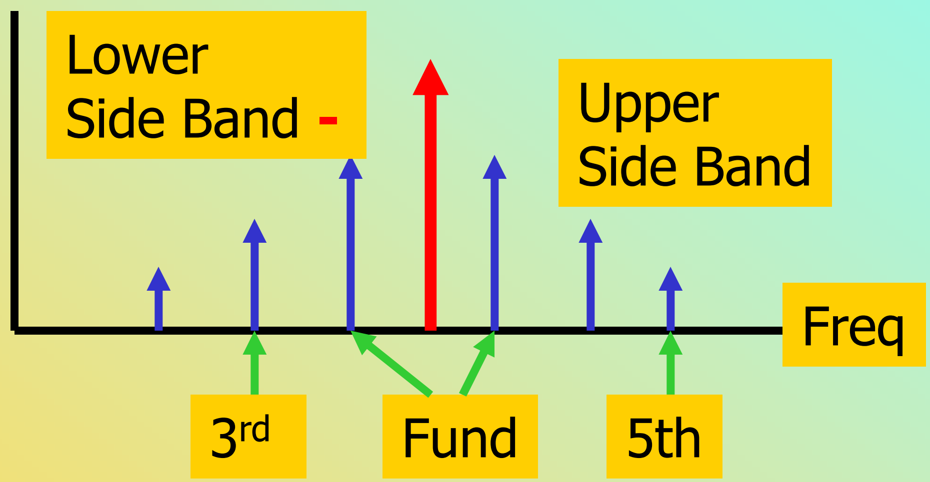


Data in the Time & Frequency Domain

- ❑ Ideal Received Data
- ❑ 20Msymbols/Sec NRZ

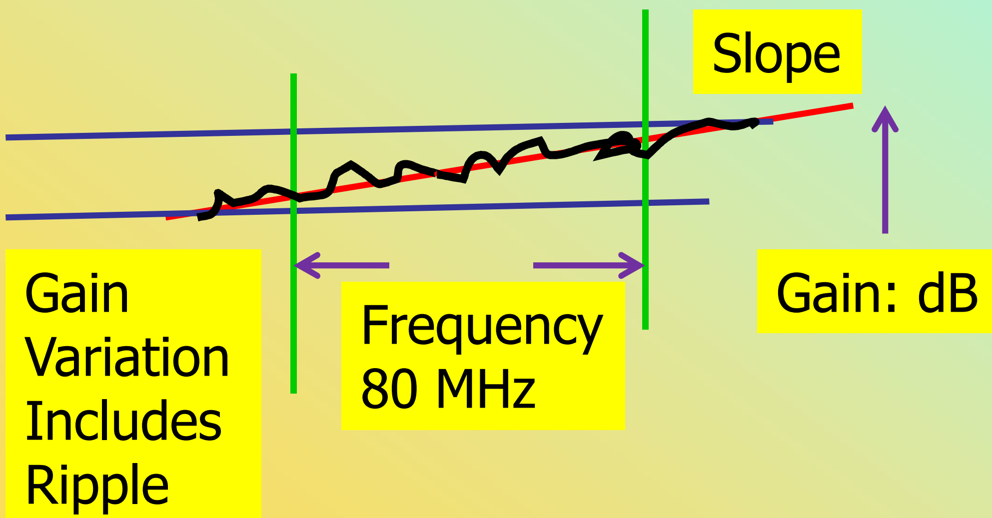


- ❑ IF Frequency Spectrum of BPSK NRZ data alternate “1”s & “0”s
- ❑ Carrier (RED) is suppressed
- ❑ Only Odd Harmonics
-



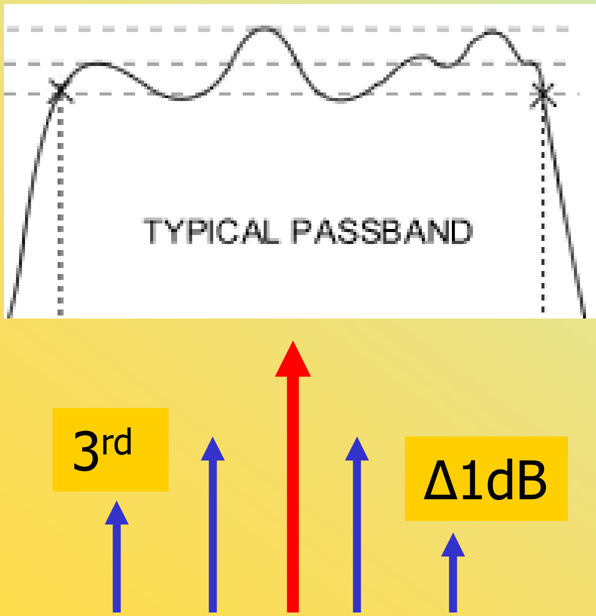
Typical Gain Specification

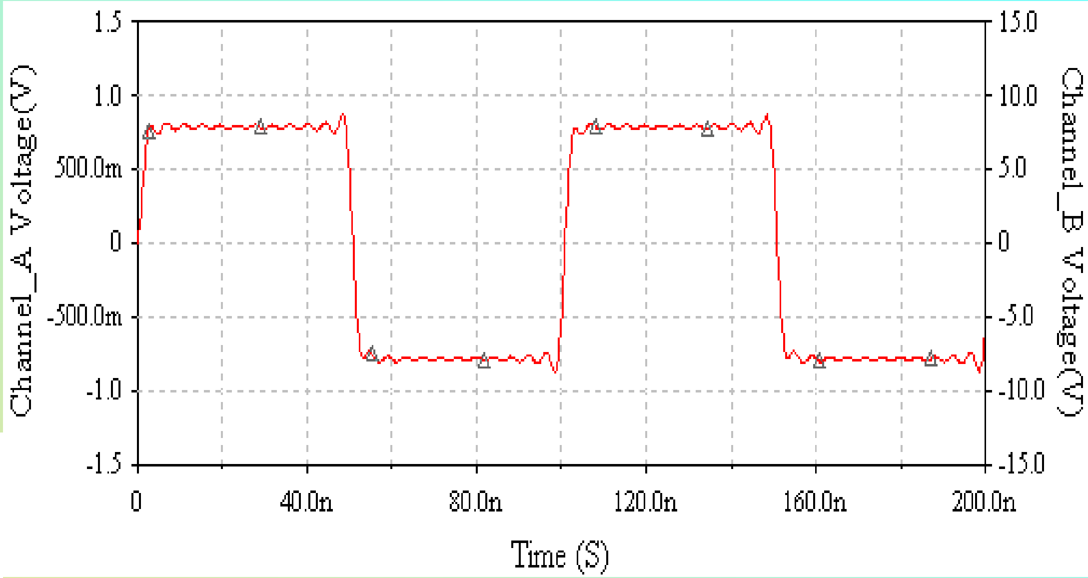
Maximum Small Signal Gain Variation Over:	
Any Narrow Band	1.0 dB per 80 MHz
Full Band	2.5 dB
Slope, maximum	+ 0.04 dB/MHz
Stability, 24 Hr maximum	+ 0.25 dB
Stability, Temperature	+ /-1.0 dB maximum over temperature range at any frequency

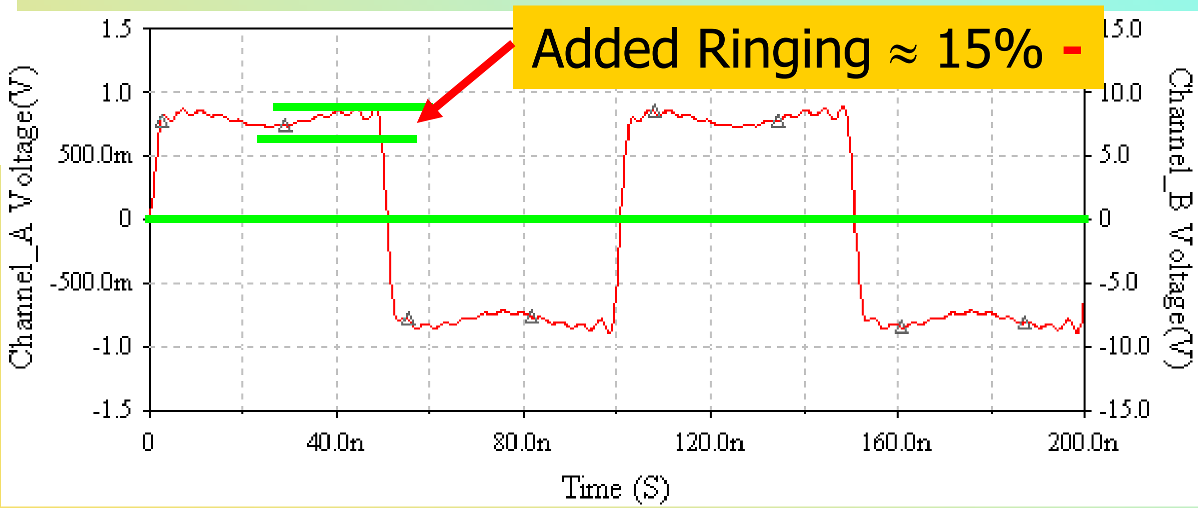


Amplitude Distortion (Gain Ripple Specification)

- Ideal Received Signal
- 1 dB peak to peak Amplitude Ripple on 3rd Harmonic







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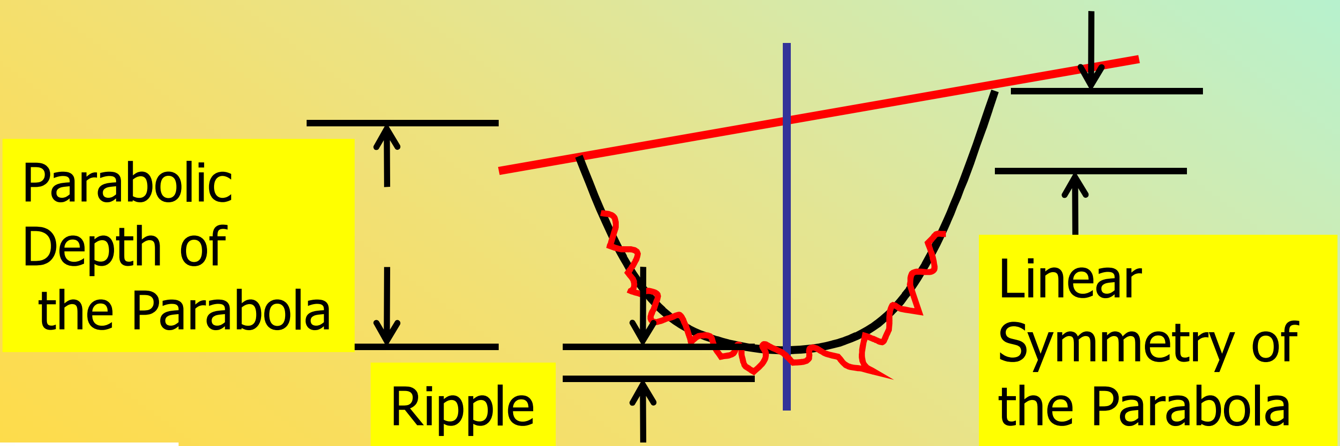
Typical Group Delay Specification

- Group Delay is usually parabolic
- Edges rise with the skirts of the filter

GROUP DELAY, maximum	10.95 to 12.75 GHz
Bandwidth	Any 80 MHz
Linear	0.01 nS/MHz
Parabolic	0.005 nS/MHz2
Ripple	0.5 nS/Pk-Pk



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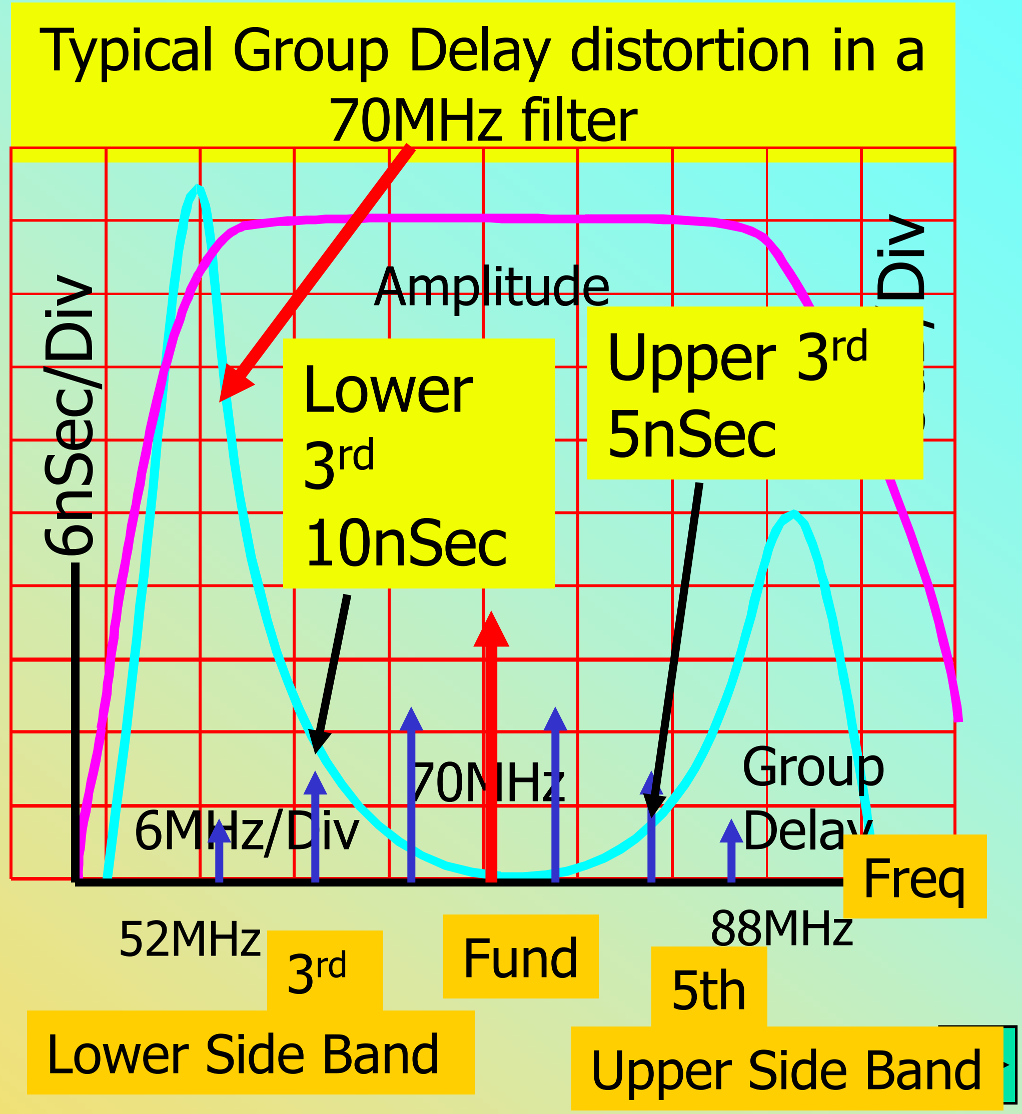
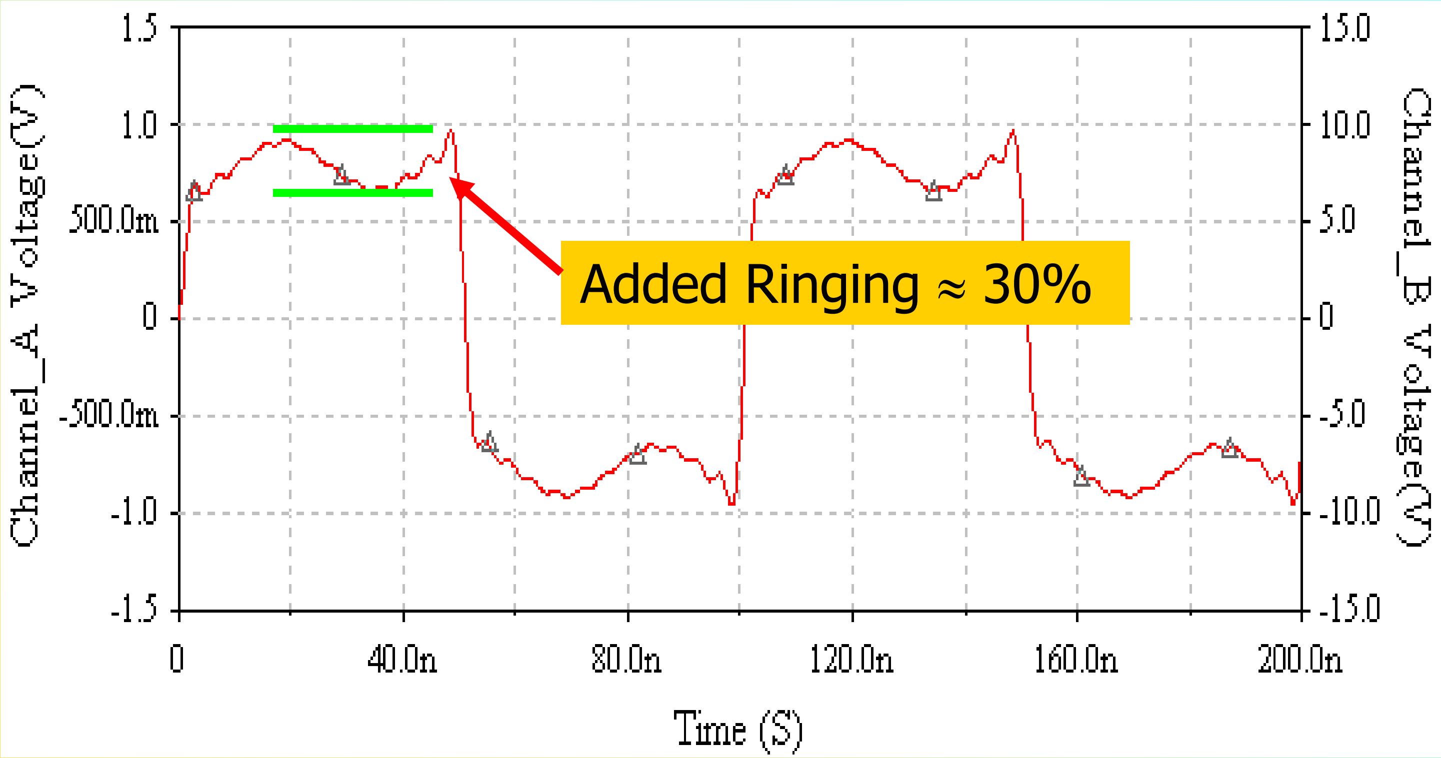
Delay Distortion
Modulated Signal through a 70 MHz Filter

- Side bands should not change in amplitude or phase (delay)
- Delay curve & effect on sidebands
  - Symmetry
    - Upper & Lower sidebands
  - Depth of Parabola
    - Side band harmonics
  - Ripple-All sidebands effected
- Upper 3rd Harmonic is delayed 5 nSec
- Lower 3rd Harmonic is delayed 10 nsec -



Effect of Delay / Phase Distortion on 20Msymbol/Sec Data



- 2nsec Delay of 3rd Harmonic on
- Ringing ≈ 30%
- Delay distortion can be more critical than Amplitude Distortion -

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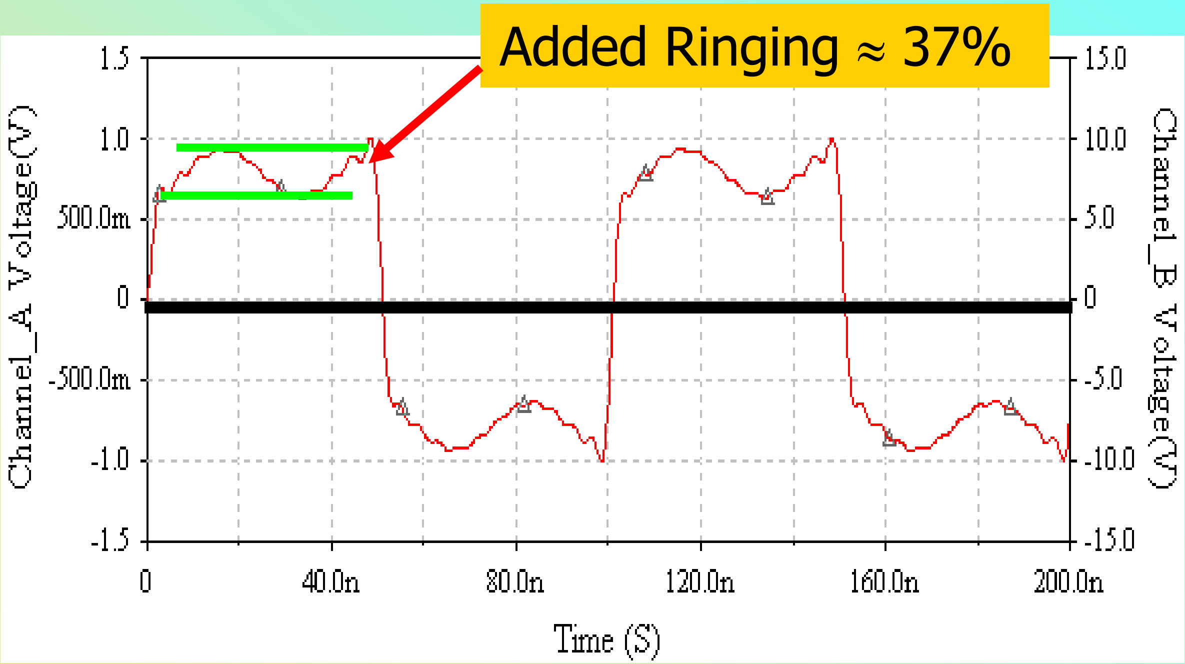
20Msymbols/Sec Data Amplitude & Phase Distortion

- 2nsec delay at 3rd harmonic + 1dB Ripple on the 3rd Harmonic
- Increased pulse ripple to ≈ 37%
- Judge how the "EYE" is closing -

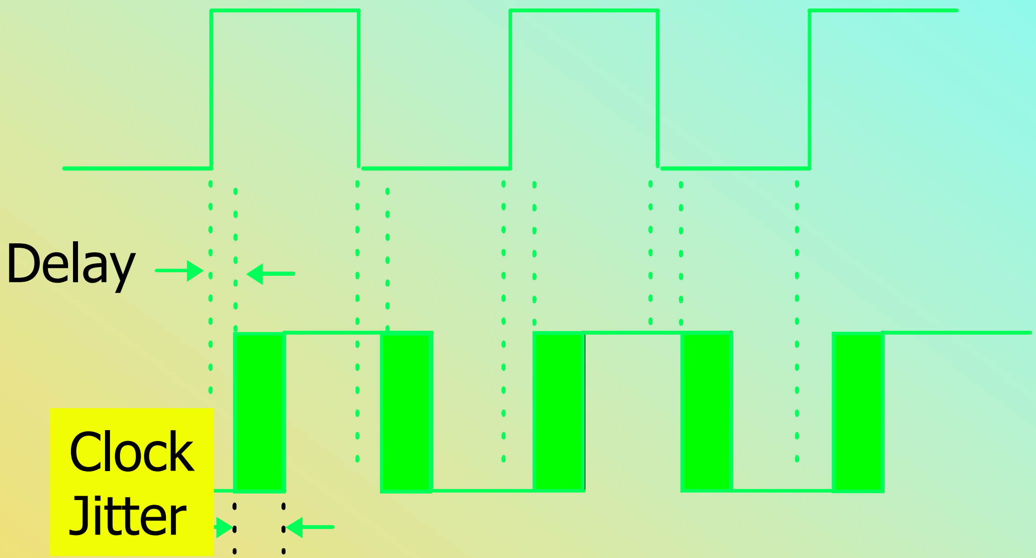


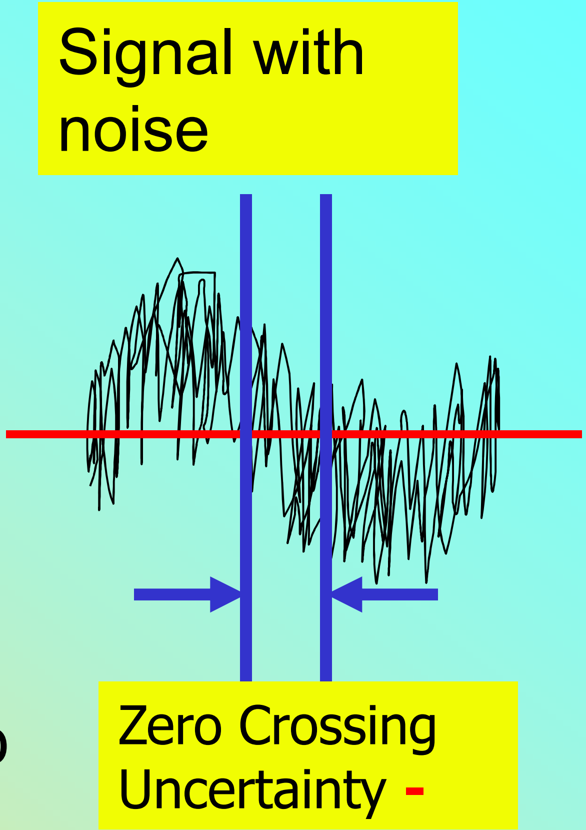
Thermal Noise – Noise Figure

A Signal Level Related Function

- Random effect in the time domain
- Thermal noise is a concern at lower signal levels
- Systems should have at least a 30dB Input signal to internal noise ratio
  - Typical effect on the system <= 0.14dB
- Minimum input signal level is –174dBm + 30dB + NF + 10Log[Bandwidth(Hz)] -

Clock Jitter



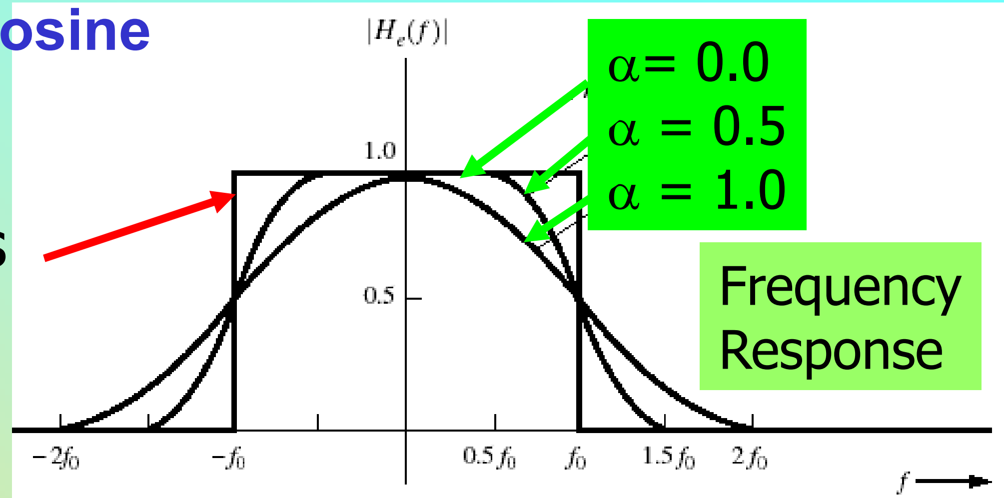


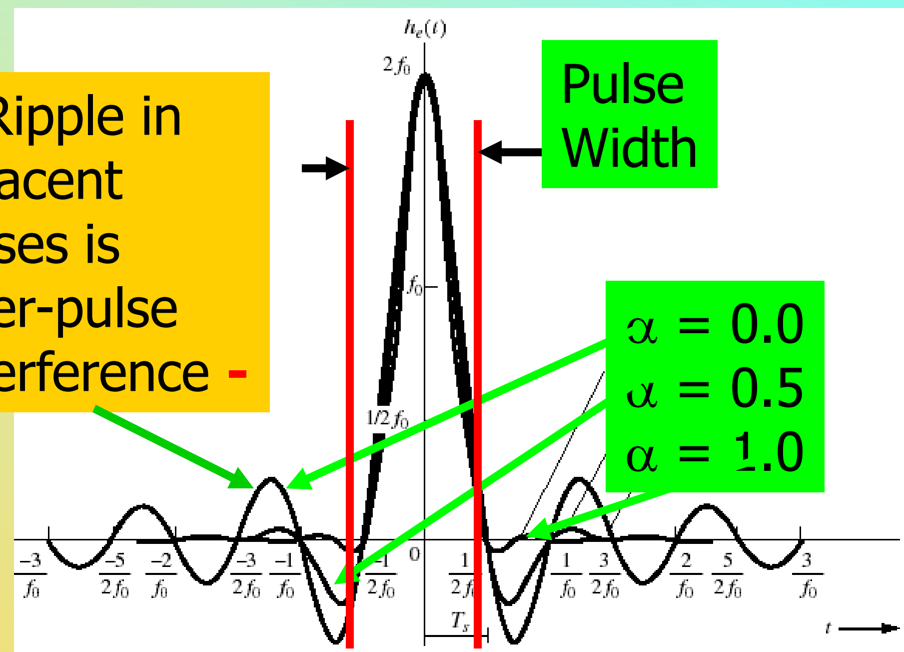
- Clock Jitter is the uncertainty related to the start of the data
- Caused by Zero crossing uncertainty on the recovered signal
- Thermal noise & Phase noise contribute to clock jitter

Inter-pulse interference

Nyquist Filtering: Raised Cosine Filter Response

- Ideal Filter (α = 0) has a poor pulse response (SinX/X)
- Filter shaping lowers Inter-symbol Interference
- Characterized by α (Frequency Response)
- Typically α = 0.35)
- Trade-Off is Frequency selectivity vs Pulse Response





Time Domain Response

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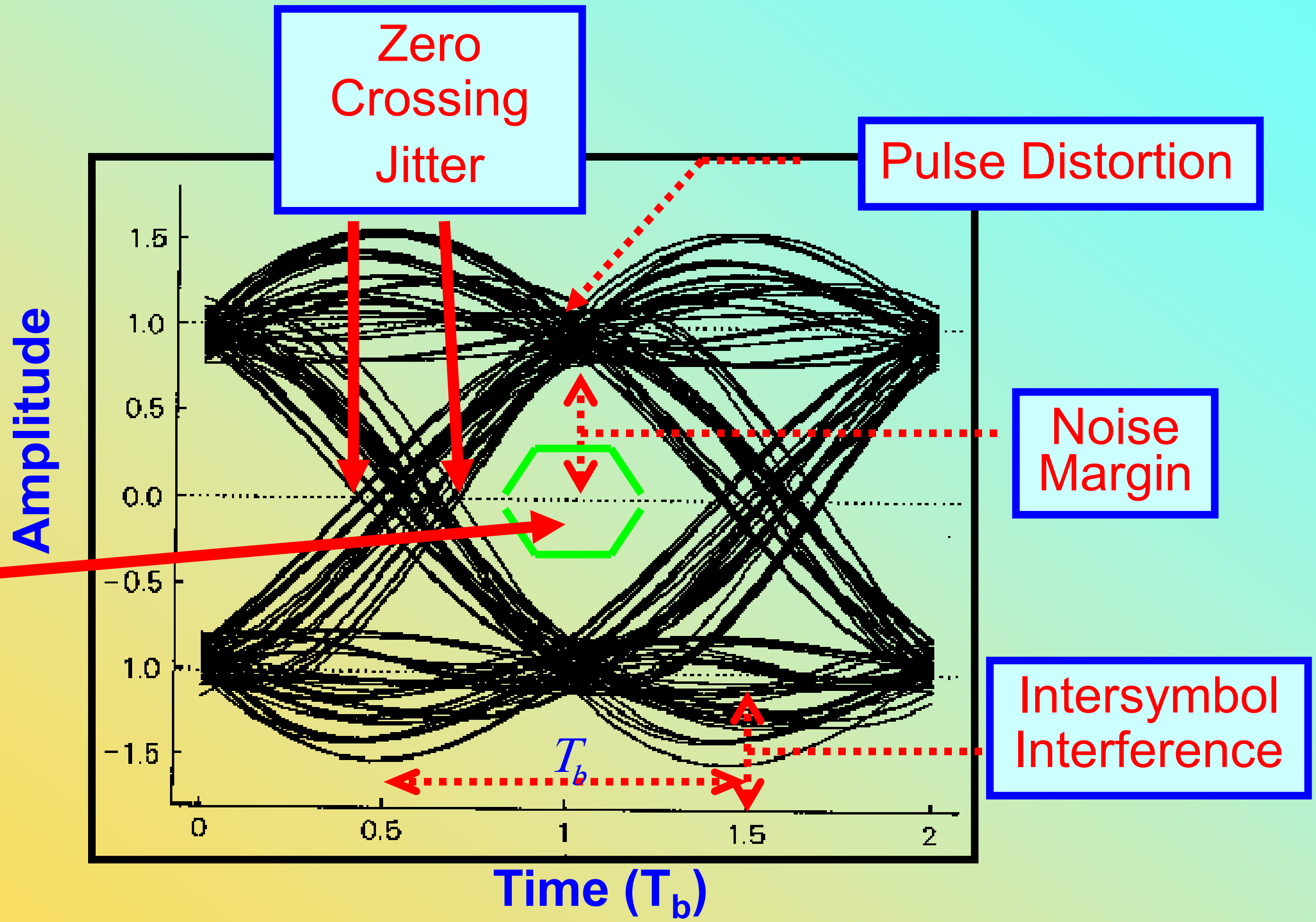
Typical Data Eye Diagrams



Optimum Sampling is in the center of the "Eye" -

Summary

- Satellite 2010 Convention in Washington
  - "The good news for satellite is that it goes where fiber and Wi-Fi don't go. It's the most versatile communications technology available, and there is not a substitute."
- Quality of received signal relates to:
  - Modulator
  - Transmitter
  - Transmission medium
  - Receiver
  - Demodulator
- Each segment requires has separate requirements & individual concerns