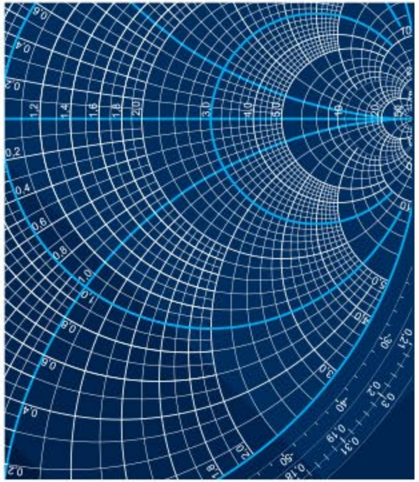


Measurement Techniques

Design Verification & Evaluation

EVERYTHING TEST

Instrument Selection & Optimization

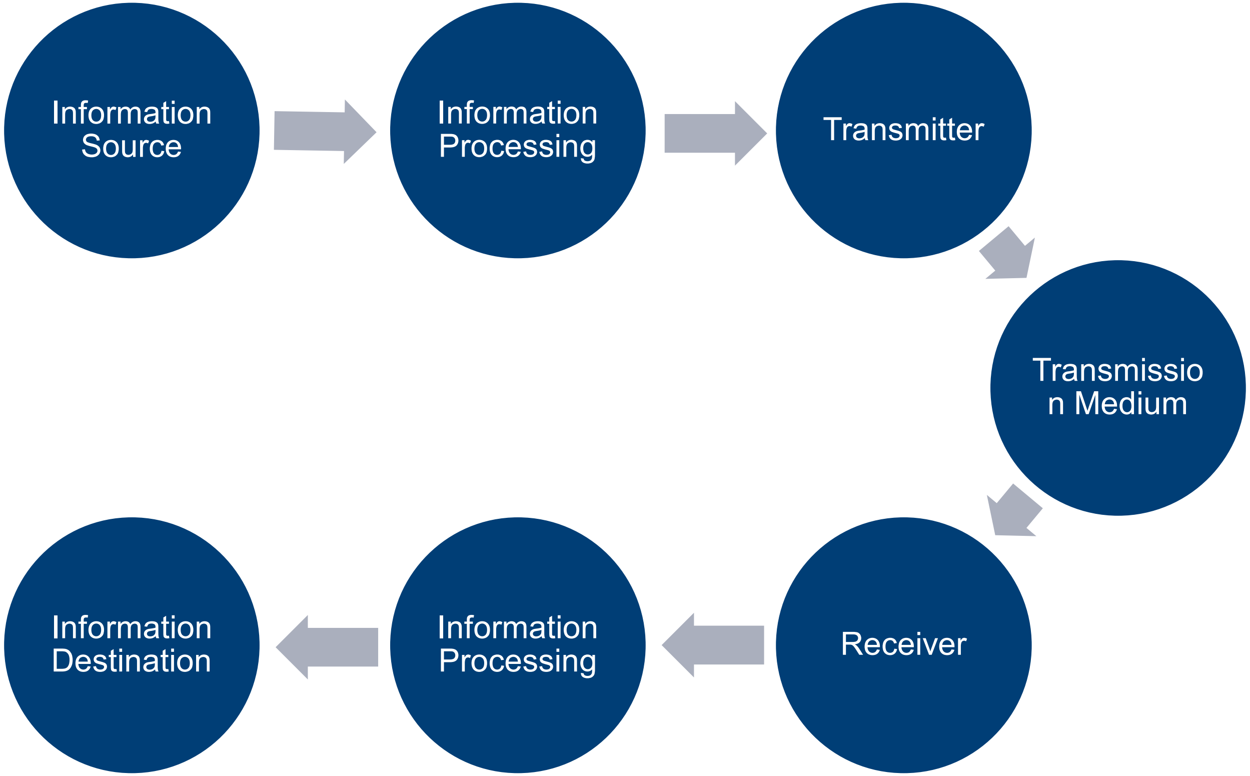
RF Test
Fundamentals of Transmitter and Receiver Testing

Neil Jarvis, RF and Microwave Applications Engineer

ROHDE&SCHWARZ

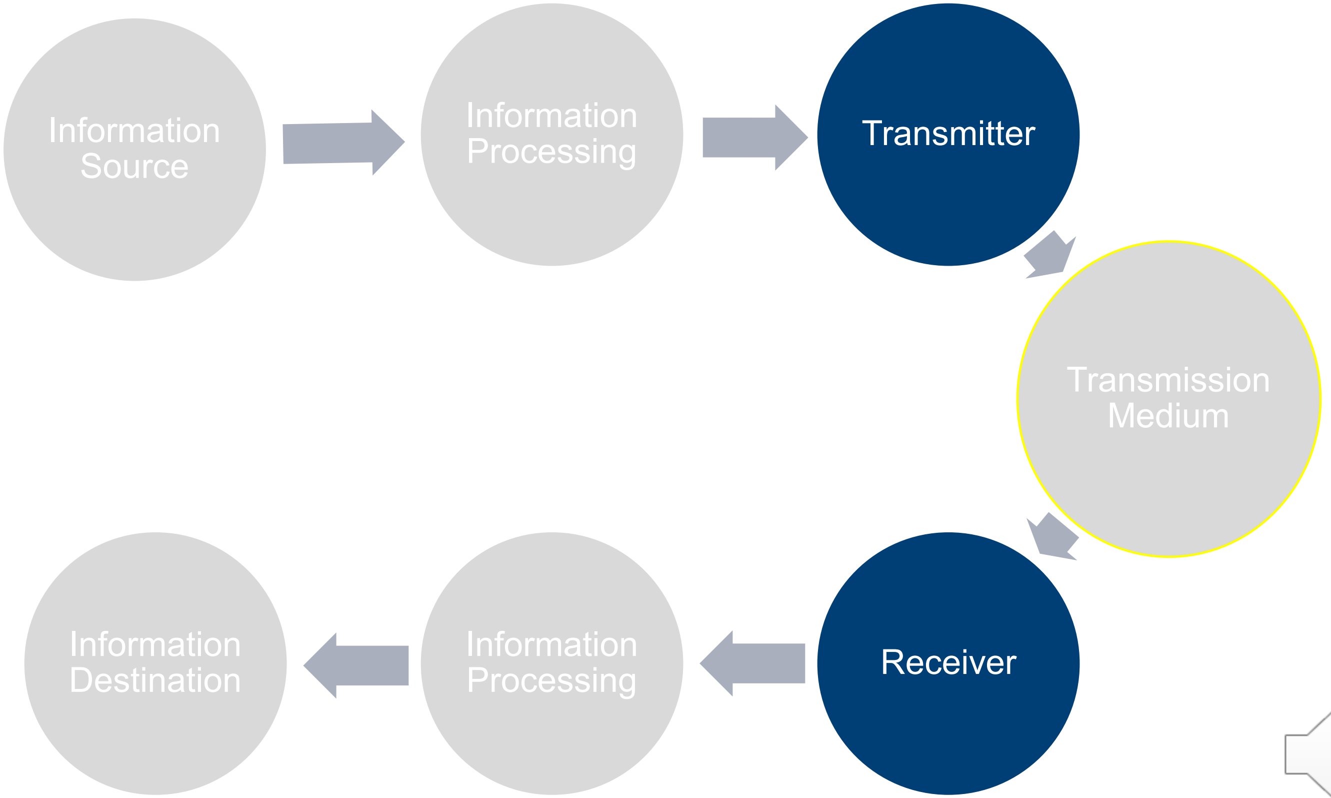
Make ideas real

Simplified Communications System Block Diagram



ROHDE&SCHWARZ

What is different about a wireless system?
Focus on the Transmission medium



Modulation: Transmitting Information

Modulate:

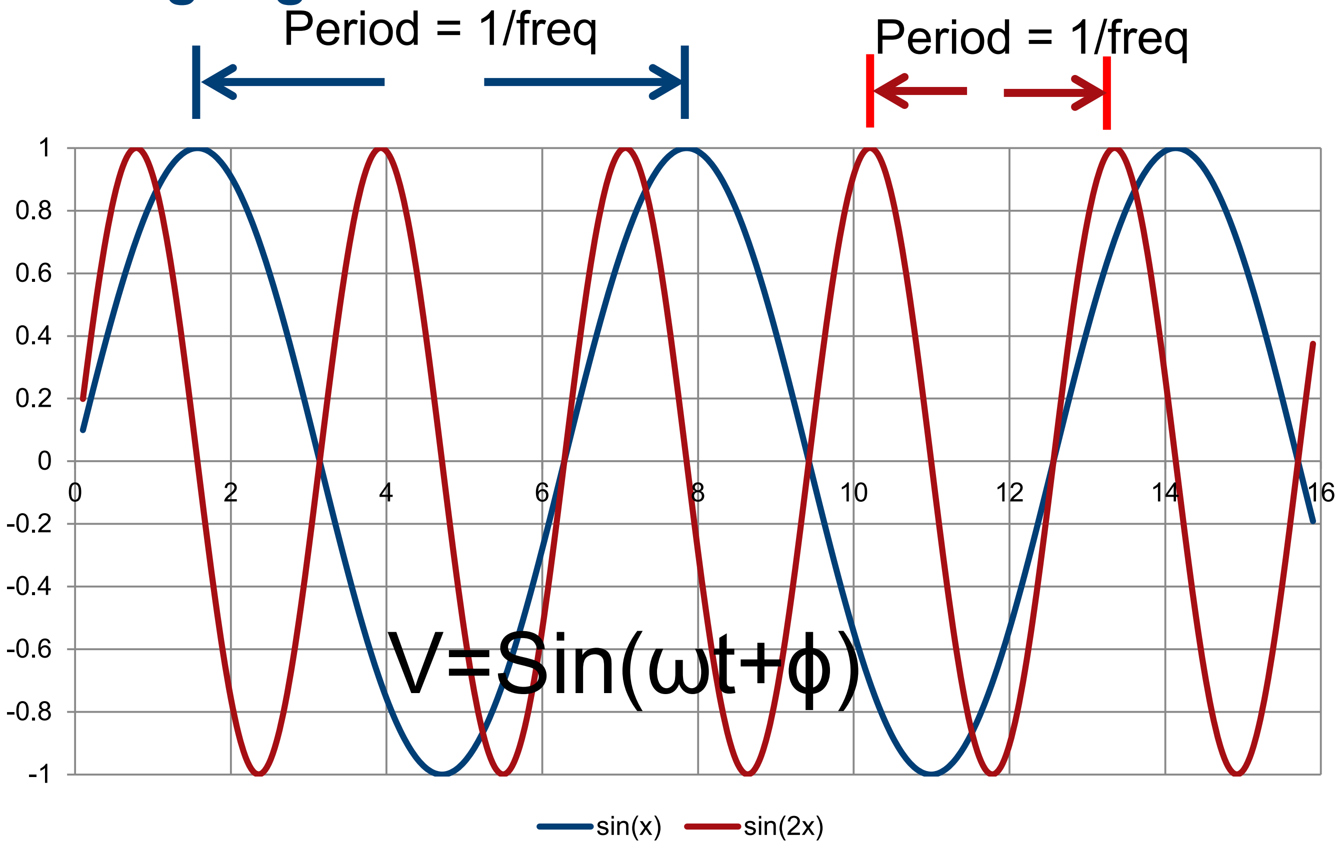
Modify some characteristic of a carrier

Demodulate:

Detect the modifications

Any *reliably detectable* change in signal characteristics can carry information

Simple Analog Signals in Time Domain



Modulation

What is Modulation

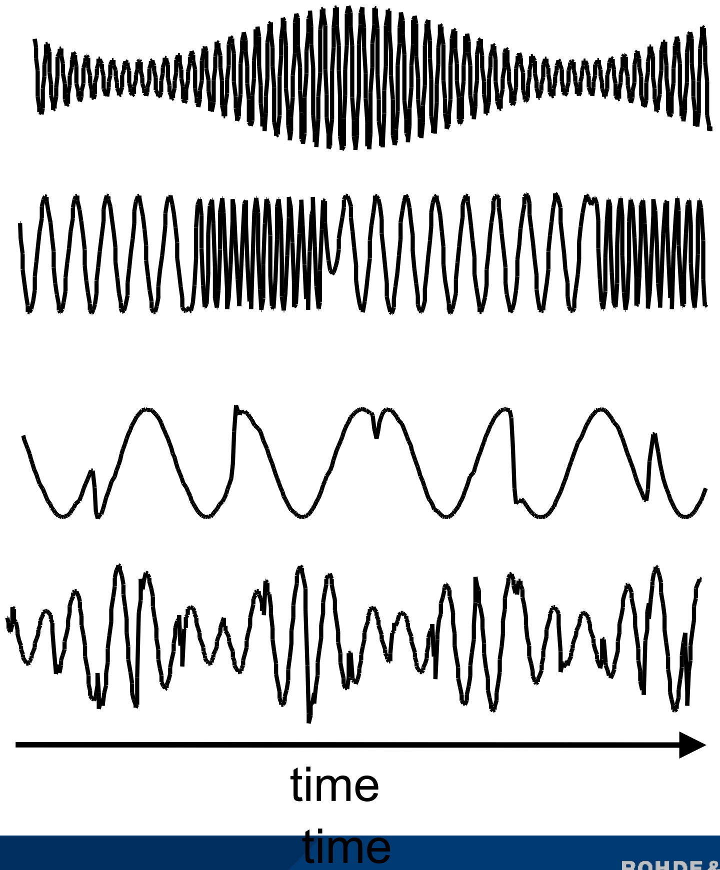
- Modulation is the process of varying one or more properties of a higher frequency periodic waveform called the “Carrier Wave”
  - Amplitude
  - Frequency
  - Phase
  - Amplitude and Phase

Why use Modulation

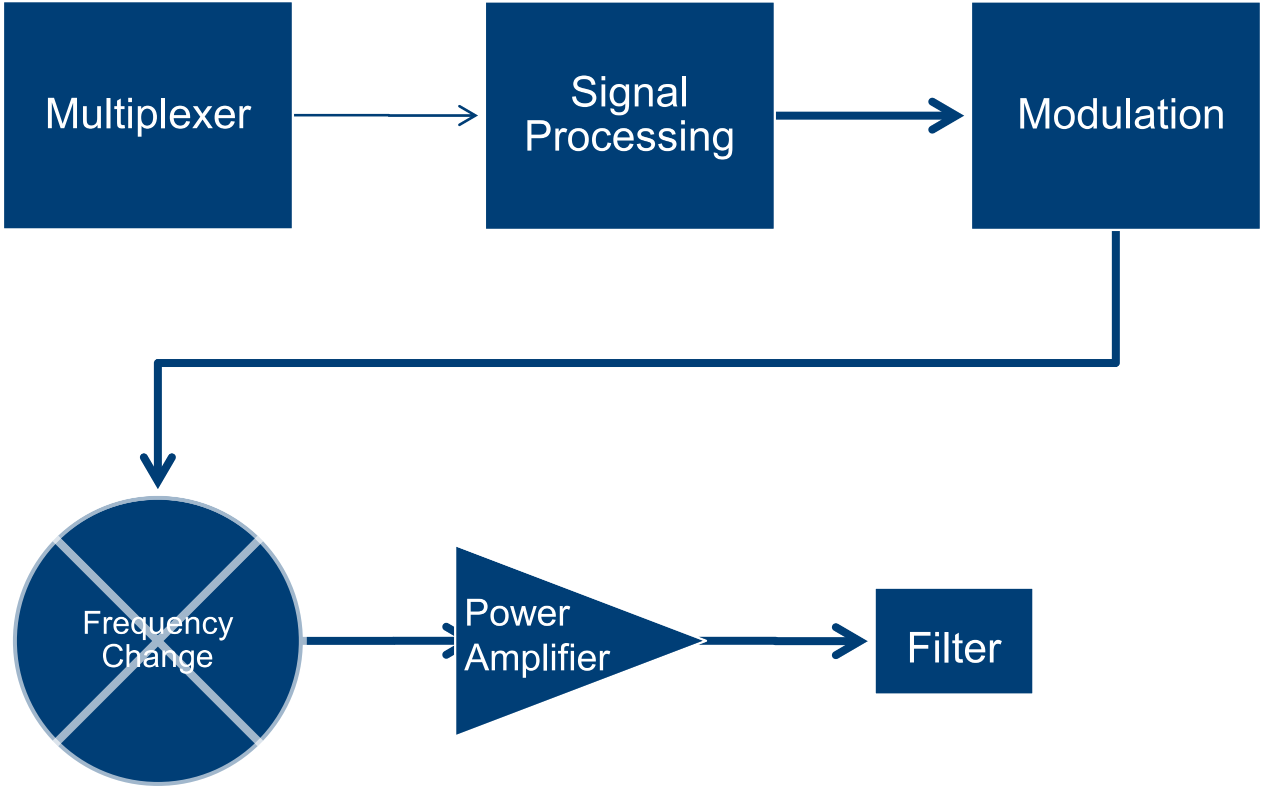
- Matching the transmission characteristics of the medium attenuation, multipath, fading etc
- Transmission efficiency is a function of antennas of dimension needing to be comparable with the wavelength of the signal, typically a quarter wavelength

Signal Characteristics to Modify

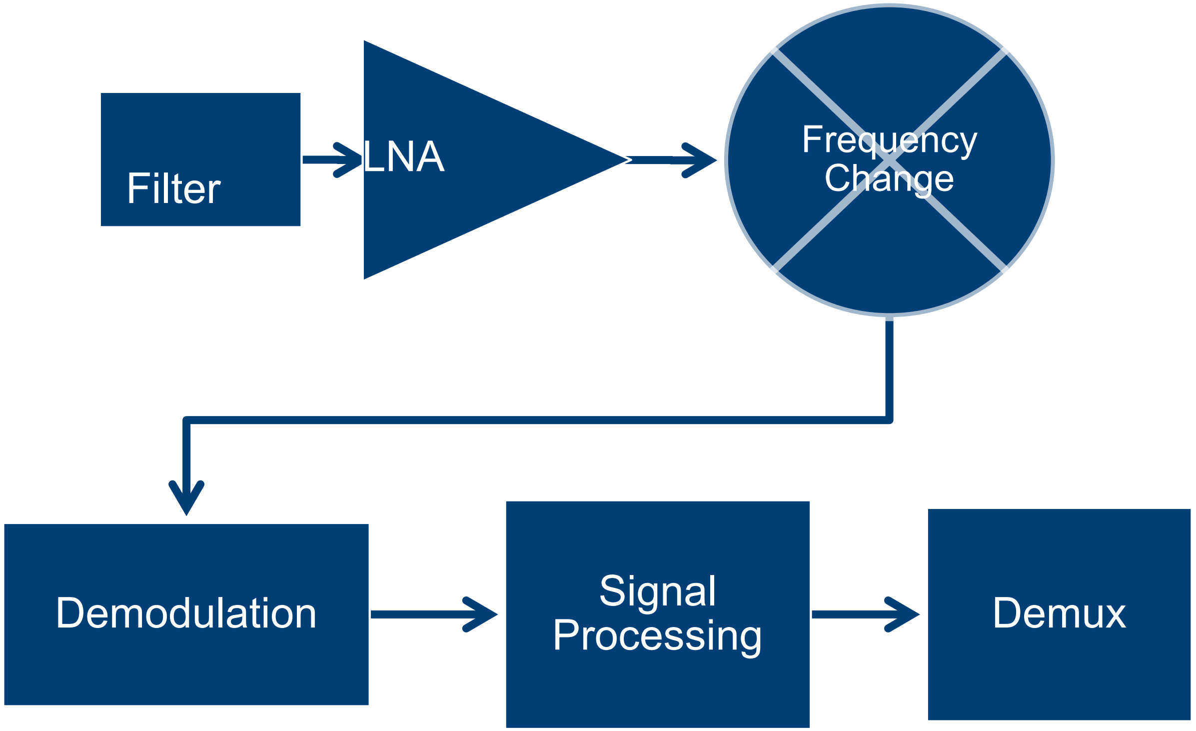
- Amplitude
- Frequency
- Phase
- Amplitude and Phase



What Does a Simple Transmitter Look Like?



What Does a Simple Receiver Look Like?



Design Considerations

Link budget?

- How big a signal do I need to transmit?
- How good a receiver or LNA do I need?
- What kind of antenna do I need?

► **Where from to?**

► **What does environment look like?**

- Weather
- Obstacles
- Direct Line of Sight
- Spectrum

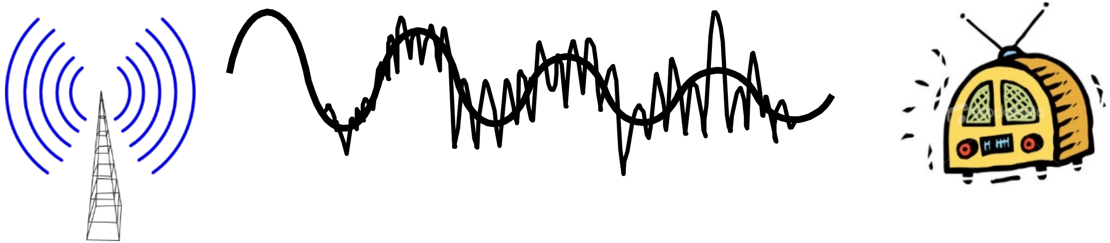
What am I sending

- Real-time
- How fast
- How much data
- Am I moving, stationary, how fast

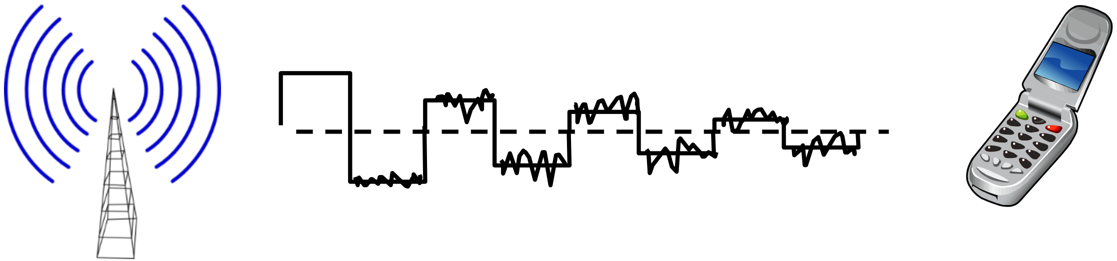
○ **Physical limitations**

- Size
- Weight
- Power

Now Noise Affects Analog and Digital Signals



- As an analog signal is attenuated in the presence of noise, it becomes increasingly difficult to detect the signal accurately



- If a digital signal's transitions are sufficiently large, bit errors don't occur at the receiver and the signal can be detected with no loss of information

What is the Input Noise?

- If we are below 100 GHz and above -150 °C (Rayleigh-Jeans approximation)

$$\text{Input Noise Power from a MATCHED Resistor is : } N_{in} = kTB$$

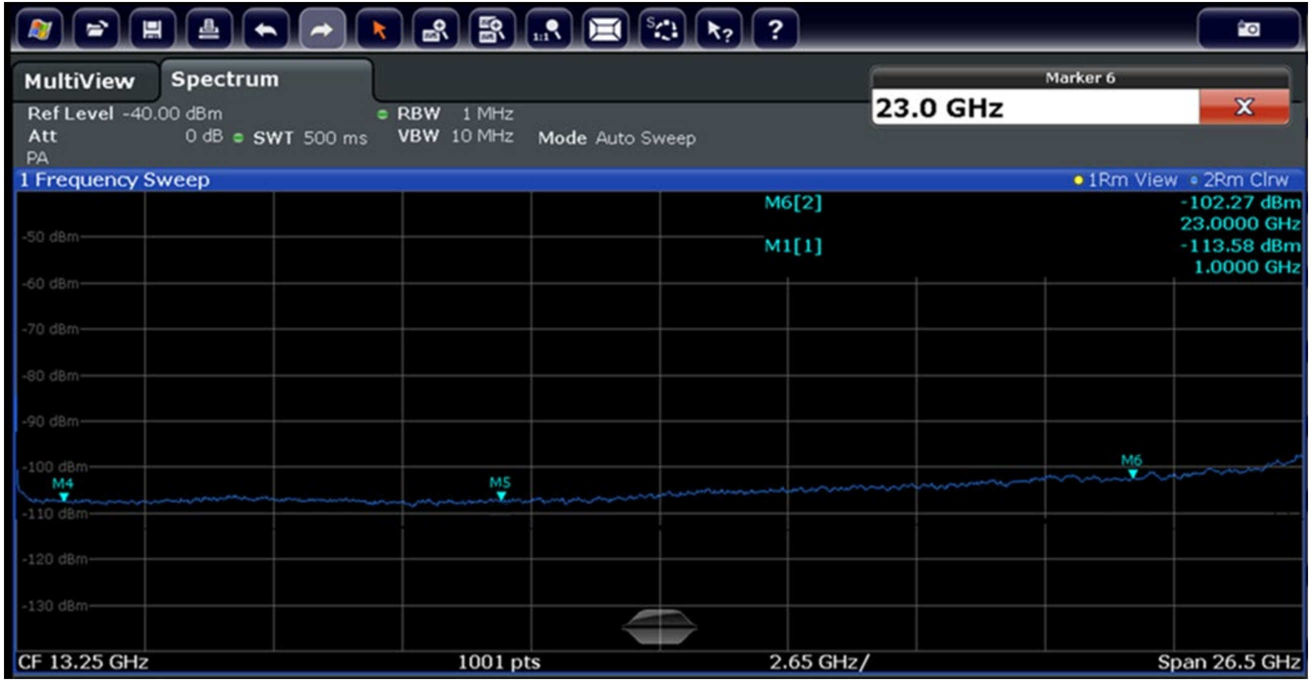
  - Where k is Boltzmann's constant = 1.38 x10-23 J / °K
  - T is the temperature in degrees kelvin (room temp ~ 19.8 °C = 293 °K)
  - To is defined as "standard temperature" and is equal to 290 °K = 16.8 °C
  - B is the noise bandwidth of the system

- At standard temperature (290 °K) , kToB = -174 dBm/Hz
  - At 85 °C, kTB = -173.1 dBm / Hz
  - At 19.8 °C, kTB = -173.9 dBm / Hz
  - At -30 °C, kTB = -174.7 dBm / Hz

Noise in a Bandwidth

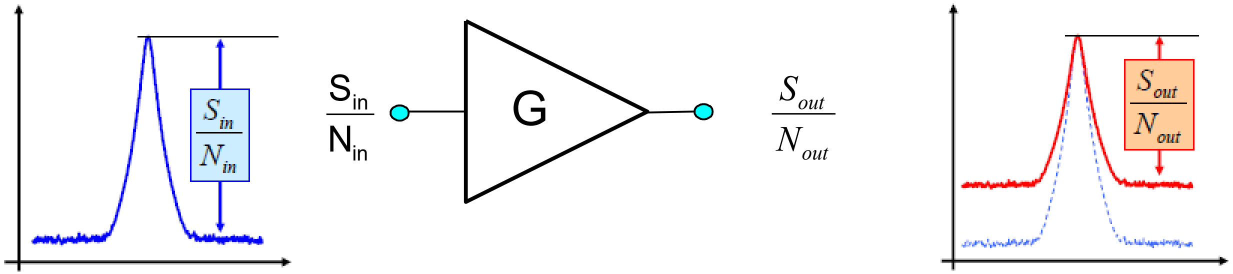
- **At standard temperature (290 °K) , kT_oB = -174 dBm/Hz**
- Determine system bandwidth, usually defined by standard or specification
- Convert Bandwidth to dB
- Add dB Bandwith to -174 dBm/Hz to determine noise floor
- Example
  - Channel bandwidth 1 MHz =1E6 Hz.
  - 10*log(1E6) = 60 dB

Noise Floor


MultiView
Spectrum
Marker 6
23.0 GHz
Ref Level -40.00 dBm
RBW 1 MHz
Att 0 dB
SWT 500 ms
VBW 10 MHz
Mode Auto Sweep
PA
1 Frequency Sweep
1Rm View
2Rm Clrw
M6[2]
-102.27 dBm
23.0000 GHz
M1[1]
-113.58 dBm
1.0000 GHz
-50 dBm
-60 dBm
-70 dBm
-80 dBm
-90 dBm
-100 dBm
-110 dBm
-120 dBm
-130 dBm
M4
M5
M6
CF 13.25 GHz
1001 pts
2.65 GHz/
Span 26.5 GHz

What is Noise Figure and Noise Factor?

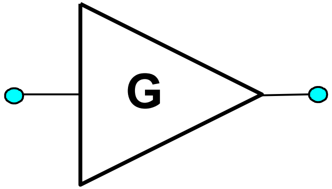
► Noise Figure and Noise factor are defined as the ratio of the SNR at the input to the SNR at the output of the device under test.



$$\text{(Linear) Noise Factor} = \frac{SNR_{in}}{SNR_{out}} = \frac{\left(\frac{S_{in}}{N_{in}}\right)}{\left(\frac{S_{out}}{N_{out}}\right)}$$

What is Noise Figure and Noise Factor?

$\frac{S_{in}}{N_{in}}$



$\frac{S_{out}}{N_{out}}$

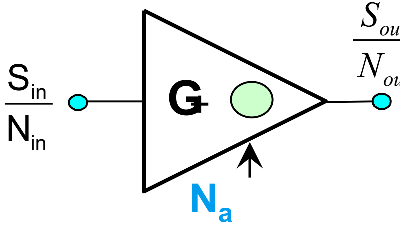
- It is a quantitative measure of a device's impact on signal to noise ratio.
  - Noise Factor → Linear values
  - Noise Figure → LOG scale values (in dB)

Noise Figure $F_{dB} = 10LOG(F)$

- Key question: Can any device improve the signal to noise ratio of a signal?

A real device…

- A **real device** adds some quantity of noise denoted N_a

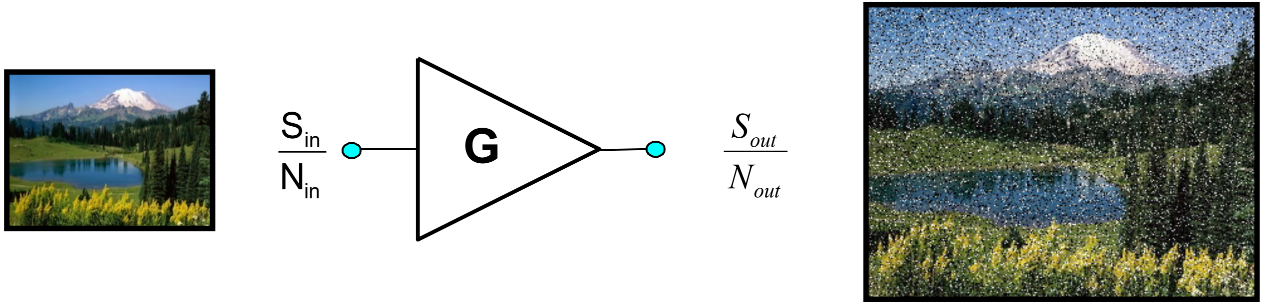


$$\frac{S_{out}}{N_{out}} = \frac{S_{in} \cdot G}{N_{in} \cdot G + N_a}$$

- **Then noise factor becomes:**

$$\text{Noise Factor } F = \frac{\left(\dfrac{S_{in}}{N_{in}}\right)}{\left(\dfrac{S_{in}G}{N_{in}G + N_a}\right)} = \frac{S_{in}}{N_{in}} \frac{N_{in}G + N_a}{S_{in}G} = \frac{N_{in}G + N_a}{N_{in}G}$$

What is Noise Figure and Noise Factor?

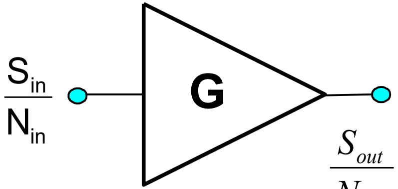


- Noise Figure and Noise factor are defined as the ratio of the SNR at the input to the SNR at the output of the device under test.

$$\text{(Linear) Noise Factor} = \frac{SNR_{in}}{SNR_{out}} = \frac{\left(\frac{S_{in}}{N_{in}}\right)}{\left(\frac{S_{out}}{N_{out}}\right)}$$

A perfect device…

- A perfect device would not add any noise to a signal



$$\frac{S_{out}}{N_{out}} = \frac{S_{in}\cdot G}{N_{in}\cdot G} = \frac{S_{in}}{N_{in}}$$

- A perfect device has a Noise Factor of 1

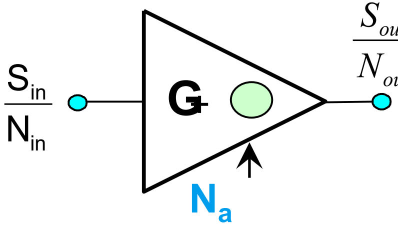
$$\text{Noise Factor } F = \frac{S_{in}/N_{in}}{S_{out}/N_{out}} = \frac{S_{in}/N_{in}}{S_{in}/N_{in}} = 1\text{ (Linear value)}$$

- A perfect device has a Noise Figure of 0 dB

$$\begin{aligned}\text{Noise Figure } F_{dB} &= 10LOG(F)\\ &= 10LOG(1)\\ &= 0\ dB\end{aligned}$$

IEEE standard definition

- $N_{in} = kT_oB$



$$\frac{S_{out}}{N_{out}} = \frac{S_{in} \cdot G}{N_{in} \cdot G + N_a}$$

- Then noise factor becomes:

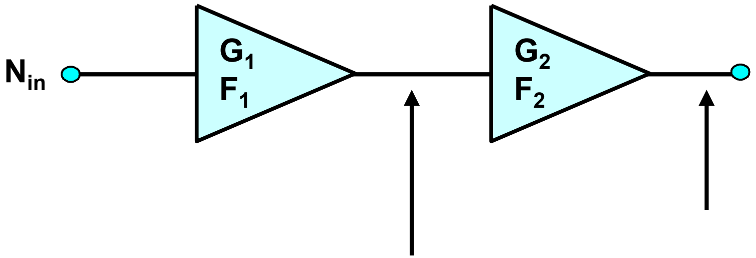
$$\text{Noise Factor } F = \frac{N_a + kT_oBG}{kT_oBG}$$

- This is the IEEE standard definition of Noise Factor

Noise Figure of Cascaded Components

Gain = 20 dB
NF = 2 dB

Gain = 20 dB
NF = 11 dB



$F_{dB} = 10LOG(F)$

N_{in}= -174 dBm/Hz

N_{a1}= -172 dBm/Hz
-154 dBm/Hz

N_{a2}=-163 dBm/Hz
-152 dBm/Hz
-134 dBm/Hz

(Linear) Cascaded Noise Figure:

$$F = F_1 + \frac{F_2 - 1}{G_1}$$

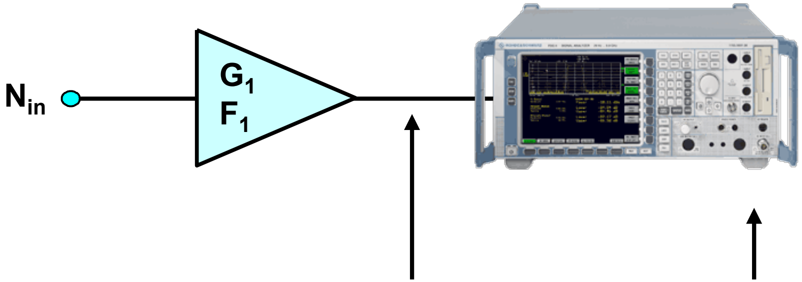
2.31 dB

Noise Figure of Cascaded Components

Gain = 20 dB

NF = 2 dB

NF = 11 dB



$F_{dB} = 10LOG(F)$

N_{in} = -174 dBm/Hz

N_{a1} = -172 dBm/Hz
-154 dBm/Hz

N_{a2}=-163 dBm/Hz
-152 dBm/Hz
-134 dBm/Hz

(Linear) Cascaded Noise Figure:

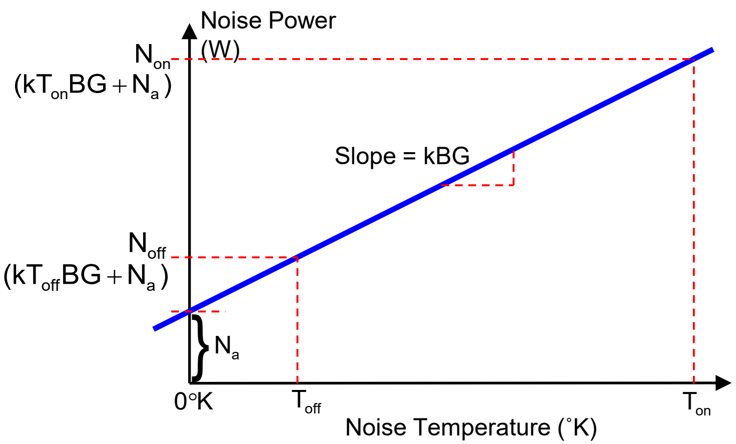
$$F = F_1 + \frac{F_2 - 1}{G_1}$$

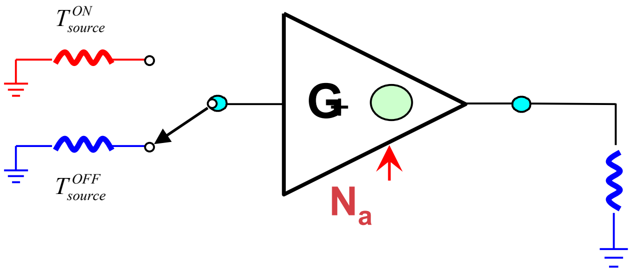
(Linear Terms: Not dB)

2.31 dB

Measuring Noise Figure

- We just described the Y-factor technique
- Make two measurements with a calibrated receiver
- Noise Source provides the “known” input signal
- Calculate Gain and Na of the device under test



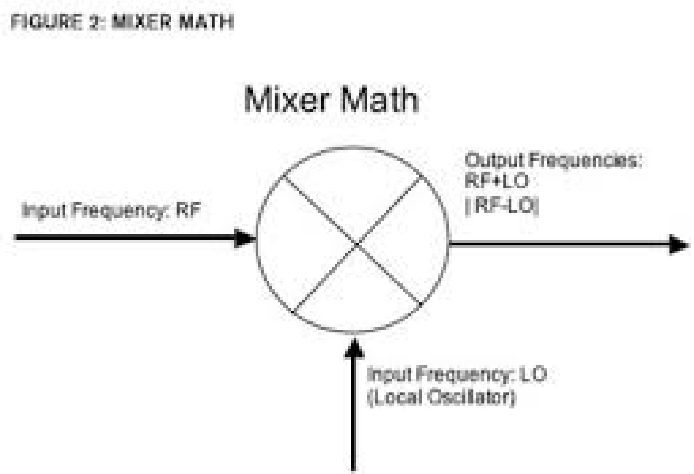


$$Y = \frac{N_{on}}{N_{off}} \quad \text{(Y-factor)}$$

Spurious Response

- In radio reception, a response in the receiver intermediate frequency (IF) stage produced by an undesired emission in which the fundamental frequency (or harmonics above the fundamental frequency) of the undesired emission mixes with the fundamental or harmonic of the receiver local oscillator.

Mixer Spurios Signal



Input
- Signal
- Difference
- RF, LO

Noisy Output
- Lo
- Reflections
- All Signals

Noisy Output
- Sum
- Difference
- RF, LO
- Harmonics
- Integer Multiples
- Reflections
- ALL Integer Multiples
- All Signals

Mixer Spurious Outputs

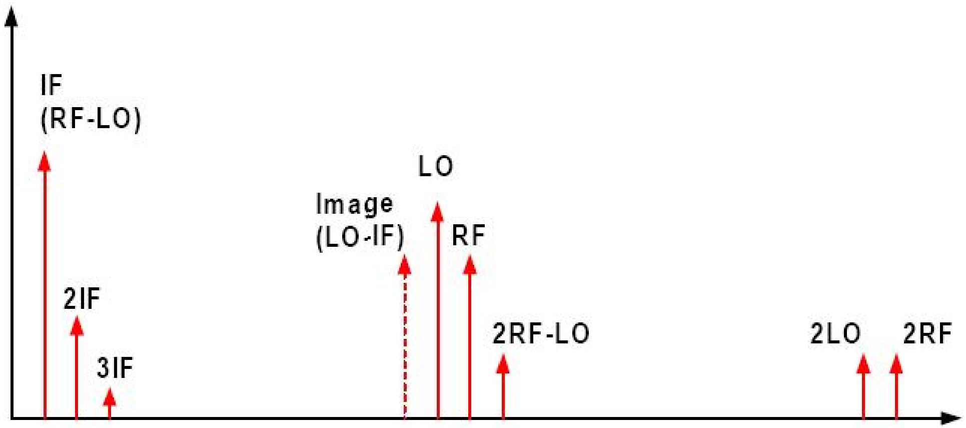


Figure 2: Mixer spectral output

Filter

- **IN BAND**
  - 3 dB Bandwidth
  - 1 dB Bandwidth
  - Insertion Loss (Max, Min Avg.)
  - Ripple
  - Phase Response
- **Out of Band**
  - Ultimate Rejection
  - 40 dB Bandwidth
  - Rejection at ?
  - Where do the signals go?

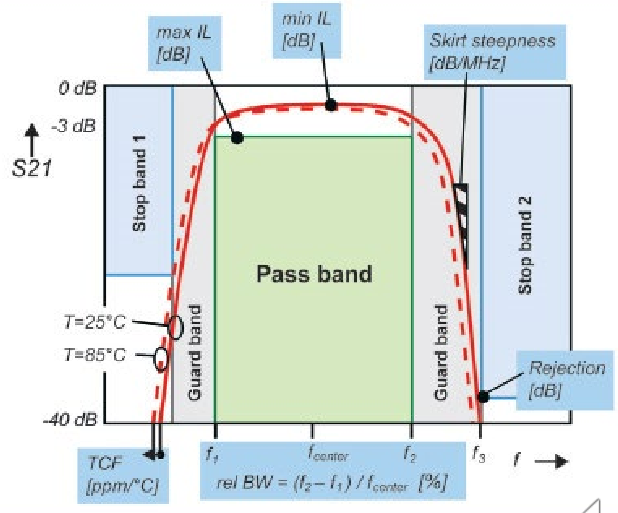
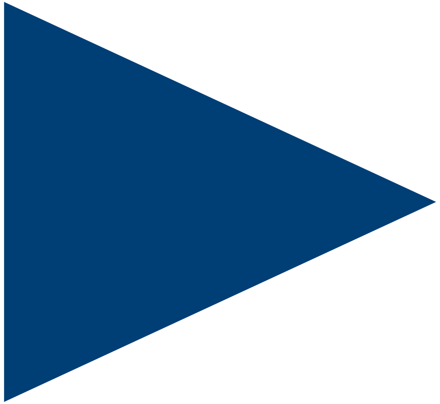


Figure 1: Illustration of RF Filter performance characteristi

Amplifier

SMALL

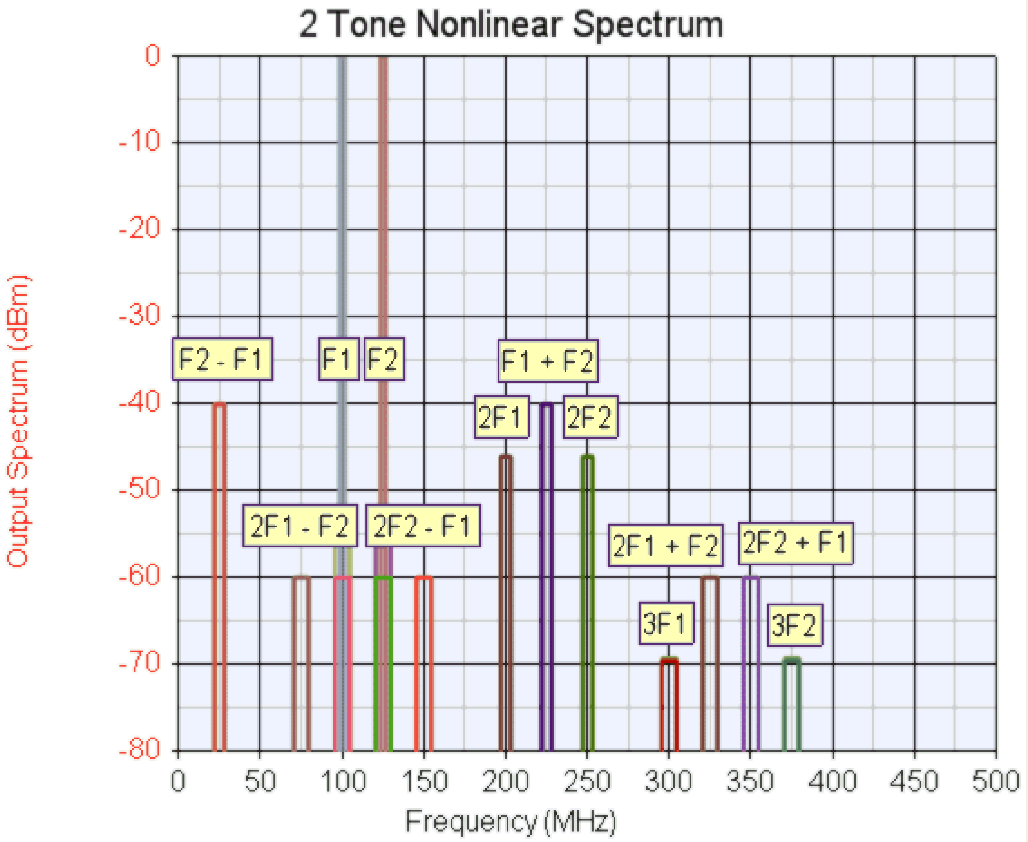
- kTB
- Noise Floor
- Noise Figure
- Dynamic Range



Large

- P1dB Compression
- OIP3
- ACPR
- Harmonics
- Spurious
- Dynamic Range

Amplifier Outputs

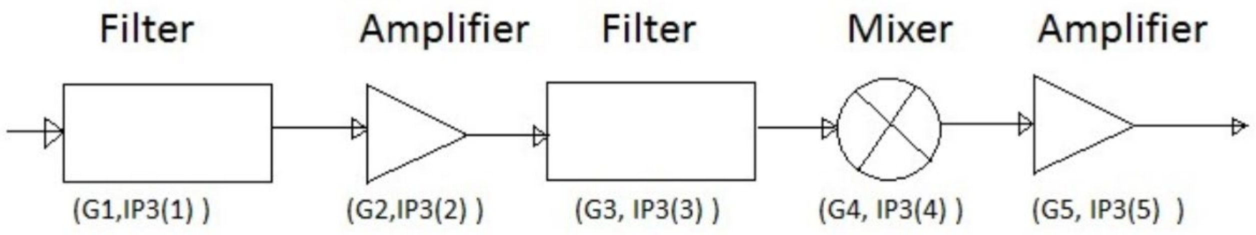


Cascade Analysis

- Cascade analysis is a simple yet powerful tool for analyzing system performance. You can analyze small-signal gain and noise figure nearly exactly, and come pretty close to modeling large-signal performance, such as predicting one-dB compression point and IP3.

- The noise figure equation is fairly simple. Adding a decent nonlinear equation for large-signal performance is a lot more complicated.

Cascade Analysis

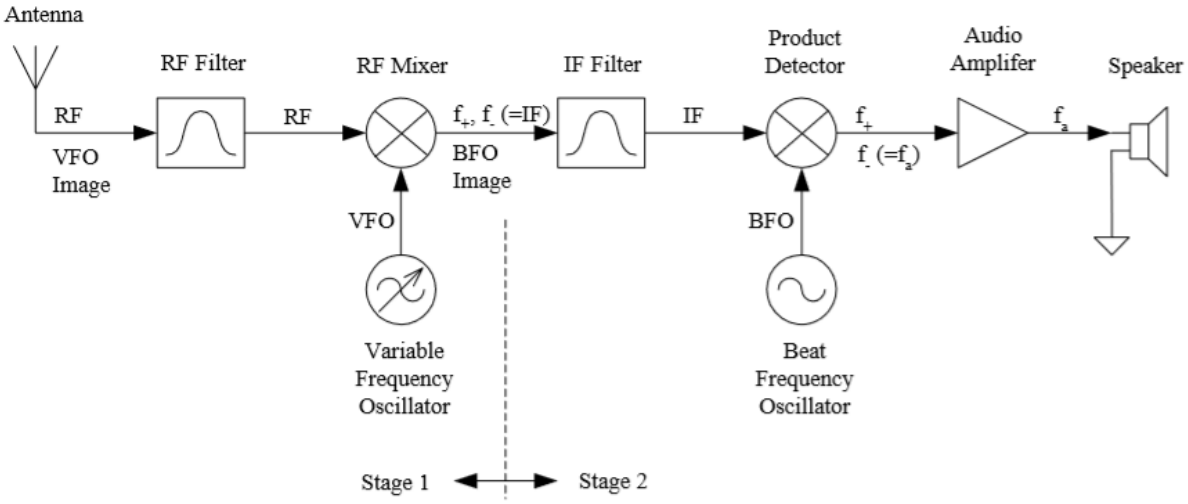


Cascaded Analysis

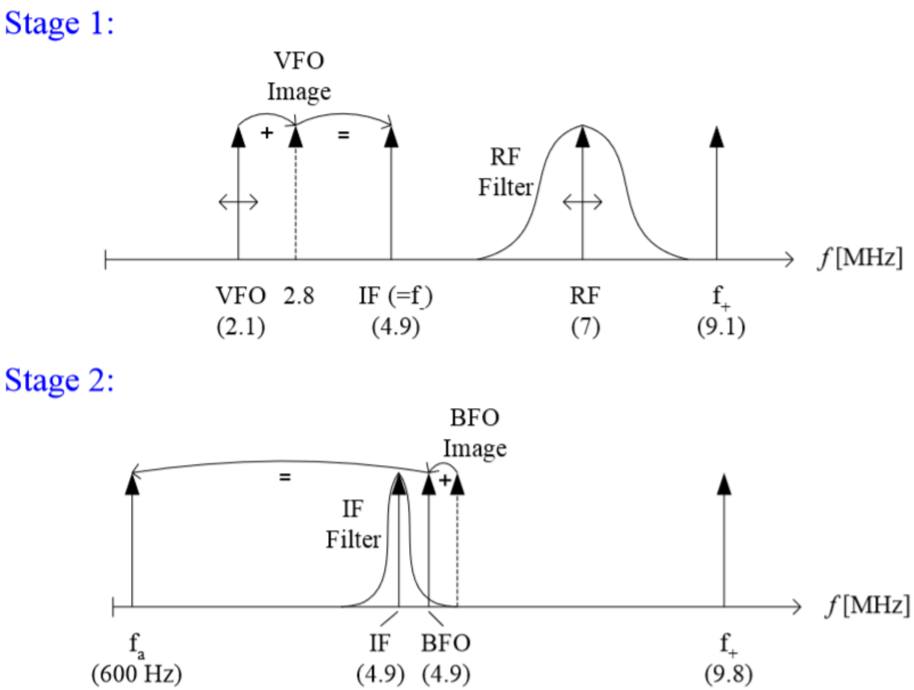
Device Parameters {@ Output}								
Component Designation	Gain (dB)	NF (dB)	IP2 (dBm)	IP3 (dBm)	P[sat] (dBm)	NBW (MHz)	Return Loss (dB) Input	Output
Amplifier	20.00	1.00	30.00	30.00	20.00	100.00	50.00	15.00
Filter	-3.00	3.00	250.00	250.00	250.00	100.00	50.00	15.00
Mixer	-7.00	7.00	25.00	25.00	15.00	100.00	50.00	50.00
Amplifier	20.00	2.00	30.00	30.00	20.00	100.00	50.00	50.00

Cumulative Output Parameters										
Gain (dB)	NF (dB)	IP2 (dBm)	IP3 (dBm)	P[sat] (dBm)	P[n] (dBm/BW)	SNR (dB)	DR (dB)	SFDR (dB)	IMD3 Power (dBm)	(DdB)
20	1	30	30	20	-72.85	92.85	92.85	68.57	0	20
17	1.03	27	27	17	-75.82	92.82	92.82	68.55	-3	20
10	1.3	16.12	18.81	10	-82.55	92.55	92.55	67.57	-7.61	17.61
30	1.48	26.51	29.46	20	-62.37	92.37	82.37	61.22	31.07	-1.07

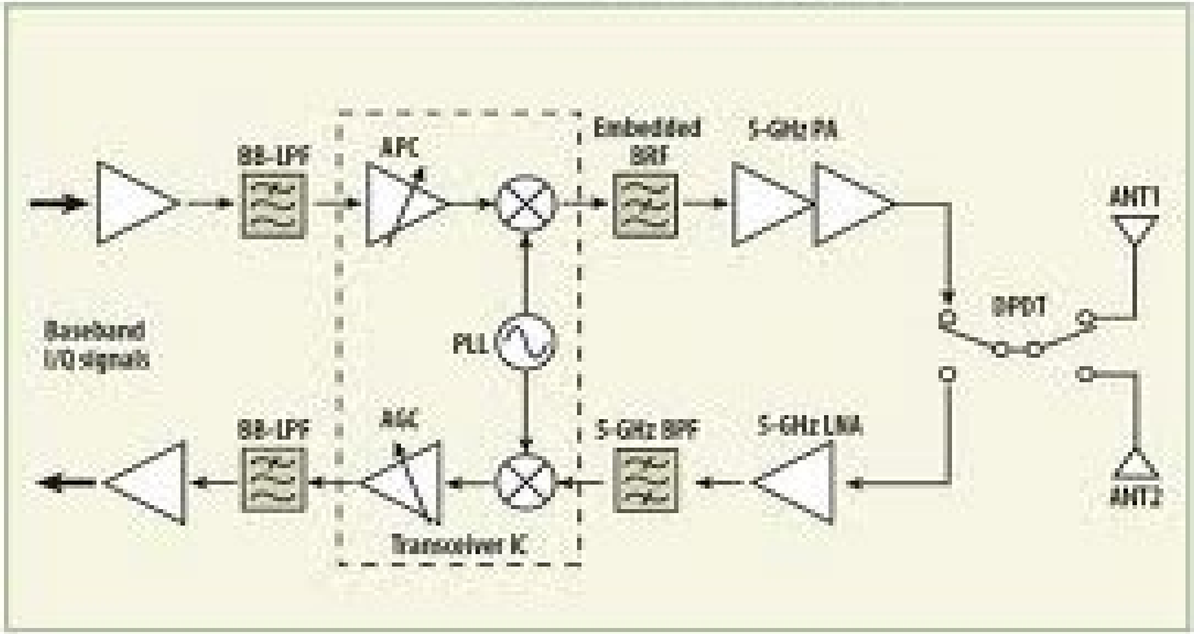
Superheterodyne Receiver



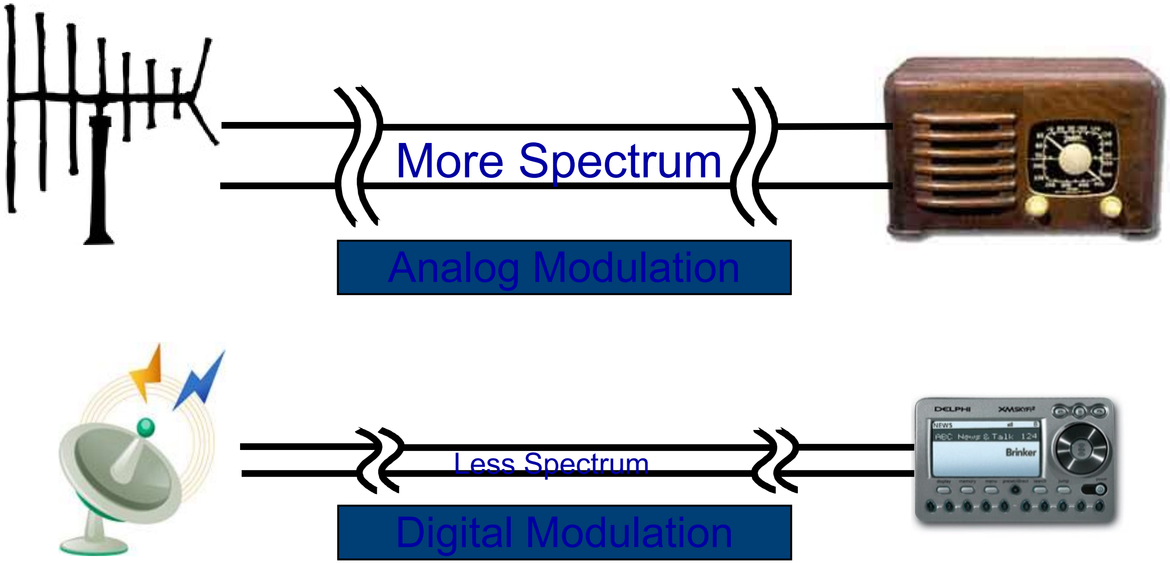
Superheterodyne Receiver Frequencies



Putting it all together

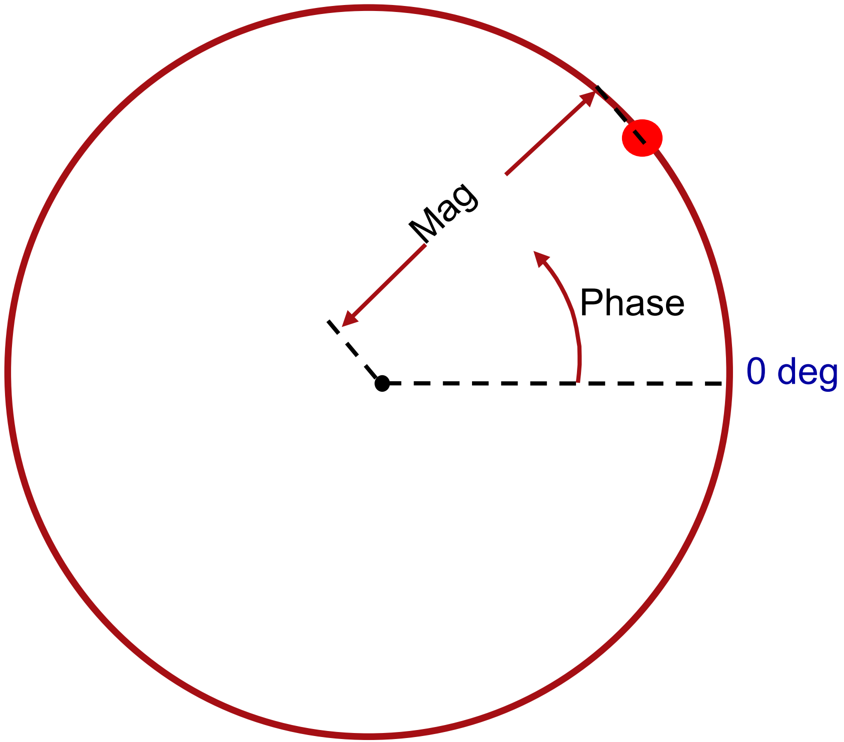


Why use Digital Modulation?



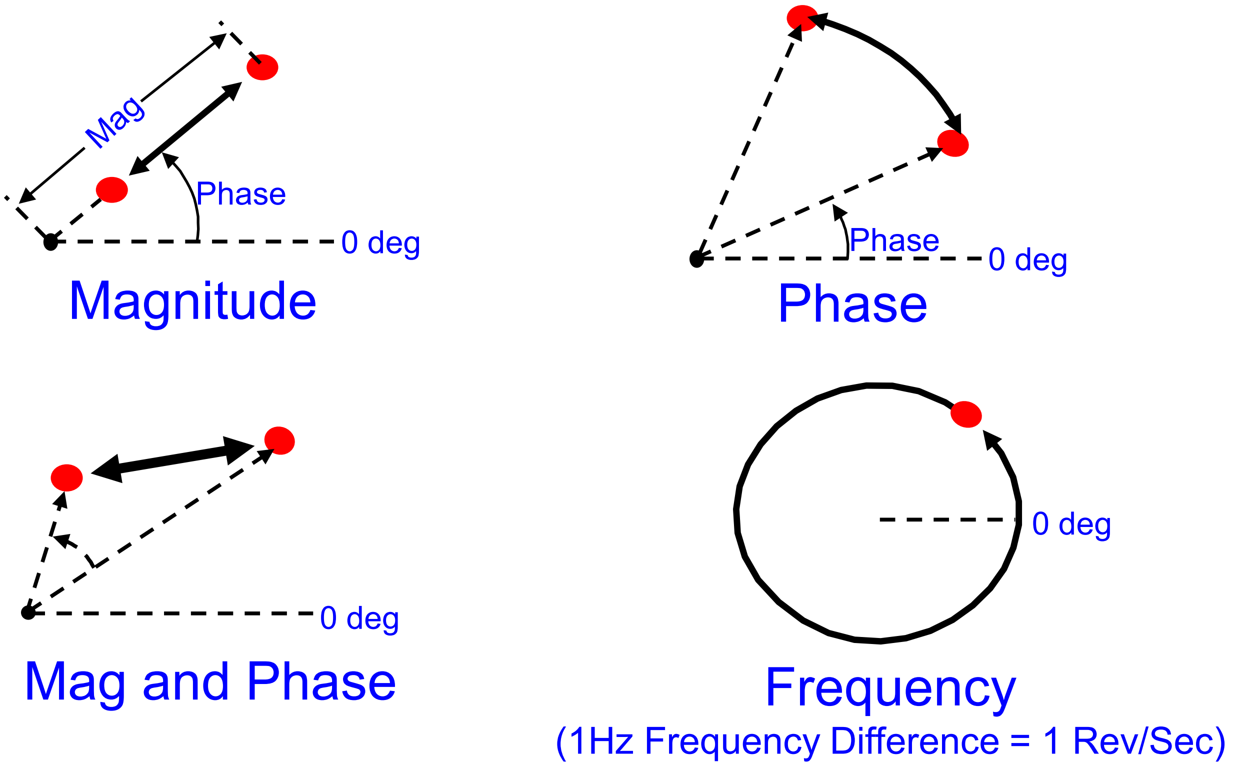
- Uses less spectral bandwidth ($$)
- Easier to transmit data than with analog modulation
- Can provide security against eavesdropping

Polar Display

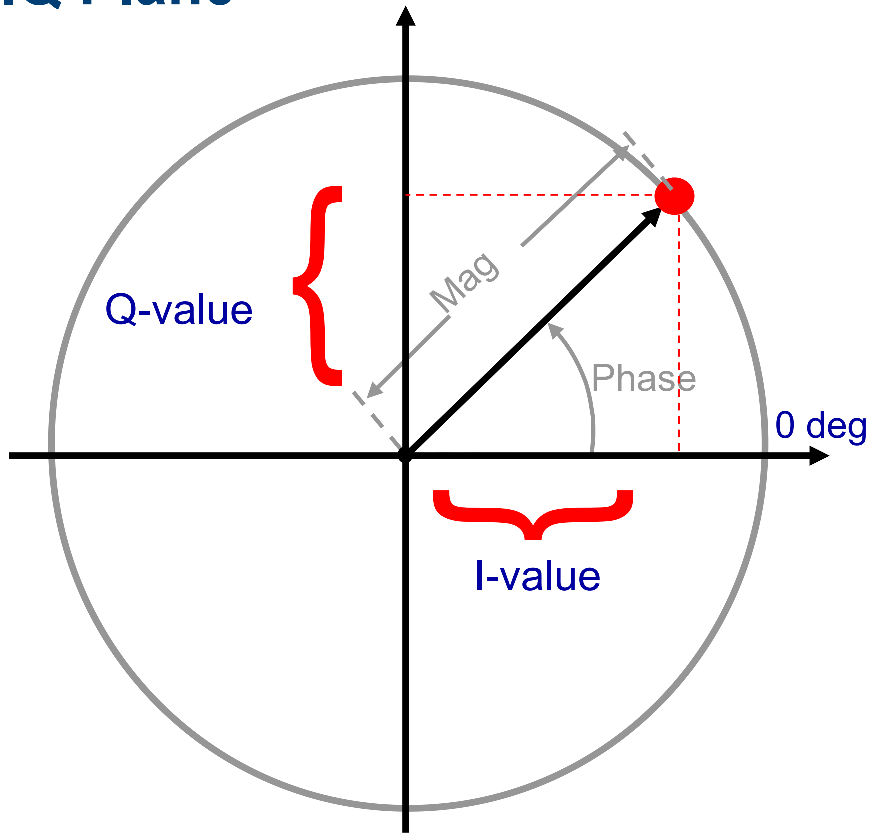


- Shows Magnitude and Phase relative to CW Carrier
  - Magnitude is an absolute value
  - Phase is relative to a reference signal (unmodulated carrier)

Carrier Modifications on Polar Display



IQ Plane



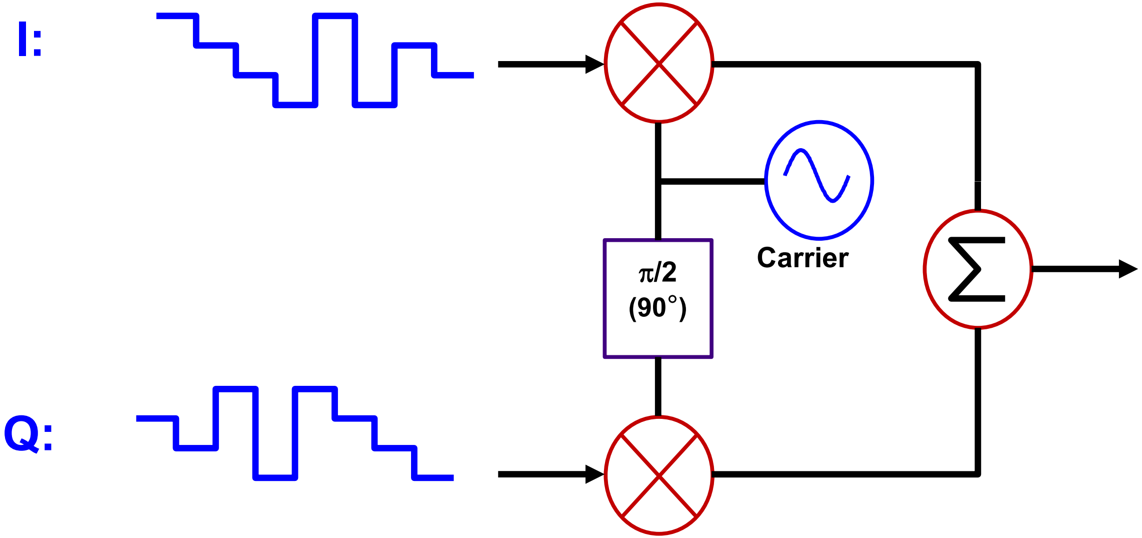
- Show Mag and Phase on "I" and "Q" Axes

- Polar to Rectangular Conversion

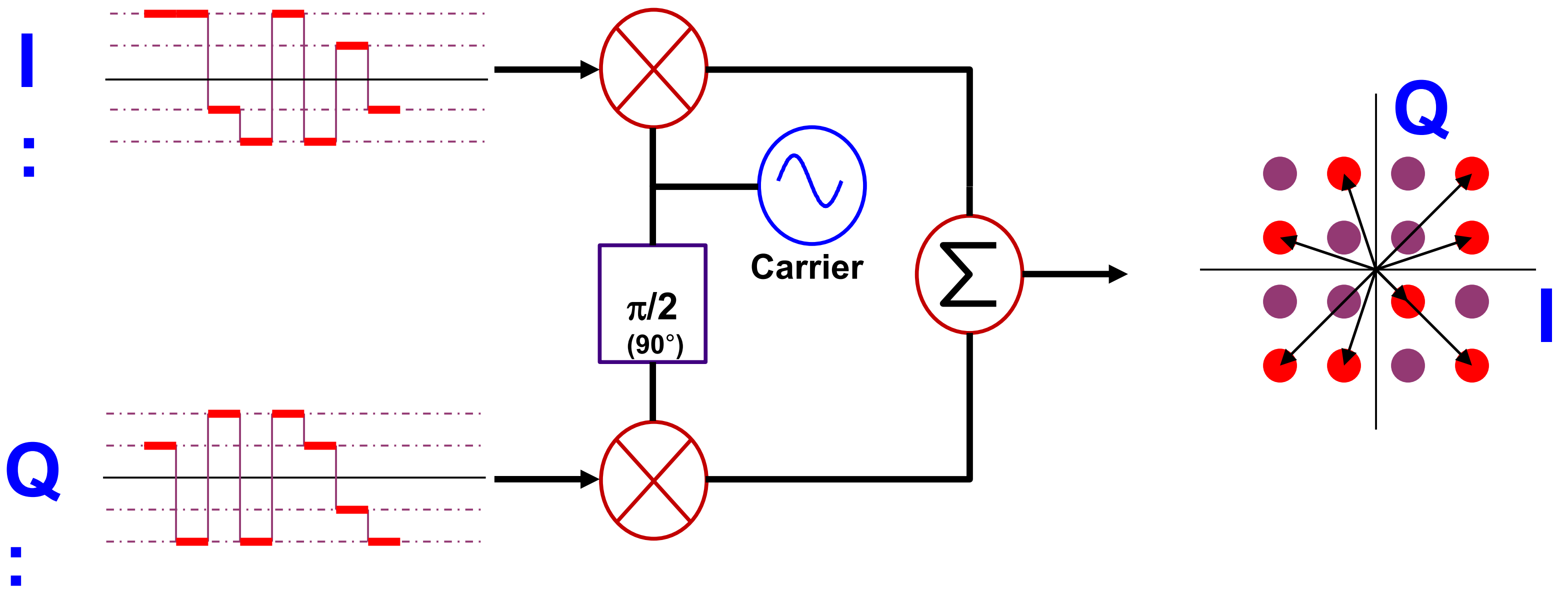
- IQ Plane Shows:
  - The phase of the modulated carrier relative to the unmodulated carrier, and
  - The baseband I and Q inputs required to produced the modulated carrier

IQ Modulation

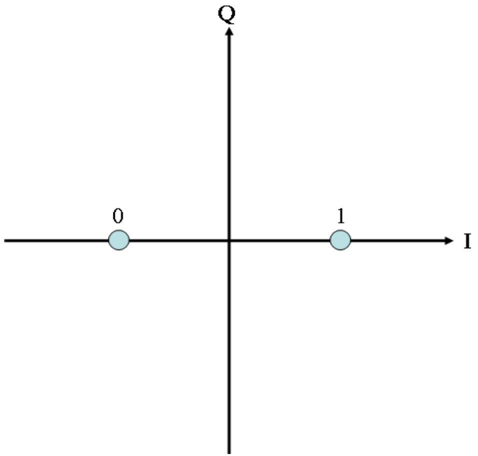
- ► Enables simultaneous amplitude and phase modulation
- ► Modulating signal can be treated as a phasor
  - – It has both an In-phase (I) and Quadrature (Q) component



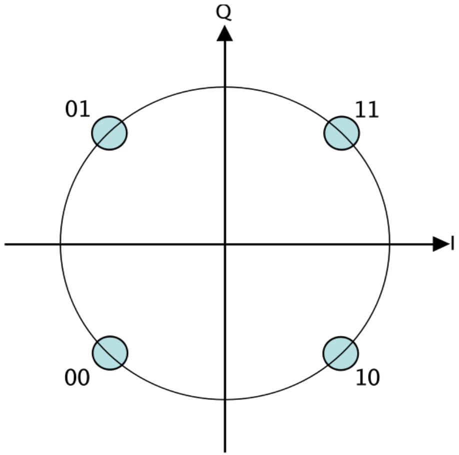
IQ Modulator



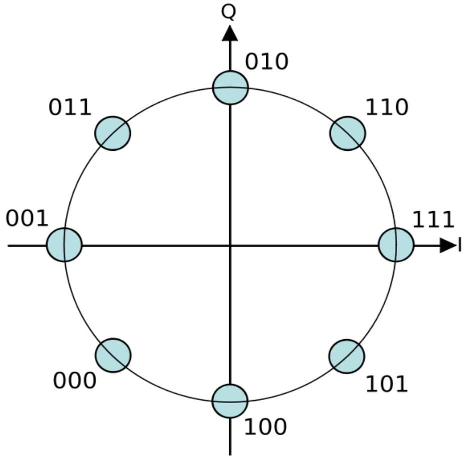
Digital Phase Modulation - Phase Shift Keying (PSK)



BPSK
(Binary Phase Shift Keying)



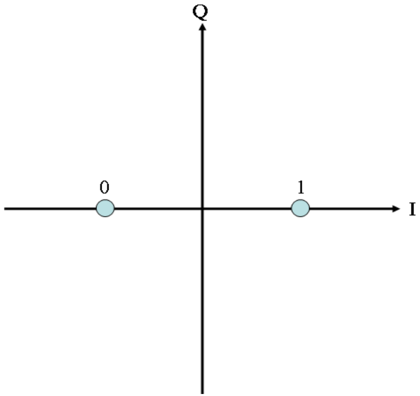
QPSK
(Quadrature Phase Shift Keying)



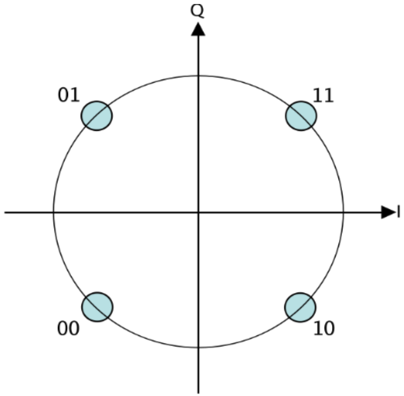
8PSK
(8 State Phase Shift Keying)

Constellation Diagrams

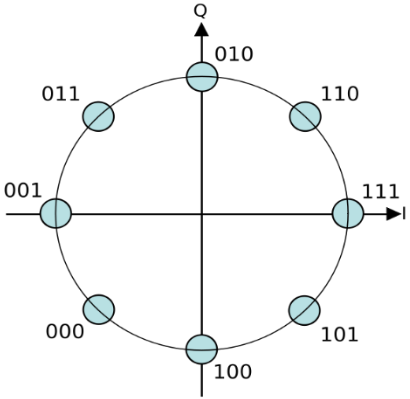
Bit Rate and Symbol Rate



BPSK
(1 bit per symbol)



QPSK
(2 bits per symbol)

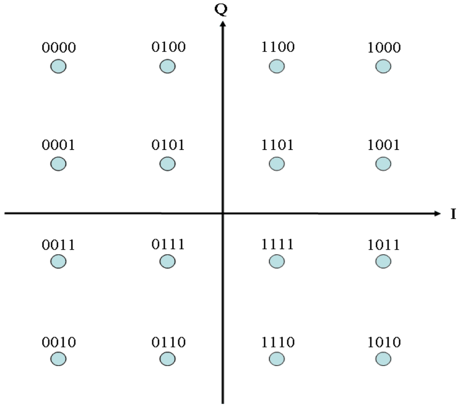


8PSK
(3 bits per symbol)

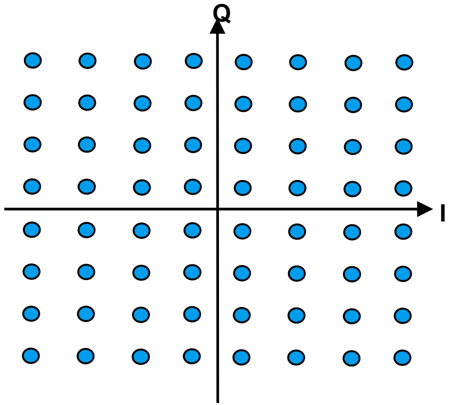
Bit Rate is the frequency of the system bit stream

Symbol Rate is the bit rate divided by bits per symbol
(Also known as Baud Rate)

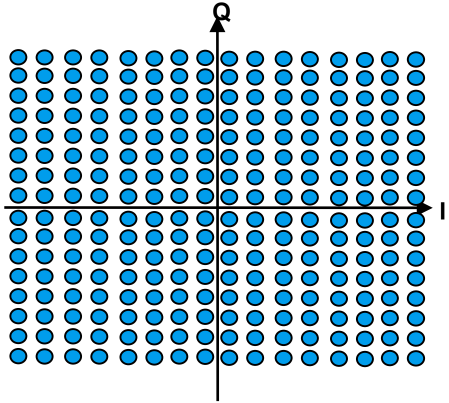
Digital Phase/Amplitude Modulation
-- Quadrature Amplitude Modulation (QAM)



16QAM
(4 bits per symbol)



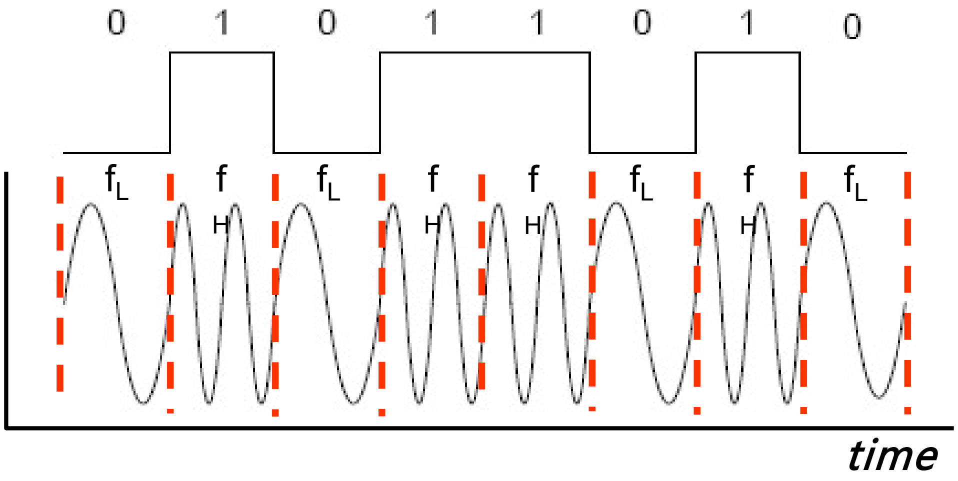
64QAM
(6 bits per symbol)



256QAM
(8 bits per symbol)

Constellation Diagrams

Digital Frequency Modulation
-- Frequency Shift Keying (FSK)



$f_L = f_c - f_\Delta$

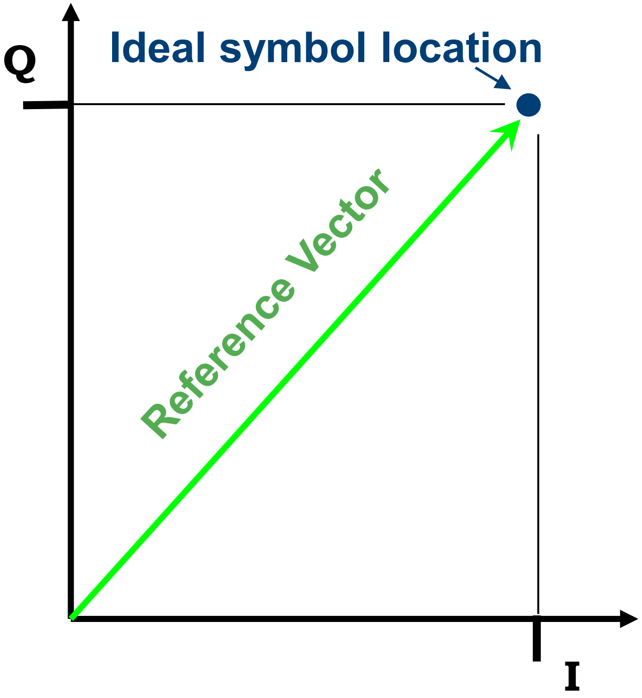
$f_H = f_c + f_\Delta$

Digital Modulation Quality Measurements

- EVM (Error Vector Magnitude)
  - Deviation from ideal signal
  - Measured at one symbol or averaged over many
- rho
  - Correlation to ideal signal
  - Only measured over many symbols
  - Can't calculate correlation with a single point

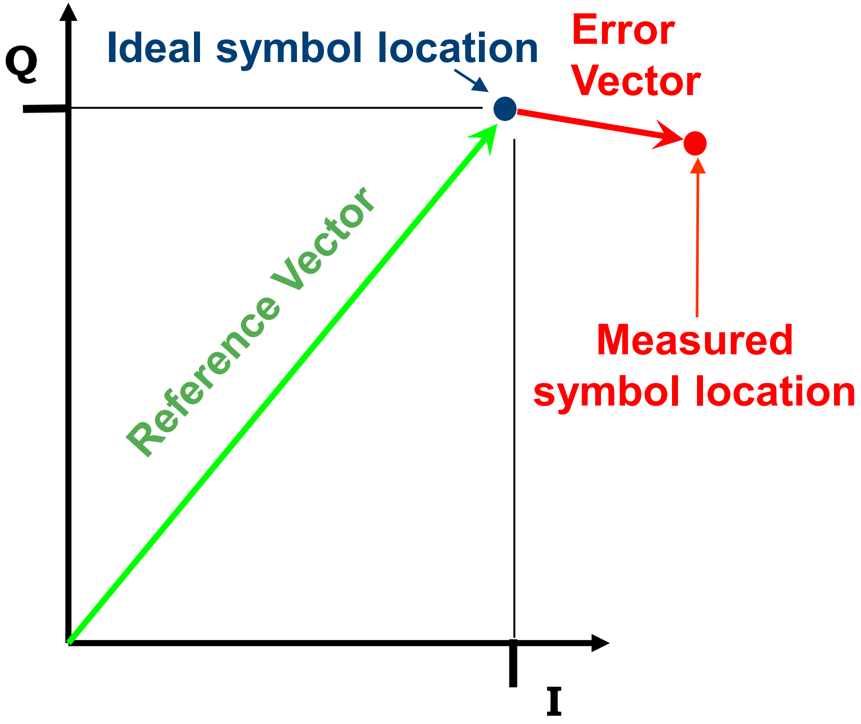
What is EVM? Reference Vector

- Must understand the Error Vector first



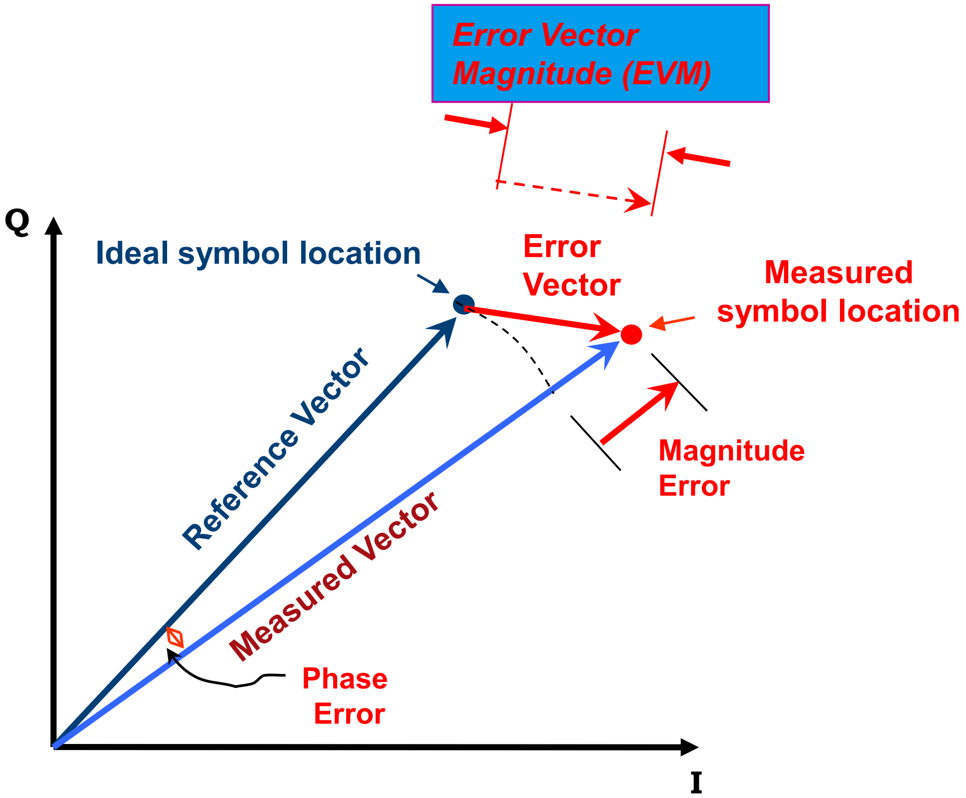
- EVM is probably the single most measured quantity on a digitally modulated signal.
- Start by defining an ideal symbol location in the IQ plane
- Then define a reference vector that points from the origin to the ideal location.

What is EVM? Error Vector



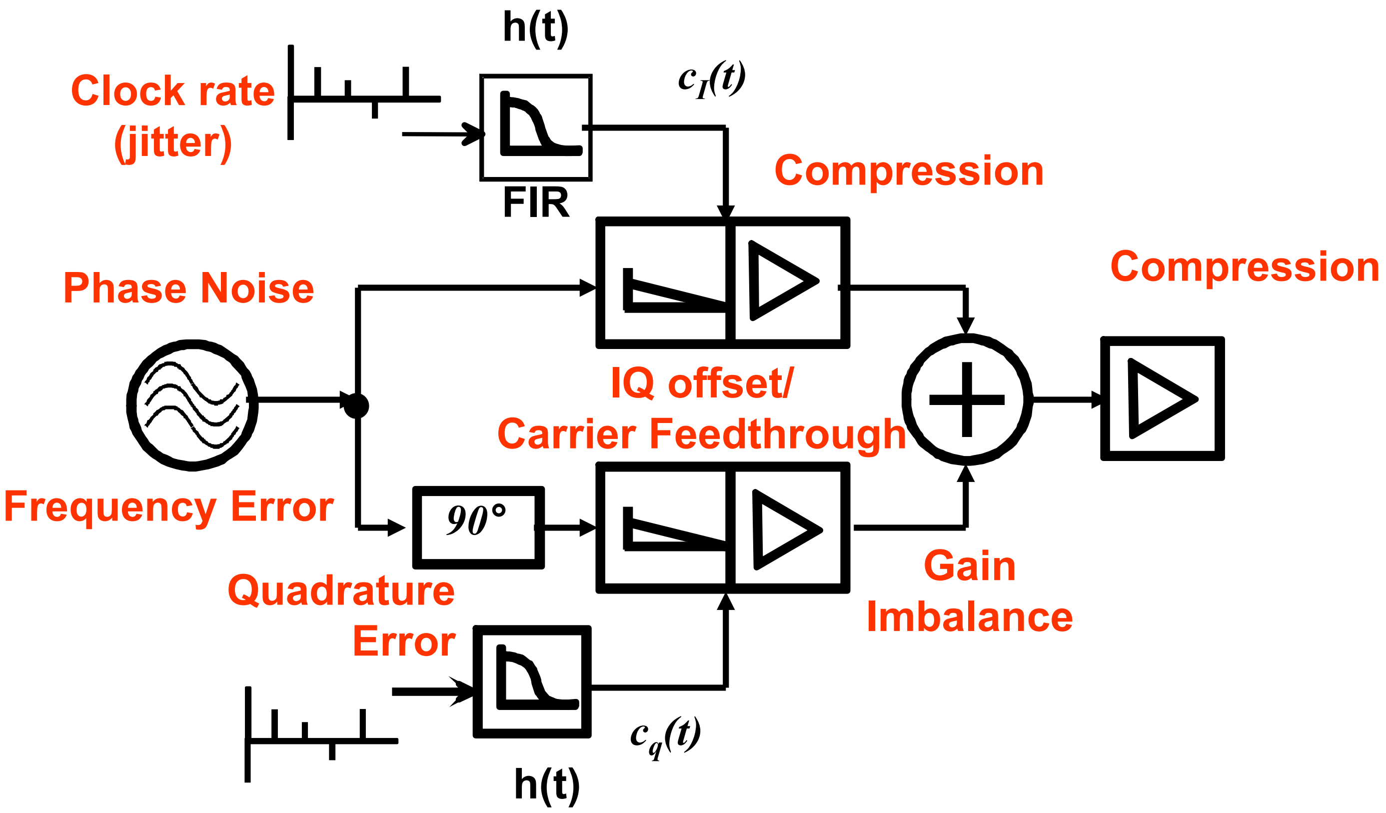
- The reference vector is (usually) the length from the origin to the ideal point that is the farthest away from the origin.
- Therefore, changing the modulation from QPSK to 64-QAM does not have an impact on the EVM result.
- This means higher order modulations require better EVM values.

What is EVM? Error Components

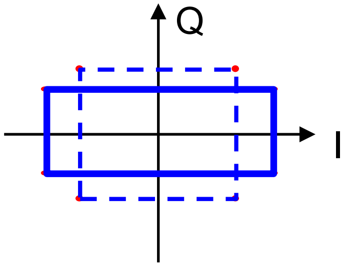


- EVM is 20 log (| error / ref |)

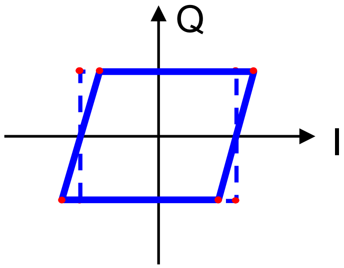
Sources of Modulation Error and How to Identify



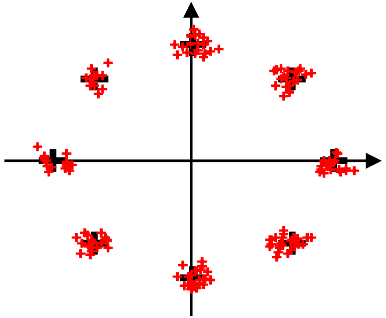
Some Modulation Errors viewed on Constellation Diagram



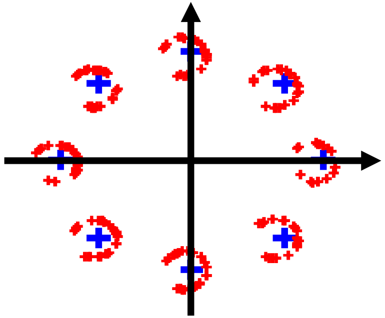
Gain Imbalance



Phase Imbalance



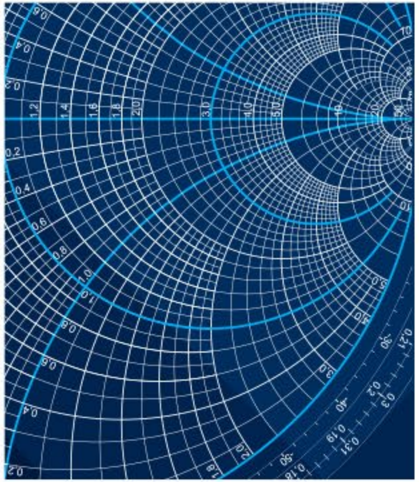
Low Signal/Noise



In-channel Spurious Interference

SUMMARY / Q&A

- Transmitters and receivers are ubiquitous in todays world
- Working in many fields of engineering requires a basic understanding of how modulation works for both Analog and Digital Signals
- Digital transmissions have good spectral efficiency but requires complex hardware
- Can provide secure communications
- Natural format for data transmission
- EVM is the standard figure of merit for modulation quality
- Constellation diagrams can be used to diagnose some problems



Measurement Techniques

Design Verification & Evaluation

EVERYTHING TEST

Instrument Selection & Optimization