AIM *RF Training for Test Engineers*

AIM *Smart Test Cell* STC8500 Strength

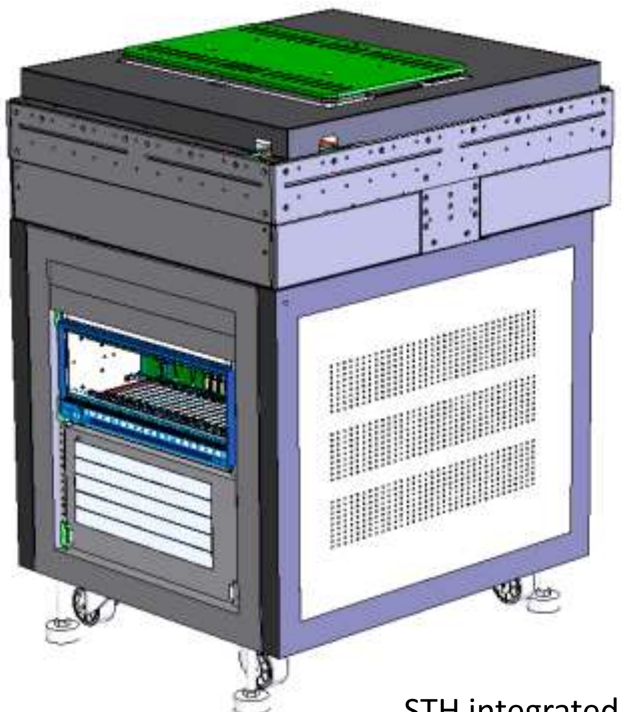
STC8500 is the only production solution for In-House ATE to Test Digital (AI/HPC), Mixed Signal and RF devices in HVM:

- High density analog and digital instrumentation for testing devices in high volume multisite
- Focused configurations optimized to deliver lowest cost of test
- Test platform’s small footprint and low power consumption delivers industry’s lowest operating costs
- Universal instrument architecture – allowing easy scaling to massive multi-site configurations for a broad range of Digital, Analog and RF options aligned with all test needs
- RF options: WiFi, BT, FEM, 5G, mmWavw, Radar/Lidar, Satellite, Optical communication
- Software Defined Testing: Protocol based programming models
- Custom Designed Hardware and Software: ODM for in-house ATE, CP, FT solutions
- Worldwide Local Technical support

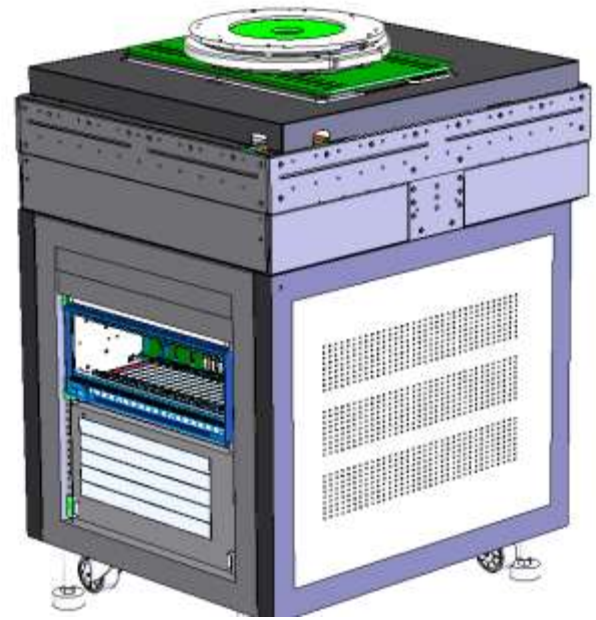
Confidential

wireless test solutions

AIM Smart Test Cell – STC8500



With POGO Tower



STH integrated with 12U chassis

AIM
wireless test solutions

Agenda

- General RF terms
- ATE RF RX tests
- ATE RF TX tests

- This presentation won’t cover DC tests, digital tests, RX/TX detector tests (Saturation/Energy/Envelope/Peak/Power)
- Won’t cover RF Loopback tests, calibration tests, BT-LPPS, RX-AGC, ADC and DAC tests

RF test acronyms

RF: Radio Frequency
IF: Intermediate Frequency
Pwr: Power
Pout: Output Power
Psat: Saturation Power
RSB: Residual Side Band (sometimes referred to as SB or LSB)
LO: Local Oscillator
CS: Carrier (LO) Suppression
IPN: Integrated Phase Noise
DCOC: DC Offset Correction
IMD: Intermodulation distortion
IP3: Third Order Intercept Point ; IIP3=Input ; OIP3=output
IP2: Second Order Intercept Point ; IIP2=Input ; OIP2=output
P1dB: 1dB compression point
NF: Noise Figure
SNR: Signal to Noise Ratio
LNA: Low Noise Amplifier
PA: Power Amplifier
TIA: Trans Impedance Amplifier
BQ: Biquad Filter (ratio of 2 quadratic functions)

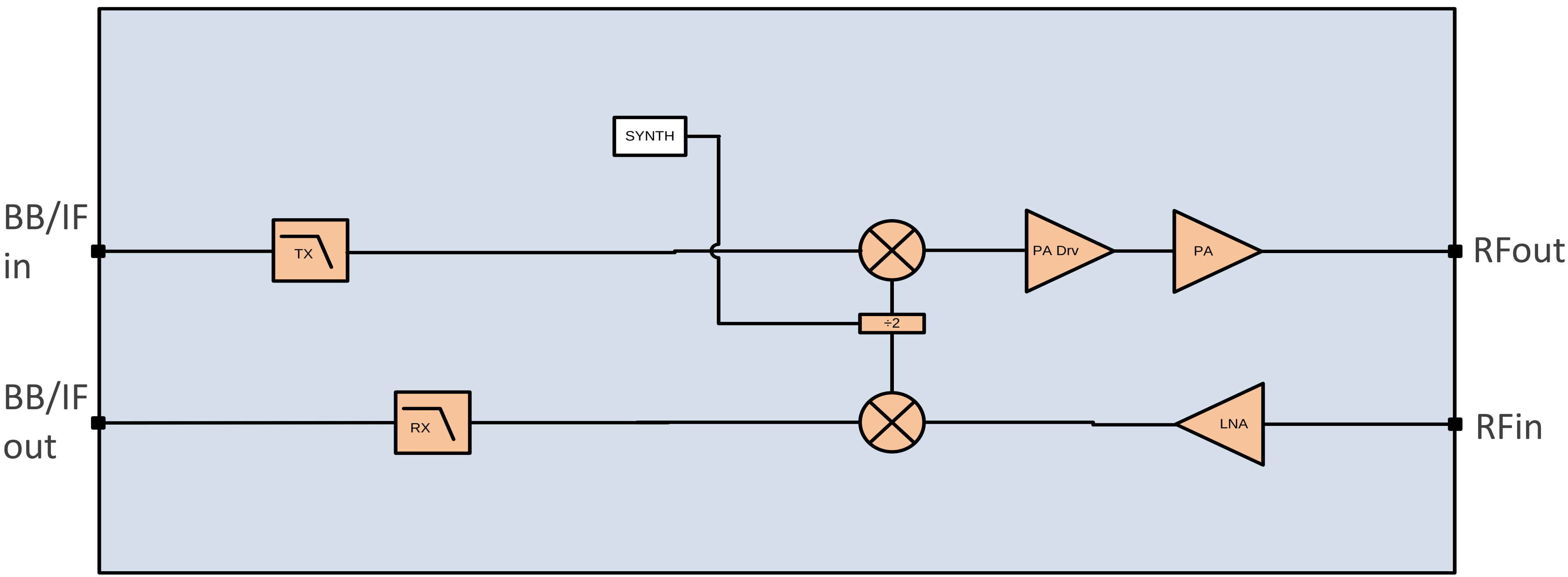
RX Test parameters

Objective specification parameters	Comments	ATE test capability
Frequency range	2.4GHz – 2.5GHz ; 4.9GHz - 5.9GHz	Yes
Maximum power gain	Power gain is defined from chip input to I and/or Q output under matched RF input conditions. Reference impedance is 50Ω.	Yes
Minimum power gain		Yes
Gain control range		Yes
Gain control step size	And gain variation over PVTF	Yes
NF over gain range		Yes
DCOC (with/without Jammer)	Static DC offset	Yes
LNA+GM IIP3/IIP2 requirements	GM=transconductance, converts voltage to current	Yes
IP3, IM3	Full RX chain	Yes
IP2, IM2	Full Rx chain	Yes
P1dB		Yes
Wide P1dB		Yes
RSB (un-calibrated)	Calculated out of amplitude/gain and phase imbalance	Yes
Phase/Amplitude imbalance		Yes
Vcm or Vcom	Common mode voltage of I/Q outputs	Yes

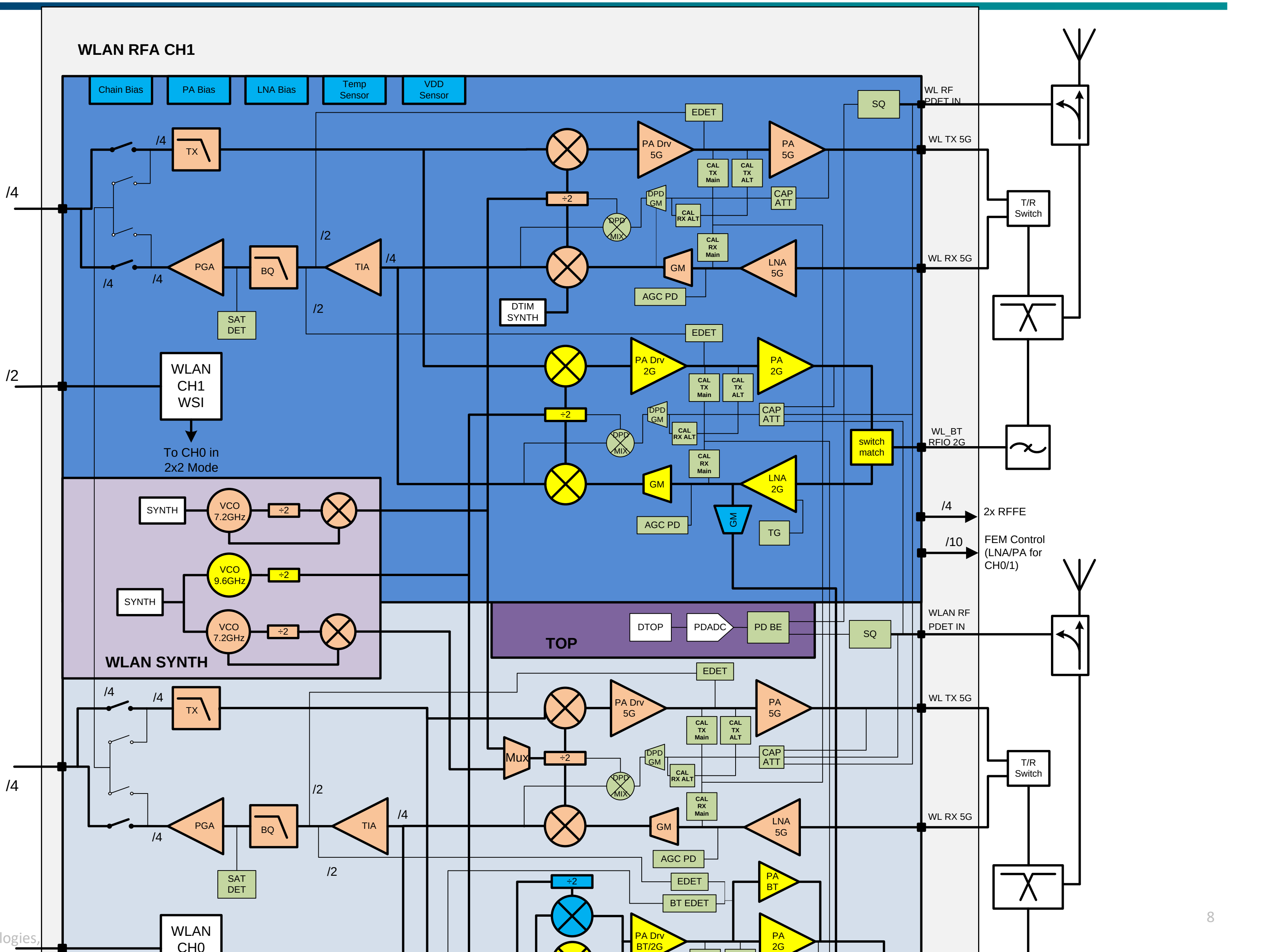
TX Test parameters

Objective specification parameters	Comments	ATE test capability
Frequency Range	2.4GHz – 2.5GHz ; 4.9 - 5.9GHz	Yes
Output power (minimum & maximum)		Yes
Gain Control Range & step size		Yes
Psat		Yes
Carrier Suppression	With cal	Yes
Sideband Suppression	Without cal	Yes
OIP3		Yes
P1dB		Yes
Harmonics		Yes

Device RF bock diagram



Cherokee block diagram



Log vs. linear

What’s up with those dB’s ?

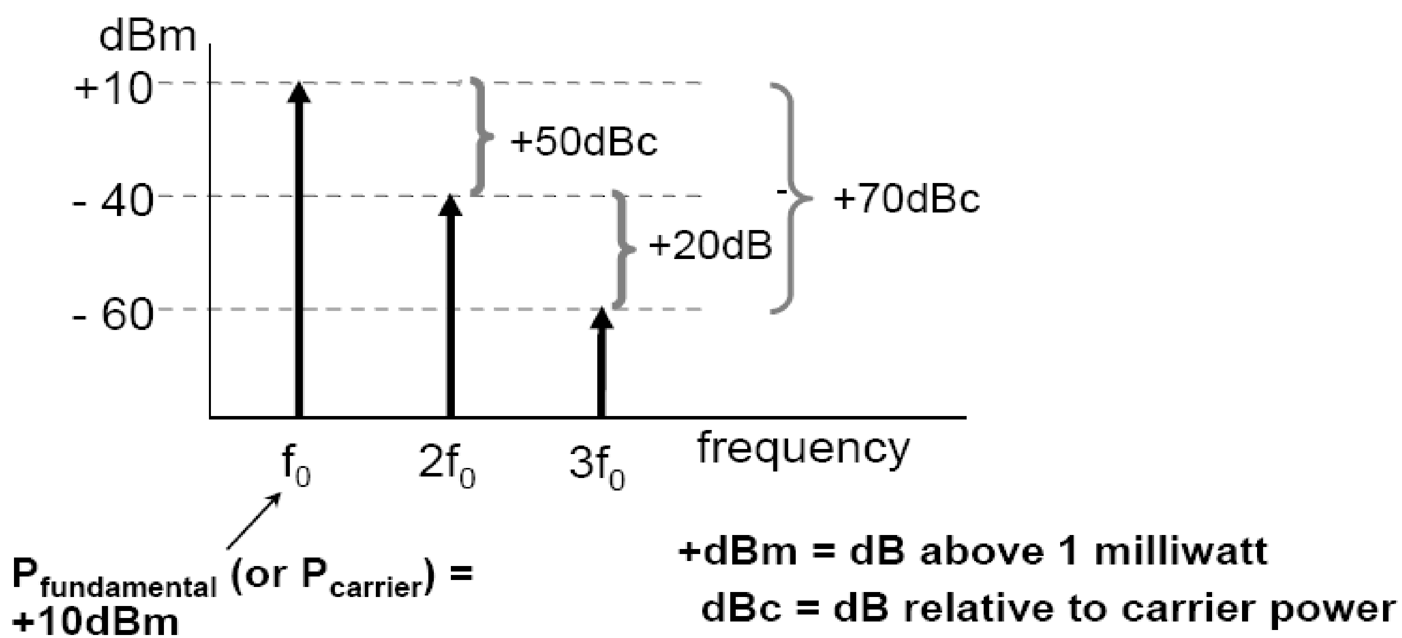
dBm – dB in reference to 1mWatt ; absolute power ; should be rather spelled dBmW

BMW

dB – refers to a relative difference

dBc – a specific relative difference (in this case, to a carrier signal)

Sometimes, dB is used in place of dBc, dBm. But remember dB and dBc are relative. They are not referenced to 1mW but rather to a predefined signal, whereas dBm is an absolute value with a reference to 1 mWatt.



Log vs. linear (cont.)

dBmW	Impedance	dBmV	dBuV	Watt	Volt	Vpp
7	**50**	43.98970004	113.9897	0.00501187	0.50059326	1.21589157

In the world of power – the calculation is 10*LOG10(P/P0) ; for dBm P0 = 1mWatt

In the world of voltage – the calculation is 20*LOG10(V/V0)

0dBm = 1mWatt ; 30dBm = 1 Watt ; how much is 3dBm in mWatt?

Logarithmic scale: multiplication is transformed to addition

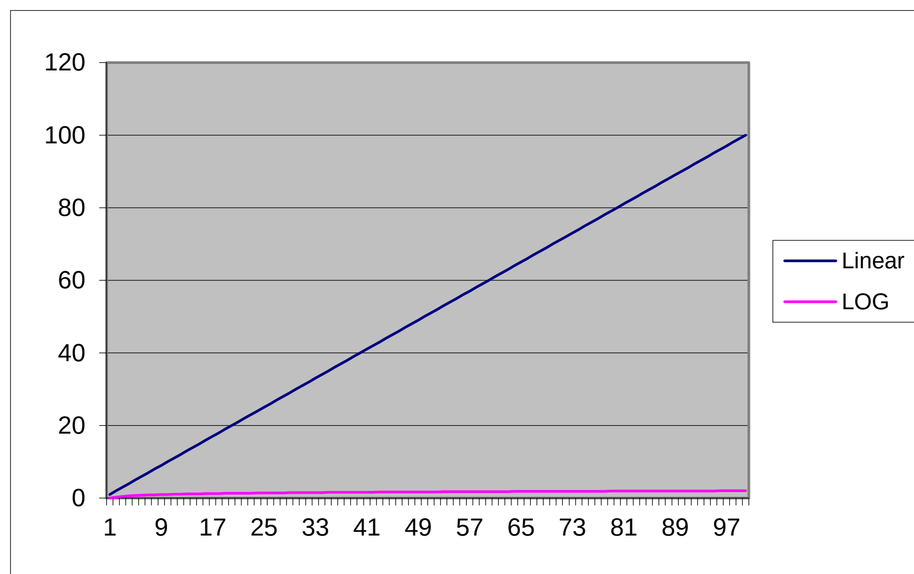
In the RF world all calculations are usually done in log format.

All numeric calculations assume an impedance of 50 Ohm.

In RF we sometimes deal with very low signals and at the same time high signals.

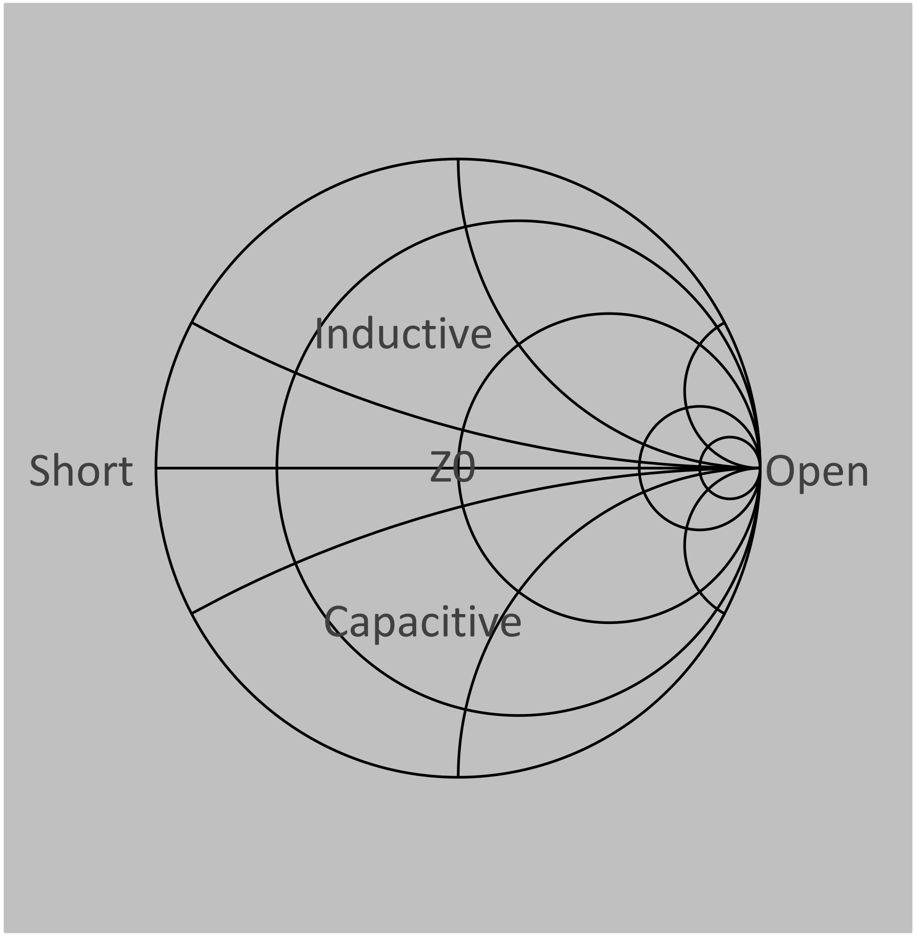
For instance -90dBm is 1Pico Watt (1E-12)

or 30dBm is 1 Watt



Smith Chart

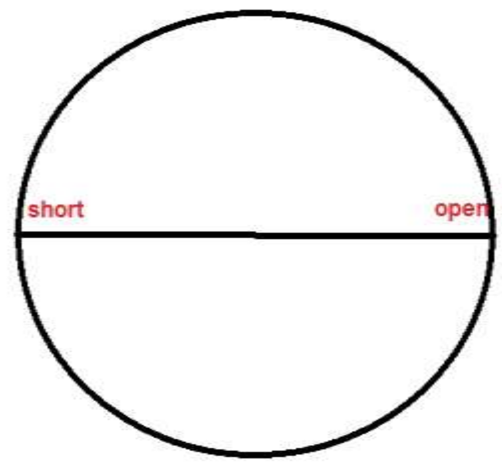
Impedance chart

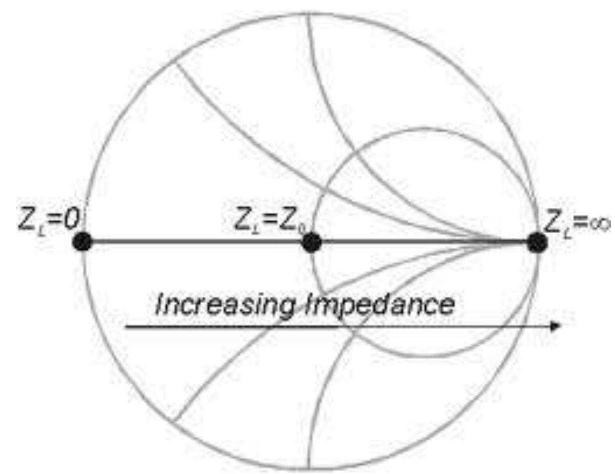


Smith Chart uses normalized impedance

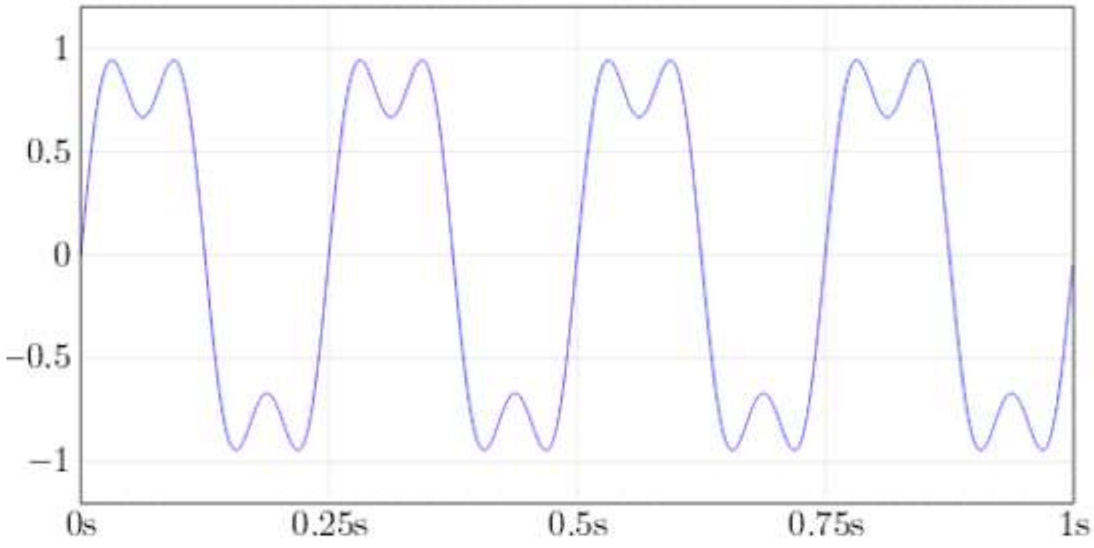
Smith Chart (cont.)

- All though the smith chart looks quite complex. It can be broken down into key elements.
- Think of line in the middle as a regular number line.
- With 0 on the left and infinity on the right.
- The points on the smith chart are represented by R +- jX= Z, The line is where jX held to zero
- Ideal Z is where Load and source impedance are equal to the system impedance. This value is 50 ohms in most of our RF cases. However it is representative of the system requirement and could be a different value.

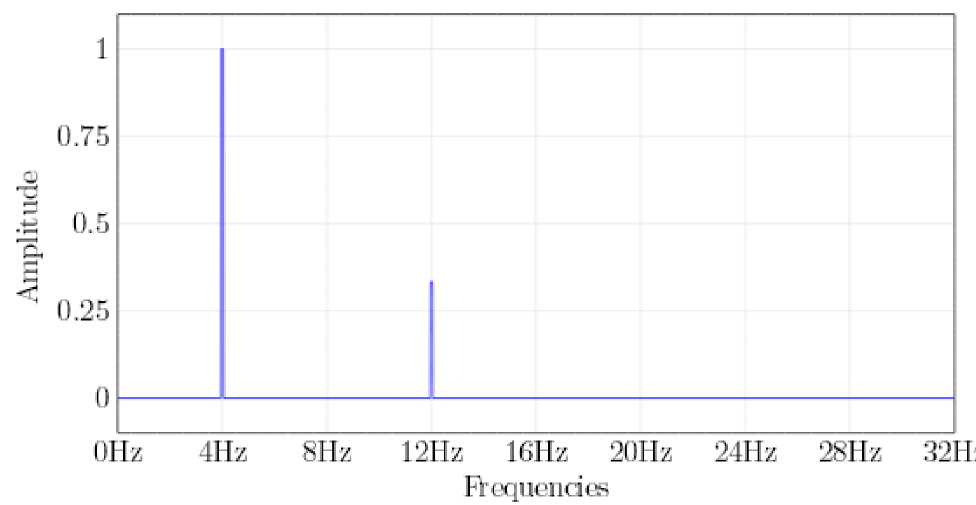




Time domain vs. Frequency domain



Digitize and process the signal using FFT = Fast Fourier Transform



Programming the ATE instruments

Coherent sampling: The phase of a signal to capture (digitize) at the point the digitize starts needs to be exactly the same phase at the time when the digitize ends.

Fs: sampling frequency
Fi: The frequency of the signal we are measuring
N: Total number of samples taken
M: Number of cycles of the captured signal

$$\frac{f_s}{N} = \frac{f_{\text{interest}}}{M}$$

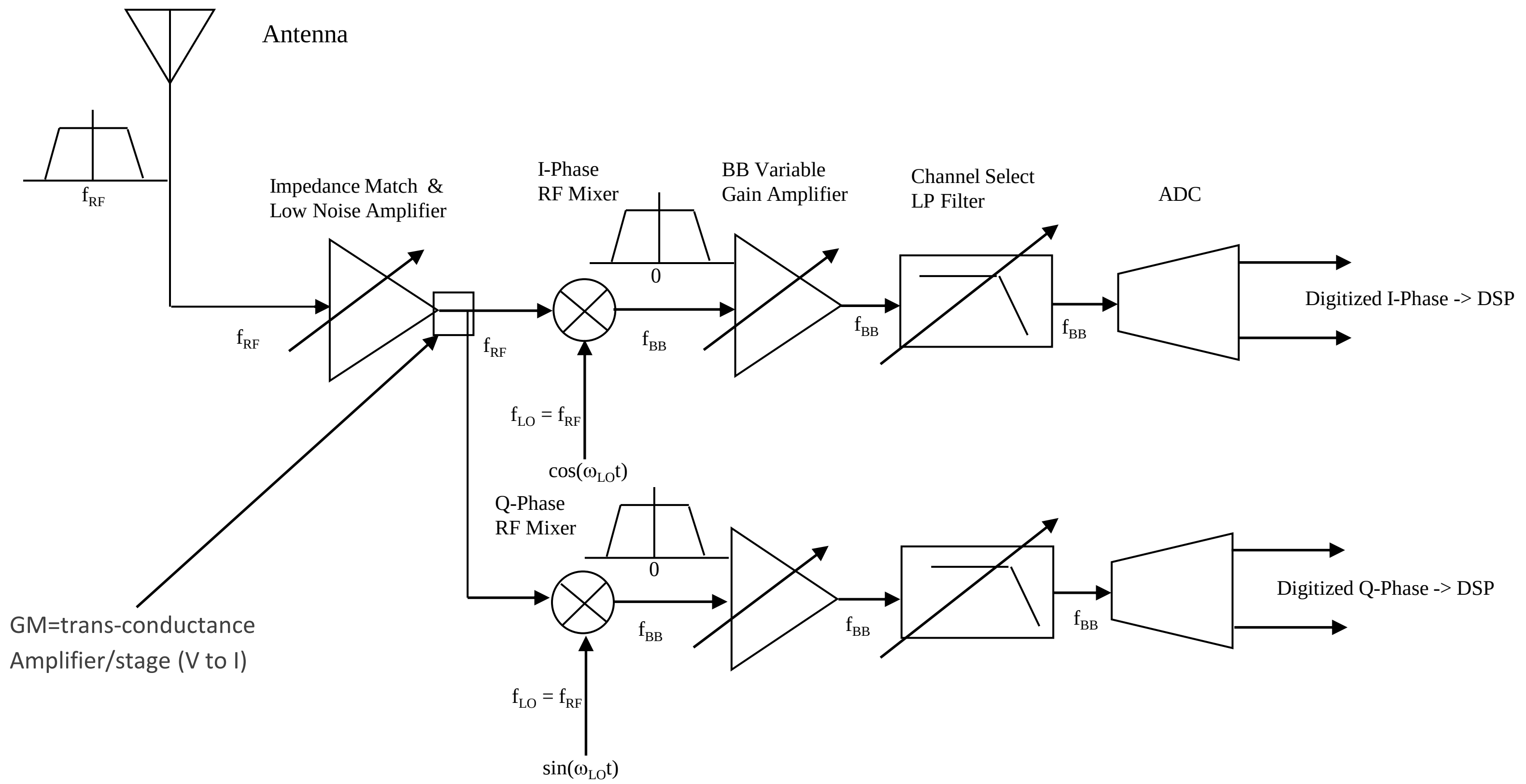
RX testing

RX tests

Basic Function of Radio Receivers (low IF or Zero IF)

- Receive signal RF Frequency band and channel selectivity
- Amplify μV-level Antenna signal to level suitable for ADCs (100s-1000s of mV)
- Down Convert (and/or demodulate) RF signal to either a Baseband (or IF) signal suitable for technology-dependent ADC conversion rates
- Maintain SNR of received signal to level above that specified for the chosen modulation and data rates
- Maintain adequate linearity of received signal to avoid inter-modulation distortion and spectral growth
- Digitize analog BB/IF signal for subsequent DSP processing

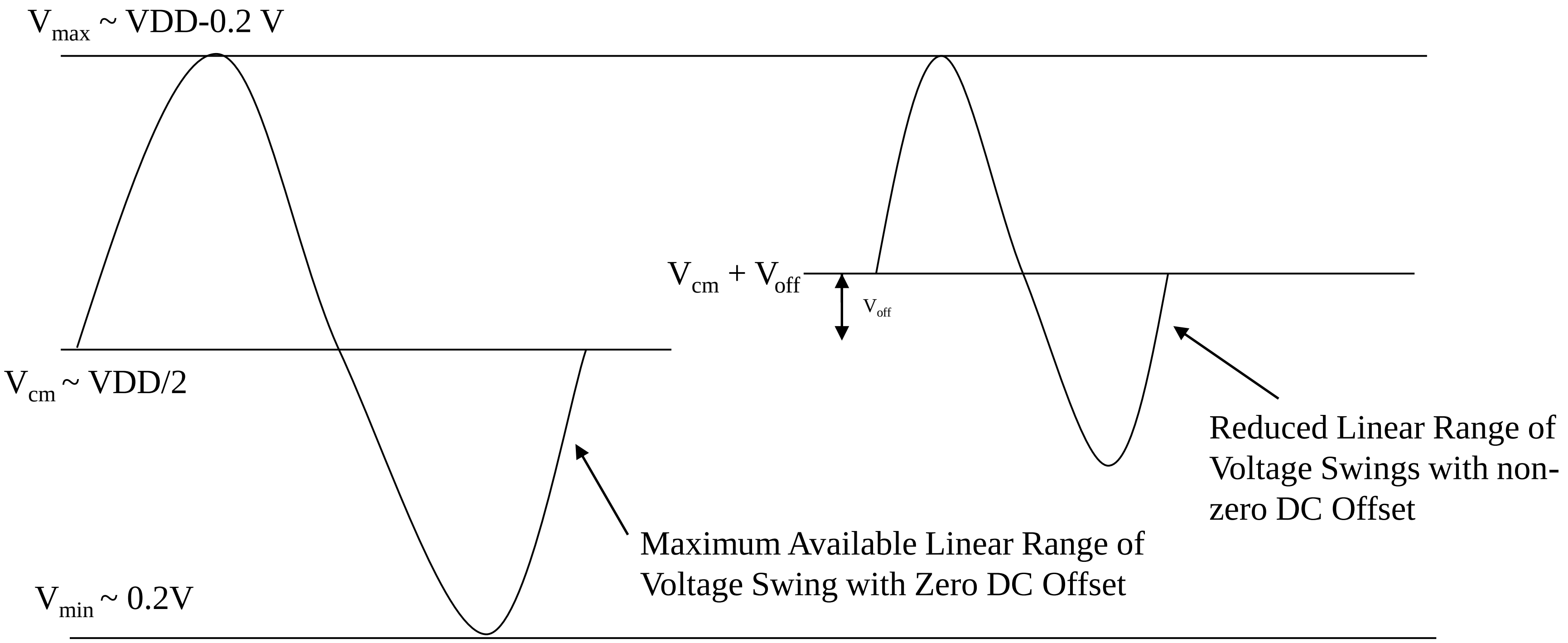
RX tests (cont.)



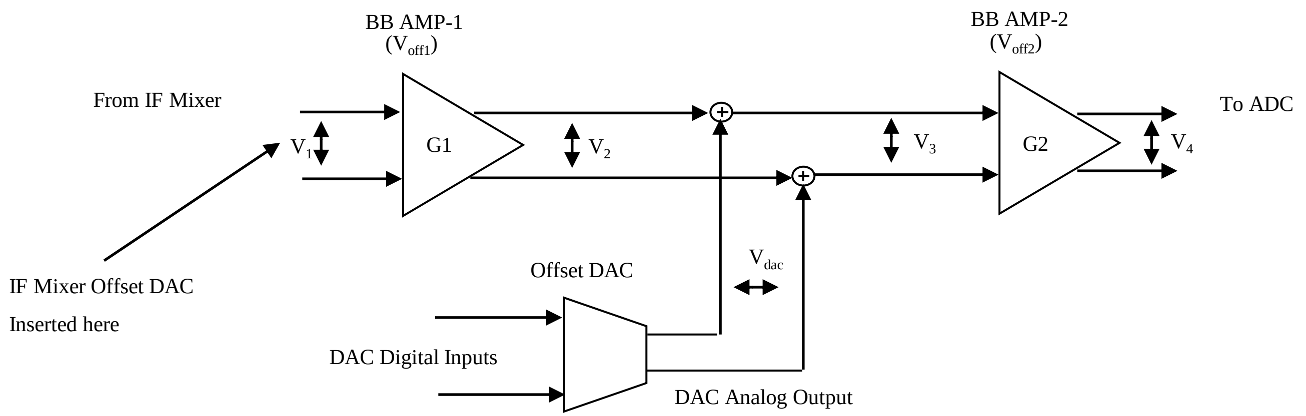
RF is AC coupled. ADC is DC coupled, so offset can cause problem. Offset can cause ADC capture range to clip.

RX DCOC

Residual non-zero offset removed by injecting equal and opposite external DC bias from a offset DAC into the BB circuits

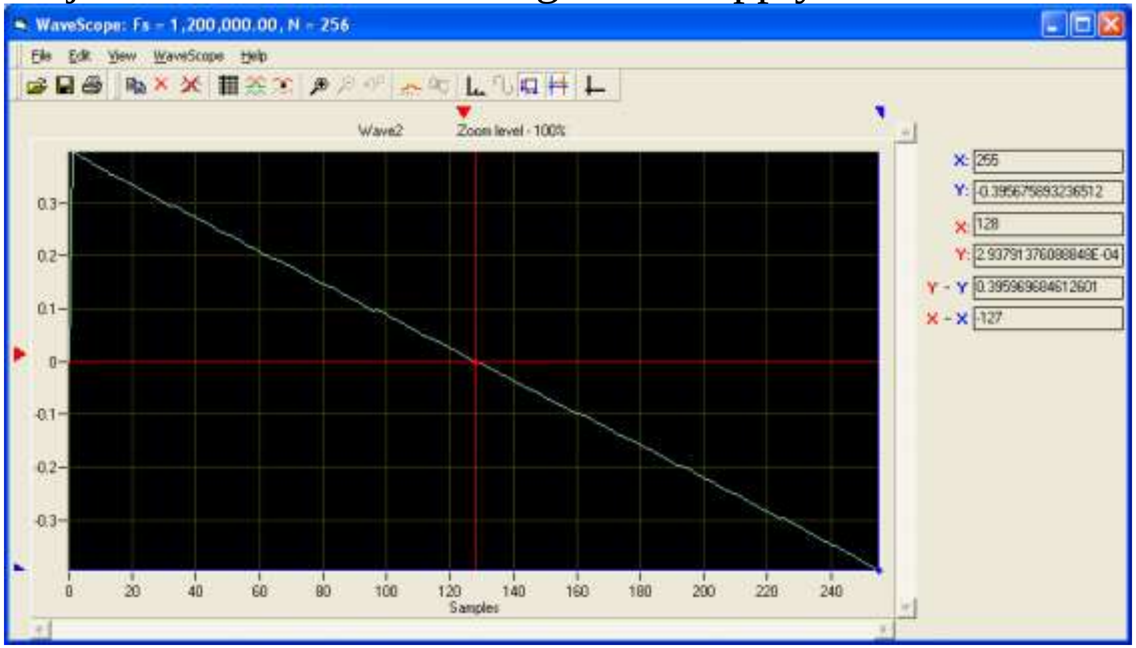


DCOC circuit concept



RX DCOC (cont.)

- The baseband I & Q outputs have DC offset correction DAC circuitry to minimize the DC offset seen at these outputs. By writing DCOC codes the DAC will compensate for any offset inherent in the default design.
- Terminate the RF input without a signal. Re-do DCOC for every gain state.
- In order to get the most accurate null code, the linear search method will be applied. This is implemented by writing the DCOC code from 0x00 to 0xFF for both I and Q paths and capturing the baseband outputs with UltraPAC instruments. Then using background DSP to search the corresponding code. In production we use more efficient search method.
- In production just test DCOC for max gain and apply correction to each gain state.



RX DCOC and Vcom ATE datalog

10000	0	WL_RX1_40M_DC_CODE_I_	1	172	250
11001	0	WL_RX1_40M_DC_CODE_Q	1	185	250
11002	0	WL_RX1_40M_DC_NJ_I	-49.0000 mV	0.4962 mV	49.0000 mV
11003	0	WL_RX1_40M_DC_NJ_Q	-49.0000 mV	-0.5463 mV	49.0000 mV

11209	0	WL_RX1_40M_DC_J_I_MAX	-40.0000 mV	-7.9395 mV	40.0000 mV
11210	0	WL_RX1_40M_DC_J_Q_MAX	-40.0000 mV	-11.3728 mV	40.0000 mV

11191	0	WL_RX1_40M_BB_VCOM_IP	480.0000 m	522.9494 m	600.0000 m
11192	0	WL_RX1_40M_BB_VCOM_IN	480.0000 m	437.4423 m	600.0000 m
11193	0	WL_RX1_40M_BB_VCOM_QP	480.0000 m	219.2283 m	600.0000 m
11194	0	WL_RX1_40M_BB_VCOM_QN	480.0000 m	543.7095 m	600.0000 m

Why DCOC and Vcom ?

Why you think DC offset correction is important?

High DCO could saturate the ADC earlier then desired

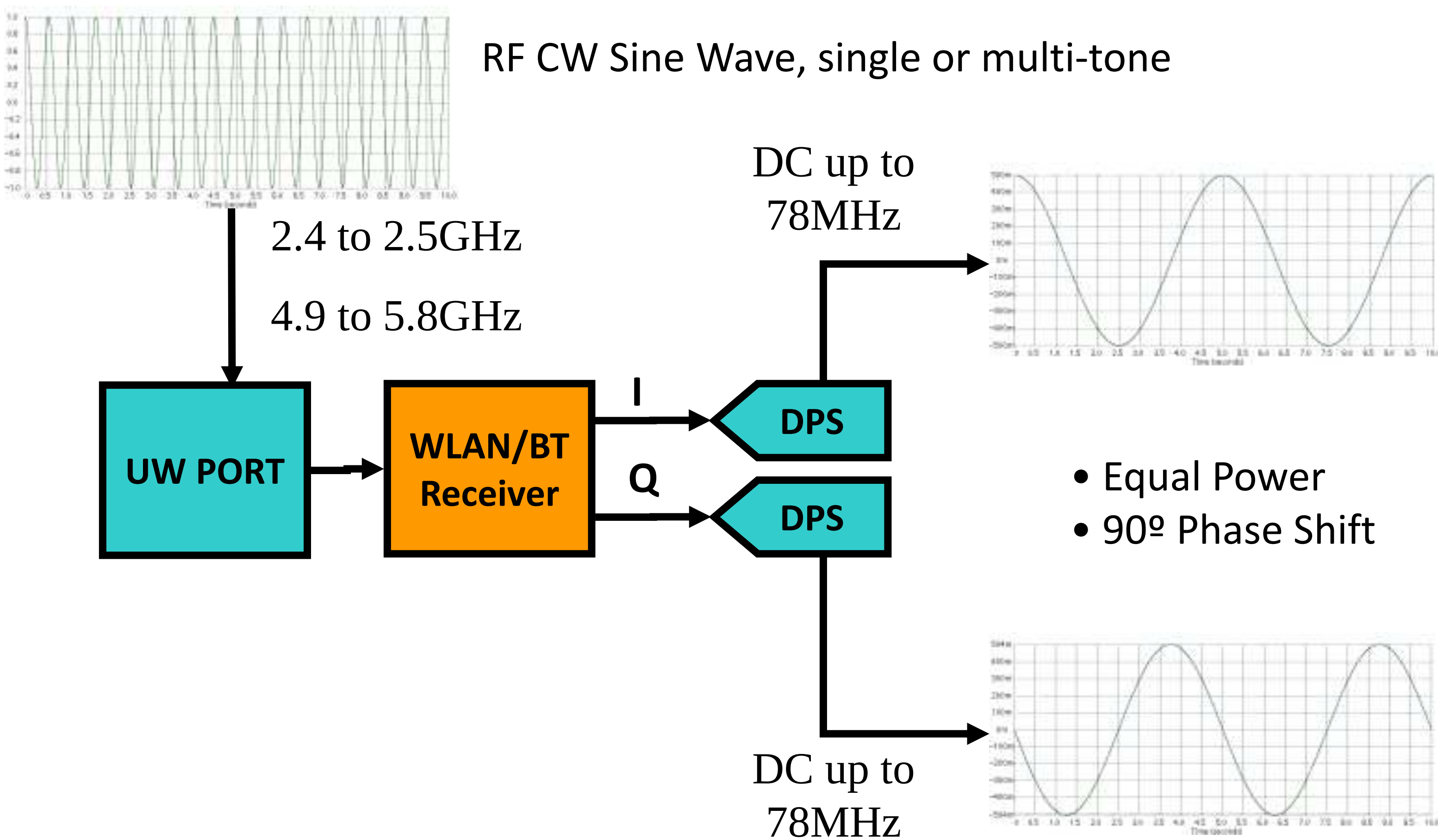
As a result, the receiver sensitivity would degrade

The user would experience less receive signal strength or loss of connection

Why you think Vcom test is important?

Similar to DCO, there would be impact to ADC dynamic range, as I/Q signals would be out of balance

ATE RX test setup



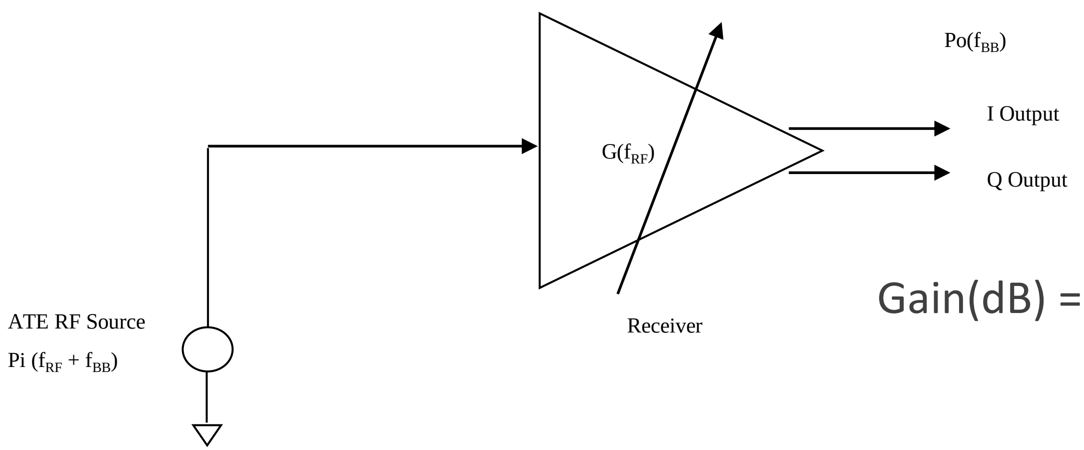
RX gain test

There are many definitions for gain.

- Voltage gain = voltage out / voltage in
- Current gain = current out / current in
- Direct power gain = power delivered to load / power in
- Insertion power gain = power into load,network out / power into load,network in
- Transducer power gain = power delivered to load / power available from source
- Available power gain = power available from the network / power available from the source
- Gi insertion gain = power delivered to a load (connected to a load through a DUT) / power delivered to a load (directly connected to the source)
- Gt transducer gain or transducer power gain = power delivered to load / power available from source
- Gp power gain or operating power gain = power delivered to a load / power delivered by the source (or power input to network)
- Ga available gain or available power gain = power available to a load (or power available from the network) / power available from the source
- Gas associated gain = Ga where GAMMAsource=GAMMAopt
- S21 forward transmission coefficient = |S21|^2dB = 20*LOG10|S21|

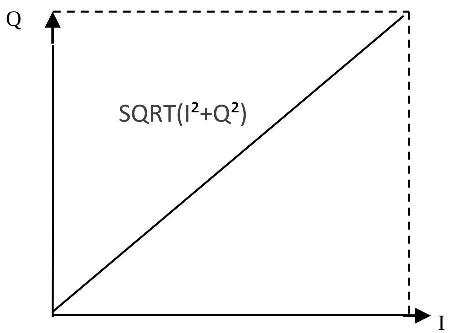
RX gain test (cont.)

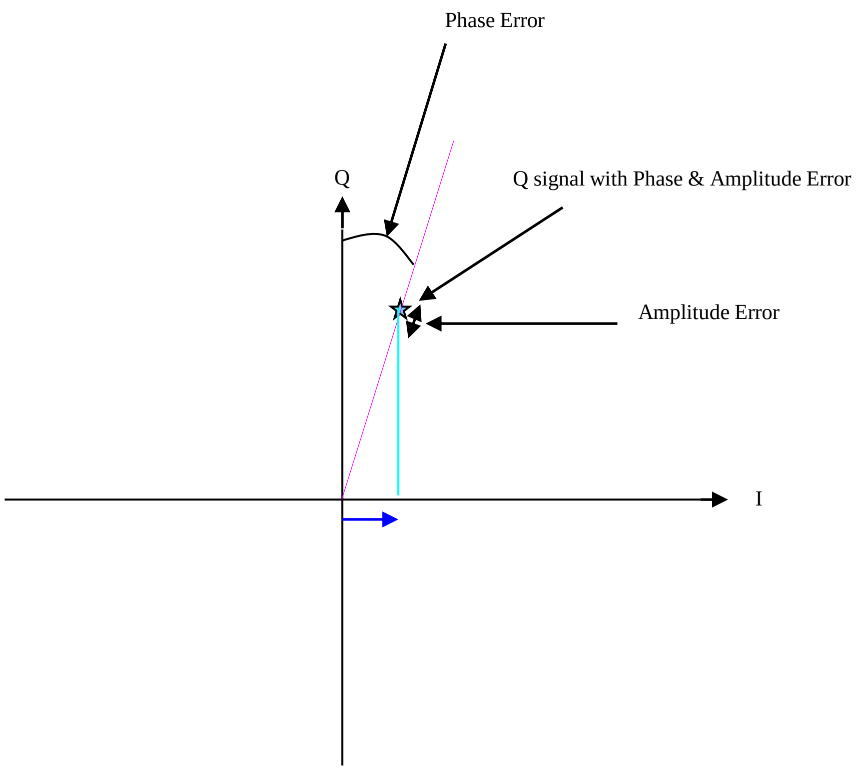
- Receiver Absolute Gain and Gain Step Range are designed to accommodate a range of received signal amplitude levels while maintaining adequate SNR and linearity
- Must also accommodate Process-Voltage-Temperature (PVT) variations of absolute gain
- All these must occur while baseband (analog) output closely matches the input range of Receiver ADC to maximize SNR
- Also, Quadrature Modulation system requires that the Receiver maintain certain minimum level of quadrature integrity (I/Q mis-match)
- Departure from ideal quadrature (both amplitude and phase) results in sensitivity degradation
- Quadrature degradation occurs due to mismatches along the Rx BB I and Q paths
- I and Q output signals need to be captured simultaneously to get real representatives of phase and amplitude imbalance.



$$Gain(dB) = Po(dBm) - Pi(dBm)$$

RX amplitude and phase imbalance test





$$\mathrm{RSB} = 10\log\left(\frac{k^2 + 2k\cos\phi + 1}{k^2 - 2k\cos\phi + 1}\right)$$

$$K = \frac{\text{amplitude of } I}{\text{amplitude of } Q} \qquad \text{gain imbalance} = 20\log(k)$$

$$\text{quadrature error} = \phi \;= (\text{phase of } I - \text{phase of } Q) - (\pi / 2)$$

Why RX gain/gain step test ?

Why you think RX gain, gain step, gain step accuracy and gain variation are important?

Saturation of ADC happens or signal into ADC is too low and loss of sensitivity

RX gain, gain step, gain range, phase/amplitude imbalance ATE datalog

11201	0	WL_RX1_40M_GAIN_I_MAX	69.0000 dB	75.1446 dB	80.0000 dB
11202	0	WL_RX1_40M_GAIN_Q_MAX	69.0000 dB	75.1617 dB	80.0000 dB
11203	0	WL_RX1_40M_GAIN_IQ_MAX	69.0000 dB	75.1421 dB	80.0000 dB
11206	0	WL_RX1_40M_RSB_UC_MAX	N/A	34.5016	N/A
11207	0	WL_RX1_40M_PH_IB_MAX	-4.5000 deg	2.1549 deg	4.5000 deg
11208	0	WL_RX1_40M_AMP_IB_MAX	-0.6500 dB	-0.0170 dB	0.6500 dB
11581	0	WL_RX1_40M_GAIN_I_MIN	N/A	-1.1547 dB	3.1000 dB
11572	0	WL_RX1_40M_GAIN_Q_MIN	N/A	-1.2134 dB	3.1000 dB
11583	0	WL_RX1_40M_GAIN_IQ_MIN	N/A	-1.1840 dB	3.1000 dB
11586	0	WL_RX1_40M_RSB_UC_MIN	N/A	34.2435	N/A
11587	0	WL_RX1_40M_PH_IB_MIN	-4.5000 deg	2.1891 deg	4.5000 deg
11588	0	WL_RX1_40M_AMP_IB_MIN	-0.6500 dB	0.0586 dB	0.6500 dB
11214	0	WL_RX1_40M_GS_I_L74	0.5000 dB	1.9865 dB	3.5000 dB
11215	0	WL_RX1_40M_GS_Q_L74	0.5000 dB	2.0200 dB	3.5000 dB
11217	0	WL_RX1_40M_PH_IB_L74	-4.5000 deg	2.5000 deg	4.5000 deg
11218	0	WL_RX1_40M_AMP_IB_L74	-0.6500 dB	0.0165 dB	0.6500 dB
11601	0	WL_RX1_40M_GAIN_RANGE_I	68.0000 dB	76.2994 dB	85.0000 dB
11602	0	WL_RX1_40M_GAIN_RANGE_Q	68.0000 dB	76.3750 dB	85.0000 dB

RX phase/amplitude imbalance vs. RSB

Noise Figure (NF) theory

Noise Figure (NF) is a measure of how much a device (such an amplifier) degrades the Signal to Noise ratio (SNR).

SNR_input$_{[linear]}$ = *Input_Signal*$_{[Watt]}$ / *Input_Noise*$_{[Watt]}$

SNR_input$_{[dB]}$ = *Input_Signal*$_{[dB]}$ - *Input_Noise*$_{[dB]}$

SNR_output$_{[linear]}$ = *Output_Signal*$_{[Watt]}$ / *Output_Noise*$_{[Watt]}$

SNR_output$_{[dB]}$ = *Output_Signal*$_{[dB]}$ - *Output_Noise*$_{[dB]}$

Noise Factor (linear not dB) of a receiver is the ratio of the SNR at its input to the ratio of the SNR at its output.

NoiseFactor_F$_{(linear)}$ = *SNR_input*$_{[linear]}$ / *SNR_output*$_{[linear]}$

NoiseFactor_F$_{[dB]}$ = *SNR_input*$_{[dB]}$ - *SNR_output*$_{[dB]}$

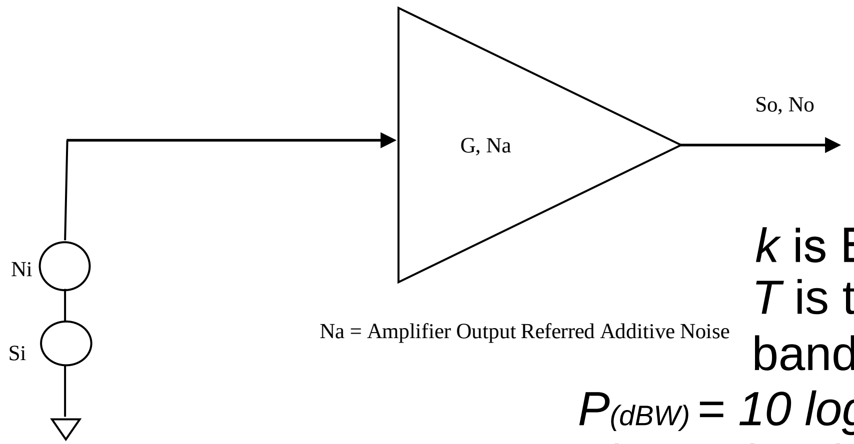
NoiseFigure_NF$_{[dB]}$ = *10*LOG (NoiseFactor_F*$_{(linear)}$*)*

Note that **SNR at the output will always be smaller than the SNR at the input**, due to the fact that circuits always add to the noise in a system

1. Thermal or *Johnson* - *Nyquist* Noise
2. Shot Noise
3. 1/f Noise (Also called Flicker or Pink noise)
4. White Noise
5. Burst Noise

RX Noise Figure (NF) test

Thermal noise is a random fluctuation in voltage caused by the random motion of charge carriers in any conducting medium at a temperature above absolute zero (K=273 + °Celsius).



$P_{(dBW)} = 10 \log(kTB)$

k is Boltzmann's constant 1.38 x 10^{-23} (J/K)
T is temperature (in Kelvin), and *B* is the bandwidth (in Hz).

$P_{(dBW)} = 10 \log(1.38 \times 10^{-23} \times 290 \times 1) = -204(dBW)$

Thermal Noise Power = -204 + 30 = -174 dBm/Hz

Definition : Noise Figure (NF) = SNR_i / SNR_o

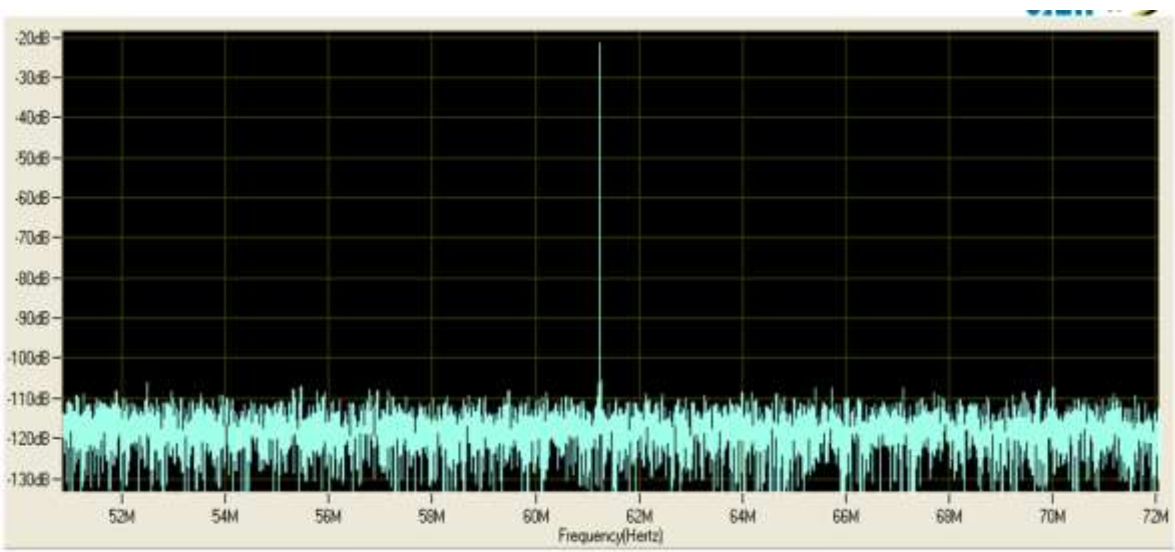
SNR_i = Input Signal-to-Noise Ratio

SNR_o = Output Signal-to-Noise Ratio

NF = (Si/Ni)/(So/No)

= (No/Ni) /G

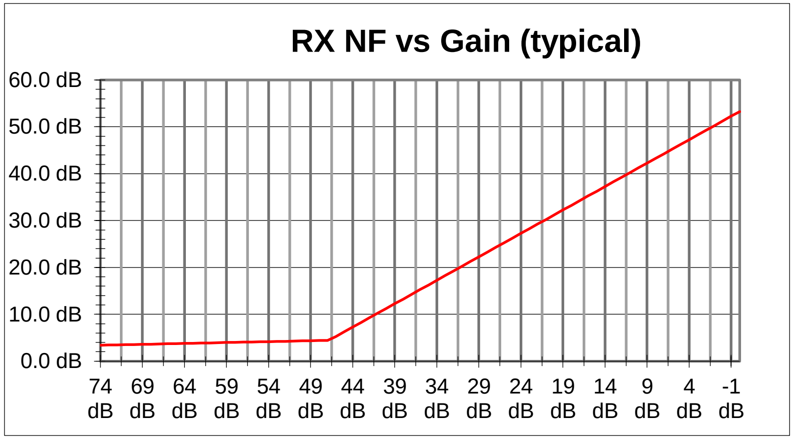
= 1 + Na/(G*Ni)



RX Noise Figure (NF) test – cont.

- Overall NF contribution is highest for first stage (LNA), and progressively lower for subsequent stages (Friis Equation)
- NF measurement done at gain settings corresponding to gain settings at receiver sensitivity limits i.e. gain settings are maximized, especially those of earlier stages (LNA, RF, IF, BB circuits in that order)
- One approach to measuring NF uses the equation NF= (No/Ni)/G
- ✓ Maximize Receiver Gain (G presumed known, usually measured by a single-tone test)
- ✓ Connect a 50ohm termination to the 50-ohm matched input of the Receiver
- ✓ Digitize the Receiver BB output, integrate the output noise power (No) over some resolution bandwidth (BW), at an in-band spot frequency of interest (e.g. 1MHz)
- ✓ May need to subtract Noise Floor component from this measurement of output noise (typically this more than 20dB lower than the measured cold level output noise)
- ✓ Use the equation above to calculate NF, where Ni = (k_BT)(BW) (or -174dBm/Hz) i.e. available thermal noise power from fundamental Thermodynamic considerations

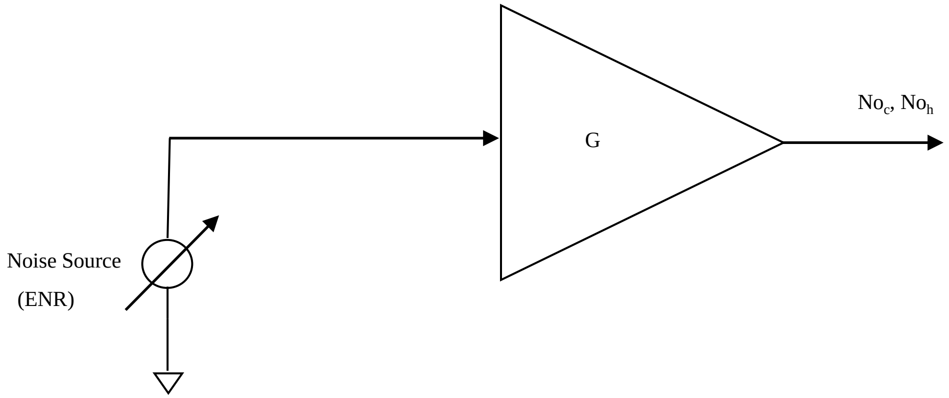
$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$



RX Noise Figure (NF) test – cont.

- Previous NF measurement method requires knowledge of small signal Receiver gain (G)
- Another method of NF measurement (so-called Y-factor method) does not require knowledge of gain to measure the Noise Figure
- Noise Figure Bench instruments (Agilent, Keysight) use this method, ATE can do it too
- Method requires a Thermal Noise (i.e. white noise) source that can be switched between two states (Hot and Cold), connected to the Receiver input
- In cold state, noise source provides available noise power ($k_B T$)
- In hot state, an avalanche diode is switched-in. Noise power available is now elevated, typically by about mid-20s dB above thermal noise floor (ENR – Calibrated Excess Noise Ratio)
- Receiver output noise power (No_c, No_h) is measured under both noise source settings at a particular spot frequency and resolution bandwidth

RX Noise Figure (NF) test – cont.



$Y = No_h/No_c$ (possibly corrected for Noise Floor of measurement system)

$NF = ENR/(Y-1)$

Receiver Gain (G) = $(No_h – No_c)/[k_{B*}(T_h-T_c)*BW_i]$,

where $T_h = T_c * (1 + ENR)$, Tc=290K by definition

Sanity checks for computations:

i) G must match single tone gain with same gain settings

ii) Connect small attenuator (3-10 dB) between noise source and Rx input. NF must increase and gain decrease by the attenuation amount

RX NF ATE datalog

70701	0	BT_RX_NF_I_HG	2.5000 dB	5.2463 dB	10.0000 dB
70702	0	BT_RX_NF_Q_HG	2.5000 dB	5.6867 dB	10.0000 dB

61611	0	WL_RX1_40M_NF_I	1.5000 dB	3.9208 dB	7.0000 dB
61612	0	WL_RX1_40M_NF_Q	1.5000 dB	4.2179 dB	7.0000 dB

The lower the Noise Figure, the better the device sensitivity.

Noise Figure can never be zero or negative, the lower limit has to be positive.

Intermodulation distortion - linearity

- The IMD can be determined by measuring the power levels of IMD products at specific frequencies at the device output in the frequency domain.
- IMD can be quantified as a figure of merit corresponding to a point on the gain/slope curve called an Intercept Point (IP).
- IP's are measured at specific frequencies relative to the fundamental frequencies defined by the order of distortion distributed throughout the frequency spectrum where IP2 is the 2nd order IMD, IP3 is the 3rd order IMD, and so forth.
- Once the IMD and fundamental signal power levels are known, the IP levels can be calculated by applying them to the following Equation 1:

Equation 1

$$IP_N = \frac{P_{\text{suppression}}}{N-1} + P_{\text{fund}}$$

Where:

N is the IP order: 2, 3, etc.

$P_{\text{suppression}} = P_{\text{fund}} - P_{\text{IMD}}$

RX linearity test

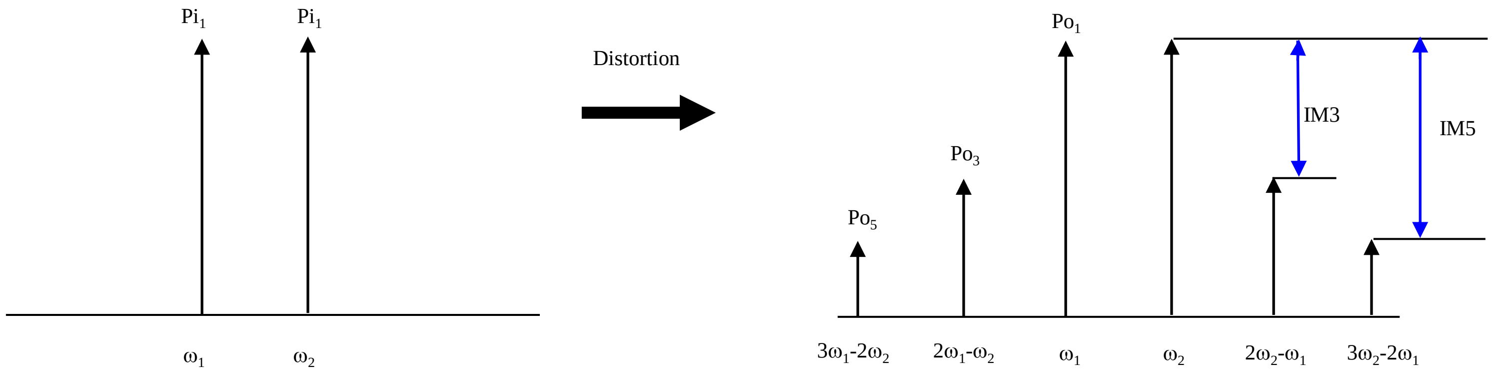
- Common measures of Receiver Linearity are Pin(1dB), IIP3 (third-order input intercept) and IIP2
- Second order (and other even order) distortion modes are getting more important. Mostly not tested due to the differential circuit designs and narrowband systems used in the RF receiver
- P1dB measurement typically requires multiple measurements to trace the gain compression curve. Not used in the production screen, but is used to validate the IIP3 test ($P_{IIP3} \sim P_{1dB} + 10$, assumes that third-order nonlinearity is dominant)
- Go/no-go 1dB tests are possible instead

$$V_o = a_1 * V_i + a_2 * V_i^2 + a_3 * V_i^3 + a_4 * V_i^4 + a_5 * V_i^5 + \ldots..$$

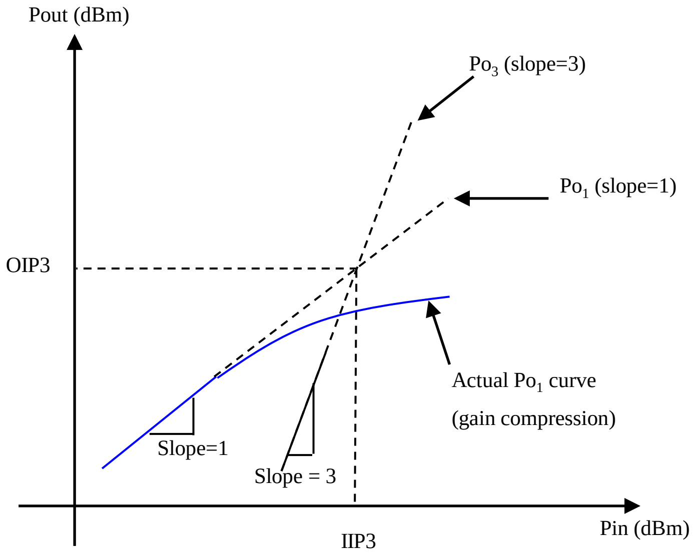
a_1=Linear Gain
a_2=Second order non-linearity (small)
a_3=Third order non-linearity and so on for a_4, a_5, ….
Two tone input assumed : $V_i = b1*\cos(\omega_1 t) + b2*\cos(\omega_2 t)$ where ω_1 is close to ω_2
Output V_o contains frequencies at :
$\omega_1, \omega_2, \omega_1-\omega_2, \omega_1+\omega_2, 2\omega_1, 2\omega_2, 2\omega_1-\omega_2, 2\omega_2-\omega_1, 3\omega_1, 3\omega_2, 4\omega_1, 4\omega_2, 5\omega_1, 5\omega_2, 3\omega_1-2\omega_2, 3\omega_2-2\omega_1$

RX linearity test – cont.

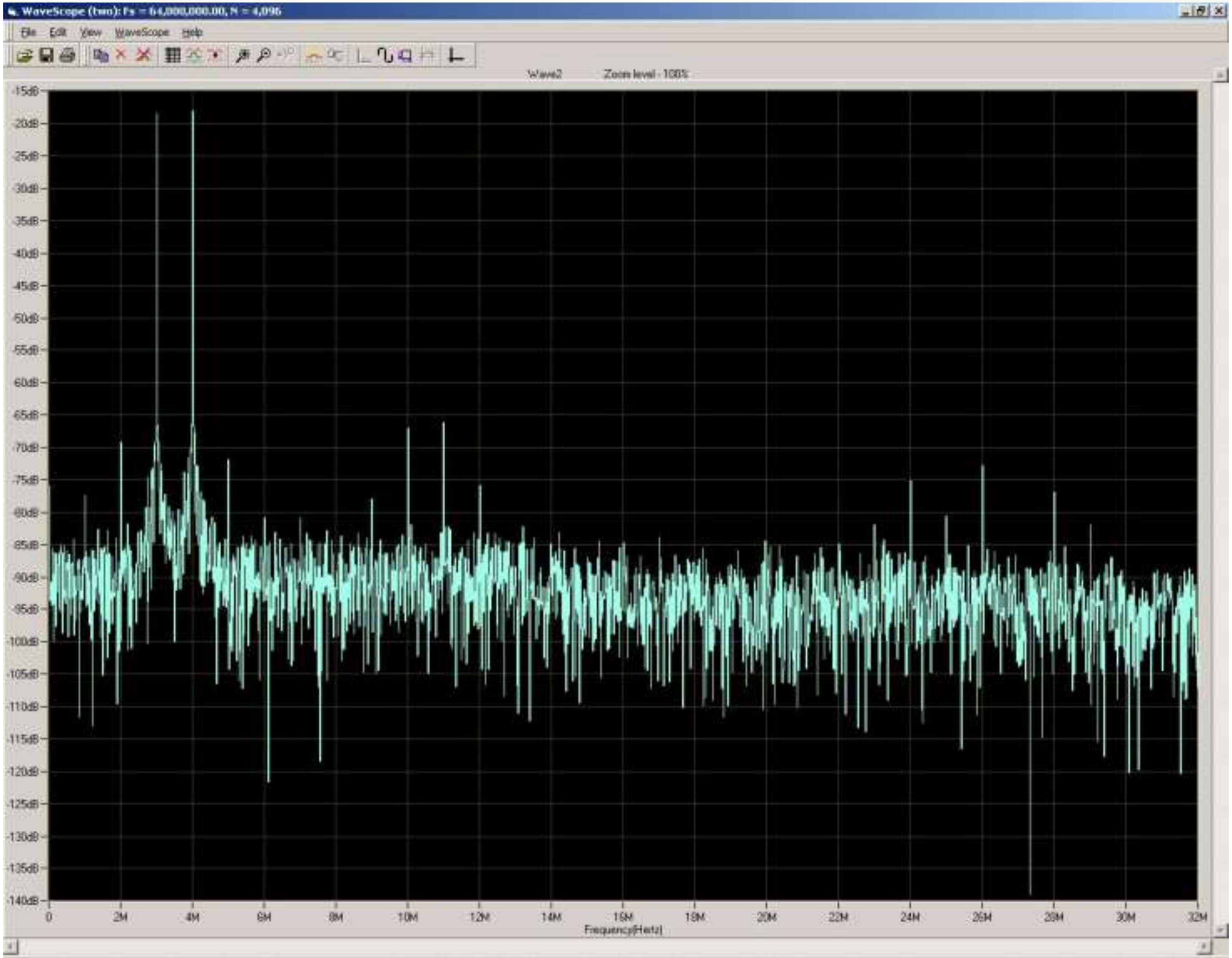
- Assume that ω_1 and ω_2 are very closely spaced in frequency (nearly equal)
- In this case, the signal frequencies that fall within our narrowband Receiver range are ω_1, ω_2, $2\omega_1-\omega_2$, $2\omega_2-\omega_1$, $3\omega_1-2\omega_2$, $3\omega_2-2\omega_1$ ($\omega_1 \sim= \omega_2$)
- Harmonic signals etc. fall outside narrowband tuned amplifier range and are largely attenuated
- Intermodulation distortion (e.g. $2\omega_1-\omega_2$, $2\omega_2-\omega_1$ etc.) terms may be generated from OFDM subcarriers. Spectral re-growth can be a problem in systems causing compliance problems



RX linearity test – cont.



RX ATE IP3 spectrum



RX linearity test – cont.

From purely geometrical analysis of the graph:

$IIP3 = Pi_1 + (Po_1 - Po_3)/2$ (definition appropriate for Receivers)

$OIP3 = Po_1 + (Po_1 - P0_3)/2$ (definition appropriate for Transmitters)

Similarly, for the 5^{th} order distortion

$IIP5 = Pi_1 + (Po_1 - Po_5)/4$ (Rx)

$OIP5 = Po_1 + (Po_1 - Po_5)/4$ (Tx)

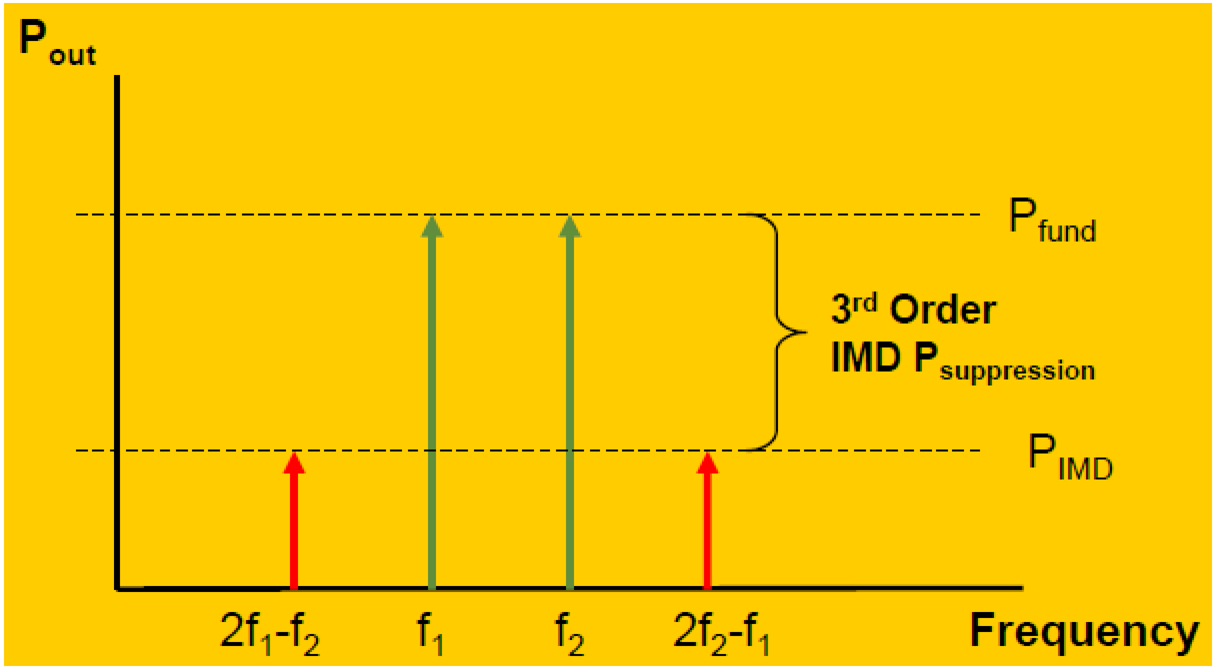
Upper and lower third-order terms sometimes unequal in amplitude because third-order coefficient (a_3) is frequency dependent

RX linearity test – cont.

- ATE test condition must be similar to an actual condition of a large received signal
- Receiver front-end stages (LNA, RF, IF etc. stages) set at minimum gain to maximize linear range and this forces compression (if any) to occur in these stages
- If designed correctly, LNA should compress first and set the Receiver compression limit
- Baseband stages can be set at higher gains to ensure adequate signal levels for repeatable digitization (be careful about this though)
- Must ensure that we don’t operate the Receiver too far up the compression curve for third-order intercept measurements – For IP3/IP2 rule of thumb, stay 10dB away from P1dB
- Sanity check : increase Rx two-tone inputs by 1dB, main output tones should increase by 1dB, 3rd-order tones should increase by 3dB, IIP3 should remain unchanged
- If 3rd-order tone increase is significantly less than 3dB, then the Rx input power is too high. Need to back off on that.
- A balancing game between the requirement above and tones well above noise floor for repeatable measurements (IP3 tone ~10-15dB above noise floor should work)
- Sometimes we are device noise floor limited and can only test IMD at certain gain states
- ATE test conditions needs to be worked out closely with design and systems engineering

IP3

- IP3 are the theoretical points where the power of the fundamental and the power in the IMD product(s) would be equal at the device output, similar to IP_2 but just at different frequency points.
- With a 2-tone signal, f_1 and f_2, applied to the device input, the primary IP_3 IMD products appear at $2f_1-f_2$ and $2f_2-f_1$ on the device output.
- Once the IMD and fundamental signal power levels are known, the IP levels can be calculated using the known Equation.



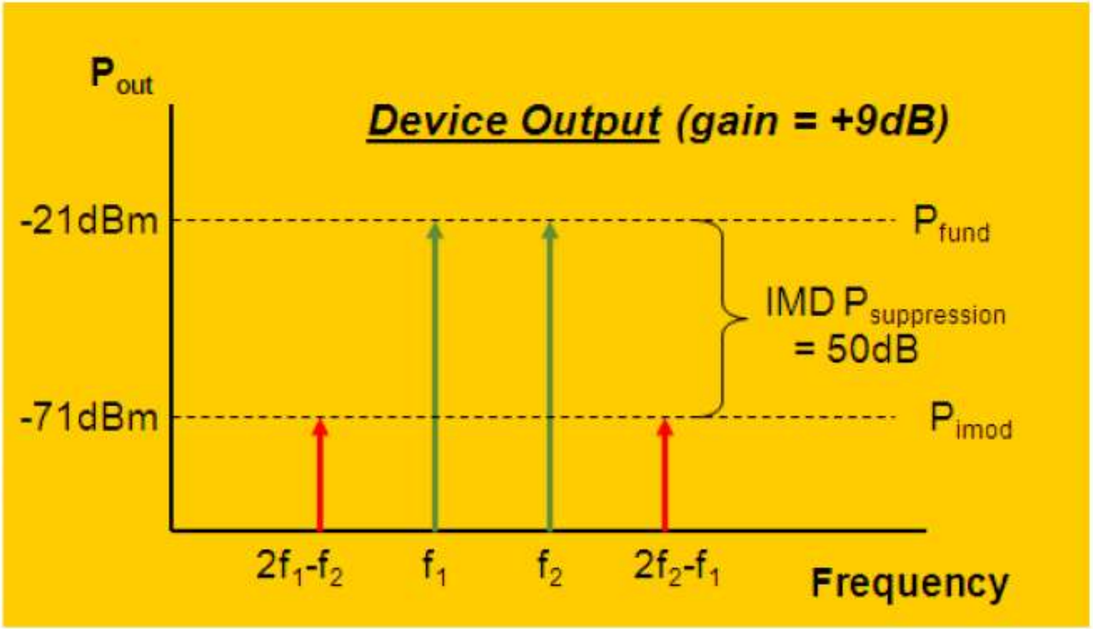
IP3 test

- Given a power input to the device of –30dB for each tone and an output spectrum that yields the following result, IP_3 can be calculated as follows:
  - Equation 1

$$\boxed{IP_N = \frac{P_{\text{suppression}}}{N-1} + P_{\text{fund}}}$$

$$IP_3 = \frac{50dB}{2} - 21dBm = 4dBm$$

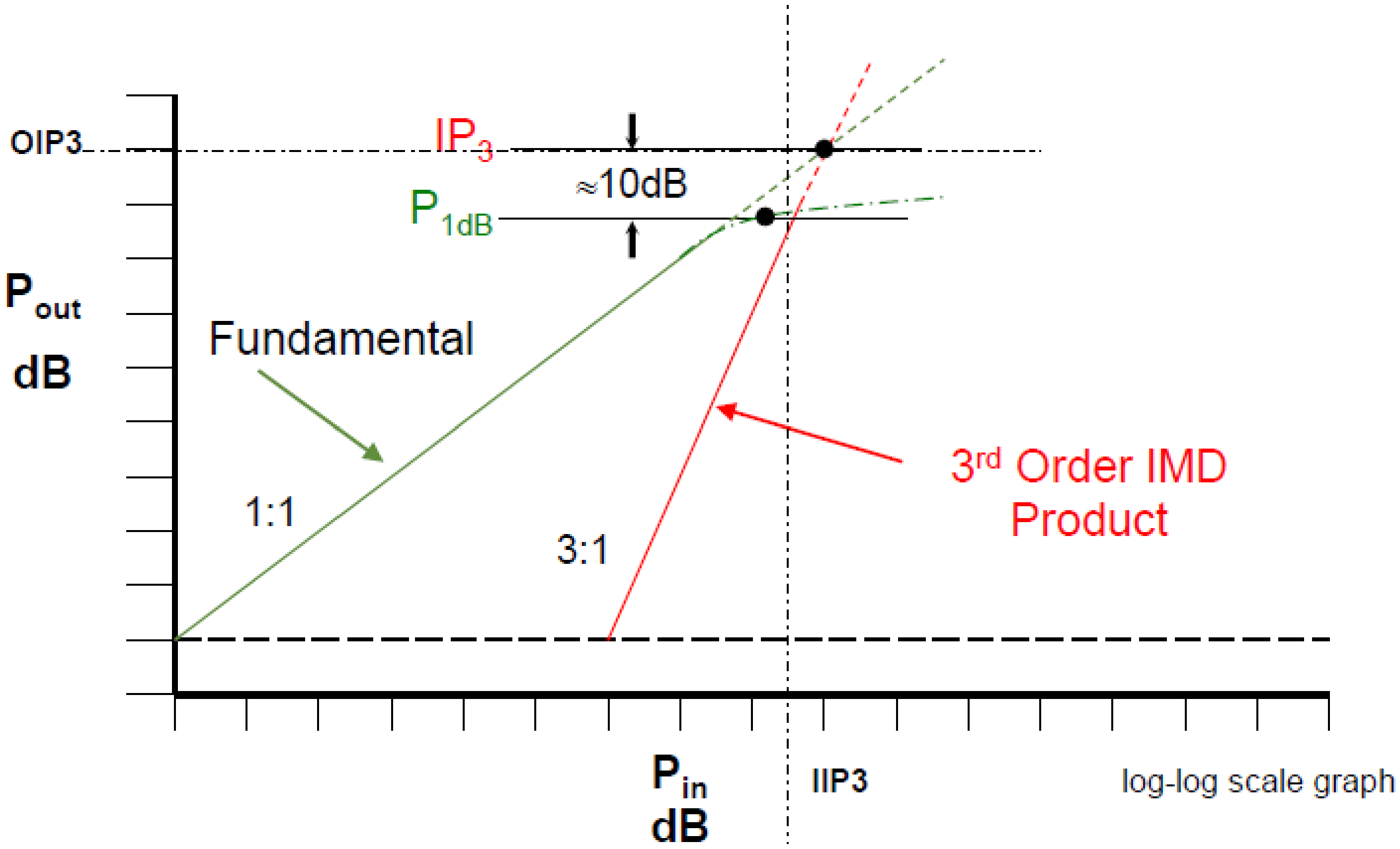
*Where order N = 3



- Note: IP_3 can be either input referred (IIP3) or output referred (OIP3).
  - The example illustrated above is OIP3 since the input power is not considered in the calculation.

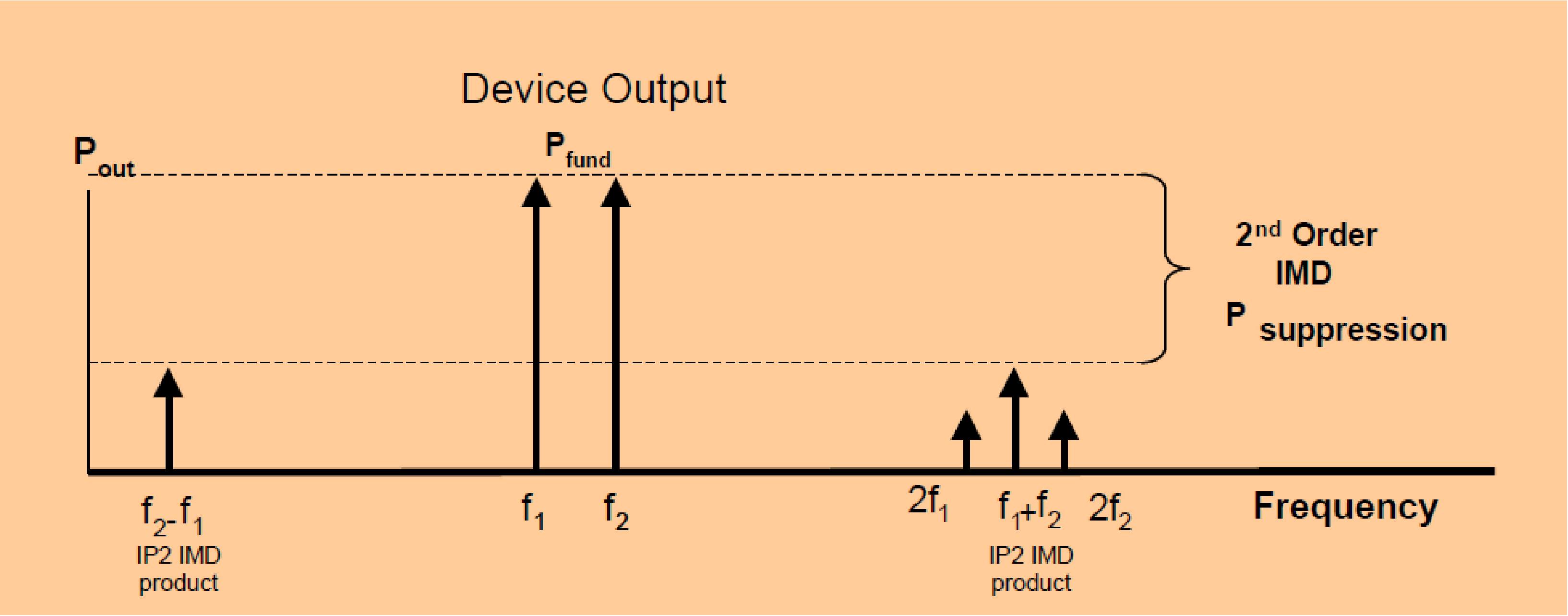
IP3 test (cont.)

- The IP_3 IMD products increase at a rate of 3 dB for each 1 dB increase in fundamental power.
- The actual IP_3 point can never be reached in reality because the device goes into compression.
- The IP_3 point is generally about 10 dB above the 1 dB compression point.



IP2

- IP2 are theoretical operating points of a device where the power of the fundamental signals and the power of the IMD products on the output are equal.
- At the output of the device, the IP2 distortion products appear at $2f_1$, $2f_2$, f_1+f_2, and f_2-f_1. IP2 measurements are usually made on the IMD product at f_1+f_2.



IP2 example

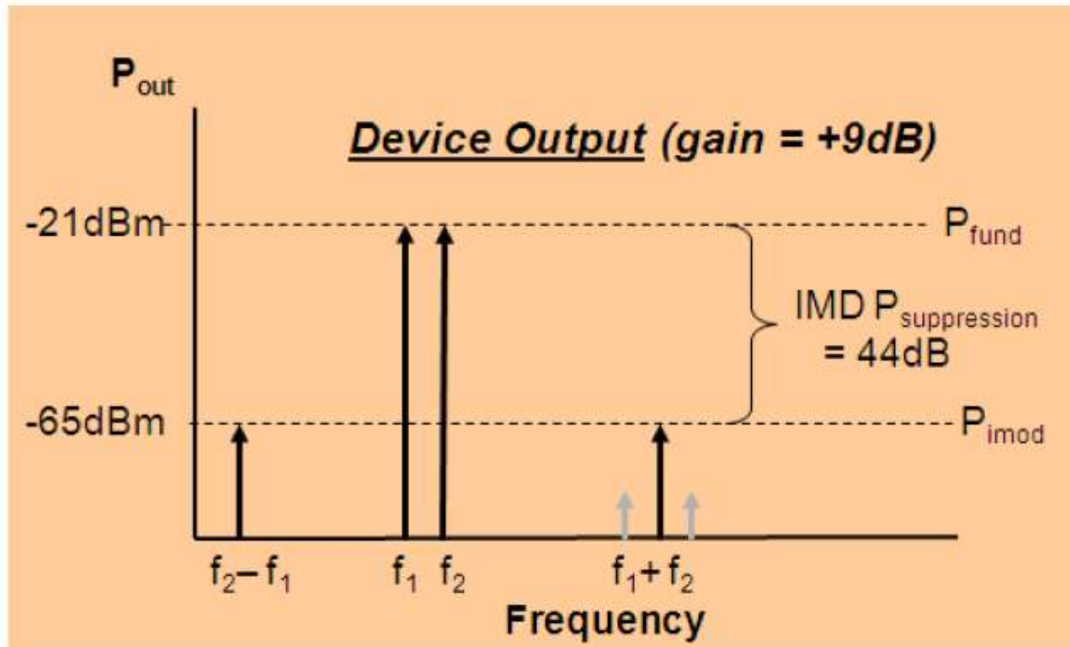
- Given a power input to the device of –30dB for each tone and an output spectrum that yields the following result, IP_2 can be calculated as follows using Equation 1:

Equation 1:

$$IP_N = \frac{P_{\text{suppression}}}{N-1} + P_{\text{fund}}$$

$$IP_2 = \frac{44dB}{1} - 21dBm = 23dBm$$

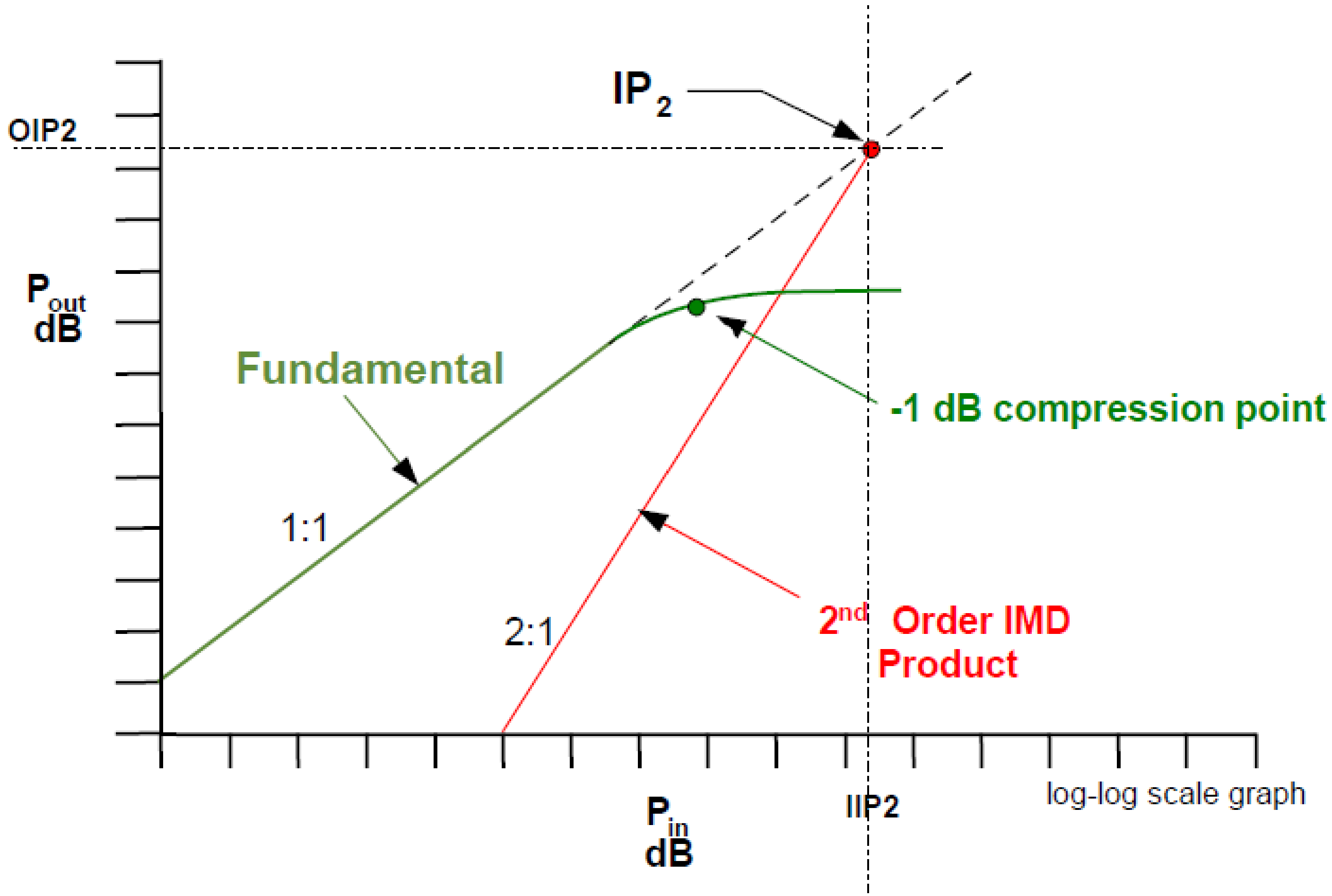
*Where order N = 2



- Note: IP_2 can be either input referred (IIP_2) or output referred (OIP_2).
  - The example illustrated above is OIP_2 since the input power is not considered in the calculation (IIP2 = OIP2 + Gain(db)

IP2 test

- The power levels of the IP_2 IMD products (F_1+ F_2 and F_2-F_1) increase at a rate of 2dB for each 1dB increase in fundamental power.
- In reality, the IP_2 points can never be reached because the device goes into compression.



IP2 test (cont.)

- IP2 testing should be performed at a signal power level at least 10 dB below the expected device 1 dB compression point, yet at a high enough level that the IP2 product to be measured (ex: f1 + f2) is expected to be at least 10 dB above the device output noise floor.
- If the input power levels are too high and the device begins to go into compression, errors will result in the measurement.
- Likewise, if the input power levels are too low, the measurement accuracy and repeatability may be unacceptable due to the separation between the IM power levels and the system noise floor.

IP2/IP3 test cases

RF test cases (CW)			Wanted signal (inband IIP3)			IM3 (out-of-band IIP3)			IM2 (out-of-band IIP2)		
Band		Absolute carrier freq	CW signal 1 freq	CW signal 2 freq	Signal IM3	CW jammer 1 freq	CW jammer 2 freq	J12 IM3	CW jammer 3 freq	CW jammer 4 freq	J34 IM2
2.4 G	Low	2212	2406.5	2404.5	2408.5	2194.25	1980	2408.5	1906.5	1910	-3.5
	High	2484	2489.5	2491.5	2487.5	2233.75	1980	2487.5	1910	1906.5	3.5

RF test cases (CW)			Wanted signal (inband IIP2)		
Band		Absolute carrier freq	CW signal 1 frequency	CW signal 2 freq	Signal IM2
2.4G	Low	2212	2406.5	2404.5	2
	High	2484	2489.5	2491.5	-2

Linearity					
Baseband saturation level (relative to level of wanted signal)	Driven by compression of wanted signal Specified headroom needs to be met over entire input range of wanted signal at applicable gain-setting and corresponding gain variation in front-end.	15			dBc
LNA+GM IIP3 requirements (out of band)	Jammers at third the frequency can fall into the 2.4 GHz band due to LNA+GM IIP3	-8 (WCDMA)			dBm
	Test case at 74 dB gain: CW jammer @ 728 MHz Level @ LNA -21 dBm (WCDMA) for worst case Measured IM3 product at 3*f (2484 MHz) IM3 = 3*J –2* IIP3-9.5			-56	dBm

RX IP3/IM3/IMR3 ATE datalog

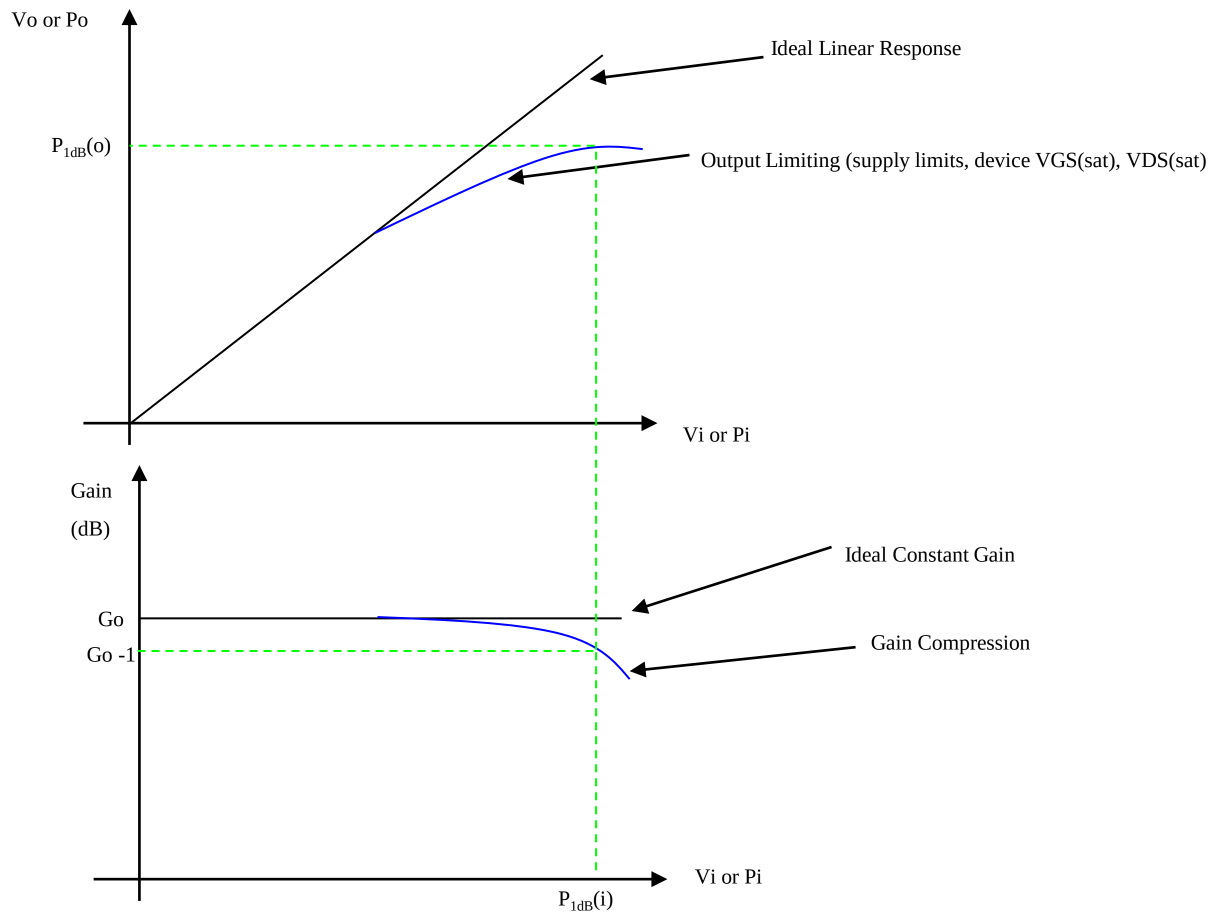
42143	0	WL_RX1_40M_IM3_I_2217M_2219M	N/A	-56.7050	N/A
42154	0	WL_RX1_40M_IM3_Q_2217M_2219M	N/A	-55.2193	N/A
42155	0	WL_RX1_40M_IMR3_I_2217M_2219M	32.00 dBc	50.69 dBc	200.00 dBc
42156	0	WL_RX1_40M_IMR3_Q_2217M_2219M	32.00 dBc	49.33 dBc	200.00 dBc
43005	0	WL_RX1_40M_BBPwr_I_2217M_2219M	N/A	-5.9854	N/A
43006	0	WL_RX1_40M_BBPwr_Q_2217M_2219M	N/A	-6.0169	N/A

21861	0	WL_RX1_40M_IM3_LNAGM_I	-200.00 dB	-64.0694 dB	-58.00 dB
21862	0	WL_RX1_40M_IM3_LNAGM_Q	-200.00 dB	-64.0364 dB	-58.00 dB

72401	0	BT_RX_IIM3_OutofBand_I_NG	-200.00 dBm	-118.3040 dBm	-50.00 dBm
72402	0	BT_RX_IIM3_OutofBand_Q_NG	-200.00 dBm	-128.6232 dBm	-50.00 dBm
72403	0	BT_RX_IIP3_OutofBand_I_NG	-20.00 dBm	0.6520 dBm	35.00 dBm
72404	0	BT_RX_IIP3_OutofBand_Q_NG	-20.00 dBm	5.8116 dBm	35.00 dBm

RX linearity test – P1dB

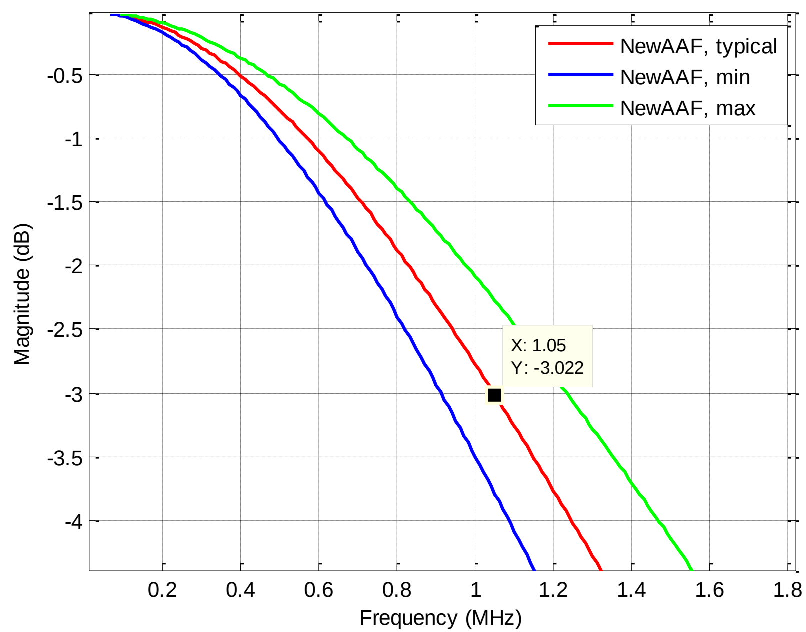
- Measures the Large Signal behavior (i.e. gain compression) of the Receiver
- Increase RF input power until the RX compresses (char)
- Production test is a single test at the P1dB spec and limit is set to <1dB (typ. 0.7dB)



RX BBF

- RX BBF is LPF
- ATE test filter BW and filter rejection at specific frequencies (per spec)
- Filter tuning may be required

Frequency (MHz)	Min	Typ	Max
F_1	1.42	1.63	1.92
F_2	22.9	26.3	21



RX PLL tuning range test

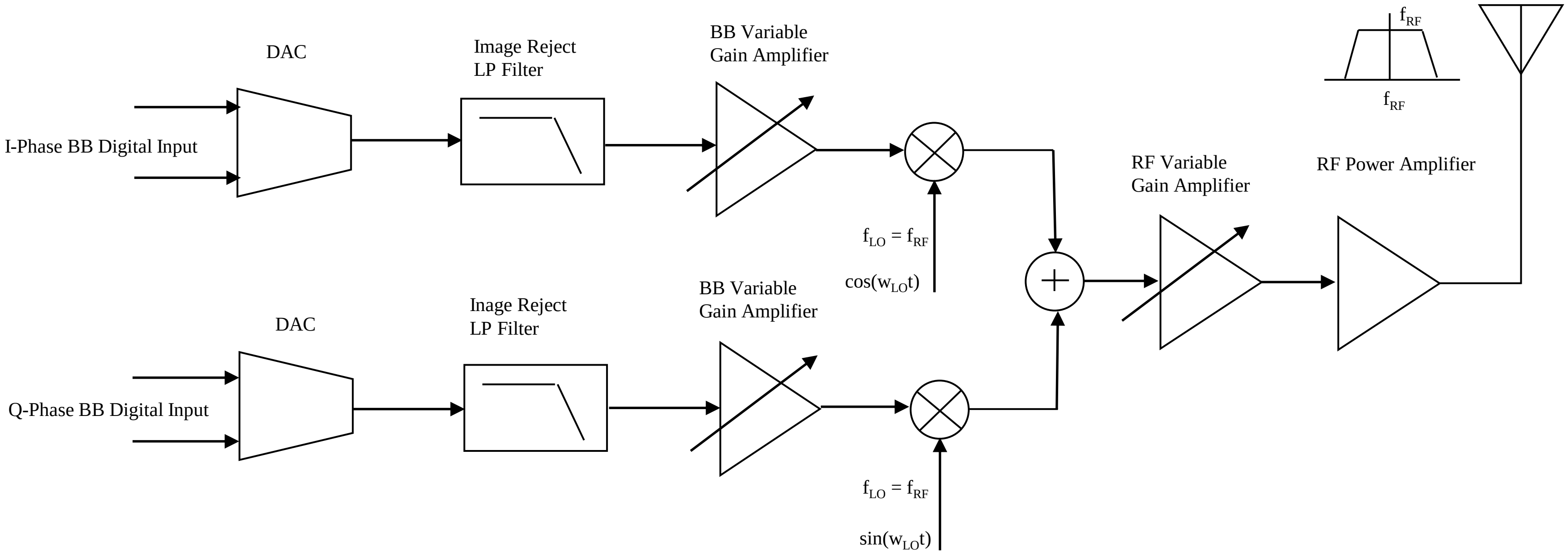
- Tuning Range over the 2.4GHz and 5GHz band is checked by performing a basic RF RX single tone test at the two extremes of the tuning range (2272MHz to 2527MHz and 4950MHz and 5910MHz), and measuring/testing the gain & I-Q matching
- Checks mainly for tuning ability of the Synthesizer (VCO tuning & divider/pre-scaler range)
- Also checks the Rx path integrity across the tuning range (LO divider, LO buffer)
- Incorporated into the Rx Gain and I-Q matching ATE test
- Many RF devices have VCO BIST which check the range of VCO with capacitor overlap by the means of a couple simple register readbacks.

TX testing

TX architecture

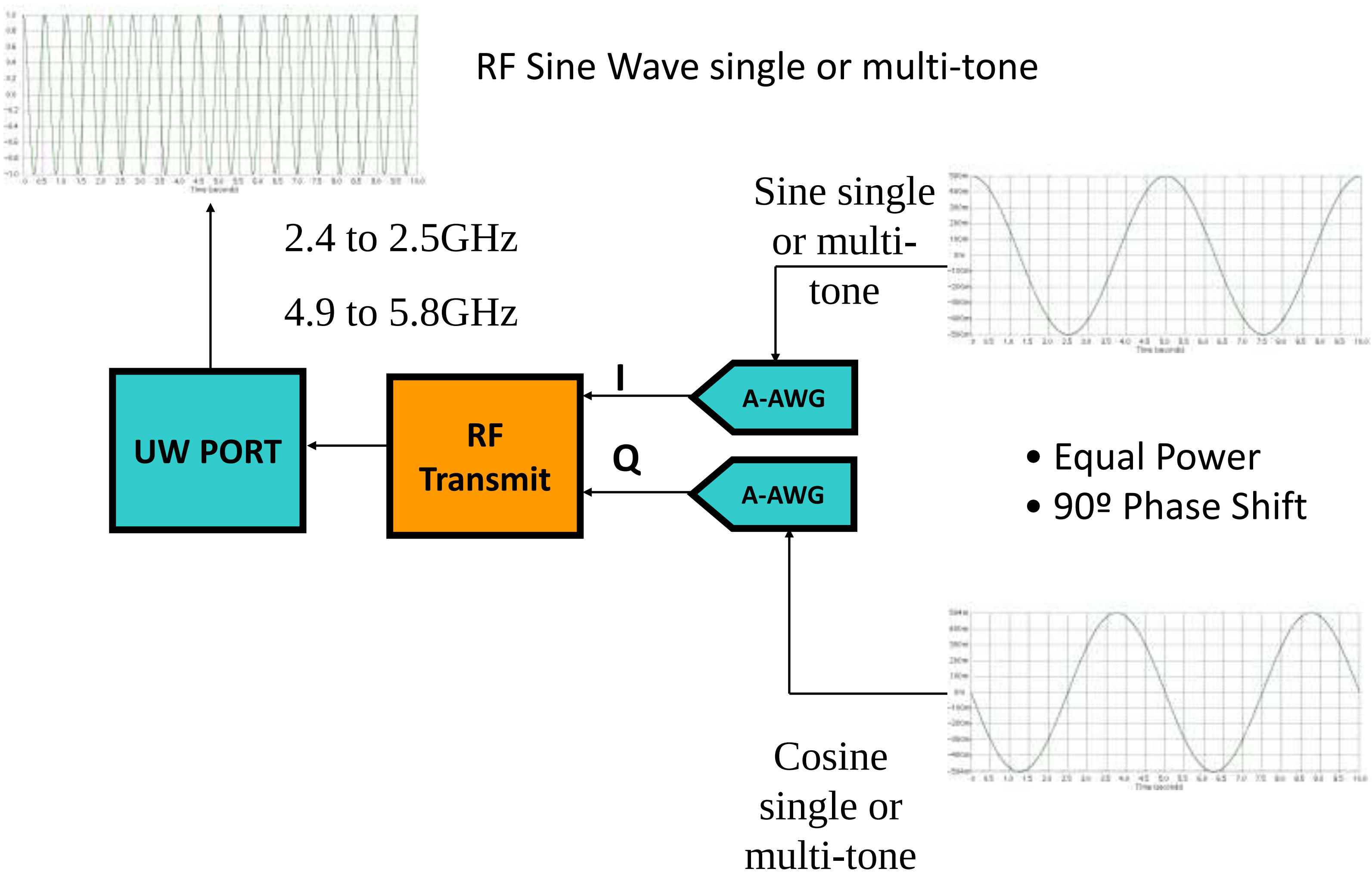
- **Basic Function of Radio Transmitters**
- Frequency shift (or modulate) DAC output (baseband signal) to the chosen RF frequency
- Adequate suppression of carrier and undesired sideband (LSB)
- Bandwidth limit the transmitted signal to avoid adjacent channel interference, and meet the Transmit spectral mask
- Drive the antenna with the specified RF power
- Maintain adequate linearity and phase noise to meet EVM considerations (affects Receiver sensitivity)

TX architecture – cont.



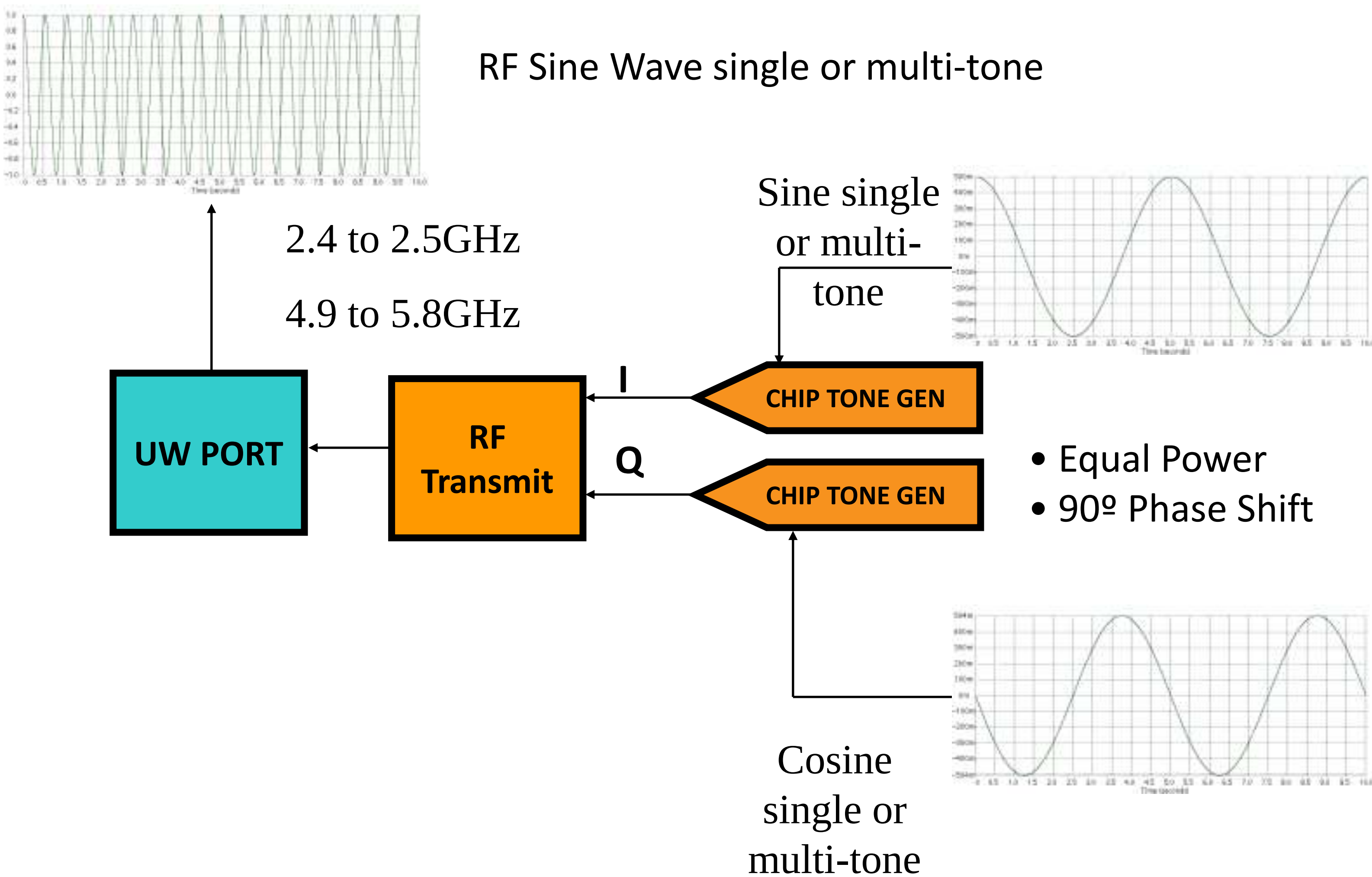
Frequency shift (or modulate) DAC output (baseband signal) to the chosen RF frequency
Adequate suppression of carrier and undesired sideband (LSB)
Bandwidth limit the transmitted signal to avoid adjacent channel interference, and meet the Transmit spectral mask
Drive the antenna with the specified RF power
Maintain adequate linearity and phase noise to meet EVM considerations (affects Receiver sensitivity)

TX ATE setup



- Equal Power
- 90º Phase Shift

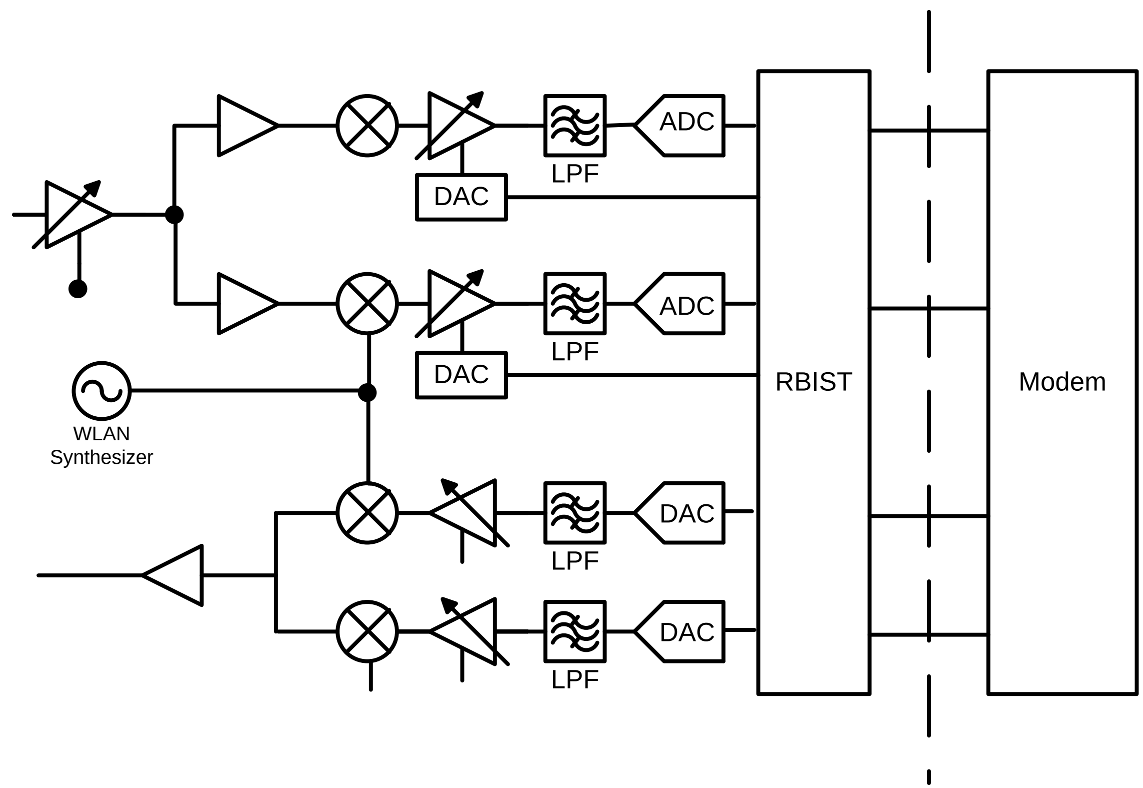
TX ATE setup with Rbist



A-Rbist

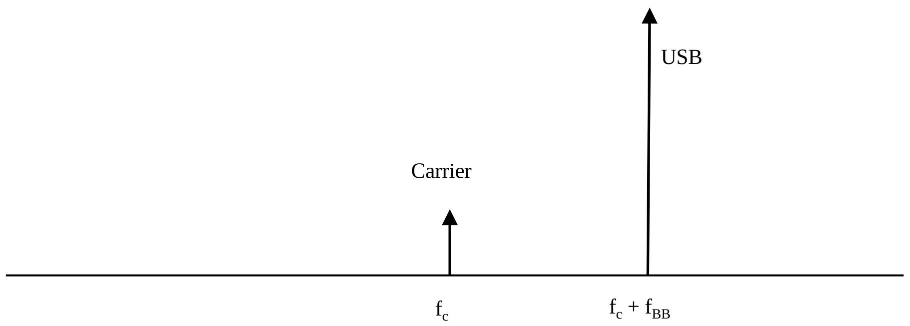
- Reduce signaling between ATE and device under test (DUT)
- Parallelize testing
- Increase test accuracy
- Reduce number of ATE Instrument options
- Simplify ATE HW

RF/Analog Front End with RBIST



TX Psat test

- Psat measures the maximum Tx power achievable in saturated mode
- Drive the TX baseband I-Q inputs with a signal amplitude that corresponds to the maximum TX-DAC output (FS)
- TX baseband driving an in-band baseband signal at full-scale (FS) amplitude
- The signal frequency needs to be selected so it falls within the passband of the TX BBF
- The measured USB signal at RF output if at the frequency of LO+BB



TX Pout test

- All Pout tests are performed similar to Psat, except the BB signal is using a back-off from FS waveform to not saturate the TX
- The measured USB signal at RF output if at the frequency of LO+BB
- TX gain step tests are performed by programming the TX gain, and then calculating the delta between 2 or more TX Pout (adjacent pair) results.

210101	0	WL_TP2_CW_L00_40M	-3.00 dBm	-0.79 dBm	8.00 dBm
210102	0	WL_TP2_CW_L01_40M	-5.00 dBm	-0.04 dBm	9.00 dBm
210103	0	WL_TP2_CW_L02_40M	-4.00 dBm	1.07 dBm	10.00 dBm
210104	0	WL_TP2_CW_L03_40M	-3.00 dBm	2.11 dBm	11.00 dBm
210105	0	WL_TP2_CW_L04_40M	-2.00 dBm	3.00 dBm	12.00 dBm
210106	0	WL_TP2_CW_L05_40M	-1.00 dBm	4.09 dBm	13.00 dBm

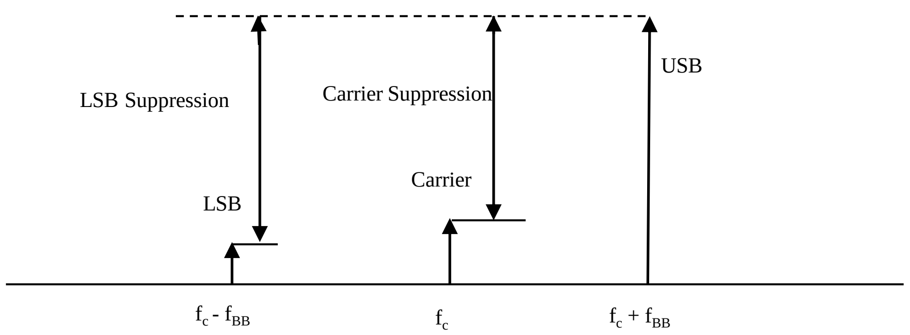
210121	0	WL_TP2_GS_L01_40M	0.30 dB	0.75 dB	2.00 dB
210132	0	WL_TP2_GS_L02_40M	0.30 dB	1.12 dB	2.00 dB
210133	0	WL_TP2_GS_L03_40M	0.30 dB	1.04 dB	2.00 dB
210134	0	WL_TP2_GS_L04_40M	0.30 dB	0.89 dB	2.00 dB
210135	0	WL_TP2_GS_L05_40M	0.30 dB	1.09 dB	2.00 dB

TX tuning range test

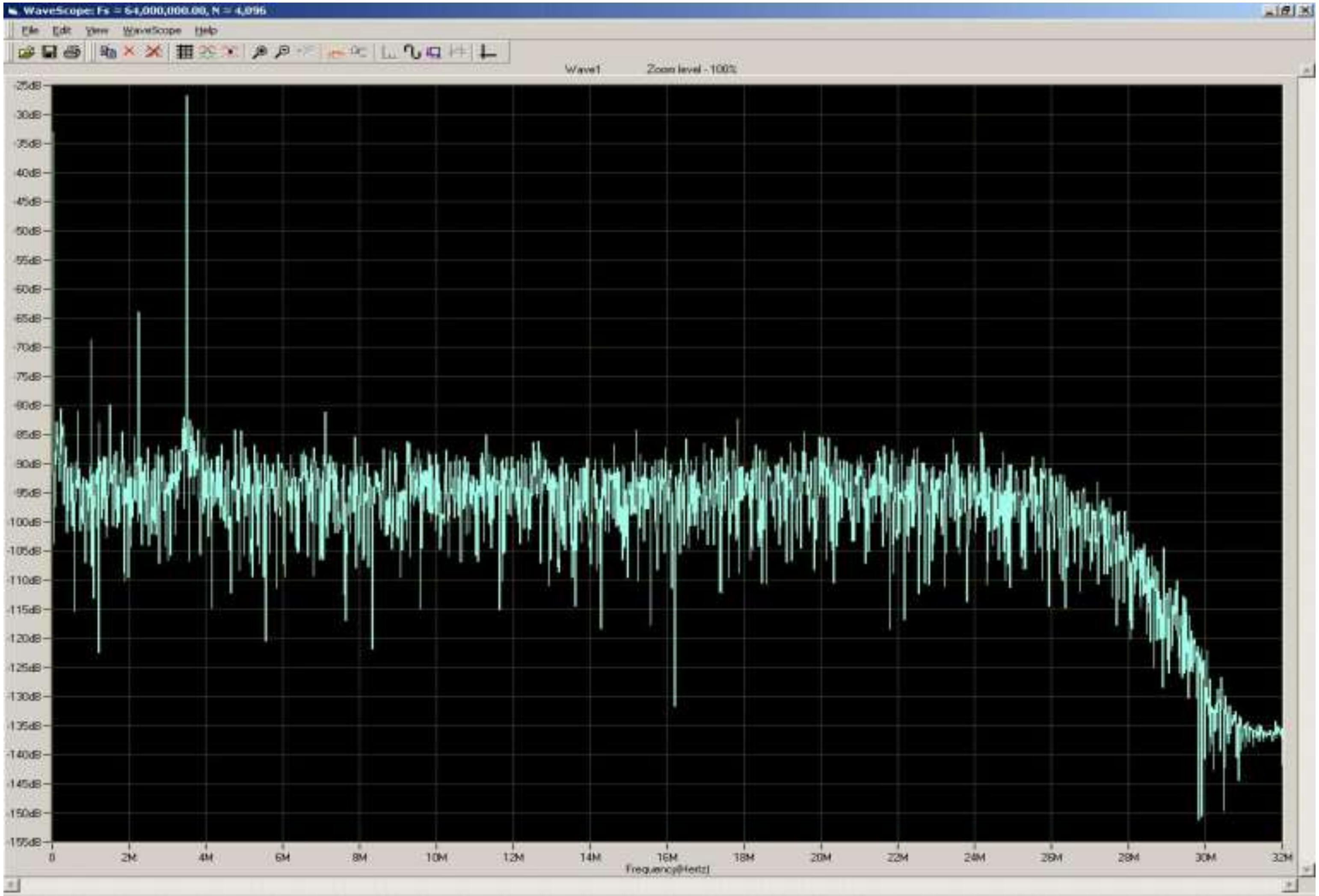
- Some duplication between this test and Rx tuning range test as far as the synthesizer is concerned
- This test additionally checks the tuning range of Tx path (Tx LO buffers, Tx LO dividers)
- Test checks across the channel decoder range
- Same extreme frequencies as the Rx tuning range tests

TX LO (carrier) and lower sideband (RSB) suppression

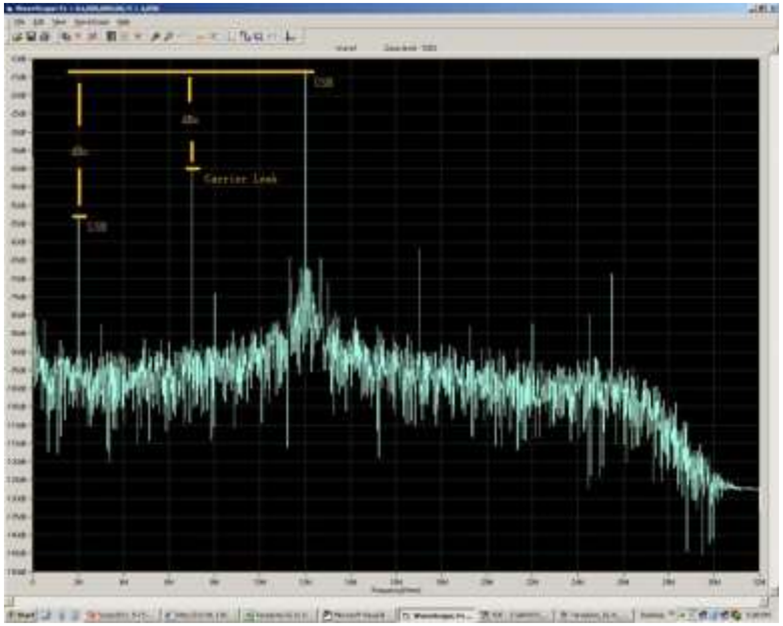
- All CS/SB tests are/can be performed at the same time as Pout tests are done
- The measured signals at RF output are outlined in below graph
- Need to be careful about 3rd order intermodulation products of Upper Sideband and Carrier leaking into the Lower sideband which may produce erroneous results for LSB suppression
- LO (carrier) calibration is done (similar to RX) by sweeping the iDAC codes in the BB section to find the lowest carrier power



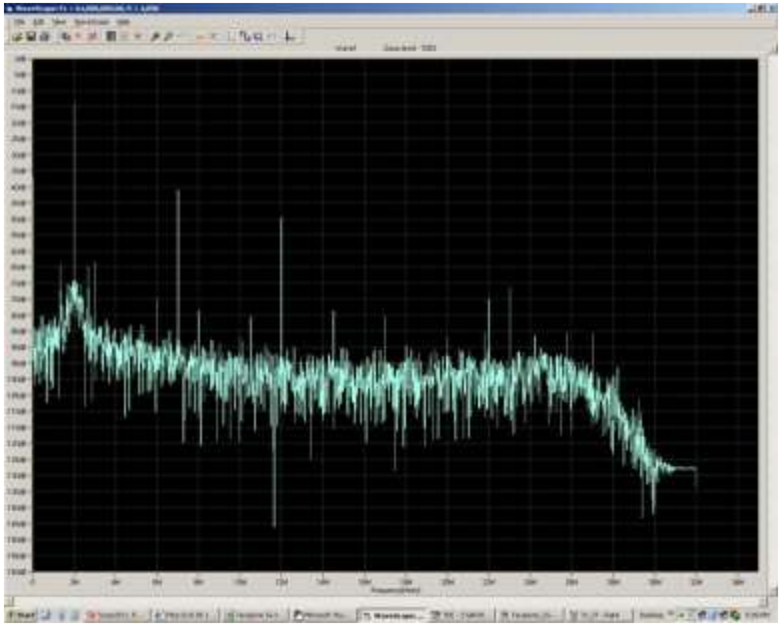
TX transmit spectrum capture



TX Pout spectrum



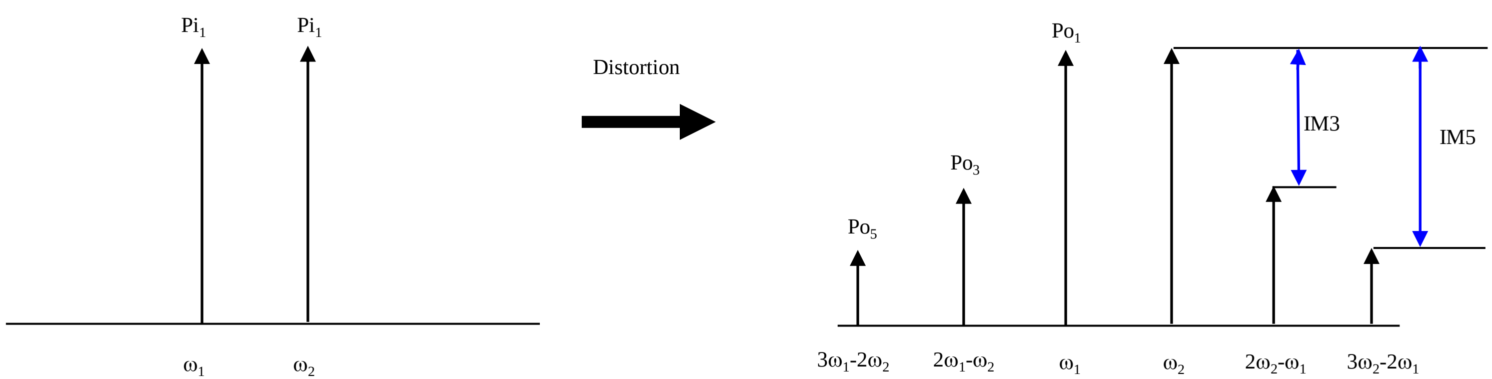
I Sine Q Cos



I Cos Q Sine

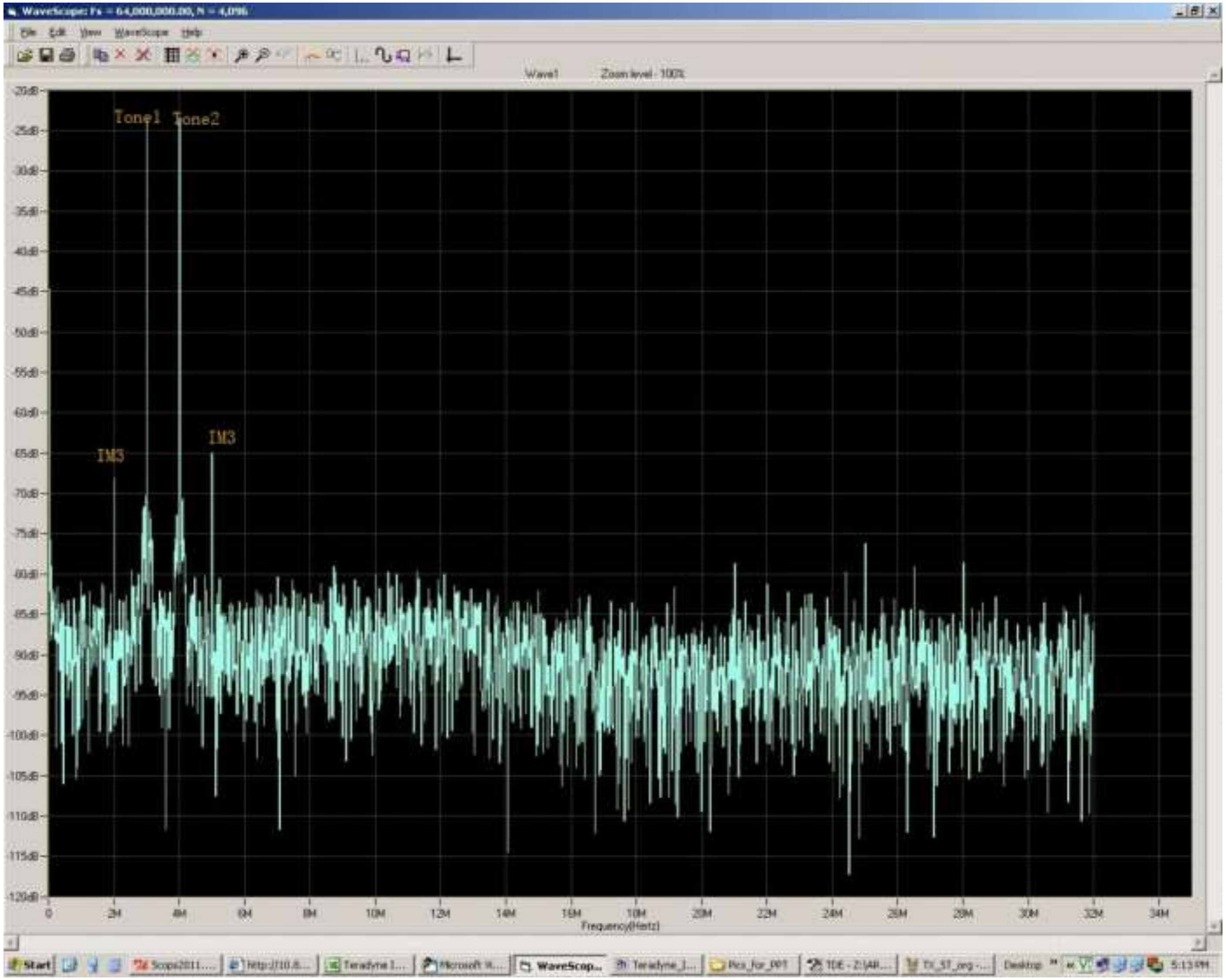
TX linearity test – OIP3

- Transmitter Linearity OIP3 test is conceptually similar to the Receiver Linearity test
- ATE test condition must be similar to a situation of a large transmitted signal (i.e. high on-chip PA power)
- Transmitter final stages (PA, pre-PA-buffer etc.) set at maximum gain to maximize the output linear power and this forces compression (if any) to occur in these stages. TX gain LUT have this build-in
- Other considerations similar to Receiver Linearity test



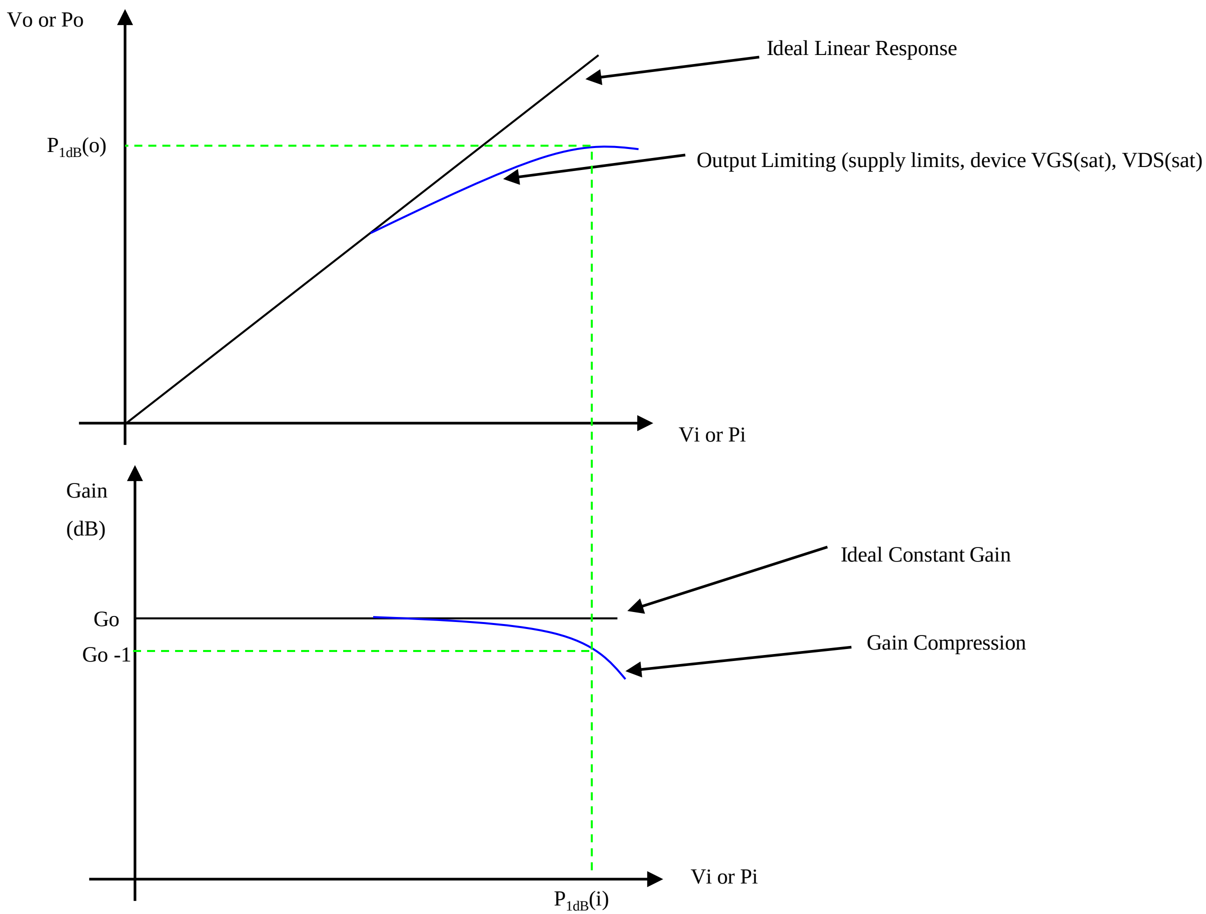
210196	0	WL_TP2_Tone_Pwr_USB_L16_backoff10_40M	5.00 dBm	9.33 dBm	20.00 dBm
210197	0	WL_TP2_Tone_Pwr_LSB_L16_backoff10_40M	5.00 dBm	9.18 dBm	20.00 dBm
210198	0	WL_TP2_IM3_USB_L16_backoff10_40M	-100.00 dBm	-27.61 dBm	0.00 dBm
210199	0	WL_TP2_IM3_LSB_L16_backoff10_40M	-100.00 dBm	-29.57 dBm	0.00 dBm
210200	0	WL_TP2_OIP3_USB_L16_backoff10_40M	23.50 dBm	27.80 dBm	N/A
210201	0	WL_TP2_OIP3_LSB_L16_backoff10_40M	23.50 dBm	28.55 dBm	N/A
210202	0	WL_TP2_OIP3_worst_L16_backoff10_40M	23.50 dBm	27.57 dBm	N/A

TX OIP3 spectrum



TX linearity test – P1dB

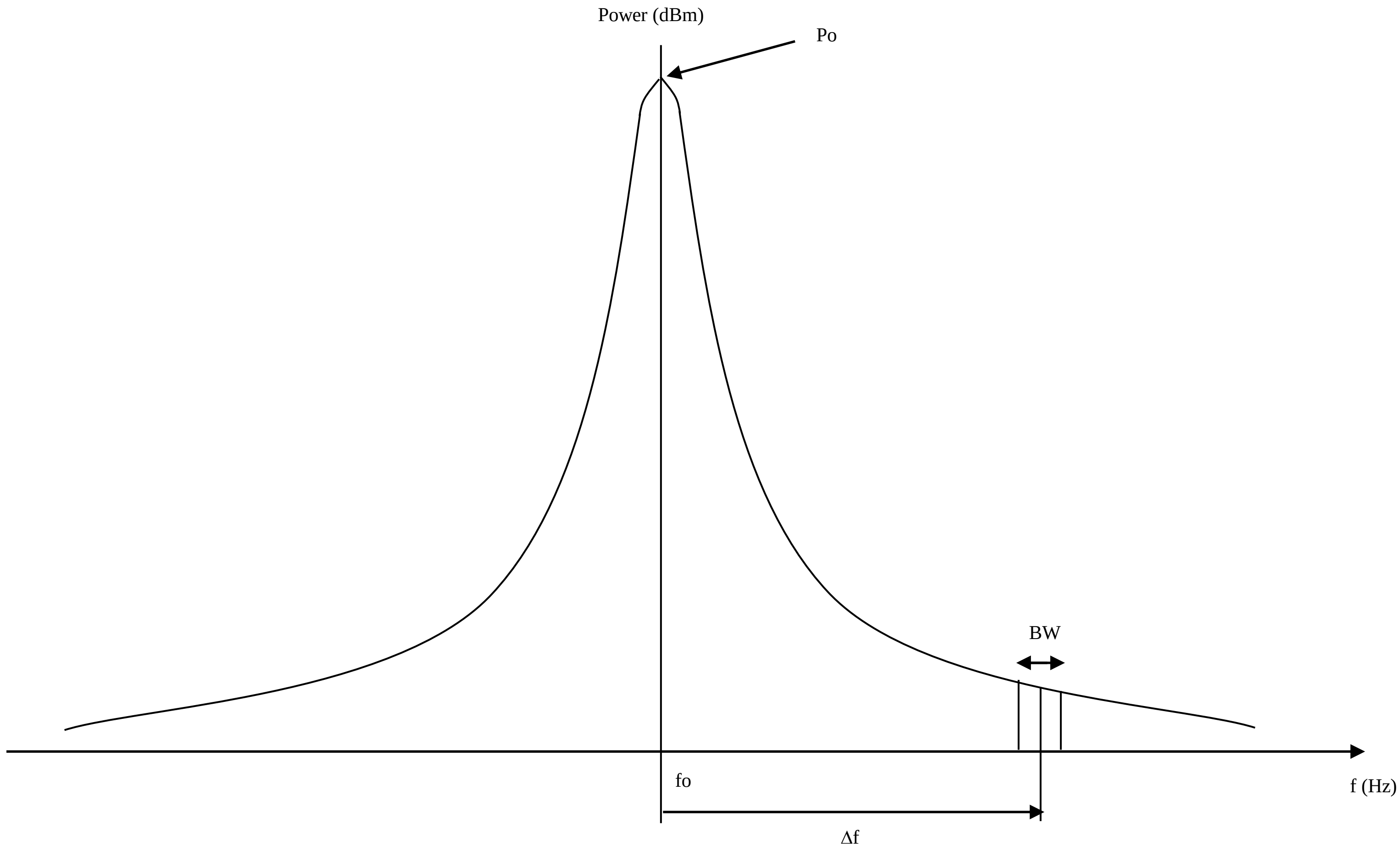
Transmitter Linearity P1dB test is conceptually similar to the Receiver Linearity test
BB input signal power is increased until the output compresses (char)
Production test is a single test at the P1dB spec and limit is set to <1dB (typ. 0.7dB)



PLL/TX Phase Noise test

- Phase Noise describes the spectral purity of a signal
- For a pure sinusoid, this means there is energy presence at frequencies other than that of the pure sinusoid (can spill out into adjacent channels and affect ACPR)
- Phase noise energy is random (distinct from spurs that are mostly deterministic)
- Timing jitter → Phase noise integrated over frequency
- Knowledge of the frequency characteristics of timing jitter are necessary for digital radios as it can directly impact EVM
- Lower frequency components of phase noise (up to several hundred kHz) can be corrected by digital DSP routines. Main contributor of these noise components is the reference clock and frequency dividers
- High frequency noise components tend to be dominated by the noise characteristics of the synthesizer building blocks (VCO, PFD)
- High phase noise can result in poor EVM (loss of sensitivity)
- Conventional method of measuring phase noise profile of the synthesizer is by observing the RF output of the transmitter

PLL/TX Phase Noise test – cont.



PLL/TX Phase Noise test – cont.

Phase Noise Spectrum : $PN(fo,\Delta f) = S(\Delta f) / Po(fo)$

$S(\Delta f)$ = Phase Noise Power Spectral Density (W/Hz)

$Po(fo)$ = RF Signal Power (W)

dB log scale : $PN(fo,\Delta f) = Po(dBm) - S(\Delta f)*BW\ (dBm) + 10*\log_{10}(BW)$ (dBc/Hz)

Source of PN:

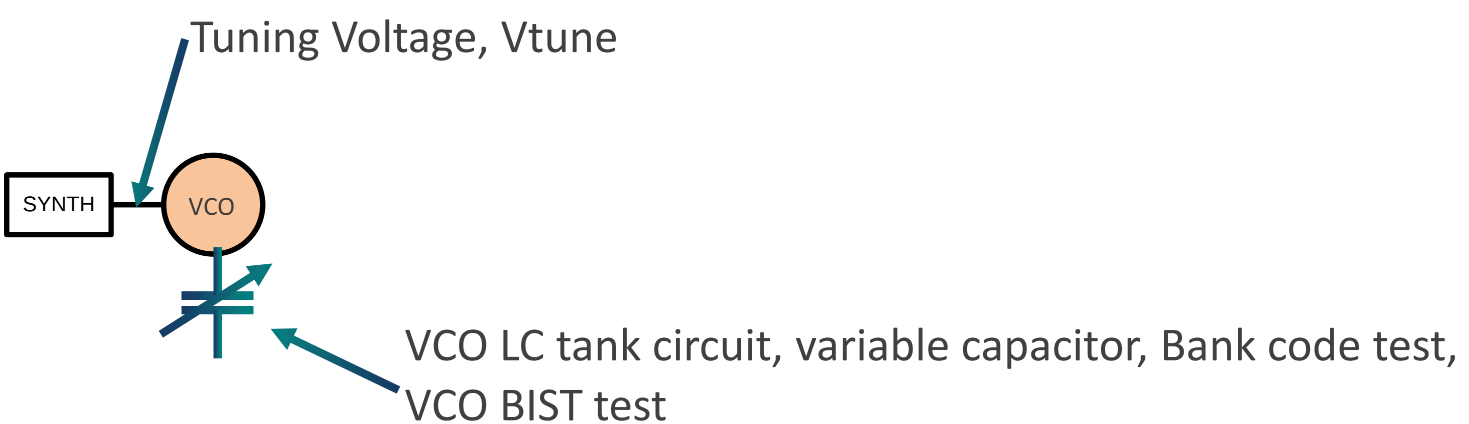
- Leakage of reference frequency in PLL
- Incomplete suppression of undesired mixer components
- Noise inherent in any signal source
- Signal timing jitter etc.

PLL/TX Phase Noise test – cont.

- Phase Noise spectrum is calculated by a SNR measurement of desired tone power to the noise power spectral density
- On ATE, need to ensure that measurement instrument and reference signal source noise floor does not limit accuracy of measurements
- Sanity check: Reduce Po by a few dB, phase noise numbers should remain unchanged if they are not limited by instrument noise floor (otherwise they get worse)
- As a practical matter, may need to 'dodge' spurs when choosing phase noise bins

- In addition to the (spot) PN test, there is often a integrated Phase Noise (IPN) requirement
- All this does is integrating the power of a higher BW signal (~100KHz to 10MHz)

- Additional PLL tests include the VCO tuning voltage and the VCO capacitor bank code. Kvco is sometimes measured on ATE but mostly in the lab with open loop mode.

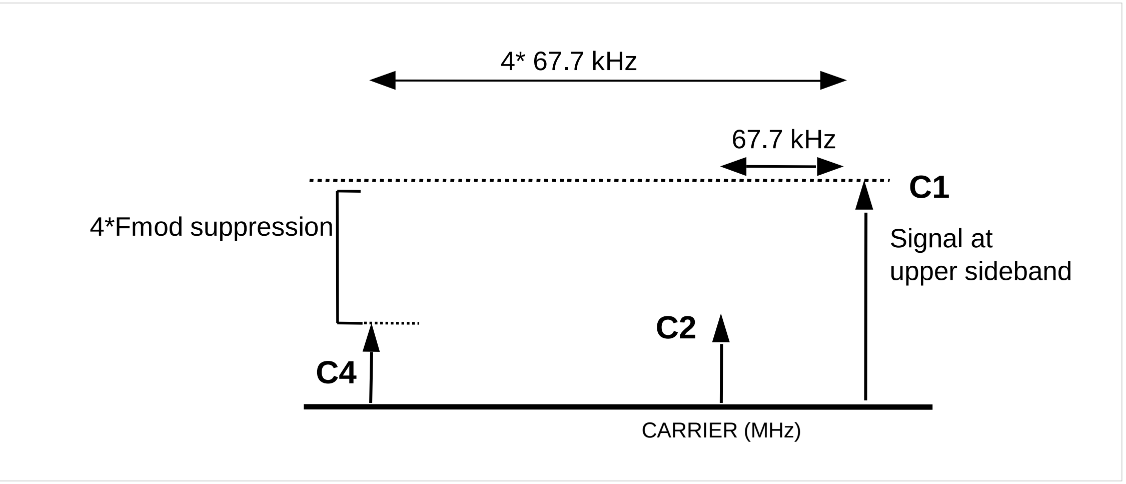


TX BBF

TX BBF design is same LPF as RX BBF, might have slightly different specs
Similar to RX BBF, ATE test TX BBF BW and rejection at specific frequencies (per spec)
Filter tuning may be required

Additional TX tests

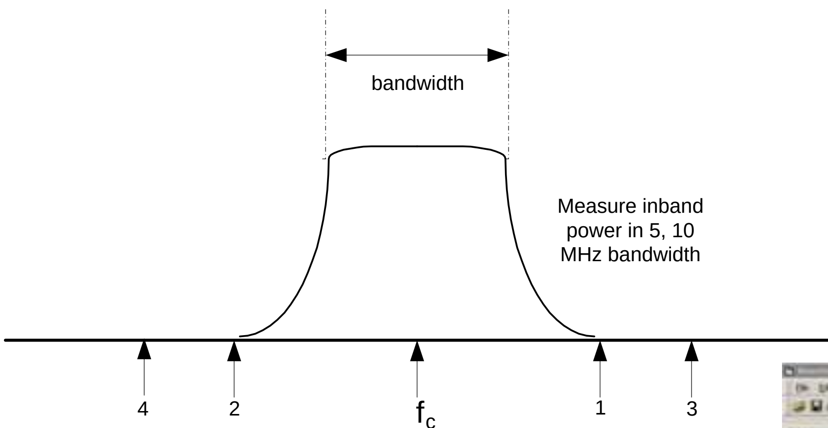
4fmod : Measure the CW power of the 4Fmod product at 4*BB_Freq below the frequency of interest.
This test is often required for cellular band transmitters

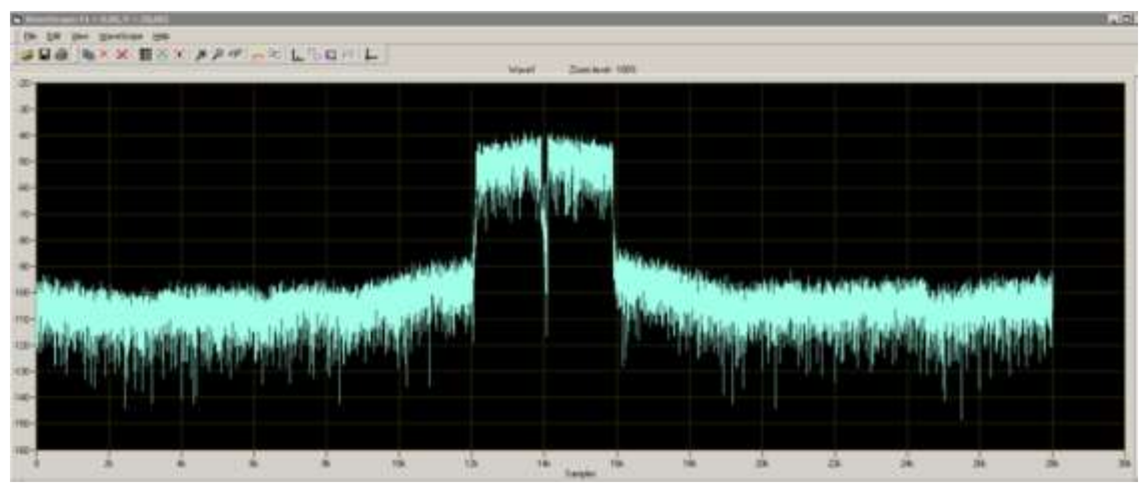


Additional TX tests (cont.)

ACLR (Adjacent Channel Leakage Ration) in some wireless standards also called ACPR (Adjacent Channel Power Ratio)

Measure the integrated in band modulated power of the TX output. Then measure the side band power of the spectral regrowth and report the relative Power to the in band power (dBc).

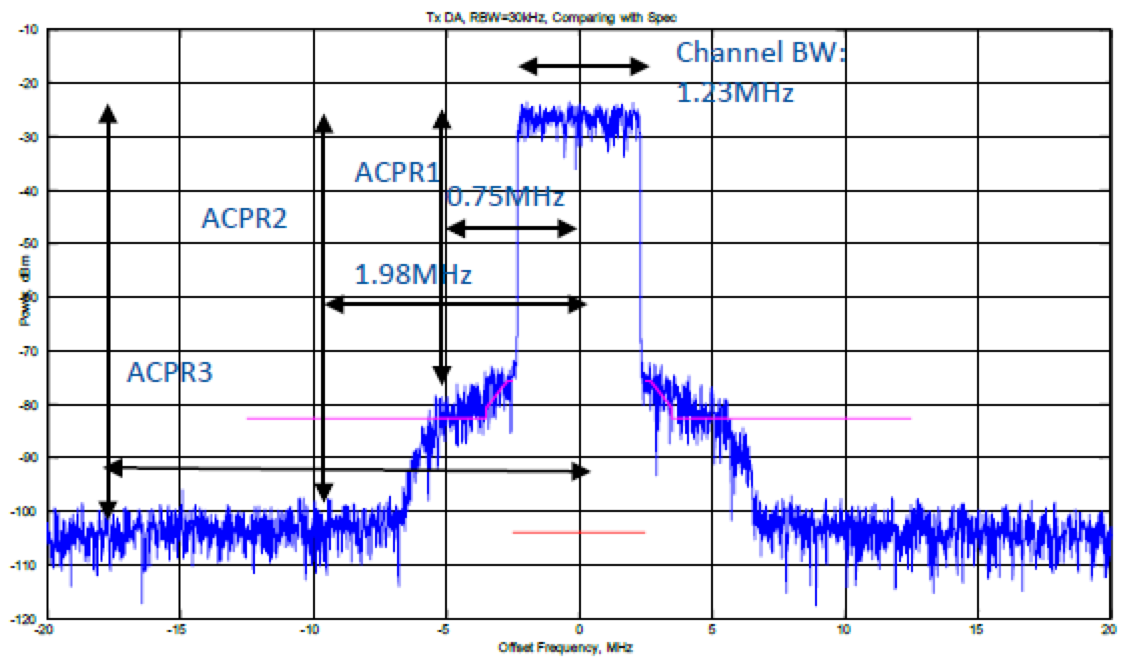




Additional TX tests (cont.)

Calculate:

- ACPR1 = Po – P1p, Po –P1m
- ACPR2 = Po – P2p, Po –P2m
- ACPR3 = Po – P3p, Po –P3m



Additional TX tests (cont.)

EVM is the measure of Modulator performance

It is essentially measure the maximum error between the measured signal and the ideal signal vector – defined by the following equation

$$\mathrm{EVM} = \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}[(I_j - \tilde{I}_j)^2 + (Q_j - \tilde{Q}_j)^2]}}{|\underline{v}_{\max}|}$$

where

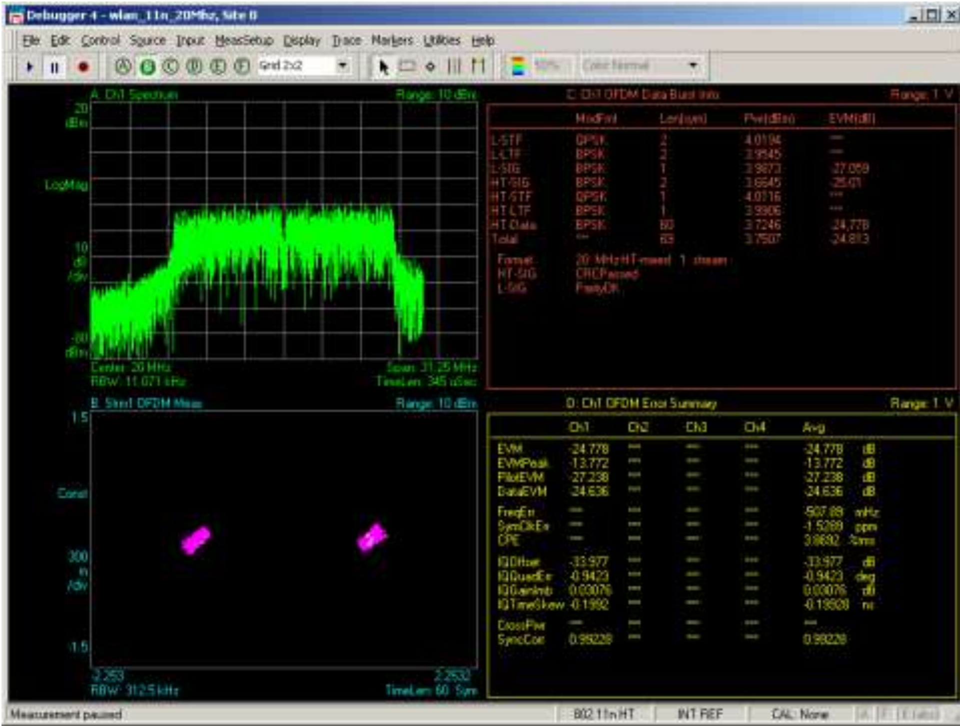
Ij is the I component of the *j*-th symbol received,

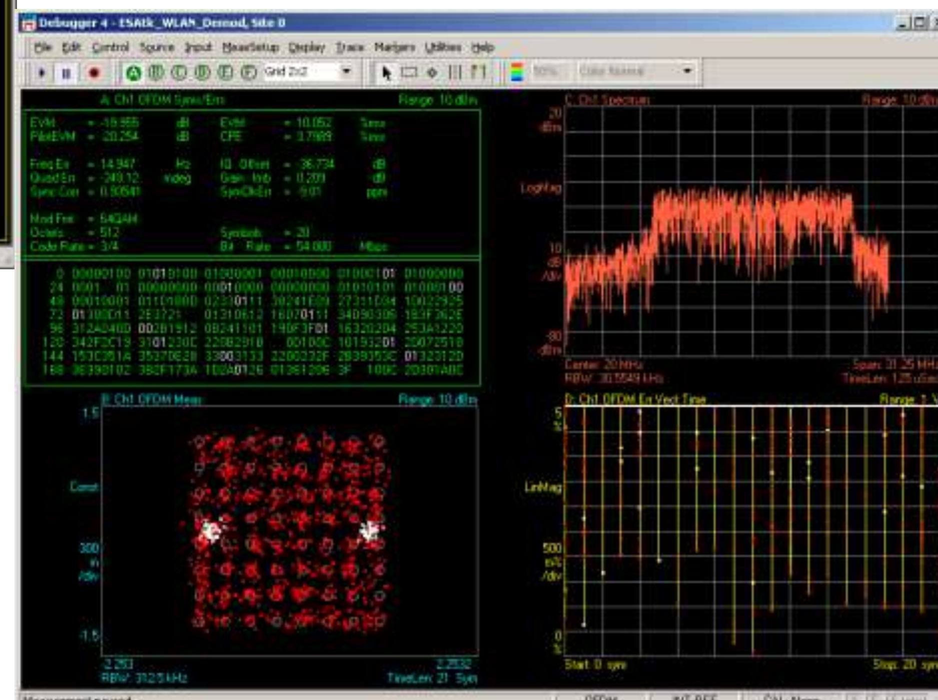
Qj is the Q component of the *j*-th symbol received,

~*I*j is the ideal I component of the *j*-th symbol received,

~*Q*j is the ideal Q component of the *j*-th symbol received.

Additional TX tests (cont.)





Appendix

RF system formulas

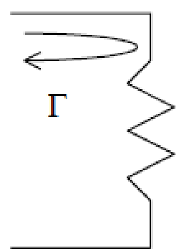
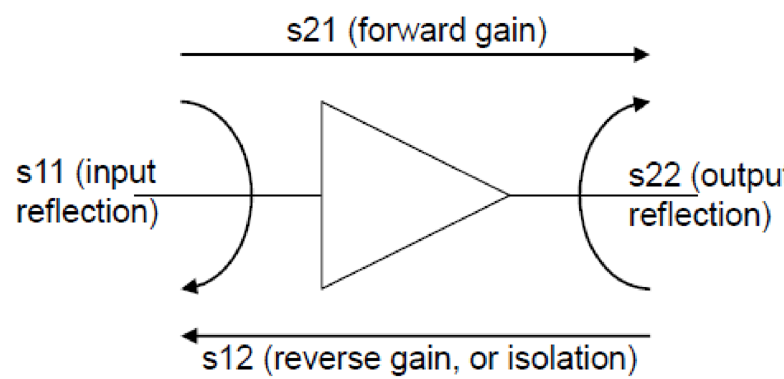
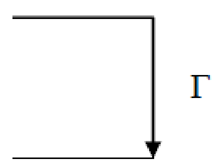
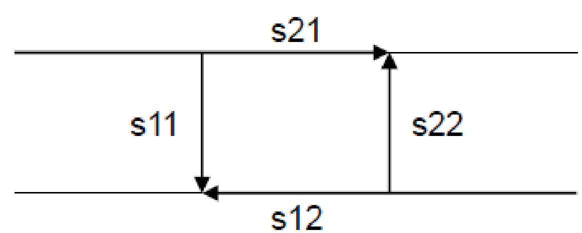
Adobe Acrobat Document

S-parameter

- Scattering parameters (s-parameters) describe the reflection and transmission characteristics of multiple-port networks.
- For example, an amplifier has two ports (input and output), while a termination resistor has only one port.
- A key concept to understanding s-parameters is impedance matching.
- When a signal is traveling along a wire with a particular impedance and encounters a different impedance, as with a termination resistor, an adapter, or a printed circuit board trace with different geometry, part of the signal is reflected back.
- These reflections affect the amplitude of the signals we source and measure when testing devices, increasing the complexity and uncertainty of our calibration
- These reflections have both magnitude and phase, resulting in constructive or destructive interference which changes with frequency as the number of fractional wavelengths between the reflections changes. This results in “ripple” as you sweep across frequency.
- For microwave testing, we try to match each port/plane to a constant 50 Ω impedance to minimize these effects. (Many devices have non-50 Ω impedances of which cable TV is probably the best known at 75 Ω.)

S-parameter (cont.)

- Coefficients of reflection are denoted by the Greek alphabet Γ (Gamma)
- Γ is related to the difference in impedance between the transmission line and the load. It is described by the formula $\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{z - z_0}{z + z_0}$, where z_0 = 50Ω

	1-port	2-port
Schematic Representation		
Flow Diagram Representation		

Return Loss and VSWR

- Once you have the Γ value, you can use it to calculate return loss (RL) and voltage standing wave ratio (VSWR)
- Return loss formula, RL (dB) = $-10 \log_{10} (|\Gamma|^2)$
  - Return loss is also commonly used for mismatch in device specifications. It is a power rather than a voltage quantity.
- VSWR formula, $VSWR = \dfrac{1+|\Gamma|}{1-|\Gamma|}$
  - VSWR refers to the standing waves formed in a transmission line (with a sine wave) when there are impedance mismatches.
  - The ratio of the high voltage to the low voltage measured in the line can be used to determine VSWR directly:
    - 1:1 is ideal
    - 1.5:1 is typically acceptable
    - 2:1 is typically considered poor

S-Parameter glossary

Term	Definition
Incident wave	Incident wave going into a port
Reflected wave	Reflected wave coming out of a port, or a wave coming out of a port which originated at another port.
Reflection Coefficient, Γ (Gamma)	$\lvert S_{11}\rvert$ or $\lvert S_{22}\rvert$
Return loss (dB)	$-20 \log (\Gamma)$
Insertion loss (dB); Gain (dB)	$-20 \log (\gamma)$; $20 \log (\gamma)$
S_{11}	V_1^- / V_1^+, Z_o load on port 2
S_{12}	V_1^- / V_2^+, Z_o load on port 1
S_{21}	V_2^- / V_1^+, Z_o load on port 2
S_{22}	V_2^- / V_2^+, Z_o load on port 1
S-parameters	Scattering parameters
S1P	One Port S-parameters
S2P	Two Port S-parameters
Transmission Coefficient, γ (gamma)	$\lvert S_{21}\rvert$ or $\lvert S_{12}\rvert$
$V_{incident}$	V_1^+, V_2^+
$V_{reflected}$	V_1^-, V_2^-

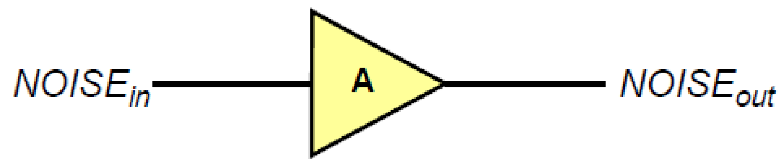
S-Parameter glossary – cont.

Term	Definition
VSWR	Voltage Standing Wave Ratio = $\frac{(1+\Gamma)}{(1-\Gamma)} = \frac{V_{\max}}{V_{\min}}$ at a given port
Γ (Gamma)	$\frac{VSWR-1}{VSWR+1}$
S_{11}	Input return loss or input match (Γ_{in})
S_{12}	Reverse transmission or isolation (γ)
S_{21}	Small signal gain or gain (γ)
S_{22}	Output return loss or output match (Γ_{out})

Noise Figure

- Noise Figure (NF) is a measurement of the amount of noise that is added by a device expressed in dB.
- Noise Figure is the logarithmic representation of the Noise Factor (F) and is assigned the symbol NF, where:

$$NF = 10 \times \log_{10}(F)$$



$$NF = SNR_{in(dB)} - SNR_{out(dB)}$$

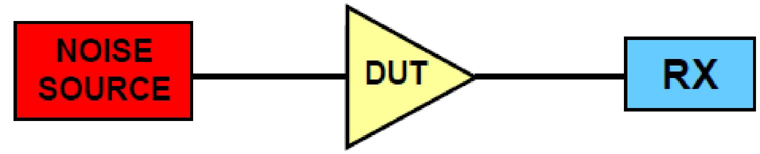
$$NF = \left(P_{RF_{in}(dBm)} - P_{NOISE_{in}(dBm)}\right) - \left(P_{RF_{out}(dBm)} - P_{NOISE_{out}(dBm)}\right)$$

- Noise Factor is represented by the symbol F and is defined as:

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{\left(P_{RF_{in}} / P_{NOISE_{in}}\right)}{\left(P_{RF_{out}} / P_{NOISE_{out}}\right)} = \frac{P_{NOISE_{out}}}{G_A \, P_{NOISE_{in}}}$$

Noise Figure (cont.)

- Y-Factor method to determine NF:
  - The Y-Factor method is a technique used to measure the noise added by a device that can be used to calculate the device's noise figure.
  - The Y-Factor technique uses a noise source that outputs a calibrated Excess Noise Ratio (ENR).
  - Two measurements are made: one with the Noise Source turned "on" (to simulate a hot temperature condition) and one with it turned "off" (cold condition).
  - Knowing the Noise Source's ratio of "on" to "off" noise power, and knowing the amount of noise measured at the output of the device, the numbers can be input to a formula to calculate the noise added by the DUT (NFdB).



$$ENR = \frac{T_{hot}}{T_{cold}} - 1 \qquad Y = \frac{N_{hot}}{N_{cold}}$$

Where:

$$T_{cold} = 290^{\circ} K (63.3^{\circ} F = 16.5^{\circ} C)$$

$$F = \frac{ENR}{(Y-1)}$$

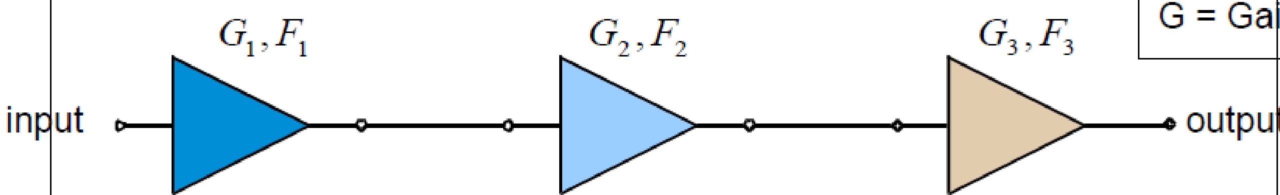
$$\boxed{NF_{dB} = ENR_{dB} - 10 \times \log_{10}(Y-1)}$$

Microsoft Excel Worksheet

Noise Figure (cont.)

- Cascaded Noise Figure can be calculated using Friis' equation
  - Given the following circuit:

F = Noise Factor
G = Gain



  - And given the following equation:

Frii's Equation: $$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2}$$

  - The total **Noise Factor** is minimally dependent on the gain of the final stage.
  - The Noise Factor of the first stage is usually the most dominant.
  - The Noise Factors of the subsequent stages **do** add to the total noise factor but are diminished by the gains of the preceding stages.
  - You need to adjust Noise Figure calculations to remove NF contribution from tester.

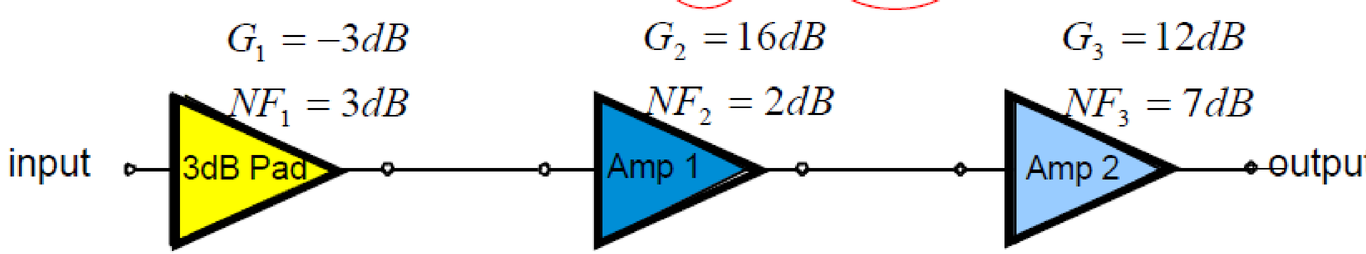
Cascaded Noise Figure example

- Consider the following two RF system configurations:

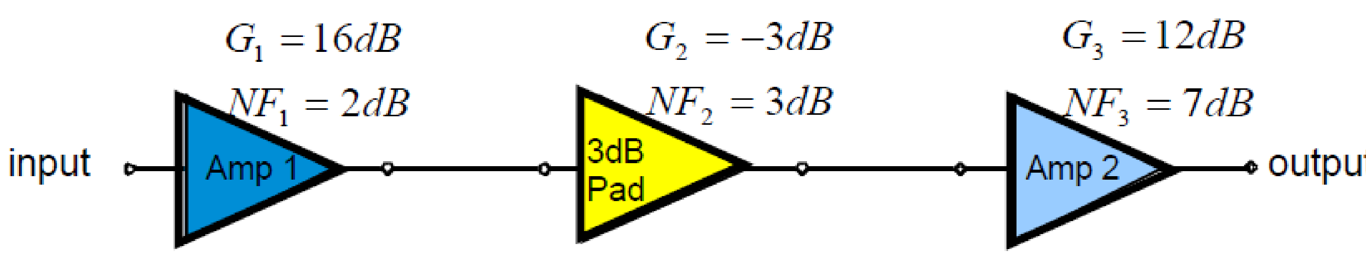
$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2}$$

F = Noise Factor
NF = Noise Figure (dB)

Configuration 1:



Configuration 2:



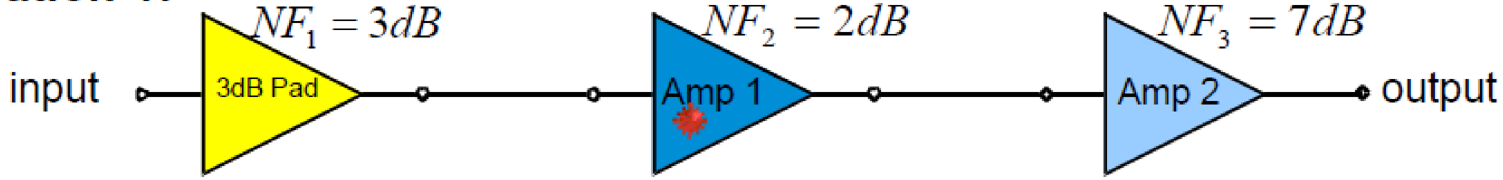
- Using Friis' equation, calculate the total cascaded Noise Figure of each system…

Cascaded Noise Figure example (cont.)

(See Power Point slide notes for equation solution details.)

Configuration 1:

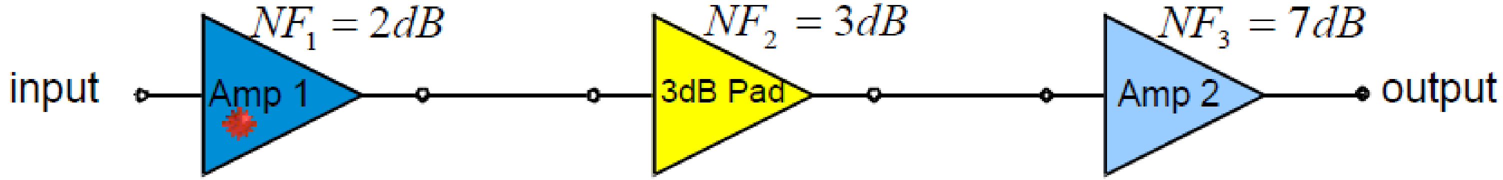
$G_1 = -3dB$, $NF_1 = 3dB$ $\quad$ $G_2 = 16dB$, $NF_2 = 2dB$ $\quad$ $G_3 = 12dB$, $NF_3 = 7dB$



$$NF = 10\log_{10}(F) = 10\log_{10}\left(2 + \frac{1.6-1}{0.5} + \frac{5-1}{0.5\times 39.8}\right) = 5.31dB$$

Configuration 2:

$G_1 = 16dB$, $NF_1 = 2dB$ $\quad$ $G_2 = -3dB$, $NF_2 = 3dB$ $\quad$ $G_3 = 12dB$, $NF_3 = 7dB$



$$NF = 10\log_{10}(F) = 10\log_{10}\left(1.6 + \frac{2-1}{39.8} + \frac{5-1}{0.5\times 39.8}\right) = 2.61dB$$

This is why the Low-Noise Amplifier appears on the receiver front end.

Noise Source glossary

Noise Source Hot	Noise source is on.
Noise Source Cold	Noise source is off.
Noise Factor	A figure of merit for noise produced by amplifiers or mixers. It is a measurement of the noise added by the DUT and can be thought of as the degradation of the signal-to-noise ratio between the input and output. Noise factor is always greater than 1.0. It can be expressed in terms of power ratios as: Noise Factor = F = SNRin/SNRout = (Pin/Pin_noise) / (Pout/Pout_noise)
Noise Figure	Noise factor, F, expressed in dB and is defined as: Noise Figure = NF = 10 * log(F)
ENR (Excess Noise Ratio)	The calibrated value for a noise source used in noise figure testing (see glossary) that represents the ratio of the difference of the noise temperature when the source is on (“hot”) and off (“cold”) as compared to a reference temperature of 290°K. ENR is often expressed in dB or ENR_{dB}. It can be mathematically expressed as: ENR = (TON - TOFF) / 290°K ENRdB = 10 * log(ENR)

Analog Modulation (cont.)

- Coherency equation:

$$\frac{f_s}{N} = \frac{f_{\text{interest}}}{M}$$

f_i = frequency of interest
f_s = sampling frequency
N = size of waveform array
M = cycles = frequency bin

- f_m coherency verification:

$$M_m = f_m\left(\frac{N}{f_s}\right) = 64kHz\left(\frac{4096}{65.536MHz}\right) = 4$$

- f_{IF} coherency verification:

$$M_{IF} = f_{IF}\left(\frac{N}{f_s}\right) = 2.048MHz\left(\frac{4096}{65.536MHz}\right) = 128$$

- **M must be an integer.**

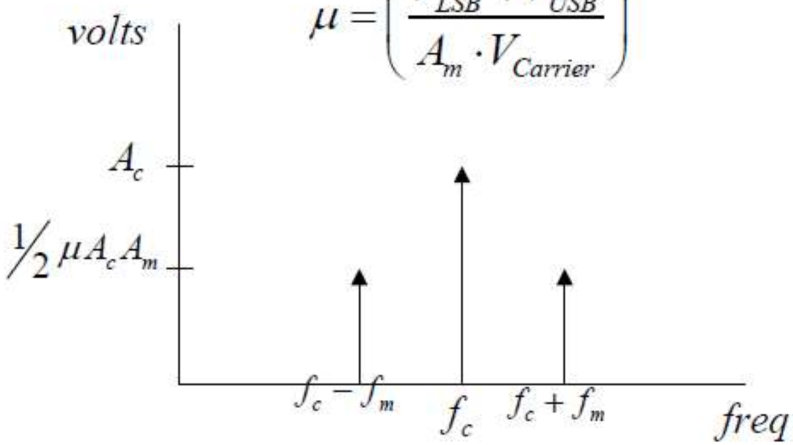
Analog Modulation (cont.)

The spectrum of the AM signal has three tones:

- the carrier
- the lower sideband
- the upper sideband

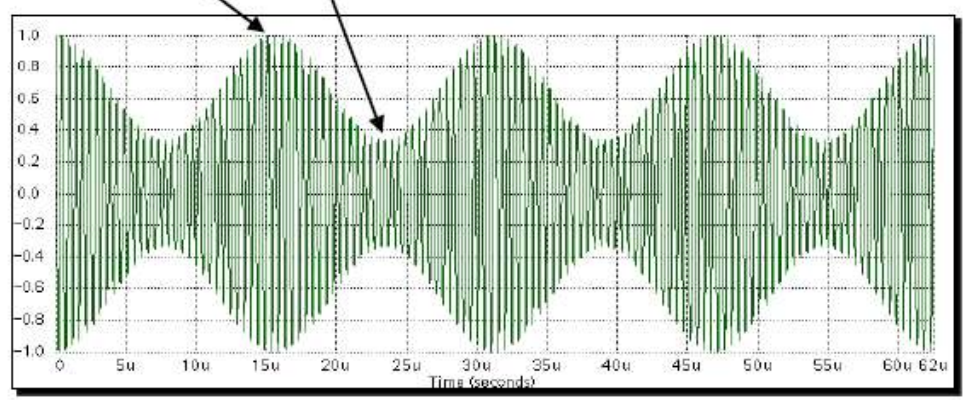
Freq domain

$$\mu = \left(\frac{V_{LSB} + V_{USB}}{A_m \cdot V_{Carrier}} \right)$$



Time domain

μ=(Vmax-Vmin)/(Vmax+Vmin)



Any Questions ?