Dana Fosmer at 9/18/2014 2:01 PM

- Typical wireless system architecture
    - Amplifiers
    - Filters
    - Mixers
    - Oscillators
    - Passives
    - Domain converters
- RF systems can be single port, two port or 3 port
- Linear two port network
    - Terminal voltages and currents related to each other

- From Microwave Engineering Book P 192 ~~Microwave Book page~~

Impedance Matrix

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{21} & & & \vdots \\ Z_{N1} & \cdots & & Z_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \quad (V = IR)$$

Admittance Matrix

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1N} \\ Y_{21} & & & \vdots \\ \vdots & & & \\ Y_{N1} & \cdots & & Y_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} \quad (I = VY)$$

The objective is always to relate the input and output voltages and currents by using certain relationships

Y parameters (admittance)

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

The scattering matrix relates the voltage waves incident on the ports to those reflected from the ports

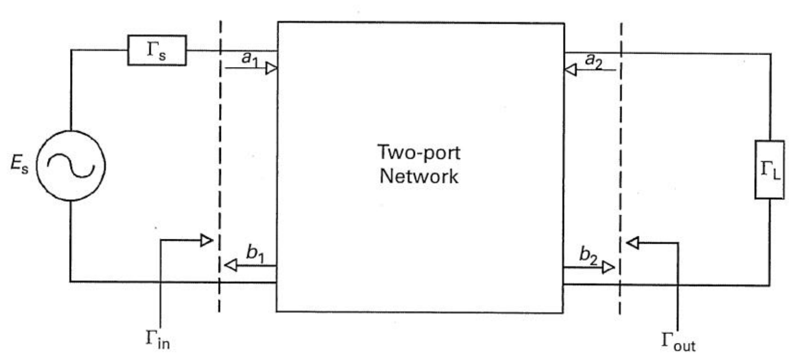
$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & & & \\ \vdots & & & \\ S_{N1} & & & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

$$[V^-]_{\text{out}} = [S][V^+]_{\text{in}}$$

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0 \text{ for } k \neq j}$$

Sij is found by driving port j with Vj+ and measuring Vi- coming out of port i

The incident waves on all ports except the jth port are set to zero, which means that all ports should be terminated in matched loads to avoid reflections



S_{ii} is a reflection because the input is at i and the measurement is at i

S_{ij} is a transmission coefficient from j to I when all other ports are terminated in matched loads. J is the input, I is the output.

Γ = reflection coefficient
T = transmission coefficient

Reflection coefficient only equals Snn when all other ports are matched

Transmission coefficient only equals Snm when all other ports are matched

You can look at a particular reflection or transmission s parameter and it's easire to isolate the port of interests contribution by matching the impedance of the other ports, rather than shorting or opening them like you have to do for admittance or impedance matrix.

Noise

RF goal - to achieve a good noise to power ratio

Linear FOMs

Voltage standing wave ratio (VSWR)

- Evaluation of port mismatch
- Measuring port mismatch - ratio of standing wave max voltage to standing wave min voltage
    - S_{11} = 0 then VSWR = 1 = matched load
    - 0 = no reflection
    - 1 = 100% reflection

$$\mathrm{VSWR_{in}} = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

$$\mathrm{VSWR_{out}} = \frac{1 + |S_{22}|}{1 - |S_{22}|}$$

Return Loss

- Input or output return loss

- RL_{in} is a scalar measure of how close the actual input impedance of the network is to the nominal system impedance

- Only for 1 port, or is the other port is matched

Gain/Insertion Loss

- S_{11} and S_{22} are always less than or = to 1
- S_{21} can be more or less than 1
- S_{21} is less than 1 (unity) for passives. This means loss - insertion loss
- S_{21} = S_{12} in passives (except ferrites)
- S_{21} not = S_{12} then S_{12} represents feedback

Noise FOMs

Noise Factor

- Noise factor is the ratio of the SNR at input to SNR at output

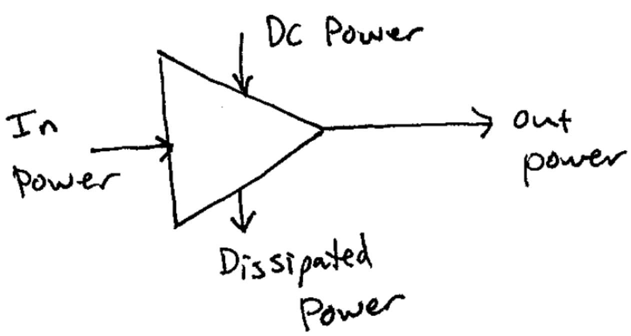
$$F = \frac{S_I / N_I}{S_o / N_o}$$

F is always > 1. It depends exclusively upon the source impedance Zs

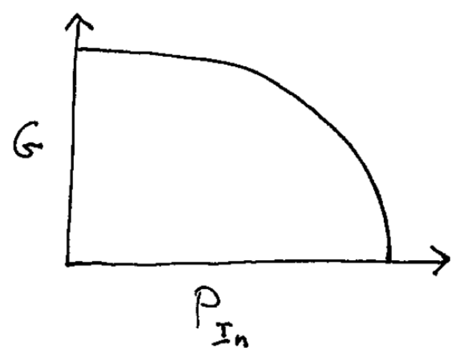
Non-Linear Two-Port Networks

Linear systems obey superposition

Most RF systems are nonlinear - like an amplifier



$$G = 1 + \frac{P_{DC} - P_{Diss}}{P_{In}}$$



Nonlinear Generation

See how inherent nonlinear phenomena can affect amplifiers, following analysis where we compare responses of simple linear and nonlinear systems to typical inputs encountered in wireless technology

In wireless systems inputs are usually sinusoids

In a typical wireless communication system, the variation of the modulated signals is usually slow compared with that of the RF carrier and thus the system does not exhibit memory effects.

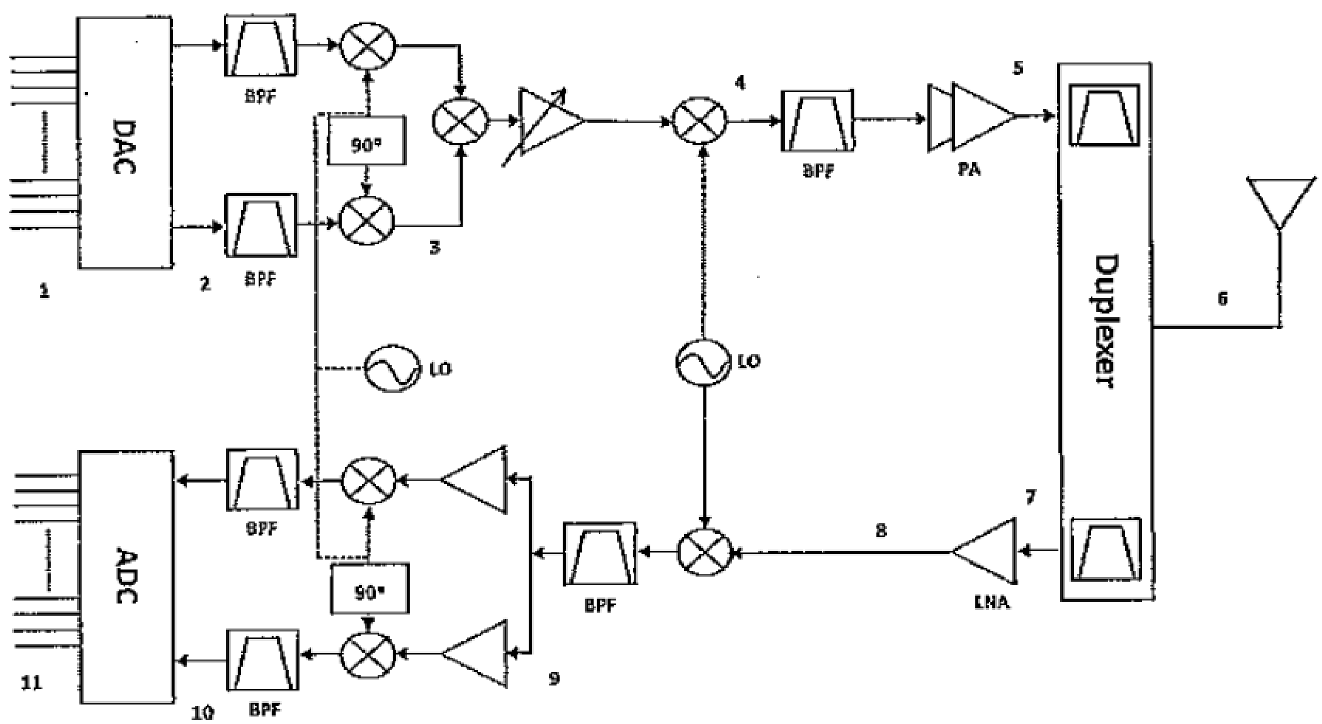
The output of a linear response is a version of the input signal but with variation of amplitude and phase. It will have the same spectral contents.

In a non-linear system, the system has other new spectral contents called spectral regrowth.

A filter is a linear component, it can only change amplitude and phase.

A non-linear element is a frequency multiplier which output spectrum is completely different than input.

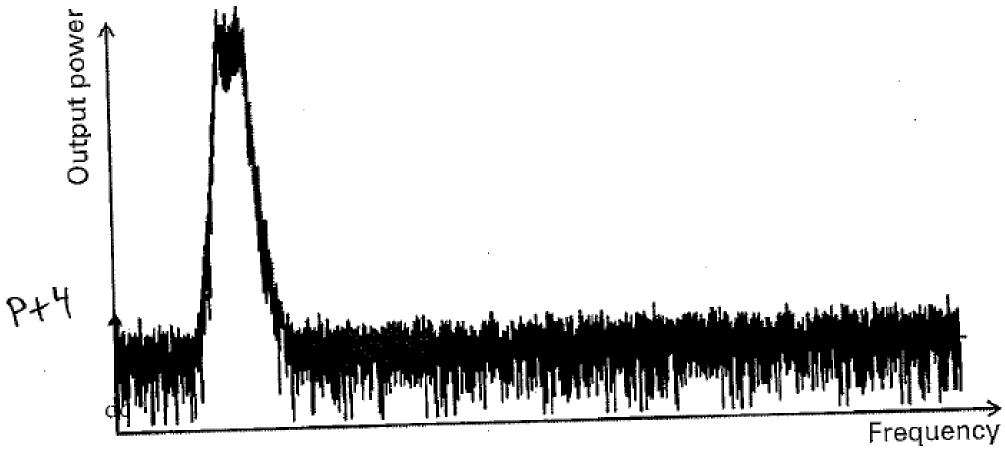
Most important source of distortion is the power amplifier



(see figure above)

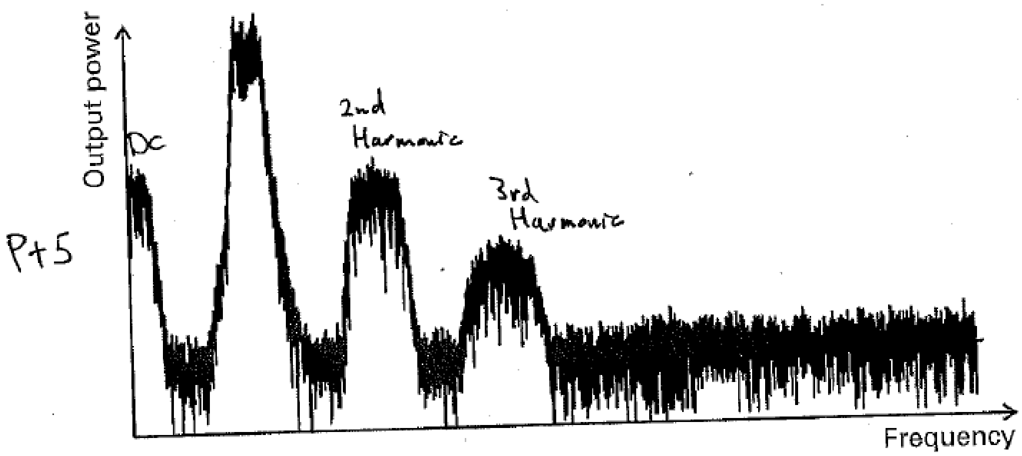
- Bit stream input
- Pt 2: convert to analog and filter
- Pt 3: up convert to IF
- Pt 4: up convert to RF
- Pt 5: amp for power
- Pt 6: transmitted over the air
- Pt 7: received is filtered and sent to LNA
- Pt 9: down convert to IF
- Pt 10: down convert to baseband
- Pt 11 convert to digital

From point 4 to 5 the spectral shape totally changes (p14)



(a)

Signal + in-band distortion



(b)

The in-band distortion is the main distortion of interest.

- Co-channel distortion - distortion in the spectra
- Adjacent-channel distortion - outside the spectra of interest

Nonlinear FOMs

How will we identify nonlinearity in a 2-port wireless system?

Use different signal excitation, to reveal different aspects of nonlinear behavior

- Single tone
- Two tone
- Multi tone
- A real modulated wireless signal

Nonlinear single-tone FOMs

Ratio of integrated power at all harmonics to power at fundamental is THD

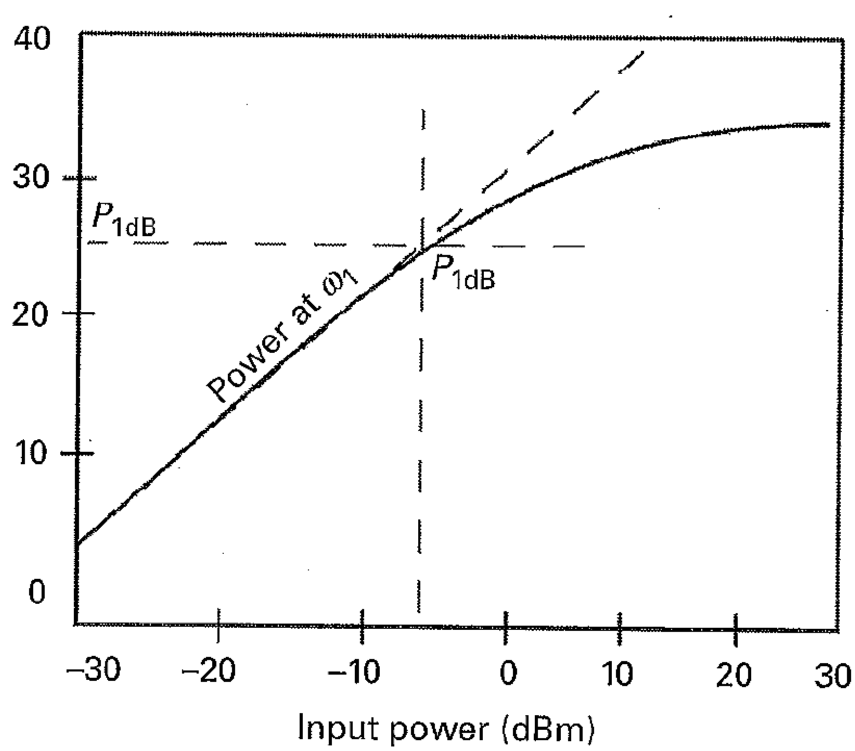
AM-AM

Describes the relationship between the output amplitude and the input amplitude at the fundamental frequency.

The 1dB compression point

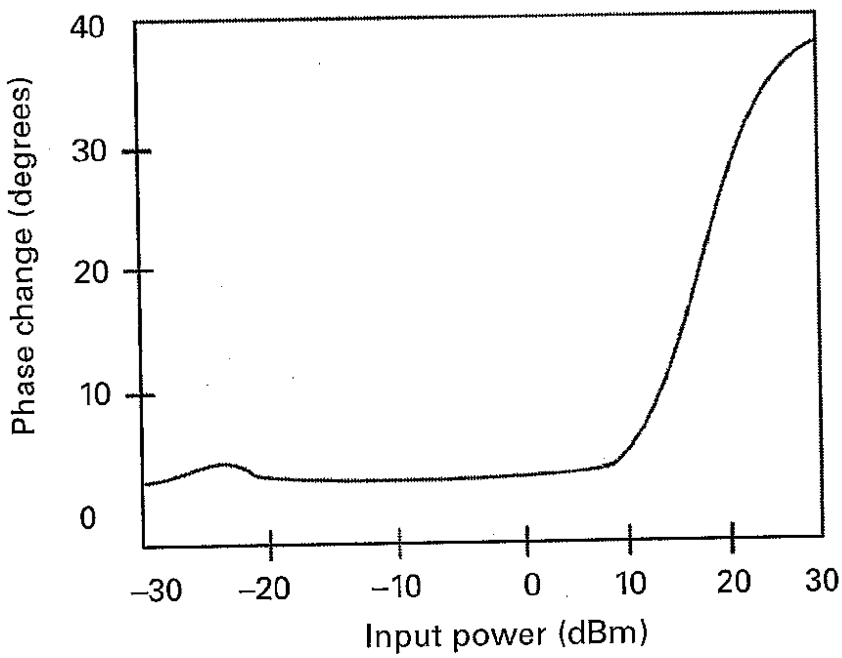
Defines the output power level at which the signal output is compressed by 1 dB, compared with the output power level that would be obtained by simply extrapolating the linear systems small signal char

This can be used to compare systems to see where they go non-linear



AM-PM

When distortion falls right on the spectrum of interest this can be expressed as vector addition -> output + distortion. The change in output signal phase with increasing input power is the AM-PM characteristic.



THD

The ratio between square roots of total harmonic output power and power at fundamental

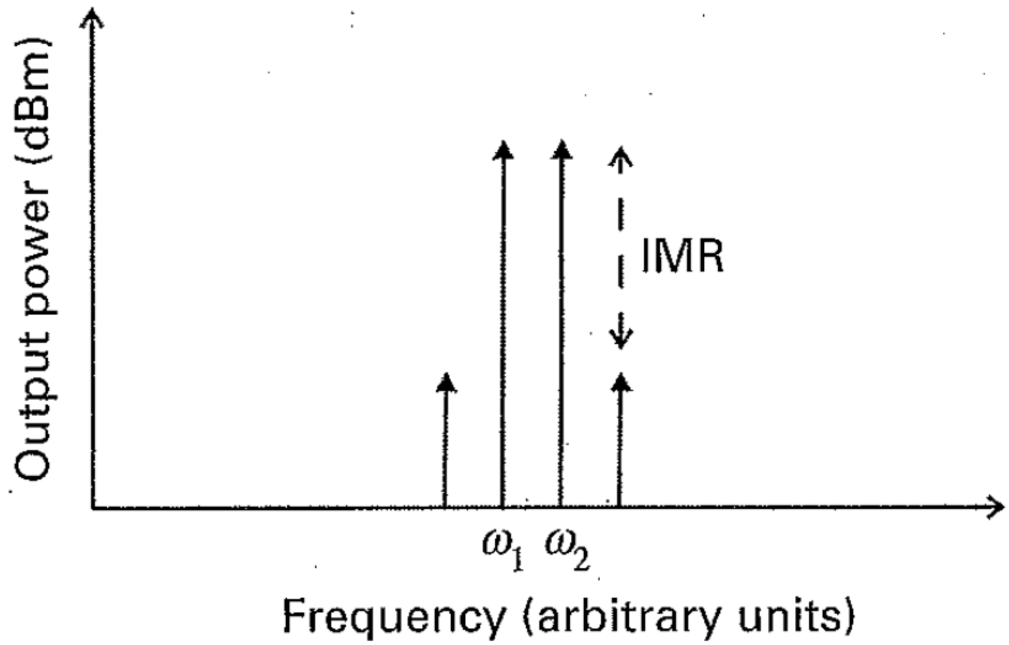
Nonlinear two tone FOMs

- Two tone needed for in-band distortion and bandwidth
- Two tone is a summation of two sinusoids
- Terms falling in the sidebands are called intermodulation distortion (IMD)
- Distortion noise can degrade EVM

  Table 1.1 p23 two-tone nonlinear distortion mixing products up to 3rd order

Intermodulation Ratio

IMR is the ratio between the fundamental and intermodulation (IMD) output powers



IMR refers to the in band nonlinear distortion, not the harmonic content. This is usually described in dBc (decibels below carrier)

Two distortion terms fall on w_1 and w_2 and two will fall in sidebands $2w_1 - w_2$ and $2w_2 - w_1$. Terms in the sidebands are called IMD.

For low-power signals the nonlinear contribution to the co-channel distortion is insignificant, sometime only linear output power is considered when calculating IMR

Underlying linear gain

ULG is the overall output that is correlated with the input signal

$$\mathrm{ULG} = \frac{P_{\mathrm{out}_{\mathrm{fund}}}}{P_{\mathrm{in}_{\mathrm{fund}}}}$$

Intercept Points

The fundamental output increases linearly (1dB out / 1 dB in)
The IMD output increases (3dB out / 1 dB in)

<u>3rd order intercept point</u> - is where the 1dB/1dB and 3dB/1dB cross. These are the extrapolated lines. This is useful for obtaining the amount of nonlinear distortion that arises from an interferer in a wireless system.

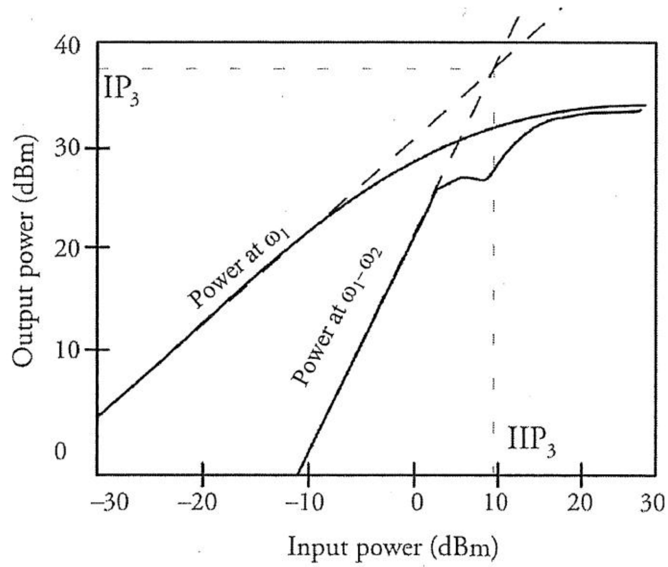
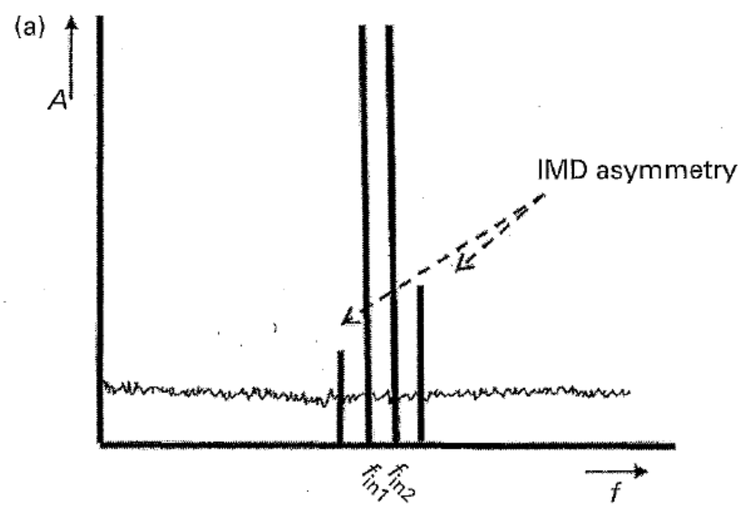


Figure 1.15 The definition of IP3. The extrapolated IP3 can be seen as the intercept of the third-order and fundamental power rises.

Nonlinear distortion in the presence of dynamic effects

Memory effects - dynamic effects that mask real IMD - arise from baseband being mixed with fundamental

Measure with two tone signal will show IMD asymmetry



FOMs for nonlinear continuous spectra

Single and two-tone figures of merit are obsolete for modern digital wireless communication that have lots of spectral content.

Other forms of excitation:

- Digital modulation carriers
- Pseudo-random baseband signals
- Multi-tones (multi-sine)
- Band limited noise

This section addresses figures of merit developed for rich spectra continuous or not.

In-band nonlinear output response of a rich spectrum

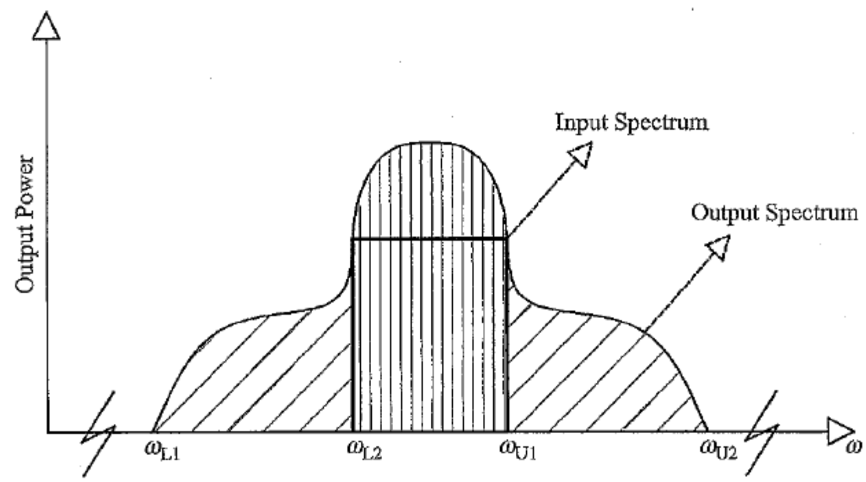
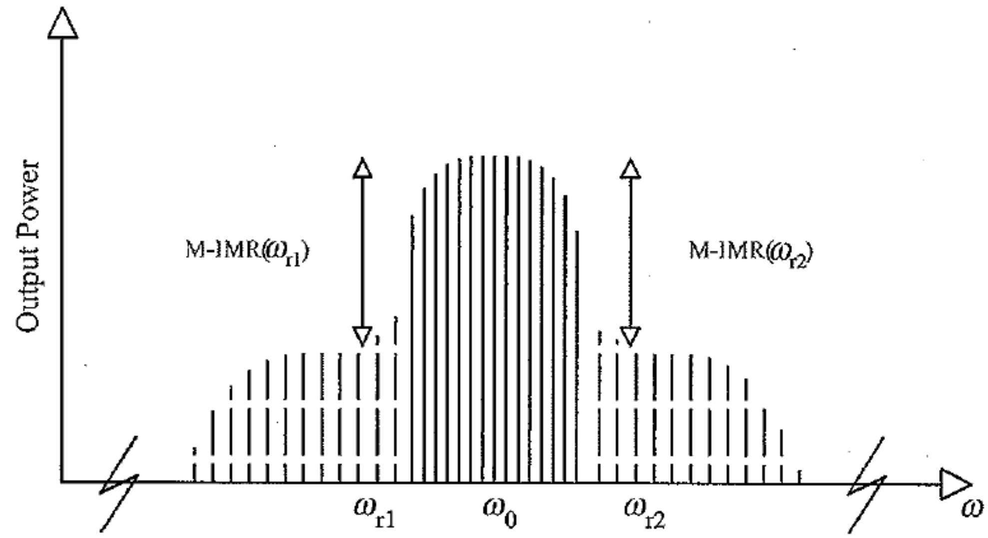


Figure 1.20 The in-band nonlinear output response of a rich input spectrum.

Multisine Intermodulation Ratio (M-IMR)

$$\text{M-IMR} = \frac{P_{\text{fund tone}}}{P_{L/U}(\omega_r)} \qquad \frac{\text{common fundamental power per tone}}{\text{Power of the } \omega_r \text{ distortion component present in the lower or upper adjacent bands}}$$



.21 The definition of the multi-sine intermodulation ratio.

M-IMR allows engineers to measure and account for each tone in the multi-sine approach

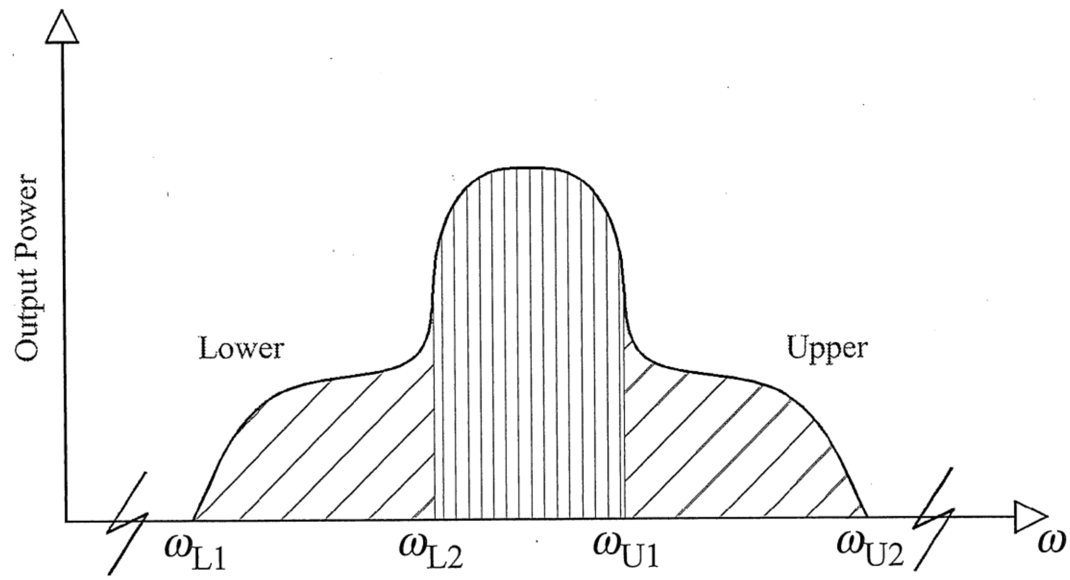
Adjacent-channel power ratio ($ACPR_T$)

Is the ratio of the total output power measured in the fundamental zone, P_{fund} , to the total power integrated in the lower, P_{LA} , and upper P_{UA} adjacent-channel bands

$ACPR_T = P_{fund} / P_{LA} + P_{UA.}$

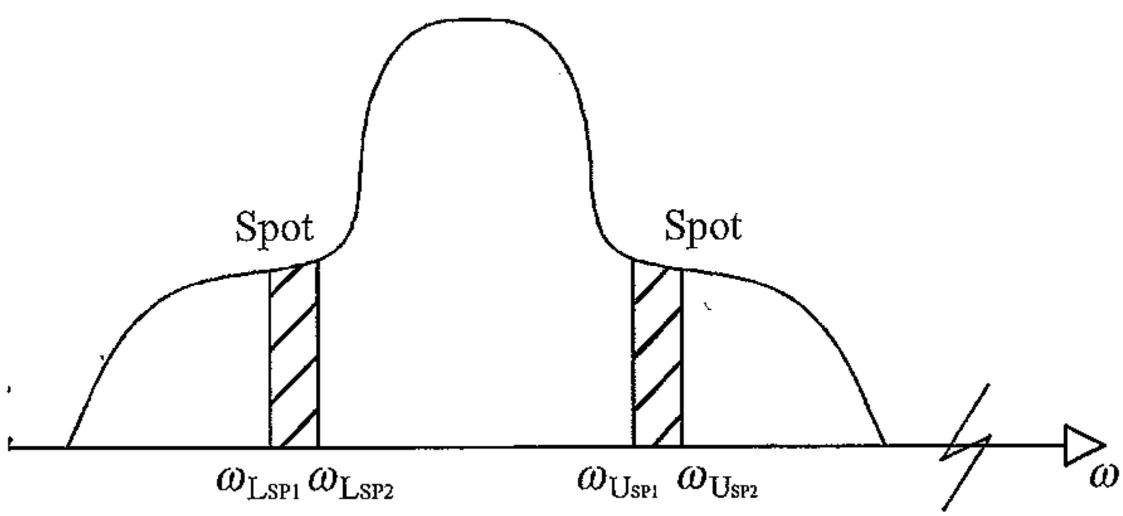
You can also have upper and lower only

$ACPR_L = P_{fund} / P_{LA}$
$ACPR_U = P_{fund} / P_{UA}$



: The definition of the adjacent-channel power ratio.

You can also have a spot or predefined bandwidth $ACPR_{SPL}$ $ACPR_{SPU}$



Co-channel distortion FOMs

Co-channel distortion falls exactly on top of the input signal spectrum, and thus on top of the linear output signal

This type of distortion can be accounted for using a FOM known as the co-channel power ratio (CCPR), but since it's right in the fundamental zone it's hard to measure.

Noise power ratio (NPR) - open a notch in the input and measure at that notch in the output to see the noise amplitude

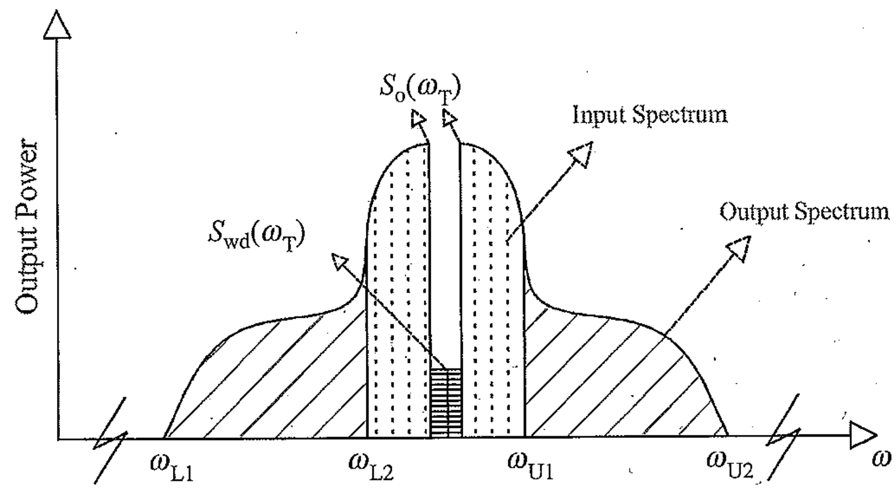


Figure 1.24 The definition of the noise power ratio.

NPR - Ratio of the output power spectral density function near the window over within the window

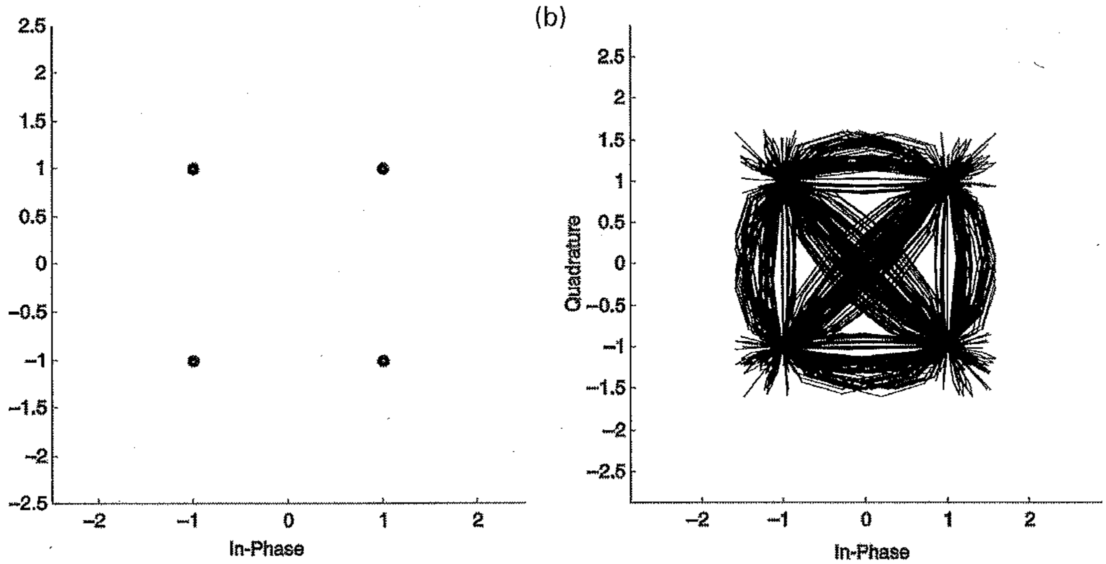
$$\mathrm{NPR}(\omega_T) = \frac{S_o(\omega_T)}{S_{wd}(\omega_T)}.$$

System Level FOMs

System level FOMs are related more to the information being sent rather than some spectrum or time characteristic

Constellation Diagram

A sine wave can be converted to complex plane of real and imaginary



re 1.27 The QPSK constellation diagram: (a) Sampled at the symbol rate; and (b) the overall ectory.

These diagrams show all the modulated points measured over time.

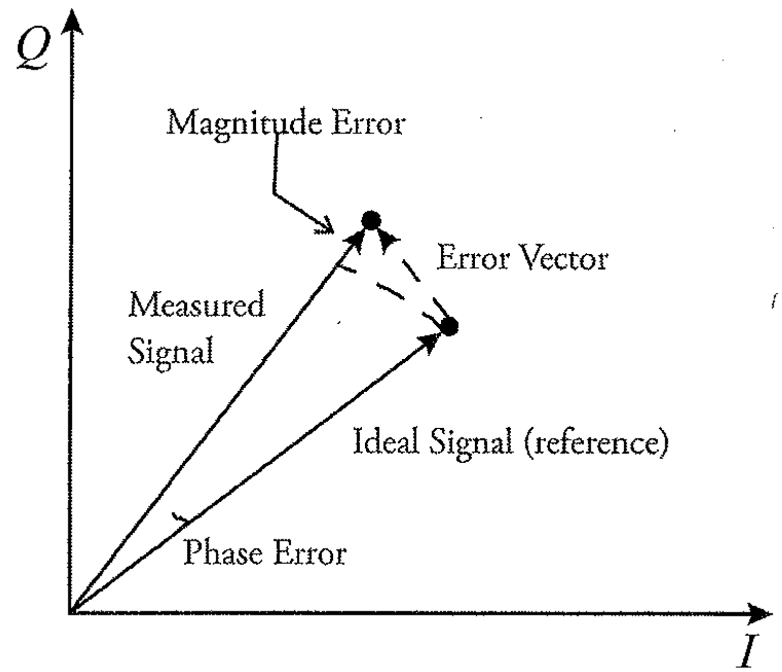
Look for distortion by comparing the transmitted constellation points vs. the received constellation points

If a transmitted point moves it's due to distortion or noise

If a receive point is closer to where another point is supposed to be it can cause an error

Error Vector Magnitude (EVM)

EVM is the vector between the ideal and the actual constellation point



You can average this and express it in terms of a percentage

$$\mathrm{EVM}_{[\mathrm{RMS}]} = \sqrt{\frac{1}{\mathrm{SNR}}}$$

Peak to Average Power Ratio

Relates to signal rather than the system

Filters

Table 1.2 A filter datasheet of electrical characteristics (guaranteed over −50 °C to +90 °C operating temperature)

Part number	Frequency band [MHz]	Insertion loss (dB)	Maximum VSWR (dB)	Typical attenuation (dB)
Filter 1	800–1000	0.35 typical (0.5 max.)	1.5	30 at $2F_0$
Filter 2	865–985	0.34 typical (0.5 max.)	1.4	27 at $2F_0$
Filter 3	1700–1900	0.37 typical (0.5 max.)	1.6	40 at $2F_0$

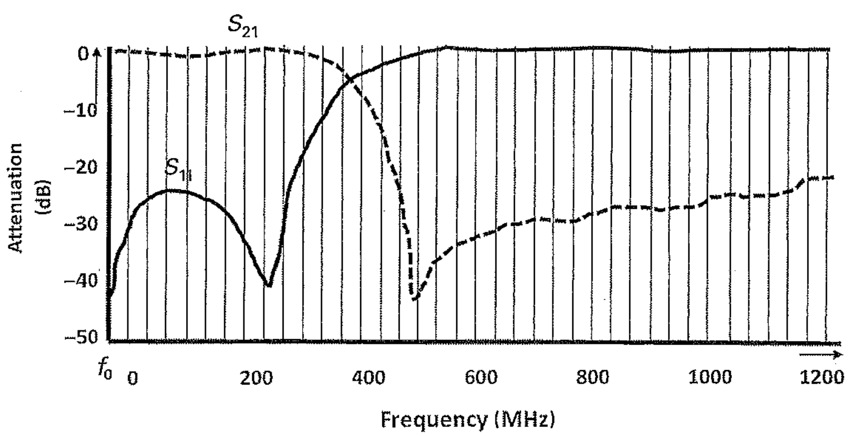


Figure 1.29 Measured S-parameters of a low-pass filter.

S_{21} is input to output, so the filter passes through low frequency
S_{11} showed little reflection at low frequency since it's passing through (matched). Showing high reflection at high frequency (bounces back and filters)

F_0 is the bw upper frequency limit. Typical attenuation at $2F_0$ is out of the bw attenuation (2x upper limit frequency)

VSWR gives you an idea of the match/mis-match of the component itself.

1.4 is like $\Gamma_{in} = 0.17$ or 35 to 70Ω

Amplifiers

Different kinds of amplifiers are: LNA, PA, GA, VGA

Linear and noise FOMs

Amplifers are two port networks and the linear FOMs from section 1.3 are applicable

An engineer should know the mismatch of an amp via the VSWR or return loss

Characteristics of a good RF amp:

- Noise figure - Friis formula - the amp should have very low noise operation
- Amplifier should have good reverse isolation

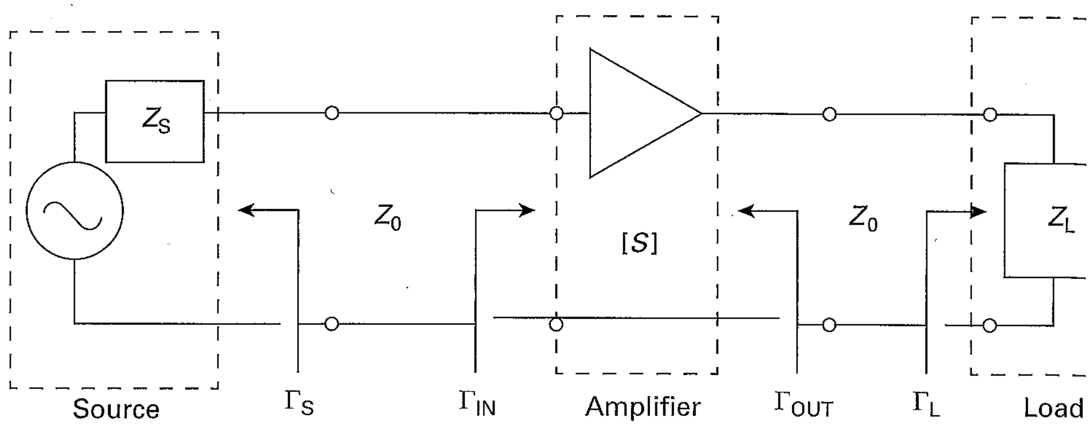


Figure 1.30 Power gain definitions.

Operating power gain stress mismatch at the output
Available power gain related to the mismatch at the input $G_{T\ Max} = G_{A\ Max} = Gm_{ax}$ (when there are no mismatches)

P_{AVS} = power available from source
P_{IN} = Power into amp
P_L = Power deliverd to the load
P_{AVN} = Power output available

3 power gain definitions:

- G_T = transducer power gain = ratio of the power delivered to the load to the power available at the source.

$$\begin{aligned} G_T &= \frac{P_L}{P_{AVS}} \\ &= \frac{(1-|\Gamma_S|)^2}{|1-\Gamma_S\Gamma_{IN}|^2}|S_{21}|^2\frac{(1-|\Gamma_L|)^2}{|1-S_{22}\Gamma_L|^2} \\ &= G_S G_0 G_L \end{aligned}$$

  The contribution of each block is expressed in three factors (Fig 1.30 above):
  - G_S = the interaction between the source network and the input of the amplifier
  - G_O = contribution from the amp itself
  - G_L = interaction between output of the amp and load

- G = operating power gain = the ratio of the power delivered to the load to the power going into the amplifier

$$G = \frac{P_L}{P_{IN}} = \frac{1}{1 - |\Gamma_{IN}|^2} |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}$$

- G_A = available power gain = the ratio of the power available from the amplifier to the power available from the source

$$G_A = \frac{P_{AVN}}{P_{AVS}} = \frac{(1 - |\Gamma_S|)^2}{|1 - S_{11}\Gamma_S|^2} |S_{21}|^2 \frac{1}{(1 - |\Gamma_{OUT}|)^2}$$

This all means that the gain is not just static, it is affected by the circuit it gets up into and it's matching

Defining efficiency and power added efficiency, the PAE is more complete becasue it accounts for the input power to the amp as well as the DC supply power. Efficiency just consideres the input supply efficiency

$$\eta = \frac{P_L}{P_{DC}}$$

Nonlinear FOMs

FOMs from section 1.5 are applicable.

Most common FOMs:

- 1 dB compression point (P_{1dB})
- Third order intercept point (IP_3)
- Saturated output power (P_{sat})
- Efficiency and Power Added Efficiency (PAE)

Transient FOMs

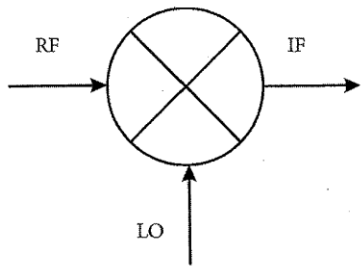
Slew rate, rise time, settling time, ringing and overshoot

Mixers

Mix signals, down convert or up convert.

Two port FOMs

Often considered two port where RF and IF are the ports (LO is local oscillator)



Conversion loss of a down converting mixer is the ratio of RF input and IF output

$L = P_{AVS, RF} / P_{AVN, IF}$

Where $P_{AVS, RF}$ is the power of the modulated input signal at the RF carrier frequency
$P_{AVN, IF}$ is the output power of the down-converted signal at IF.

FOMs that measure linearity in a mixer:

- Input 1dB compression point
- Input third-order intercept point
    - These refer to the input in mixers, output in amps

Mixers also have a noise contribution.
Single-sideband noise figure for a mixer is the decibel value of the signal to noise ratio at the input of the mixer at RF divided by the single to noise ratio at the output of the mixer at IF.

Mathematically, the noise factor for a mixer F_{mixer} is

$$\begin{aligned} F_{\text{mixer}} &= \frac{S_{\text{I,RF}}/N_{\text{I,RF}}}{S_{\text{O,IF}}/N_{\text{O,IF}}} \\ &= \frac{N_{\text{O,IF}}}{N_{\text{I,RF}}L} \end{aligned} \tag{1.90}$$

where $S_{\text{I,RF}} = P_{\text{AVS,RF}}$ is the signal power at the input of the mixer at RF, $S_{\text{O,IF}} = P_{\text{AVS,IF}}$ is the signal power at the output of the mixer at IF, $N_{\text{I,RF}}$ is the available noise power at the input of the mixer at RF, $N_{\text{O,IF}}$ is the available noise power at the output of the mixer at IF, and L is the conversion loss.

Consequently, the noise figure is given by

$$\text{SSBNF} = 10 \log_{10} F_{\text{mixer}} \tag{1.91}$$

Three-Port FOMs

Down converting mixers usually have filters in the package to remove unwanted spectral components

Isolation and leakage between the ports is specified, we want good isolation from LO to IF since the high LO power needed to drive the mixer into nonlinear operation could damage the sensitive low IF input.

Leakage definitions:

- The LO/RF leakage of a mixer is equal to the ratio of the power at LO requency at the RF port and the LO power
- $$\text{LO/RF leakage} = \frac{P_{\text{RF,LOfreq}}}{P_{\text{LO}}}$$
- The LO/IF leakage of a mixer is equal to the ratio of the power at LO frequency at the IF port and the LO power.
- $$\text{LO/IF leakage} = \frac{P_{\text{IF,LOfreq}}}{P_{\text{LO}}}$$
- The RF/IF leakage of a mixer is equal to the ratio of the power at IF frequency at the RF port and the IF power.

$$\text{IF/RF leakage} = \frac{P_{\text{RF,IFfreq}}}{P_{\text{IF}}}$$

Oscillators

Types of oscillators

- Free running
- Voltage controlled
- Synthesized

It is expected that an oscillator is a pure sine wave

Frequency Stability

- How well the frequency is maintained over time

    Can be expressed in short and long term stability

Phase Noise

- Phase noise is observed in distortin to the phase
- Phase noise is used to characterize the frequency stability's randomness

Frequency-multiplier FOMs

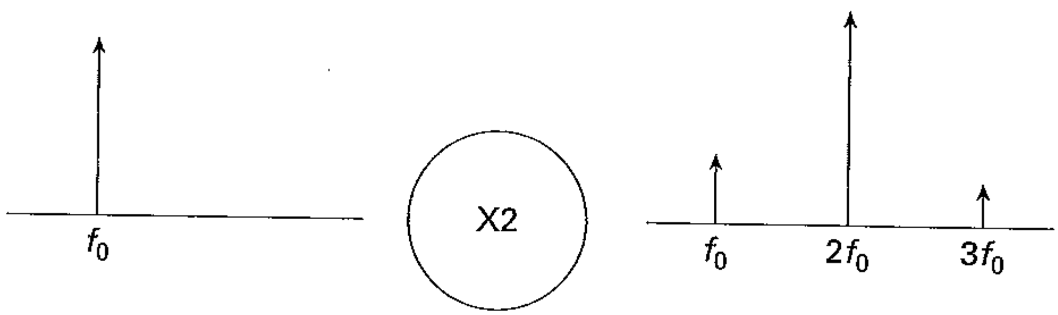


Figure 1.37 Frequency doubling, showing the input and output spectrum components.

A frequency multiplier converts an input at frequency f_o to an output at a frequency multiple of f_o

Frequency multipliers are used because fast oscillators are hard to design and implement. So, slow oscillators are designed and implemented and then up converted with a frequency multiplier.

Typical multiplication factors are 2 - 4

The conversion loss of an n times frequency multiplier is the ratio of the input power at frequency f_o and the output power at frequency nf_o

$$L = \frac{P_{\mathrm{AVS},f_0}}{P_{\mathrm{AVN},nf_0}}$$

Frequency multipliers typically contain filters to remove unwanted output frequencies

Fundamental Rejection is the ratio of the output power at frequency nf_o and the output power at frequency f_o

$$\text{fundamental rejection} = \frac{P_{\mathrm{AVN},nf_0}}{P_{\mathrm{AVN},f_0}}$$

Harmonic Rejection is the ration of the output power at frequency nf_o and the output power at frequency f_{mo} where n and m are not equal to zero.

$$\text{harmonic rejection} = \frac{P_{\text{AVN},nf_0}}{P_{\text{AVN},mf_0}\big|_{m \neq n \neq 0}}$$

Digital Converter

P56

Dana Fosmer at 9/25/2014 11:01 AM

Chapter 2 Instrumentation for Wireless Systems

To be covered:

- Power meters
- Spectrum analyzers
- Vector signal analyzers
- Real-time signal analyzers
- Vector network analyzers
- Nonlinear vector network analyzers
- Oscilloscopes
- Logic analyzers
- Noise-figure meters

Power Meters

Two main quantities to measure

- Transmitter power
- Sensitivity - the minimum power that the system should receive for a predetermined SNR

The demand of for power is so high that a correct measurement of its value is fundamental during design and use.

P = Energy/delta t

How to measure power

- Hard to measure V and I at high frequency
- Instantaneous power (peak power)
- Average value (just power)

Thermocouple principle

- Temperature change can be converted to power

The diode probe principle

- Since we want to measure square of voltage over a resistor, any element that behaves quadraticly with applied RF voltage could be a candidate for power measurement. Like a diode
- Power as low as -70 dBm can be measured

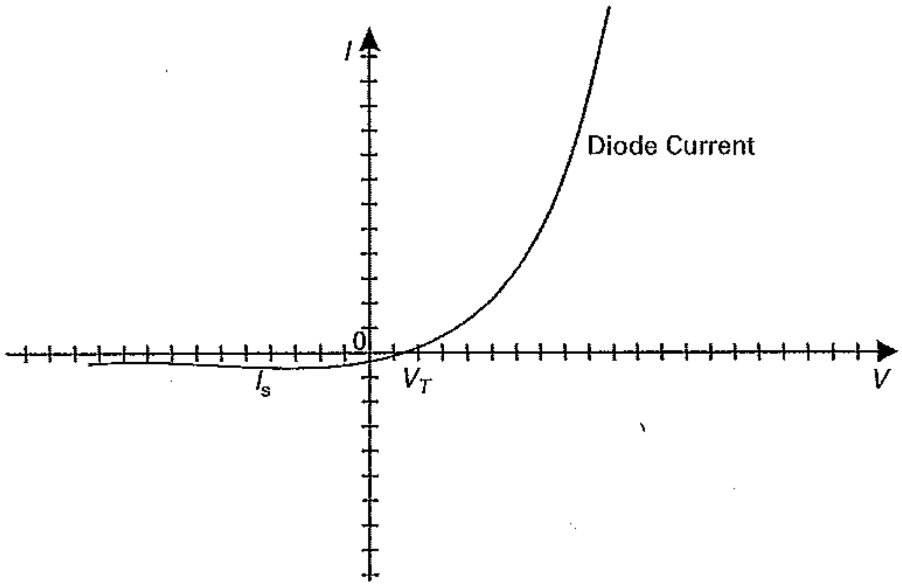
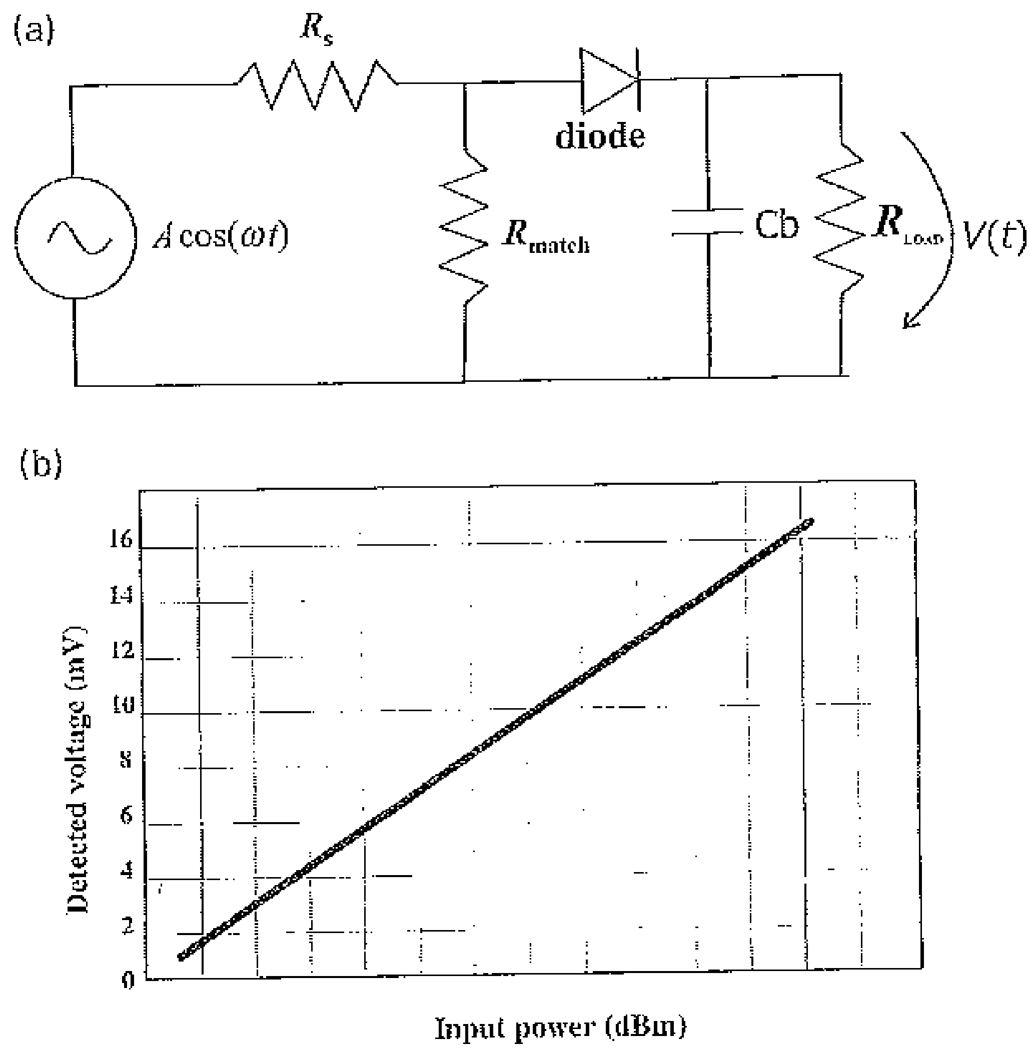


Figure 2.8 A typical diode $I-V$ characteristic.



$$I_D = I_{D0} + \frac{K_2}{2} A^2$$

RF power is transformed into DC power

Power meter architecture

Sensor <- Modulator <- Correction Factor

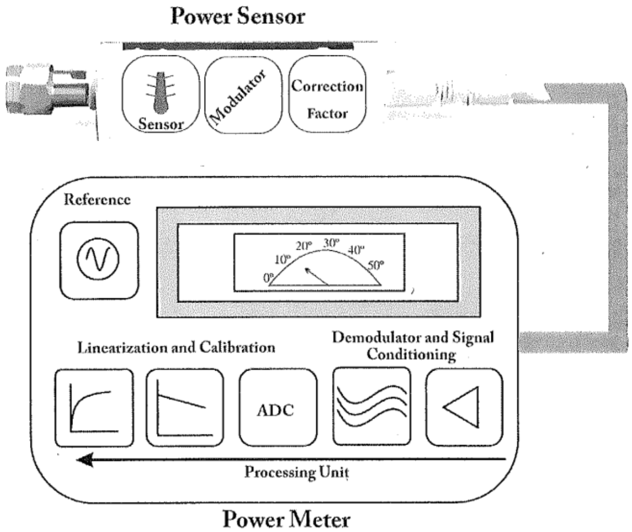


Figure 2.10 Power-meter block architecture, including a power sensor and the power-meter reading display.

Power meter sources of error

A reference oscillator is used for calibration
Power reference uncertainty (error in power ref) can contribute 1% uncertainty over 1 year.
Uncertainty - difference between the value and true value
Other uncertainty errors - 0.5%

The engineer should verify the power sensor by applying a swept CW input

Mismatch and cause uncertainty - measuring a DUT that is not matched to the power probe impedance.
A match can be forced by using a low VSWR attenuator between the DUT and the power sensor.

Some power presented to a power probe is lost in the sensor itself as heat. A calibration factor is used to account for this error.

$$\mathrm{CF} = \frac{P_{\mathrm{measured}}}{P_{\mathrm{incident}}} \times 100\%$$

$$= K_{\mathrm{b}} = \eta_{\mathrm{e}} \frac{P_{\mathrm{gi}}}{P_{\mathrm{i}}}$$

This frequency dependent cal factor is unique to each power meter and is measured at the manufacturing stage

Calibration of the power meter

The need for calibration is mainly due to the fact that the operation of the power sensor is dependent on the environmental temperature. For this reason power meters have embedded reference oscillators that will allow their calibration in situ.

Spectrum Analyzers

Power meters work over a large BW - total power over the BW of operation of the probe.

Power Spectral Density (PSD) is how power spans the whole spectrum

The Spectrum

Time domain goes to frequency domain by use of Fourier decomposition

Spectrum-analyzer architectures

Spec analyzer implements the Fourier transform in hardware

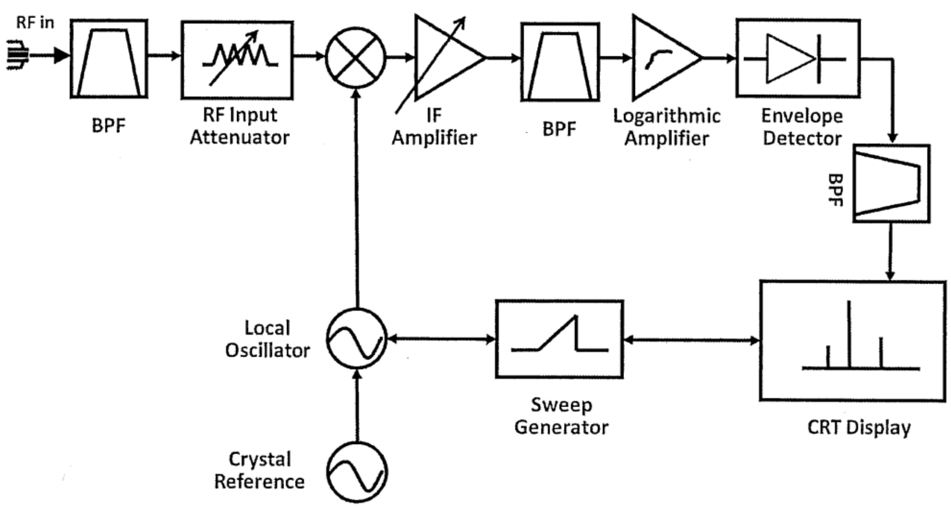


Figure 2.18 Superheterodyne configuration.

Blocks of the spectrum analyzer above (fig 2.18)

The input attenuator

The goal is to match the impedance of what you are measuring.

- System is designed to be 50 Ω
- Input attenuation can help fix mismatch problems
- Limits distortion created in the spectrum analyzer
- If input is attenuated the noise factor can increase and degrade the noise floor

Mixer and Oscillator

- Up or down convert the input signal to IF

- Selects the frequency to be sampled and measured
- Problem - image frequencies can occur - filter them out
- DC can damage mixers and so it is blocked
- The oscillator has to be very good
    - It's sweep steps in a digital SA have to be less than the resolution BW
- Harmonic mixing - mixing with harmonics of the oscillator for measuring very high frequencies

The IF Filter

- Controls the amount of energy that is going to be captured in each sampled frequency
- The BW of this filter is the RBW
- The combination of the RBW with the sweep time and span are the most important characteristics to be selected in a SA. This allows a trade-off among frequency selectivity, measurement speed and signal to noise ratio.
- As the RBW is narrowed, the selectivity is improved.

Envelope detector and video filter

- Diode detector that measures all the power captured by the IF filter and returns the final value for the video filter.
- The video filter filters out the visual noise

Basic Operation of a Spectrum Analyzer

Driving input blocks into compression?

- Attenuator block
- Up/down convert using the IF block and LO selects which frequency to be sampled
- IF filter, filters out the signal, BW of this filter controls the resolution BW
- Output to envelop detector for power measurement.
- Display

Specifications of a Spectrum Analyzer

<u>Span</u>

Frequency range to measure

<u>Resolution Bandwidth</u>

- Frequency resolution we have on the spectrum analyzer display
- Narrow RBW increases resolution (1kHz better resolution than 1 MHz)

<u>Sweep Time</u>

- Speed at which the frequencies will be covered
- RBW narrow = longer sweep time
- RBW wide = shorter sweep time

Sweep time (ST) = k(SPAN) / RBW^2

Rise time = k / RBW

k is a proportionality constant, typically 2.5

Amplitude-related characteristics

Noise Floor
Need to know the noise floor to determine the smallest signal that can be measured

Sensitivity - the minimum signal level that can actually be measured

N_{floor} = power level at which noise is present

Video Filter (VBW)

- Video filtering can be used to reduce noise, acts as an averaging filter to the input signal
- Not related to RBW has it's effect after RBW is done.
- The video filter should have a BW less than or equal to the RBW filter.
- VBW does not relate to RBW sensitivity, it is just for averaging the baseband signal.

Maximum sensitivity can be achieved with minimum RBW, 0 dB input attenuation and minimum VBW

The maximum power

- A single tone at the input of the spectrum analyzer will generate harmonics at a certain amount of input power, and a two-tone signal will generate harmonics and intermodulation distortion products.
- A practical test to see if nonlinear distortion is corrupting our measurements. On changing the attenuator level from 0 dB to 10 dB or higher, we should observe an increase in noise on the SA display and no increase or reduction in the signal being measured. If the signal changes with the attenuation, this means that nonlinear distortion must be present

The dynamic range

- Difference between the max power the circuit or system can handle and the min power determined by the noise floor
- Measurement rand and display range are different

Accuracy of a Spectrum Analyzer

Amplitude and frequency accuracy
Typical amplitude accuracy is less than 1 dB

Vector Signal Analyzers

- Update to the SA.
- Same concepts as the SA but the signal is samples and converted to a digital form.
- Dynamic range is now determined by sampling and quantization
- Includes a digital I/Q demodulator
    - This allows the VSA to acquire a digital waveform and compare amplitude and phase between the I, Q branches
    - Measures amplitude and phase of digitally modulated signals
    - Looking at the baseband signal, not the RF part

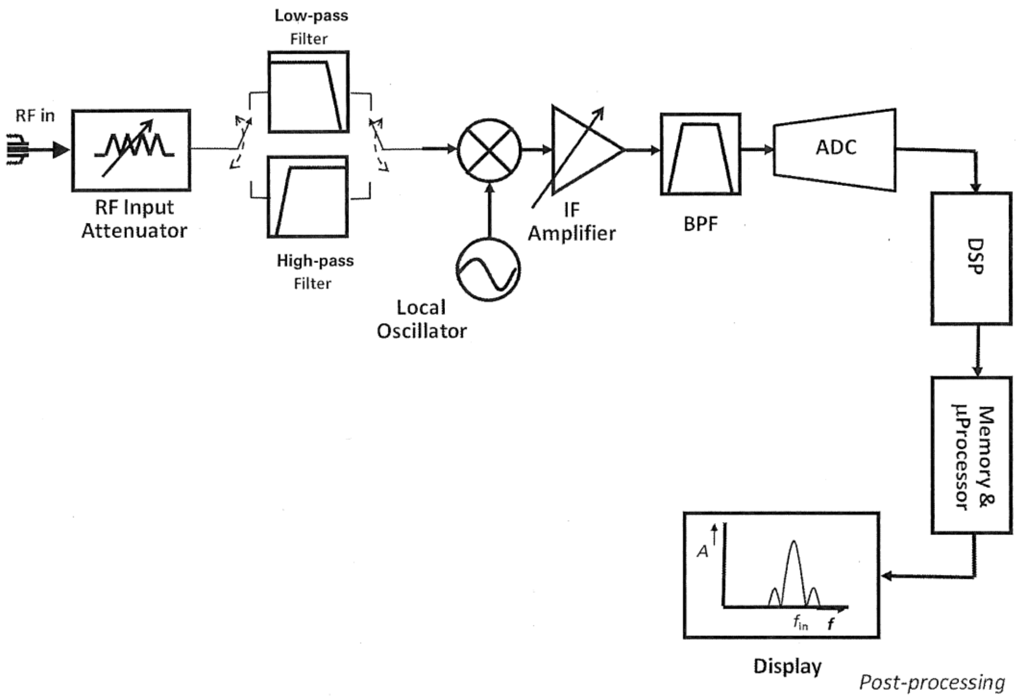


Figure 2.33 The basic architecture of a vector signal analyzer.

Real Time Signal Analyzers

VSAs have to take time to process the FFT, so some information can be missed

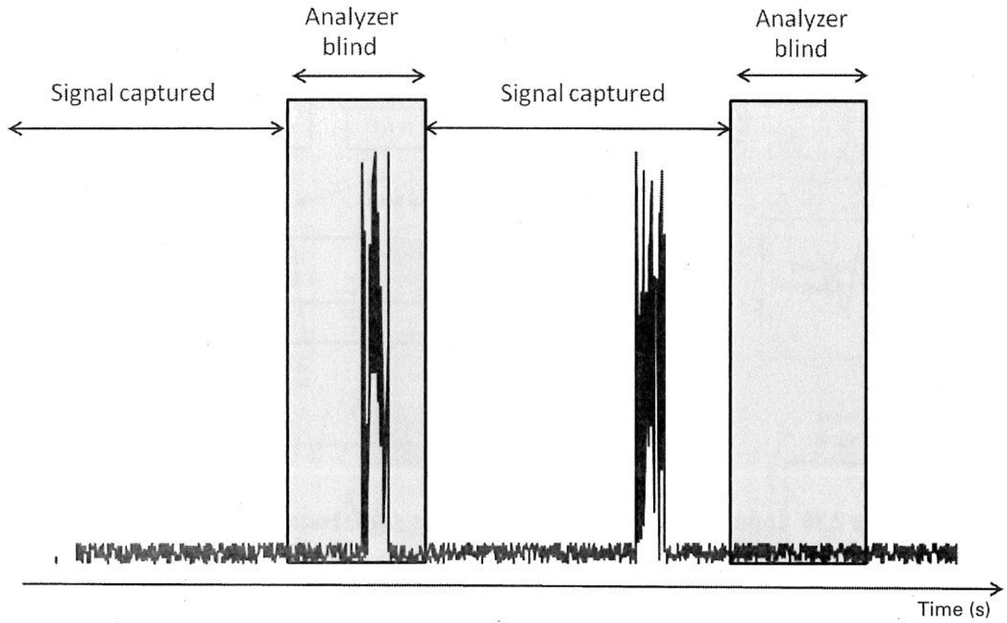


Figure 2.37 Blind spots for a vector signal analyzer.

RTSA has multiple parallel processing ASICS for FFT. This reduces or eliminated the blind spots from VSAs

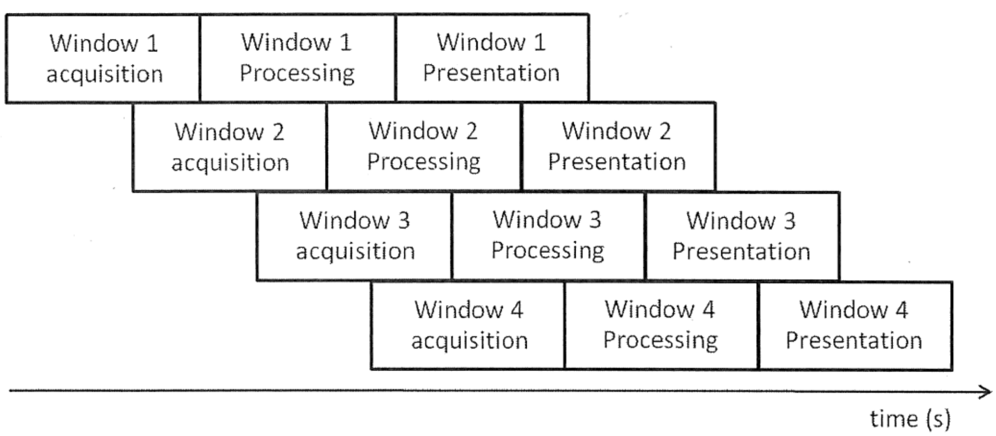


Figure 2.38 Real-time analyzer FFT processing.

RTSAs keep spectrum's history saved in memory. Concepts such as spectrograms, persistence displays and spectrum triggers allow the user to gain new vision of spectrum analysis.

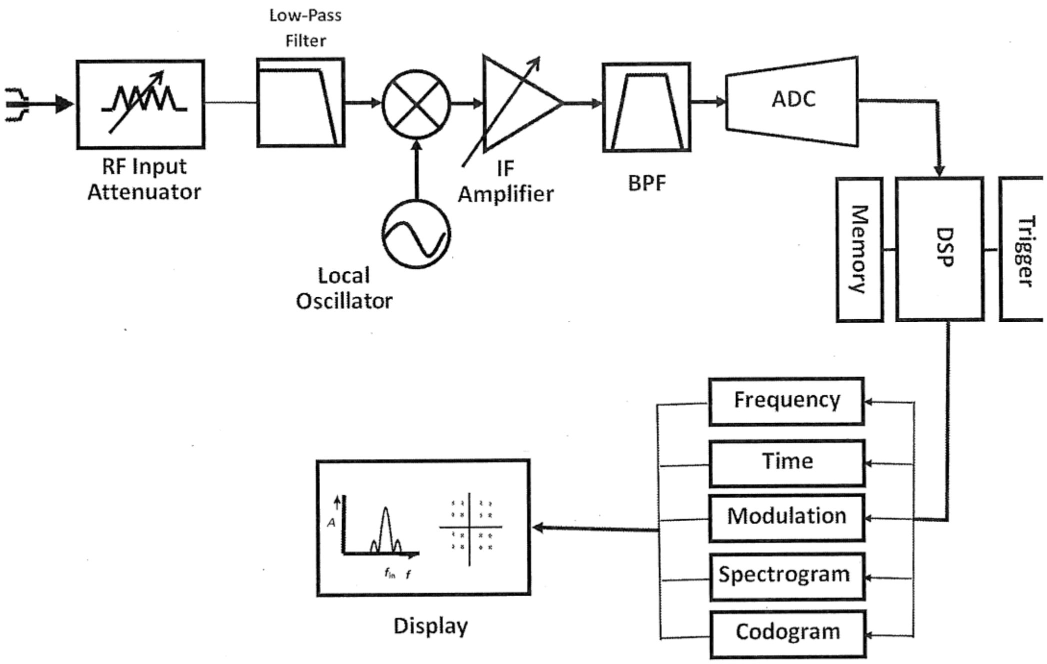


Figure 2.39 The block diagram of a real-time analyzer.

RTSA spectrogram

3D form that visualizes the spectra through time

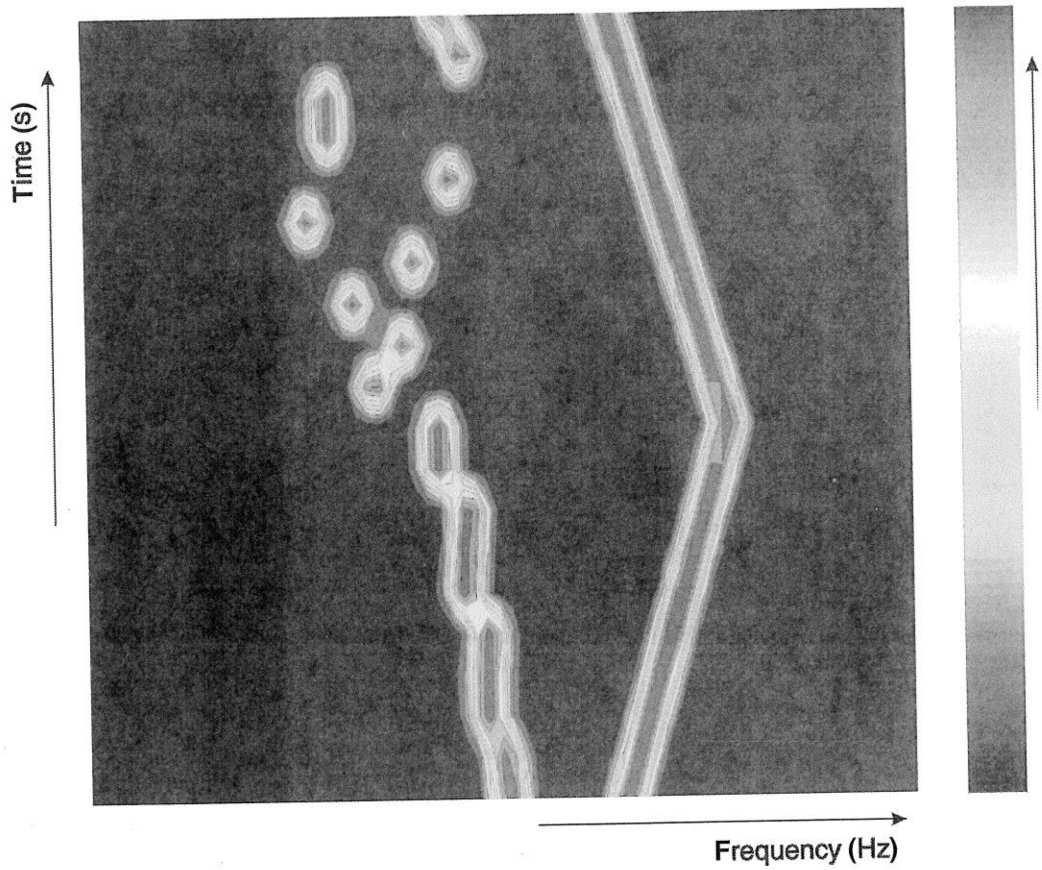


Figure 2.42 The digital spectrogram of a real-time signal analyzer.

RTSA persistence

Persistence plot - shows transient behavior persistence granularity - time duration and the graph is restarted.

RSTA spectrum trigger

Mask an area and only trigger if it touches that level

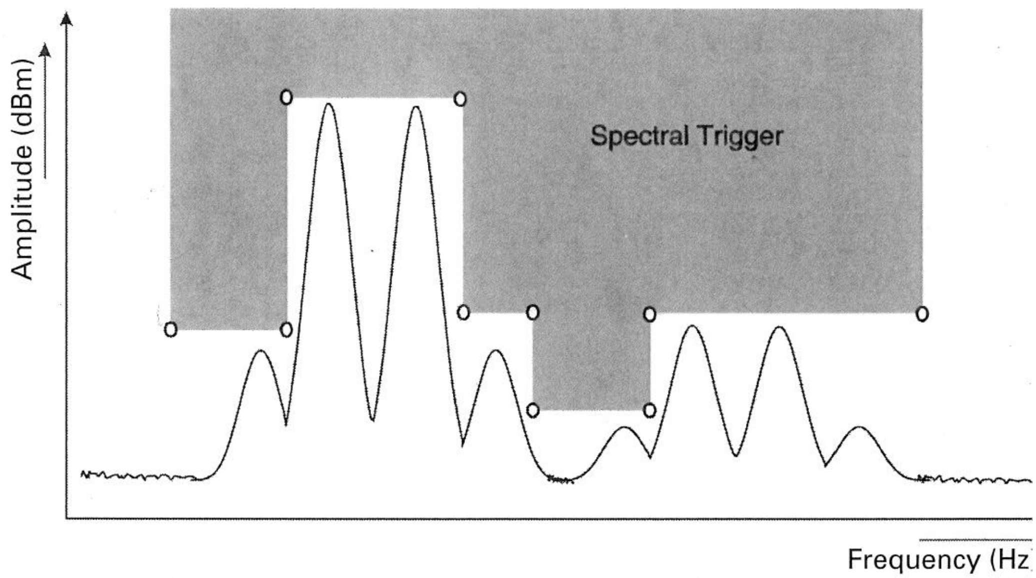


Figure 2.45 A spectral trigger for a real-time signal analyzer.

Vector Network Analyzers

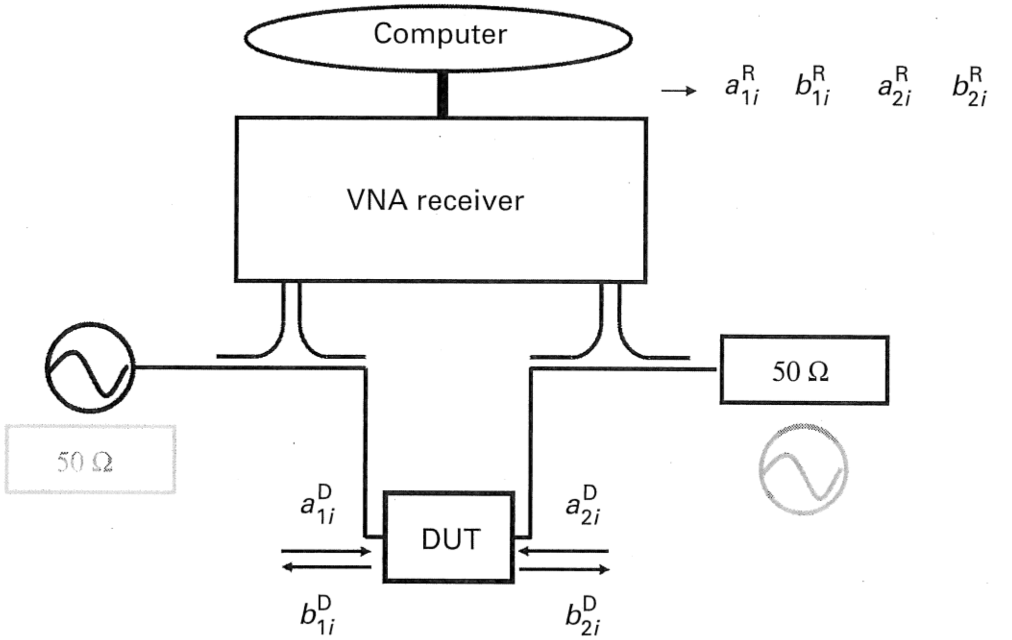
- Enables the measurement of s-parameters
- s-parameters relate incident and scattered traveling voltage waves at the ports of a microwave circuit.
- s-parameters correspond to <u>ratios</u> of scattered to incident traveling voltage waves.

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

a is incident (going in)
b is scattered (reflected)

VNA Architecture



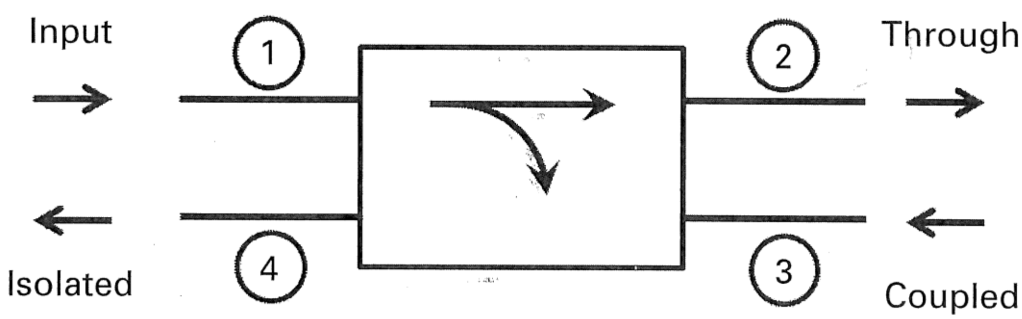
2.47 The fundamental blocks of a VNA.

RF Signal Generator

- The signal generator is switched between two ports or there are two separate generators

Directional Coupler

- Used at each port to separate the incident and scattering traveling voltage waves

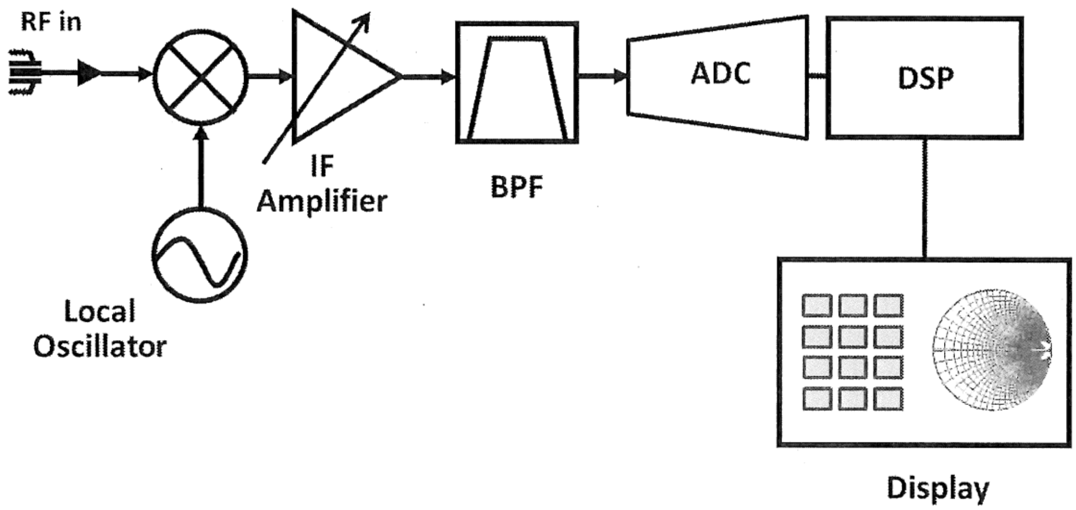


e 2.48 A directional coupler.

- Input goes to the DUT and Coupled ports, isolated port contains no input signal, measure input at coupled
- When measuring scattered, the isolated port now becomes coupled and coupled port is now isolated. It's working backwards.

Receiver

- Measures the incident and scattered traveling waves at each port.
- Measure both amplitude and phase



2.49 The receiver of a vector network analyzer.

Skipping calibration details

Nonlinear vector network analyzers

- A vector network analyzer returns only ratios of waves, absolute measurements can be obtained with a nonlinear vector network analyzer

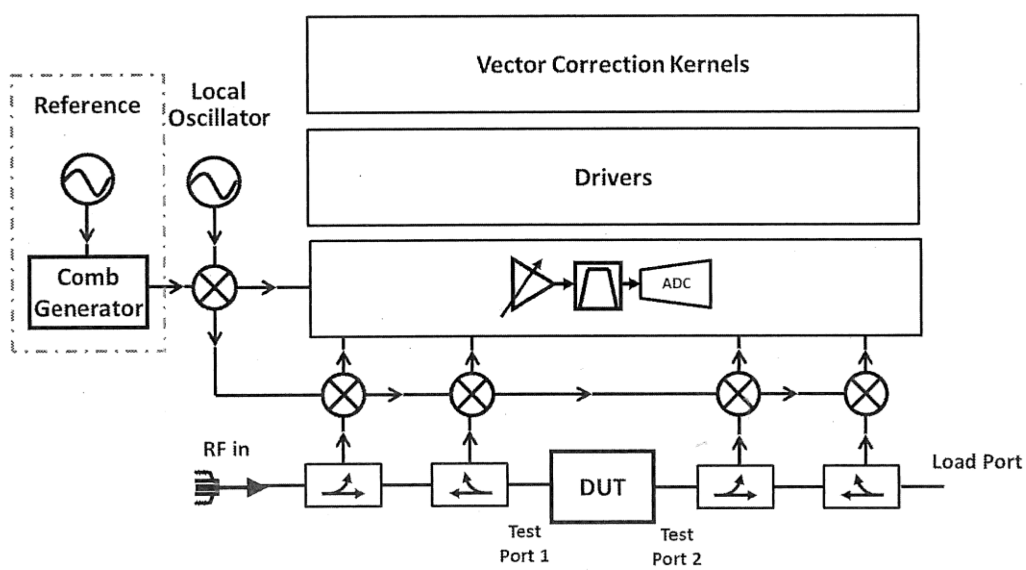


Figure 2.53 The mixer-based NVNA architecture [15] © IEEE.

Logic Analyzers

- A logic analyzer is like having a large number of time domain oscilloscopes, one for each input
- Capture logic states in a predetermined input, essentially a digital signal where anything above a certain threshold is a 1, anything below a certain threshold is a zero
- Select probes carefully, each probe should have a ground line

Triggering

- Can be setup to trigger off of complex digital sequences
- The trigger event could be a glitch

Analyze the signal

- Can view the digital data or convert it to analog levels or perform other analysis like FFT, constellation

Noise Figure Measurement

- Can be measured with or without a noise source

Noise-figure measurement using a noise source

- Measure with the noise source on and off with a SA
- Measure the noise source without the DUT

Noise-figure measurement without a noise source

- Apply a sinewave into the DUT and measure with a network analyzer
- Measure the average and RMS values. Average will average out the noise, RMS will account for the noise. Take RMS - Average = Noise

Dana Fosmer at 9/29/2014 10:10 AM

Chapter 3: Signal Excitation

One-tone excitation

- Single tone excitation is best for measuring the FFT and the steady-state spectrum contents
- Good for measuring linear systems, phase and amplitude are all that are affected by linear systems.

One-tone generation mechanisms

- When a single tone signal is converted to the frequency domain it should ideally be a perfect impulse at the frequency
- It is important to evaluate the phase noise, output power and frequency stability of the signal

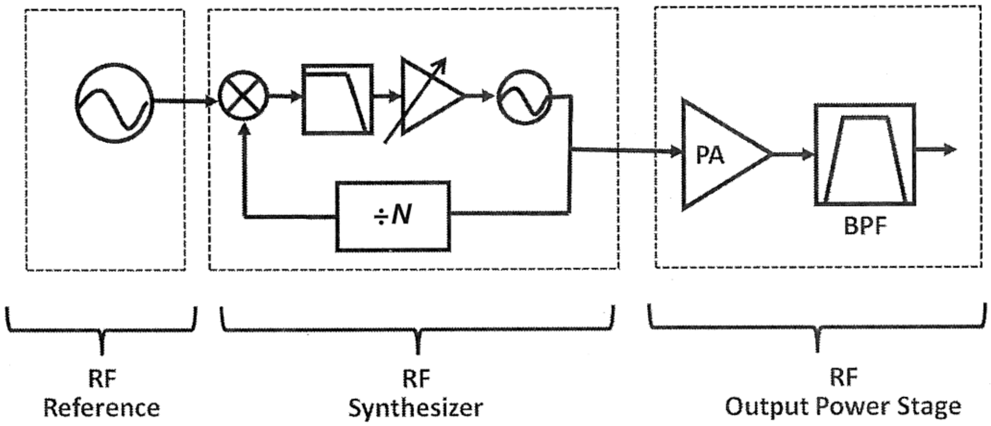


Figure 3.2 The three RF generator blocks, namely the RF reference, the RF synthesizer a
RF output power stage.

The reference signal

- Provided by any good oscillator
  - Crystal
  - Temp compensated

The synthesizer block

- Typical approach is with a PLL
  - Feedback until the reference frequency and the frequency division are equal
  - The high frequency part of the mixer signal is filtered, when the two mixed signals are the same the output of the filter is DC and the output frequency is held steady.
- PLL is not good for very high frequency generation. In that case successive frequency mixers and filters are used to build up the desired frequency

Output Stage

- Circuitry to level up the output and control the amplitude
- Don't operate generators at their max range, you may get an out of cal warning

One tone instrumentation

Frequency parameters

- Frequency range
- Frequency resolution
- Settling time - how fast can a generator change from one frequency to another.
- Typically different specifications for different frequency bands

Output power parameters

- Important to know the max and min stable power levels
- The output power can change when switching to a new frequency band

- Amplitude switching speed
- Output impedance for each frequency band (50 Ω ideally)
- VSWR for each frequency band, this should stay below 2

Spurious-signal generation parameters

- Spectral purity - creation of harmonics, generation of phase noise
- If the generator creates harmonics you want to be able to tell if you DUT creating them.
- Broadband noise is important when generating low power signals

Two-tone excitation

- Single tone signals are used to characterize linear systems
- Two-tone signals are necessary to characterize nonlinear systems

Two-tone generation mechanisms

- One method is to combine two single tone instruments
    - Have to pass each through an isolator and filter
    - Combine with a power combiner
- Arbitrary waveform generator (AWG) is another method

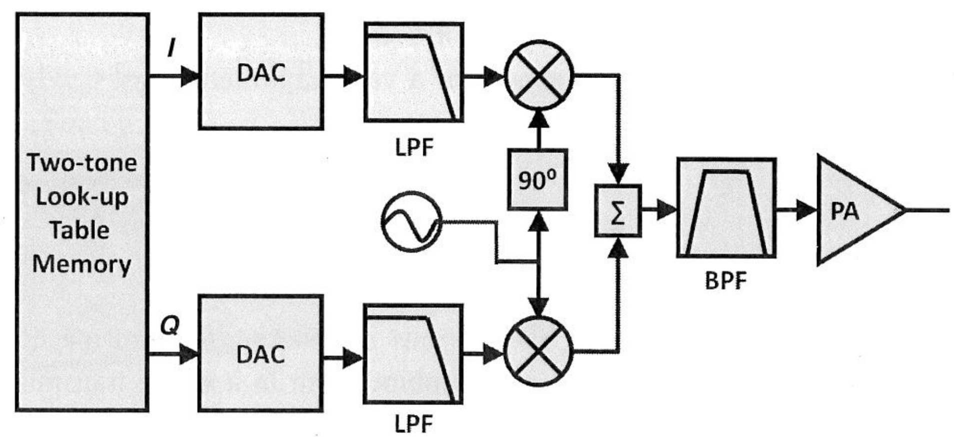


Figure 3.12 The internal architecture of an arbitrary-waveform generator using an I/Q modula
stage followed by a PA.

Up converted using an IQ modulator might not be good for high output power

Digitally modulated signals

- Most important type of excitation
- Ideally we would want to generate test signals that are the real signals the system would see, but that is not always possible.

The multi-sine

- Multi-sine signals are the sum of several sines (tones)
- Integer spaced sines will create a periodic signal

- Random sines combined will be non-periodic
- Multiple different multisine waveforms are possible from the same inputs if those inputs amplitude and phase vary

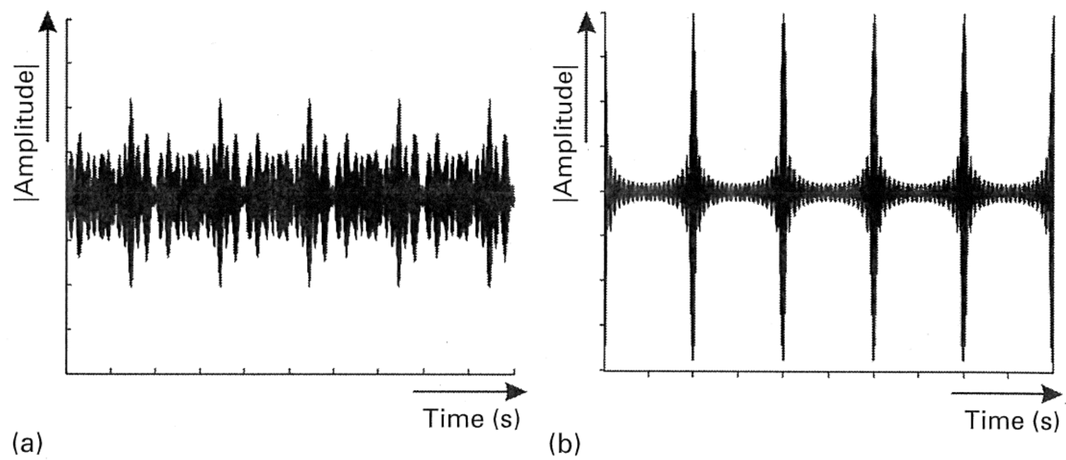


Figure 3.14 Time-domain waveforms of two signals composed of ten evenly spaced tones of equal amplitude: (a) independent tones with a randomized phase arrangement and (b) all ten tones phase-locked to a common reference.

- Probability density function, pfd(x) is a function that describes the relative probability of a random variable existing at a given point in the space of observation. The probability of a random variable falling within a given set is given by the integral of its density over the set.

Multi-sine with predetermined statistics

They take a statistical approach to these multi-sine signals. Real signals have a higher or lower probability that certain amplitudes will be reached or how often they are seen. So, you should make a test signal that emphasizes the high probability amplitudes.

What matters is not the instantaneous amplitude, but the value weighted by pdf(x)

Approximating the multi-sine pdf

- Different multi-sines can have different signal statistics despite having the same power spectral density and average power.

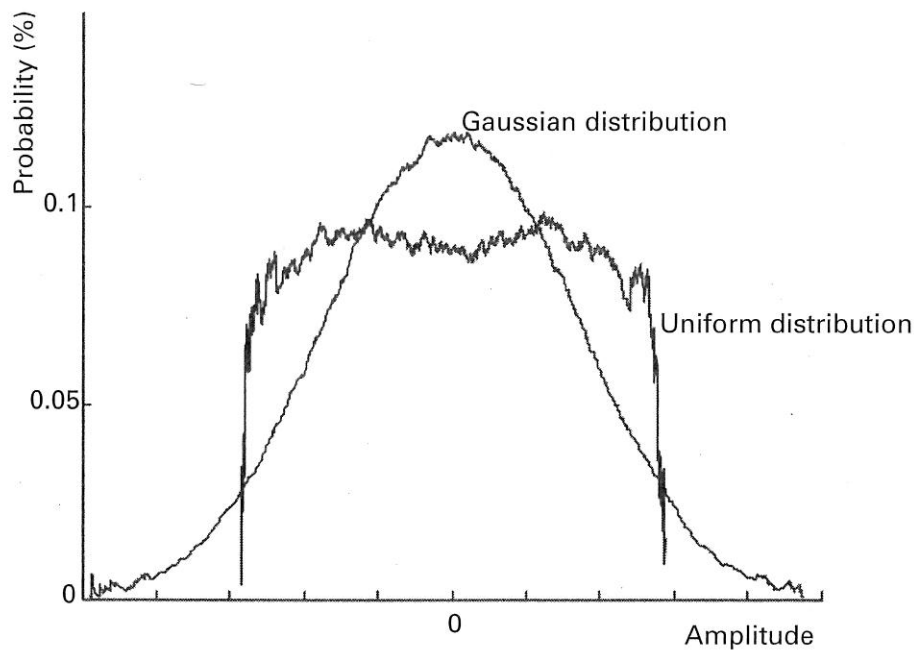


Figure 3.16 The pdf(x) of two multi-sines of uniform and Gaussian distribution, all with the integrated power. © IEEE.

- Algorithm for generating a multisine with predetermined statistics (Fig 3.17)

Skip some stuff on this

Complex Modulated Signals

- Modulated signals are in fact the core type of characterization excitation that most of the new wireless systems use, since they are closer to the real environments in which most RF systems operate.
- Similar to multi-sine generation
  - Digital data input
  - Modulate with IQ circuit

Chirp signals

- A chirp signal is a signal whose frequency varies through time.
- Mimic switched-mode real signals - like time division duplex (TDD)

Comb generators

- The comb generator was developed to provide precise phase calibration for an NVNA's instruments
- Produces a sinusoidal wave and it's harmonics, the objective is it contains a huge number of harmonics from low to high frequency. 10MHz to 50GHz
- Create this with a very narrow pulse in the time domain. The repetition period of the pulse will impose the frequency spacing on the spectrum content.

Pulse generators

- At the device level, pulsed excitation is adopted to evaluate semiconductor technologies for the presence of memory effects, such as traps and thermal heating.
    - A memory effect is when the circuit is affected by a previous input signal that occurred a short time ago. So, if a quickly pulsed DC input shows no difference from pulse to pulse versus a long duration DC input, then there are no memory effects.

Dana Fosmer at 9/29/2014 2:23 PM

Chapter 4: Test Benches

Introduction

Test Benches include

- Power meter measurement
- Noise-figure measurement
- Two-tone measurement
- VNA measurement
- NVNA measurement
- Modulated signal measurement
- Mixed domain measurement
- Temperature-dependent measurement

Test Benches for Characterization

Power-meter measurements

Selection of the power probe

- Frequency and power range
- Fast instantaneous probe or average power probe

Calibration

- Calibration factors related to temperature and frequency
- Zeroing - the instrument calculates the zero value of power at its input

Procedure p168

Sometimes we want to measure peak power and have to define the time window within which we want to measure power.

Noise Figure Measurements

Noise figure measurements can be performed with or without a noise source

When measuring with a noise source follow the hot and cold method - hot, with a noise source - cold, without.

Procedure p170

1. Measure noise source on and off
2. Connect noise source to DUT input
3. Measure DUT with noise source on
4. Measure DUT with noise source off

Noise Figure Calibration

Noise factor = $Y_{factor} = P_{noise\ on} / P_{noise\ off}$

Reset the noise figure to 0 dB after these measurements. This compensates for noise figure of the instrument.

Two-tone measurements

AWG or two CW generators can be used to create a two tone signal

AWG Method

- Larger amounts of spurious signal at output

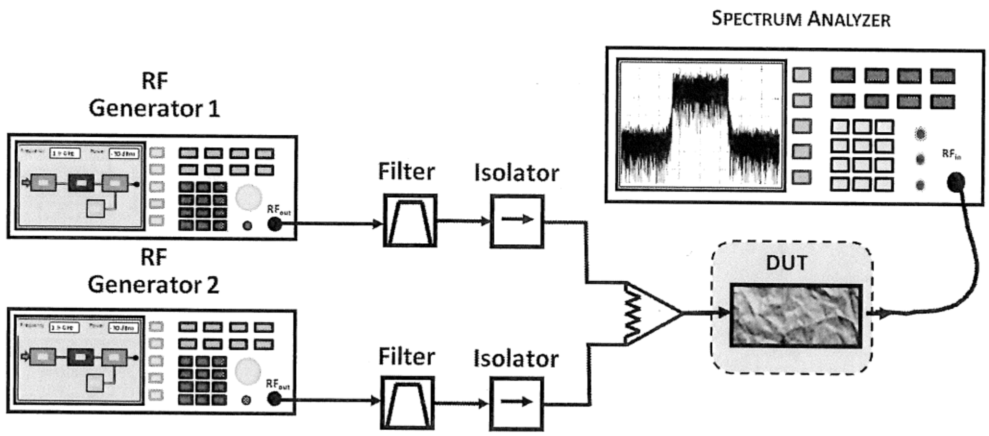
Two CW Method

- The main problem is how to combine the two signals
- Signals can travel backwards and cause distortion
    - This is fixed with isolators
    - Filter out harmonic generation

Two-Tone Amplitude Measurement

- The main goal of two-tone measurement is to measure the nonlinear distortion generated in the DUT

- Apply the signal to the DUT
- Measure the output with SA



re 4.9 A two-tone measurement bench, where two signals can be seen being combined in a
/er combiner.

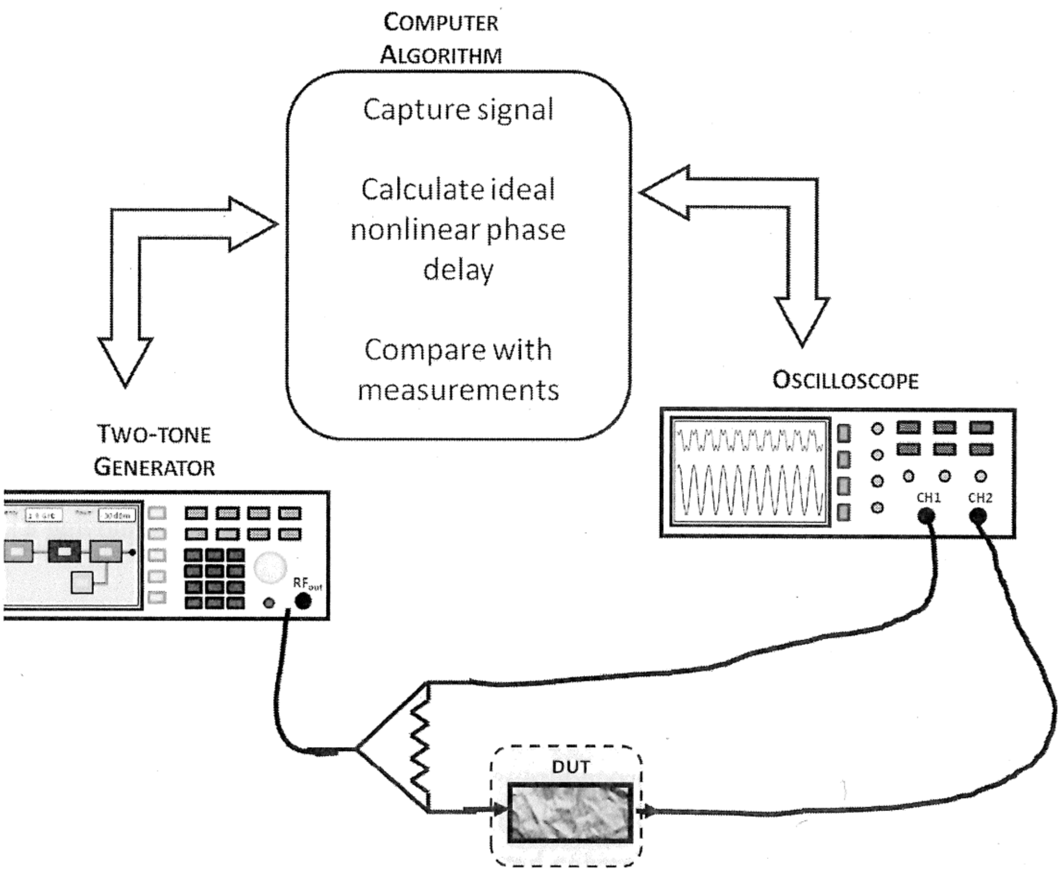
Make sure the input signal is within the dynamic range of the SA. To test adjust the SA attenuation - if the signal amplitude changes that means the signal you are seeing is actually being generated in the SA itself. If the measured values are constant, then the analyzer is measuring the input signal only.

Two-Tone Phase Measurement

Sometimes it's important to measure the phase delay between input and output tones, and for each tone itself. This will evaluate the impact of dynamics effects on signal degradation.

Method for phase measurement

- Measure directly
- Measure through DUT - look at the difference



e 4.11 A two-tone measurement bench for phase evaluation with correlated signals loying a known nonlinearity.

VNA Measurements

Procedure for S-parameter measurements

- Select the number of points
- Select the power range
- Attenuation at instrument input if the DUT has gain
- Perform calibration on the instrument
- Validate the calibration - measure a standard that was not part of the calibration procedure
- Perform the s-parameter measurements. S parameters are usually the first measurement conducted on a new microwave circuit.

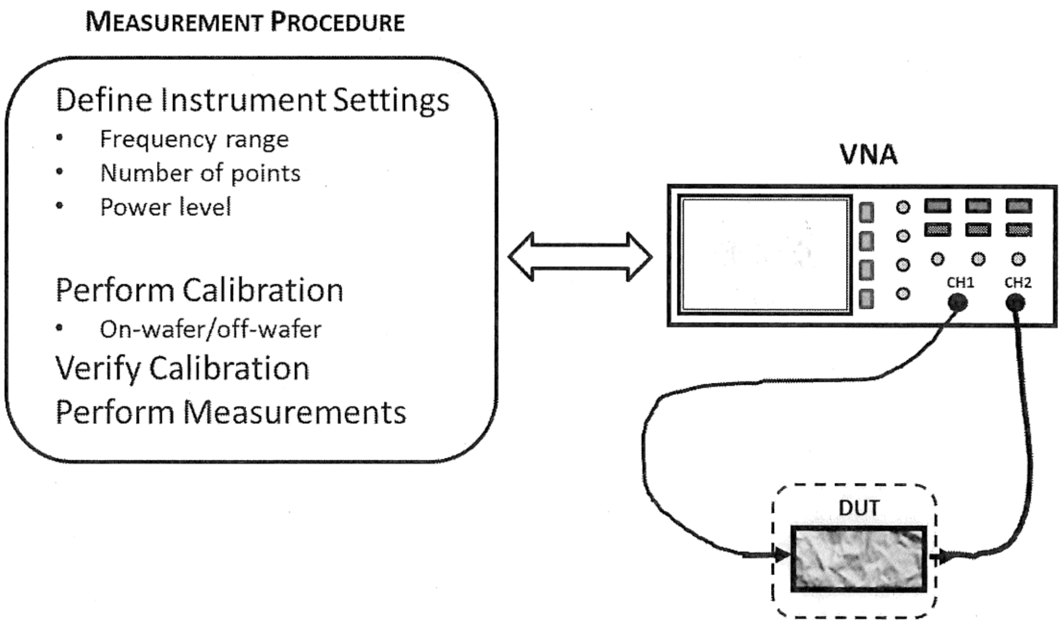


Figure 4.14 The VNA measurement sequence.

Extended Measurements

You can use a VNA to measure magnitude but a NVNA is required to determine phase.

- Calibrate the source
- Calibrate the receiver
- Measure power, gain, output power, drain efficiency, PAE
- Mixer measurements
- Noise figure measurements
- Two-tone measurements

NVNA Measurements

Measurement Procedure

NVNA over a VNA allows the response around the harmonic frequencies to be characterized as well.

NVNA over a SA advantage is both amplitude and phase of the spectral components can be characterized. This allows the time domain representation to be seen.

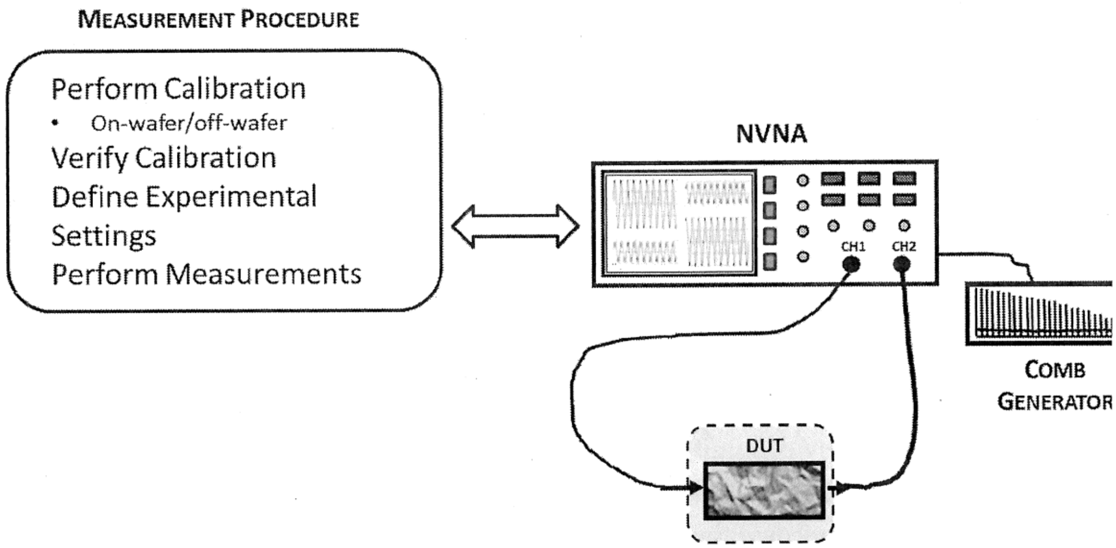


Figure 4.17 The NVNA measurement procedure.

Load-pull measurements

Load-pull is the term applied to the process of systematically varying the load impedance presented to the DUT

Source pull is also a thing

- Most common application is characterization of the noise parameters of transistors

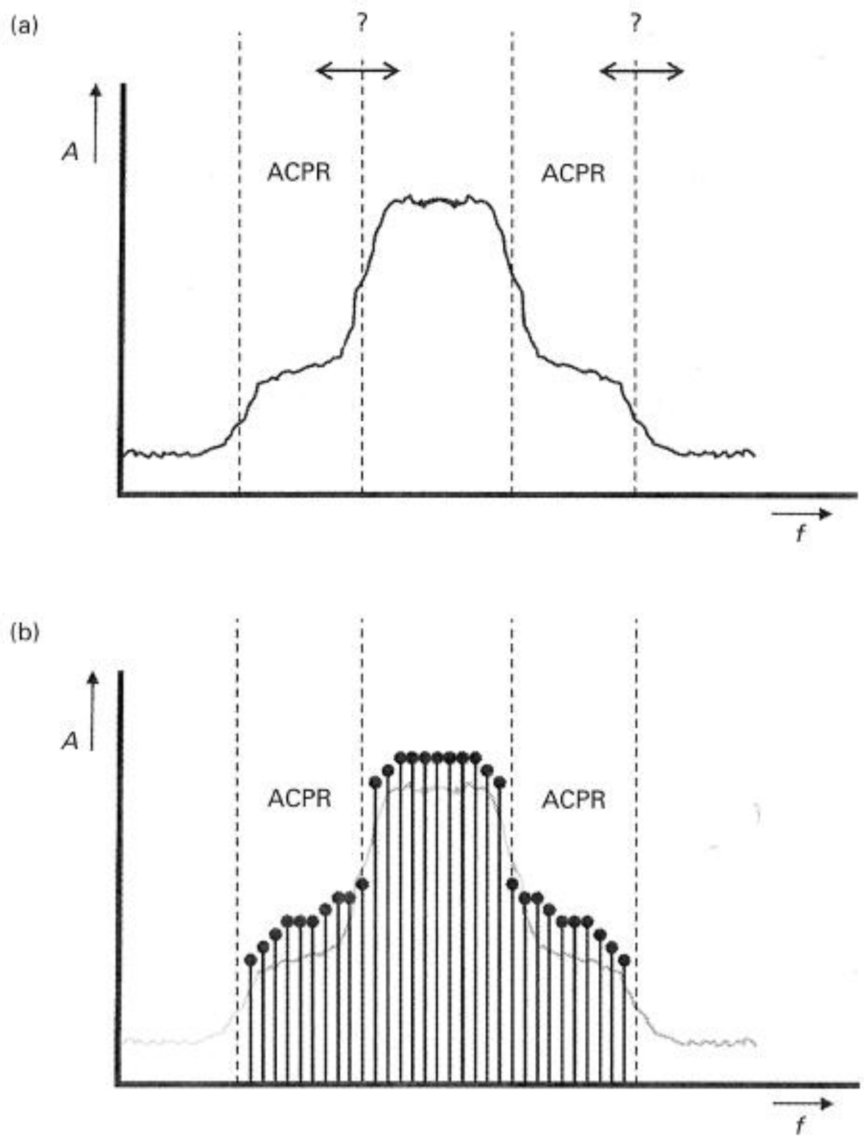
Load pull is inherently connected to the design of Pas.

Modulated signal measurements

- Modulated signal or multi-sine test benches
- Always based on an AWG generator
- FOMs
    - ACPR
    - NPR
    - CCPR
    - EVM
- Measure with VSA, RTSA or NVNA

Adjacent-Channel power measurements

- Modulated signal evaluation
    - Important measurement - amount of spectral regrowth that a nonlinear device can generate
- Measure adjacent channel power ratios
    - Mask the fundament and spectral regrowth and measure both



ıre 4.24 ACPR measurement: (a) typical ACPR in continuous spectra and (b) typical ACPR nulti-sine spectra.

Noise power ratio measurements

The most important aspect for modulated signals is co-channel frequencies, since those will decrease the SNR and thus degrade BER.

The first co-channel evaluation is NPR (noise power ratio)

- Need to create a spectrum notch to measure
- May be done with multi-sine by switching off middle terms
- Careful of LO leakage in the notch
- Measure with VSA of SA

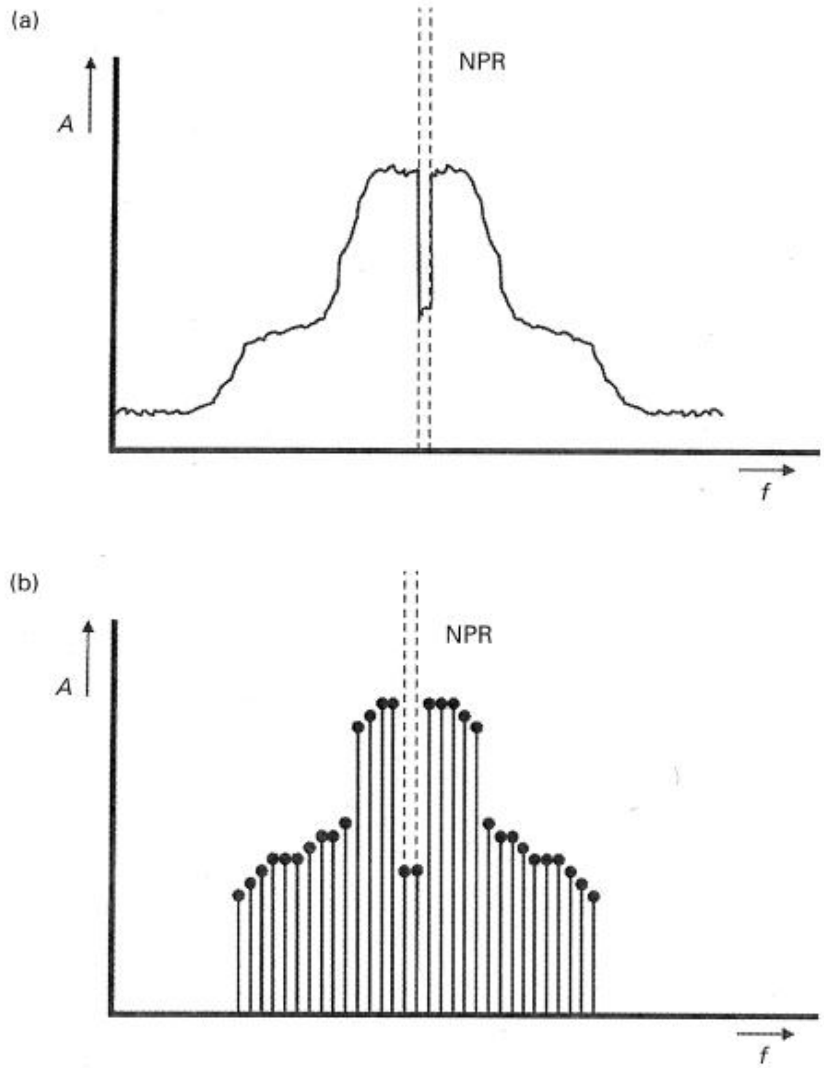


Figure 4.26 NPR signal generation: (a) a typical NPR measured signal for a continuous spectrum and (b) a typical NPR measured signal for a multi-sine spectrum.

Co-channel power-ratio measurements

- NPR does not capture the overall impact of nonlinear devices excited by a modulated signal. This is because the modulated signal is not a real signal
- The idea behind CCPR is to measure the real nonlinear distortion noise, which means the nonlinear distortion at co-channel frequencies that are not correlated with the fundamental signal.
  - Problem is they lie on top of each other in the spectrum
  - Have to eliminate the fundamental from the measurement

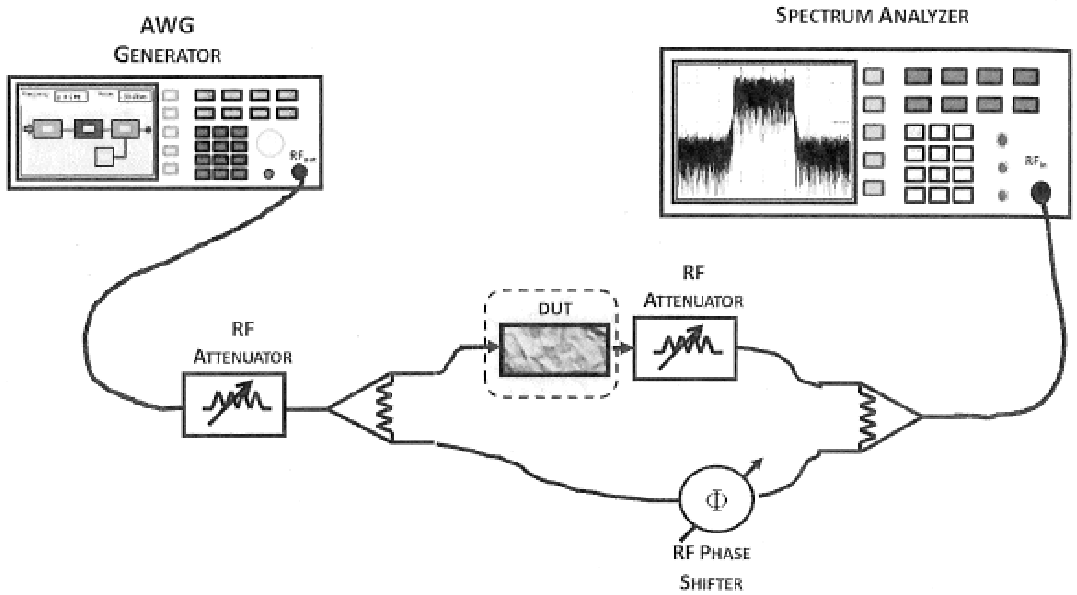
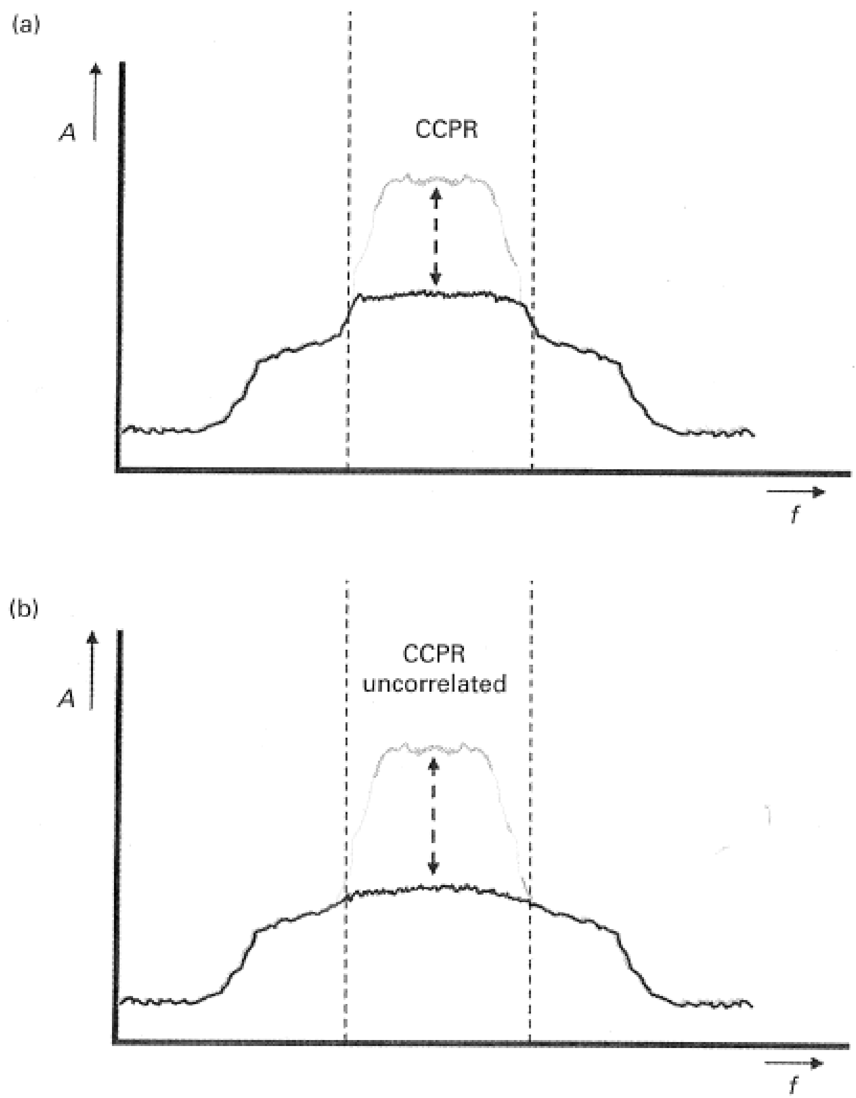


Figure 4.27 A typical CCPR measurement bench.



e 4.28 A CCPR measurement: (a) a typical CCPR canceled signal, when the system is tuned ıall signal condition; and (b) a typical uncorrelated CCPR measurement, when the system is ɟ at large signal condition.

Modulated information

RF FOMs give a nice perspective on the overall performance of the system, they do not give direct readings about the information being transmitted

This info is usually found by evaluating real modulated signals, either after demodulation or at the envelope layer.

One FOM important to measure in this context is EVM

VSA should be used for EVM since it allows I/Q signals to be captured over time, and further evaluation over time.

Fig 4.29

Time-division signal measurements

Newer wireless systems change their operation over time: (TDMA) time division multiple access, (FH) frequency hopping, (CSMA) carrier sense multiple access

For these schemes use similar FOMs as discussed, but perform them over time

Mixed signal measurement

Software defined radio (SDR). One side digital, one side analog. Measure in both domains