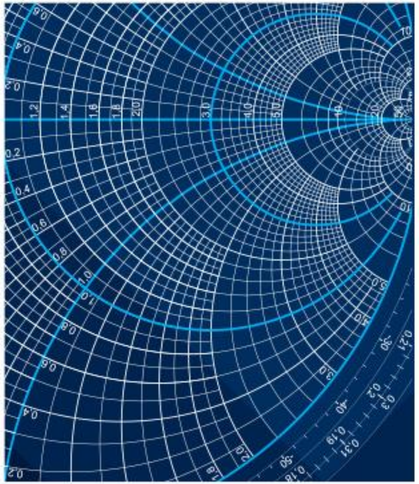
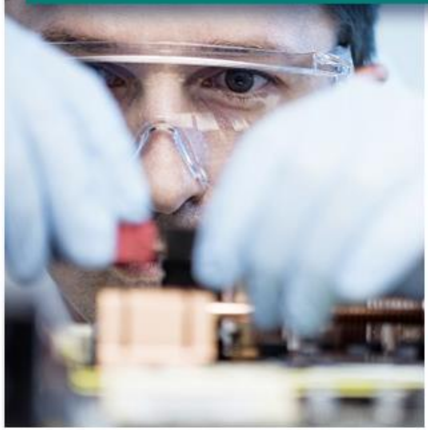


Measurement
Techniques

Design
Verification
&
Evaluation

EVERYTHING TEST

Instrument
Selection
&
Optimization



RF TEST: RF Communications System Overview

Rick Daniel, Application Engineer

ROHDE&SCHWARZ

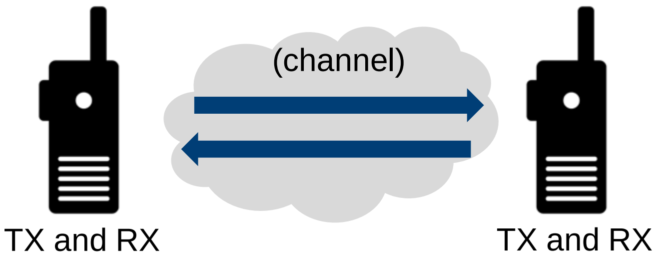
Make ideas real

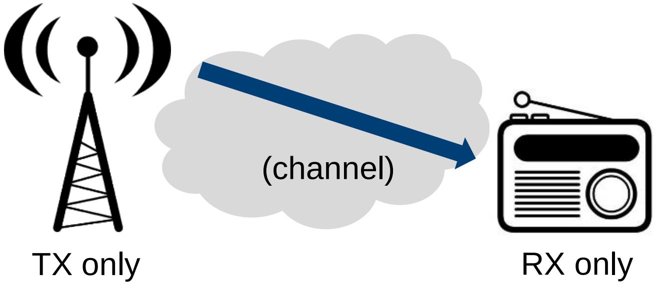
Agenda

- What is an RF Communications System?
- Example Systems
- Design Considerations
- What's in the Transmitter?
- What's in the Receiver?
- What Parameters Do We Test?
- Decibel Review
- Sample Measurements

RF Communications Systems

- What is an RF Communications System?
  - A system designed to get information from one location to another
- What kind of information?
  - Audio, video, or any other kind of data, analog or digital
- How is the information transmitted?
  - Using a high frequency (RF, microwave, mmWave) carrier and modulation
- What's in an RF Communication System?
  - Transmitter, Receiver, and a Channel (air, space, wire, coax, waveguide, optical fiber, etc.)



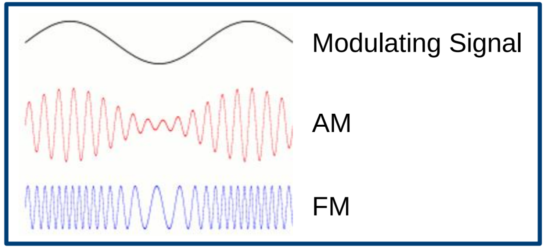


Modulation

- Modulation: Changing some characteristic of a CW carrier
  - Amplitude, frequency, or phase (or some combination of these)

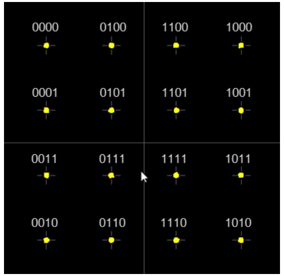
$$V(t) = A \cos(2\pi f t + \phi)$$

- Analog Modulation
  - AM, FM, ϕM
  - Simple concept – used since early 1900's
  - Good for analog signals, such as audio
  - Generally narrowband



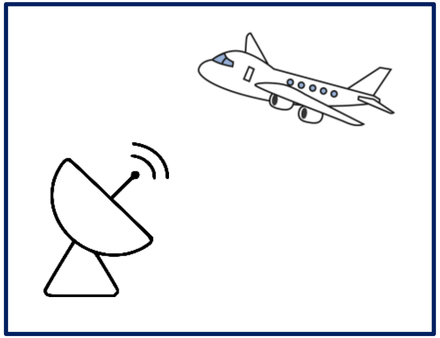
- Digital Modulation
  - ASK (Amplitude Shift Keying)
  - PSK (Phase Shift Keying: BPSK, QPSK, OQPSK, etc.)
  - QAM (Quadrature Amplitude Modulation: 16QAM, 64QAM, 256QAM, etc.)
  - APSK (Amplitude Phase Shift Keying: 16APSK, 64APSK, 256APSK, etc.)
  - Increasingly used since the 1970s and 80s
  - Narrowband and wideband

16 QAM



Where Do We See RF Communications Systems?

- Everywhere!



Example System: Commercial FM

- Data Type: Analog (voice, music)
- Bandwidth: 200 kHz
- Modulation: FM
- Frequency Band: 87.5 MHz to 108 MHz in most of the world
- Duplex: none
- Transmission Medium: Air
- Transmission Distance: up to 40 miles
- Multipath Interference: Yes
- Co-channel Interference: Not legally!
- Transmitter Power: up to 80 kW
  - $10 \log_{10}(80000/1) = 49$ dBW

Example System: DOCSIS 3.1 (Cable Internet)

- Data Type: Digital
- Data Rate (max): DS 10Gbps, US 2Gbps
- Bandwidth: up to 192 MHz channels (channel bonding allowed)
- Modulation: 16QAM to 16384QAM
- Frequency Band: 5 MHz to 2 GHz
- Duplex: FDD
- Transmission Medium: Coax (and optical fiber)
- Transmission Distance: up to a few miles (CMTS to CM)
- Multipath Interference: Yes (called 'micro reflections' in cable industry)
- Co-channel Interference: No (but sometimes strong LTE signals leak into system)

DOCSIS
Data Over Cable Service Interface Specification

Example System: 4G LTE

- Data Type: Digital
- Data Rate (max): DL 300Mbps, UL 75Mbps
- Bandwidth: 1.4 MHz to 20 MHz (per channel, up to 5 aggregate channels possible)
- Modulation: QPSK, 16QAM, 64QAM, 256QAM
- Frequency Band: Many defined bands below 6 GHz
- Duplex: FDD and TDD
- Transmission Medium: Air
- Transmission Distance: up to a few miles (mobile to base station)
- Multipath Interference: Yes
- Co-channel Interference: Not legally!
- Transmitter Power: Mobile: up to 200 mW, Base Station: up to 50 W

Design Considerations

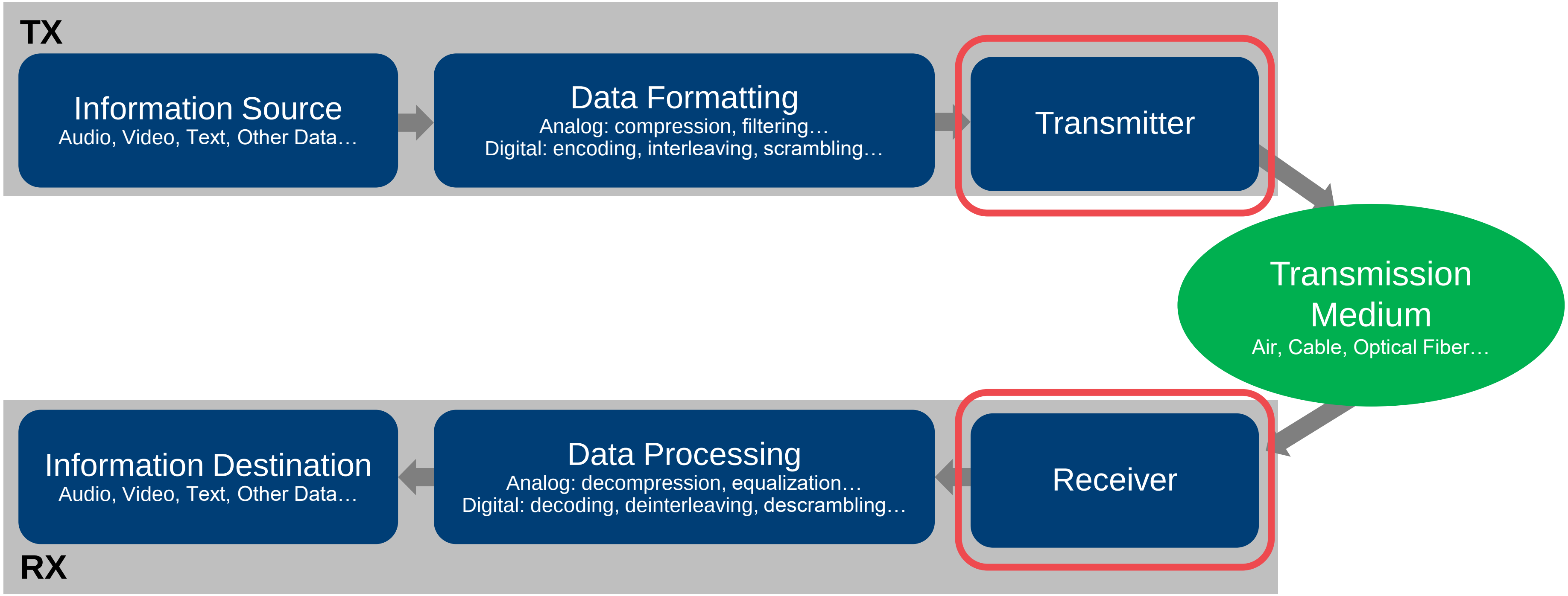
- **Link budget**
  - Transmit power
  - Receiver sensitivity
  - Transmission distance
  - Signal to noise requirements
  - Signal bandwidth
  - TX and RX antenna types
- **What is the data payload?**
  - Data rate
  - Real-time?
  - Are TX / RX fixed? moving? how fast?
- **Environment (Channel Conditions)**
  - Weather
  - Obstacles
  - Multipath
  - RF Interference
- **Regulatory requirements**
  - Standards bodies (3GPP, FCC, ETSI, etc.)
- **Physical limitations**
  - Size
  - Weight
  - Power (battery powered?)

Industry Trends

- System bandwidths increasing
  - Cellular: 1G - 25 kHz 2G - 1.3 MHz 3G - 5 MHz 4G - 20 MHz 5G - 400 MHz
  - Satellite Comms: 4 – 6 GHz channel bandwidths
  - WLAN (802.11): a/b/g - 20 MHz n - 40 MHz ac - 160 MHz ad - 1.76 GHz
- Modulation complexity increasing
  - Cellular up to 256 QAM
  - Satellite up to 256 APSK
  - DOCSIS up to 16384 QAM
- Channelization largely moving to OFDMA
  - Cellular: 1G - FDMA 2G – TDMA and CDMA 3G - CDMA 4G and 5G - OFDMA
  - WLAN: OFDMA

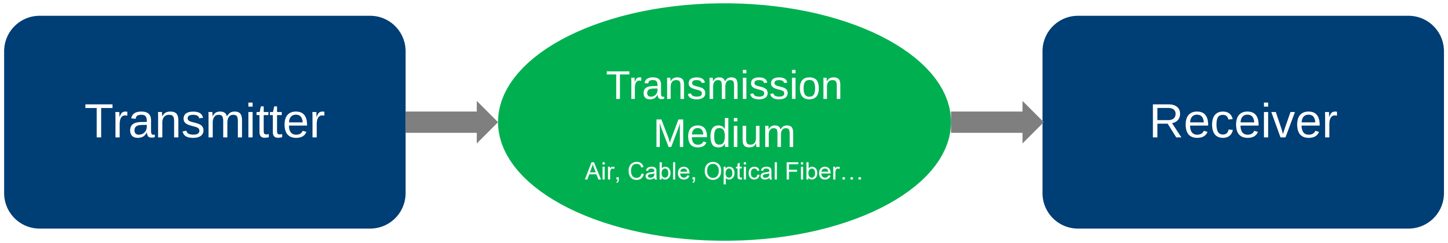
FDMA: Frequency Division Multiple Access
TDMA: Time Division Multiple Access
CDMA: Code Division Multiple Access
OFDMA: Orthogonal Frequency Division Multiple Access

Basic Communications System Block Diagram



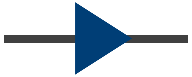
Basic Communications System Block Diagram

- ► Transmitters and receivers generally consist of many common components:
  - – Oscillators/VCOs, mixers, switches, filters, combiners/splitters, couplers, amplifiers, antennas…
  - – Transmitters also have a modulator and a power amplifier
  - – Receivers also have a low noise amplifier and a demodulator
- ► These must all be tested at the component level, module level, and top level

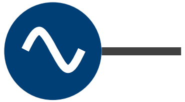


Typical Component Level RF Measurements

- Amplifiers
  - Gain, Gain Flatness, 1dB Compression Point, AM/PM Conversion, Noise Figure, Group Delay/Deviation from Linear Phase, Third-Order Intercept…



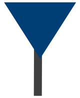
- Oscillators/VCOs
  - Output Level, Phase Noise, Harmonics, Spurious, Frequency Error, Settling Time, Tuning Sensitivity…



- Mixers
  - Conversion Loss, R-L / R-I / L-I Leakage, Distortion Products (mRF x nLO), 1dB Compression Point…

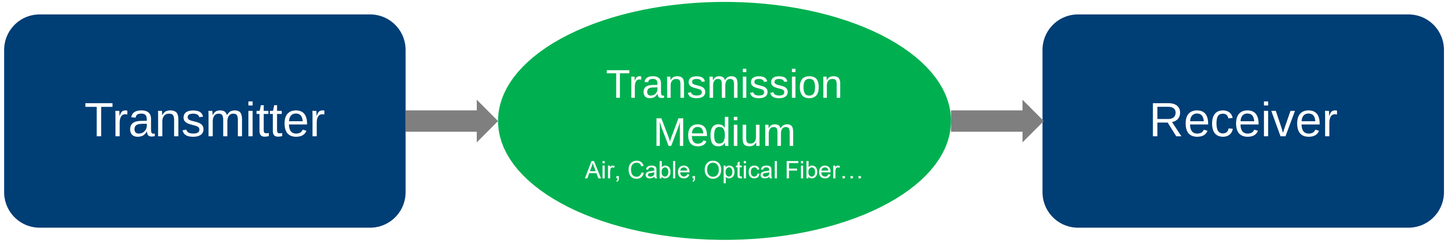
- Filters
  - Passband Loss, Stopband Rejection, Frequency Response, Passband Flatness, Group Delay…

- Antennas
  - Return Loss (VSWR), Gain, Antenna Pattern…



Typical Top Level RF Measurements

- Transmitter
  - TX Power
  - EVM (Error Vector Magnitude) – a measure of digital modulation quality
  - ACLR (Adjacent Channel Leakage Ratio)
  - Frequency Error
  - Tuning Speed (Settling Time)
  - Occupied Bandwidth
- Receiver
  - RX Sensitivity (using BER)
  - Selectivity
  - Frequency Error
  - Multipath Tolerance

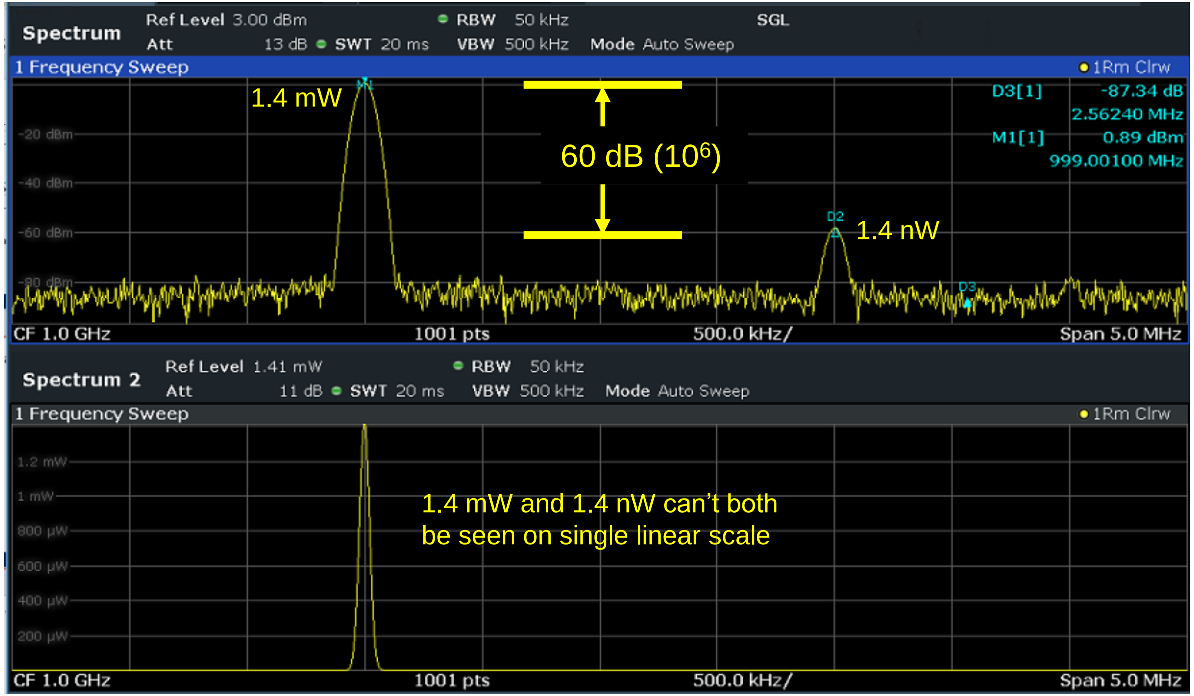


Decibels (dB) Review

- Many RF measurements are in units of dB so let's review
- Decibels provide a manageable way to deal with both large and small numbers using logarithms
- bel = $\log_{10}$ (ratio), decibel (dB) = 1/10 of a bel = 10 $\log_{10}$(ratio)
- dB's are used for power ratios like gain and loss (unitless)
  - Example: an amplifier has a gain of 25 dB
- An unwieldy ratio of 1,000,000,000,000,000:1 is elegantly expressed as 150 dB
- Decibels are also used to represent absolute levels
  - dBm (dB relative to 1 mW): dBm = 10 $\log_{10}$(P/0.001)
  - dBW (dB relative to 1 W): dBW = 10 $\log_{10}$(P/1)
  - dBc (dB relative to carrier): dBc = 10 $\log_{10}$($P/P_{carrier}$)
- RF engineers generally think in terms of dB without regard to the equivalent power ratio

dB	power ratio	amplitude ratio
100	10 000 000 000	100 000
90	1 000 000 000	31 620
80	100 000 000	10 000
70	10 000 000	3 162
60	1 000 000	1 000
50	100 000	316.2
40	10 000	100
30	1 000	31.62
20	100	10
10	10	3.162
3	1.995	1.413
1	1.259	1.122
0	1	1
-10	0.1	0.316 2
-20	0.01	0.1
-30	0.001	0.031 62
-40	0.000 1	0.01
-50	0.000 01	0.003 162
-60	0.000 001	0.001
-70	0.000 000 1	0.000 316 2
-80	0.000 000 01	0.000 1
-90	0.000 000 001	0.000 031 62
-100	0.000 000 000 1	0.000 01

dB (log) vs Linear Scales



Y-axis logarithmic
- shows full range of signal, including the noise floor.

100 dB of range (10 Billion)

Y-axis linear
- shows small fraction of signal, cannot see difference between Lower level signal and noise floor

ROHDE&SCHWARZ

Some Common Log (dB) Values to Remember

$1\text{x} = 0\ dB$

$2\text{x} = 3\ \text{dB}\ \ (3.01\ dB)$

$4\text{x} = 6\ \text{dB}\ \ (6.02\ dB)$

$\frac{1}{2}\text{x} = -3\ \text{dB}\ (-3.01\ dB)$

$\frac{1}{4}\text{x} = -6\ \text{dB}\ \ (-6.02\ dB)$

$10\text{x} = 10\ dB$

$100\text{x} = 20\ dB$

$1000\text{x} = 30\ dB$

What is a factor of 250x?

Hint: It’s ¼ of 1000x…

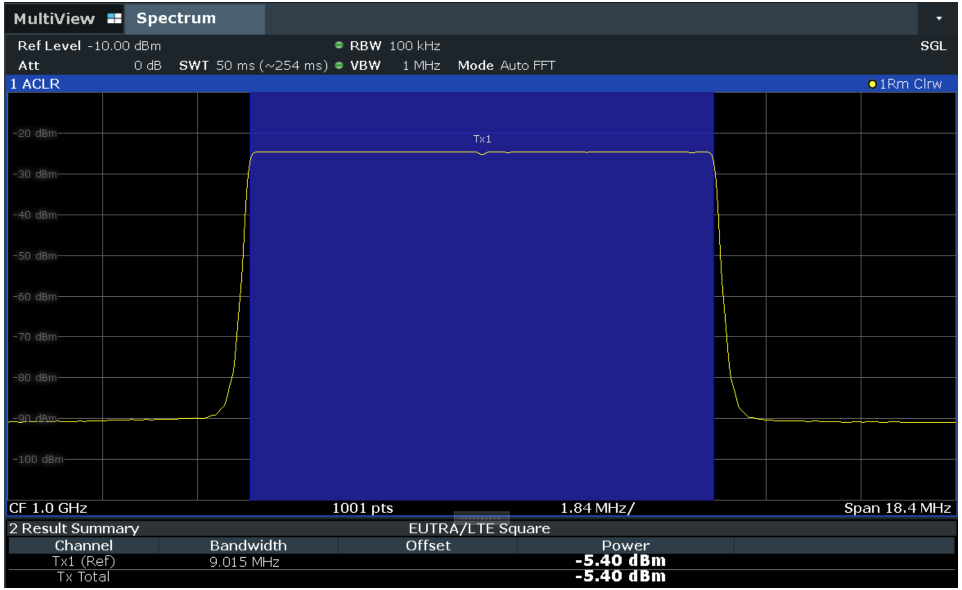
30 dB – 6 dB = 24 dB

Some RF Transmitter Measurements

- Output Power
  - Maximum power
  - Power level accuracy (relative to a commanded level)
- ACLR (Adjacent Channel Leakage Ratio) – also called ACPR
  - A relatively modern measurement of output linearity (spectral regrowth)
- TOI (Third Order Intercept Point)
  - A more traditional measurement of output linearity
  - Usually measured on amplifiers or at the module level
- Occupied BW
  - How much bandwidth does the signal occupy? (typically 99% of the signal energy)
- EVM (Error Vector Magnitude)
  - A figure of merit for the overall quality of a digitally modulated signal

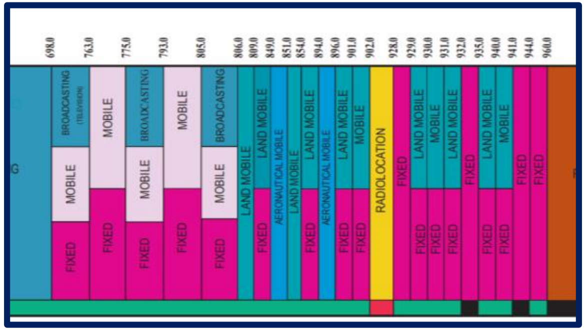
Transmitter Output Power

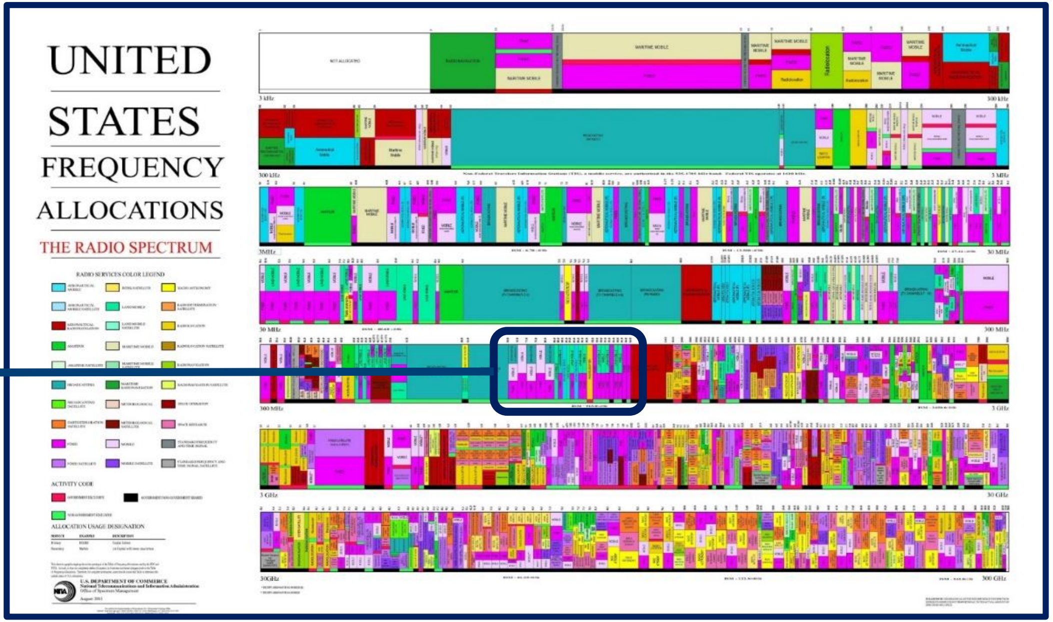
- This is an output power measurement of a 10 MHz BW LTE signal
- Modulated signals such as this require a channel power function on the spectrum analyzer to integrate the total power across the bandwidth of the signal (shown in blue)
- This signal has a total power of -10.27 dBm



Importance of Transmitter ACLR

- RF spectrum is a precious commodity
- Cellular service providers have spent *billions* of dollars on licensed blocks of spectrum
- It is very important that transmitters constrain their transmitted energy to their allotted spectrum
- ACLR is a quantitative measurement of the energy transmitted outside the allotted channel or band

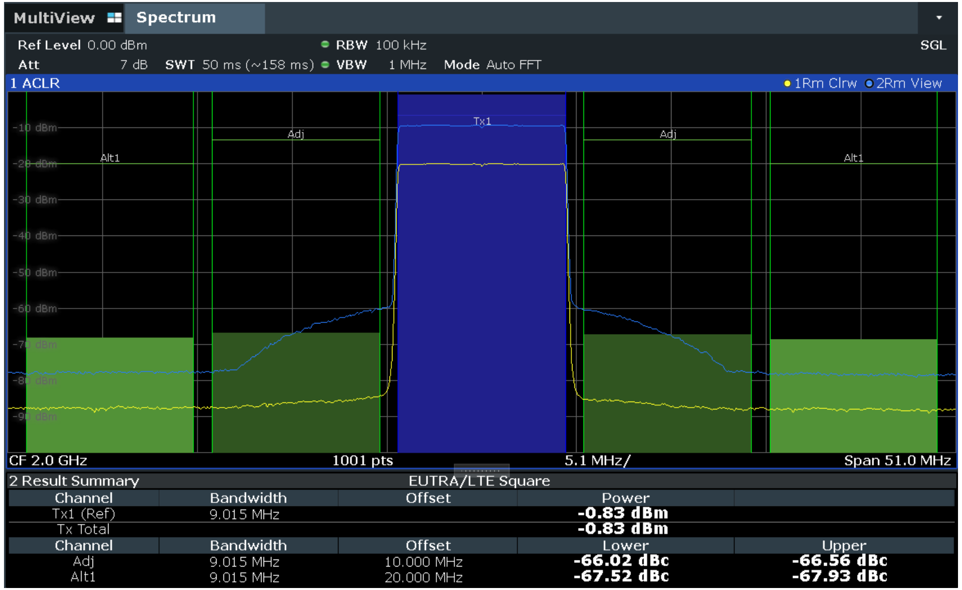




Source: NTIA

Transmitter ACLR

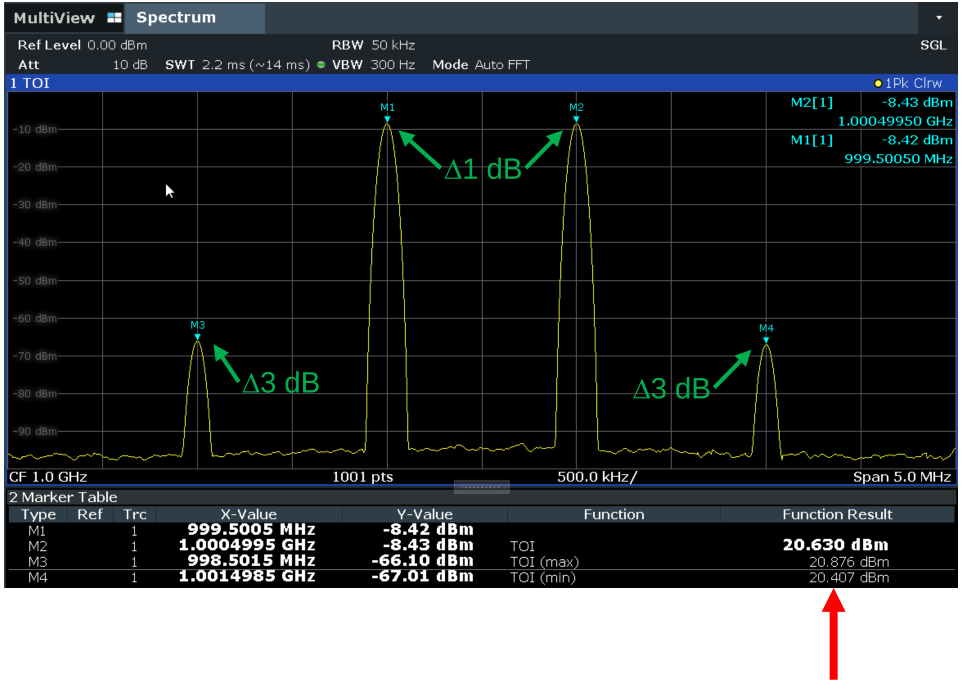
- This measurement is similar to the output power measurement, but includes measurements of the adjacent channels (one or more)
- The transmit power is measured and used as a reference for the leakage power measured in the adjacent channels
- The results are in dB, dBc, or dBm (depending on the standard)
- The bandwidth and spacing of the adjacent channels are generally set by the standards body
- The two traces show an amp driven with two different output levels 10 dB apart
- Note the higher distortion on the blue trace



ROHDE&SCHWARZ

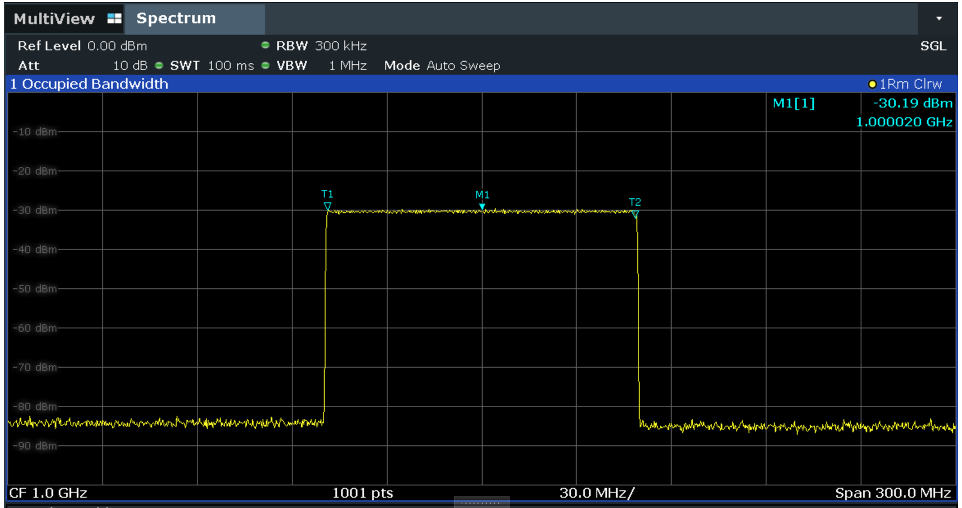
TOI (Third Order Intercept)

- TOI is a traditional measurement of amplifier linearity (also called two-tone intermodulation)
- Two CW signals (f_1 and f_2) are input to the amplifier and non-linearities cause the two undesired low-level distortion products at $2f_1$-f_2 and $2f_2$-f_1 (3^{rd} order)
- As the level of the two input tones are increased, the desired output tones increase by $1dB_{out}/1dB_{in}$, but the 3^{rd} order tones increase by $3dB_{out}/1dB_{in}$
- There is a theoretical point where all four tones would be at the same output level – the Third Order Intercept point
- This point is never reached because the amp will saturate at a much lower level
- TOI is expressed in dBm



Occupied Bandwidth

- OBW measures the bandwidth occupied by a percentage of the total signal power (99% is typical)
- This is a measurement of a 100 MHz bandwidth 5G NR signal
- 99% of the signal power is contained in a bandwidth of 97.3 MHz



Type	Ref	Trc	X-Value	Y-Value	Function	Function Result
M1		1	1.00002 GHz	-30.19 dBm	Occ Bw	97.265831629 MHz
T1		1	951.316 MHz	-30.03 dBm	Occ Bw Centroid	999.948943673 MHz
T2		1	1.048582 GHz	-32.02 dBm	Occ Bw Freq Offset	-51.05632719 kHz

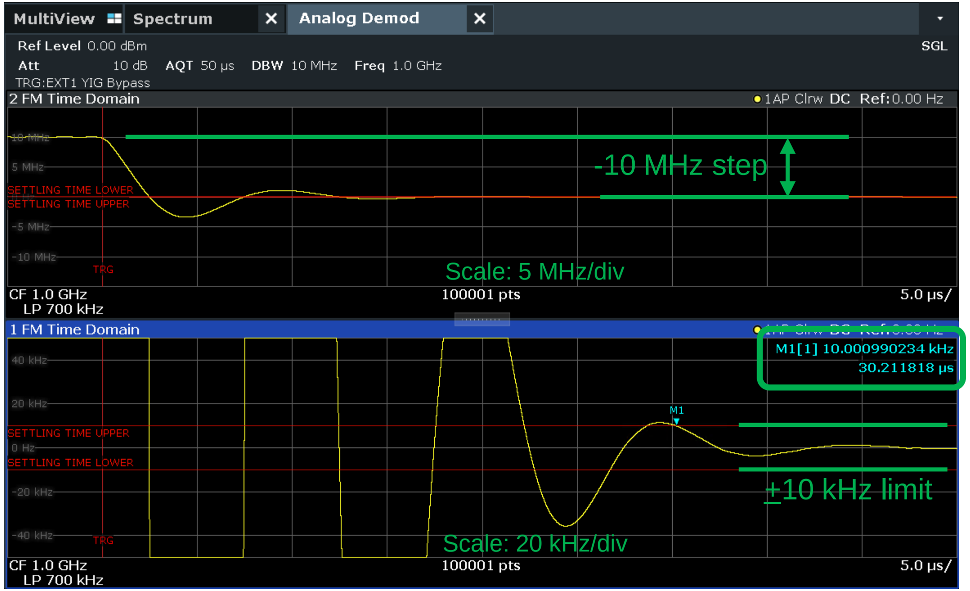
EVM (Error Vector Magnitude)

- EVM is a measure of overall modulation quality for a digitally modulated signal
- EVM quantifies the deviation of the measured constellation to the ideal constellation
- EVM is expressed in units of % or dB
- The EVM of the QPSK modulation in this 5G NR signal is 0.29%

ROHDE&SCHWARZ

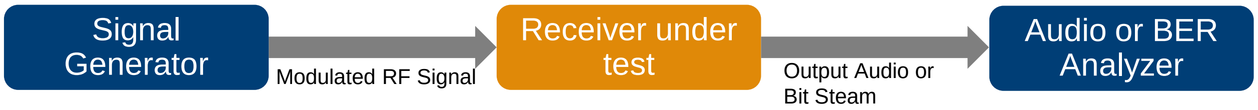
Tuning Speed or Settling Time

- When a transmitter or receiver has the ability to tune to different channels, the channel switching time is often specified
- The settling time is typically defined as the time between a command to change channel and when the TX or RX is within some tolerance of the final frequency
- Settling time is usually measured at the VCO or module level
- In the screenshot, “settled” is defined as being within 10 kHz of the final frequency and the measured settling time is 30.21 us (10 MHz step settles within 10 kHz in 30.21 us)



RF Receiver Measurements

- The most important receiver measurement is Receive Sensitivity
- For **analog** receivers this is a SINAD (**si**gnal to **n**oise **a**nd **d**istortion ratio) measurement
  - The signal source is a modulated audio tone at (or near) 1 kHz
  - The RF signal level is reduced until the measured SINAD is below a specified level (typically 12 dB)
- For **digital** receivers this is a measurement of the lowest input signal that is received within a maximum specified bit error rate (BER)
  - The receiver will either self-report BER or the decoded bits can be analyzed externally to measure BER
  - The signal source for this test is a vector signal generator that produces a modulated RF signal with a known data pattern
  - The RF signal level is reduced until the measured BER just reaches the specified maximum



SUMMARY / Q&A

- RF communications systems are commonly used in many ways in the modern world
- Transmitters and receivers must meet increasingly demanding performance requirements
- RF spectrum is very crowded and these systems must operate within their designated frequency bands
- Testing is required at every level of integration – top level, module level, and component level
- Modern test equipment and techniques are needed to ensure proper performance


Measurement
Techniques
Design
Verification
&
Evaluation
EVERYTHING TEST
Instrument
Selection
&
Optimization