What is this chapter about?

- Introduce concepts of radio-frequency (RF) testing in a production environment
- Focus on
  - Fundamental RF concepts
  - RF measurement instruments and their working principles
  - Challenges in production test – accuracy concerns
  - Future upcoming technologies
Introduction to RF

- RF stands for ‘Radio Frequency’
  - Usually very high frequencies where signals can be transmitted wirelessly
  - Range of frequencies $\rightarrow$ 300MHz $\sim$ 3GHz
- RF is used synonymously with ‘wireless’
- Significant growth during the last decade in the consumer segment
  - Increased consumer applications
S-parameters

- At very high frequencies, electrical signals act as light waves
  - Exhibit reflection and transmission characteristics

- S-parameters tell us how much of incident energy is transmitted and reflected
S-parameters (contd.)

- Transmission = C/A (see prev. slide)
  - Computed parameters: Gain/loss, $S_{21}/S_{12}$, Transmission coefficient ($T$),

- Reflection = B/A
  - Computed parameters: Reflection coefficient ($\Gamma$), $S_{11}/S_{22}$, VSWR

Reflection Coefficient

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_O}{Z_L + Z_O}$$

Return loss = $-20 \log(\rho)$

VSWR

$$\text{VSWR} = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 - \rho}$$
Applications of RF

- Earlier, consumer applications of wireless technology were limited
  - Military, space communications, air traffic control
- Currently, consumer applications are on the rise
  - Cell phone, laptop, PDA, satellite radio
  - Radiofrequency identification (RFID)
Challenges with RF testing

- Tests are performed in two steps
  - Characterization test
  - Production test
- Various challenges make production test expensive
- RF devices need extra attention during testing (challenge #1)
  - Impedance matching @ input and output ports to ensure optimal power transfer
  - Shielding from external wireless signals during testing
Challenges (contd.)

- RF measurements are sensitive to noise and need highly accurate instruments to
  - Verify the functionality of the design
  - Ascertain that all the specifications are met
  - Ensure high repeatability of the measurement system

- Production test needs to perform all of the above with
  - Cheaper instrumentation \(\rightarrow\) a low-cost commercial tester (challenge #2)
  - Perform tests in a short duration (challenge #3)
  - Achieve a high degree of accuracy (challenge #4)
Summary of Challenges

- Challenge #1 is very specific to RF devices → needs careful measurement setup

- Challenge #2 and 3 are also specific to RF
  - RF testers are very expensive (> $2M) compared to the analog and digital counterparts
  - RF tests are usually longer compared to analog tests due to inherent low levels of signals involved

- Challenge #4 is general for all electronic devices
  - However, these are more prominent in RF due to the large amount of noise involved
A note on voltage and power transfer

To get the maximum voltage transfer

- Make $R_S$ small and/or make $R_L$ large.

The transfer voltage $V_L$ can be calculated as:

$$V_L = \left( \frac{R_L}{R_S + R_L} \right) V_S$$
Maximum power transfer

- Sometimes, power transfer is more important than voltage transfer.
  - The power delivered to $R_L$ can be determined by
    \[ P = VI = \left( \frac{R_L}{R_S + R_L} \right) V_s \times \left( \frac{1}{R_S + R_L} \right) V_s = \frac{R_L}{(R_S + R_L)^2} V_s^2 \]

- The power transferred is maximum when $R_L = R_S$. 
Instruments used in RF Measurements

- All RF measurements can be divided into three categories
  - Frequency domain measurements
  - Power domain measurements
  - Noise measurements

- Various instruments aid in each type of measurement
  - Spectrum analyzer (Frequency, Power, Noise)
  - Network analyzer (Power)
  - Noise figure meter (Noise)
Structure of a Spectrum Analyzer

- Input
- Signal conditioning amplifier
- Input filter
- Down-conversion mixer
- Voltage controlled oscillator
- Amplifier
- Filter bank
- Log amplifier
- Detector
- Video filter
- Filter bank
- Display
- User interface
- Digital control block
- Sawtooth waveform generator
Network Analyzer

Structure of a Network Analyzer

User interface

Digital control block

Receiver block

Digitally Controlled Source 1

Port isolator 1

Port 1

Digitally Controlled Source 2

Port 2

Receiver block

Display

Amplifier

Voltage controlled oscillator

Mixer

Port isolator 2

Filter

SOC Test Architectures

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Noise Figure Meter

- Noise figure is a measure of amount of noise contributed by the system

\[ F = \frac{SNR_{in}}{SNR_{out}} = \frac{S_i/N_i}{S_o/N_o} \quad \Rightarrow \quad NF = 10\log_{10} F \]

- Noise measured at output depends on system gain
- To measure noise figure, output noise is measured at two input noise power levels and computed as follows:

\[ N_{DUT} = \frac{(N_{o1}N_{i2} - N_{o2}N_{i1})}{(N_{i2} - N_{i1})} \]
Noise figure meter

- User interface
- Digital control block
- Bias control
- Noise source
- Receiver

Input:
- Port 1: DUT input

Output:
- Port 2: DUT output

Graph:
- Noise power vs. Temp
- Slope = kBG_{DUT}
- N_{DUT}
Semiconductor development flow

Design
Simulation
Layout
Fabrication

Characterization Test
Qualification
Bench Test

Prototype

Test Development

Production Test (ATE)
Wafer Test
Package Test

Customer feedback

Time

SOC Test Architectures
Characterization vs. Production

Characterization Test
- Test Complexity

Production Test
- Yield 100%

Start of production
- Time

SOC Test Architectures
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Typical RF system
Super-heterodyne RF system

Super Heterodyne Architecture

- Receiver Oscillator
- Transmitter Oscillator
- Frequency Synthesizer
- Phase Splitter
- Baseband Amplifier
- Modulator
- Data Converter
- Digital Signal Processor
Homodyne system (direct down conversion)
RF specifications

- Linearity specifications
  - Gain, conversion gain, output power

- Non-linearity specifications
  - Third-order intercept (TOI), adjacent channel power ratio (ACPR)

- Noise specifications
  - Noise figure (NF), signal-to-noise ratio (SNR), sensitivity, dynamic range

- System specifications
  - Error-vector magnitude (EVM), bit error rate (BER)
A note on decibel

- Decibel is a very commonly used unit in wireless domain
  - Notation for decibel $\rightarrow$ dB
  - Any number $N$ can be converted to decibel by
    \[ N_{dB} = 20 \log_{10}(N) \]

- A similar unit is mili-decibel (notation $\rightarrow$ dBm)
  - Used to denote power with reference to 1 mW
  - $P$ watts of power is converted to dBm by
    \[ P_{dBm} = 10 \log_{10}(P/1 \text{ mW}) \]
  - Thus $1W = 1000\text{mW} = 30 \text{ dBm}$; $10\mu W = 0.01\text{mW} = -20 \text{ dBm}$
Gain

- Measures the small-signal gain of the device/system
- Input is a single-tone stimulus within the operating frequency
- Amplitude is within linear range of operation
- Gain = (Output amplitude / Input amplitude), usually expressed in dB

\[ Gain = \frac{A_2}{A_1} = 20 \log_{10}(\frac{A_2}{A_1}), \text{ in dB} \]
Conversion Gain

- Measures the small-signal gain of mixers
  - Mixers translate the input frequency at a different output frequency
- Input is a single-tone stimulus within the input operating frequency, amplitude within linear range of operation
- Gain = (Output amplitude @ \( f_2 \) / Input amplitude @ \( f_1 \)), usually expressed in dB

\[
\text{Gain} = \frac{A_2}{A_1} = 20 \log_{10} \left( \frac{A_2}{A_1} \right), \text{ in dB}
\]
Third-Order Intercept

- Measure of nonlinearity for a device/system
- Two-tone input, within operating range
  - Frequencies are closely spaced, difference is usually <1% of the device bandwidth
- Amplitude is larger than linear range of operation
- \[ \text{TOI} = P_{out} + |(P_{out} - P_{IMD})/2| \]
A note on TOI

- Usually, RF devices exhibit third-order nonlinearity

\[ y(t) = A_0 + A_1 x(t) + A_3 x(t)^3 \]

- TOI is denoted in dBm
  - It indicates the output power level where the fundamental and intermodulation tones attain same power
Calculating TOI from a two-tone input

\[ (P_3 - P_1) = 3 \times (\text{TOI} - P_{\text{in}}) \]

\[ (P_3 - P_2) = 1 \times (\text{TOI} - P_{\text{in}}) \]

So,

\[ (P_2 - P_1) = \Delta P = 2 \times (\text{TOI} - P_{\text{in}}) \]

\[ \text{TOI} = \frac{\Delta P}{2} + P_{\text{in}} \]
Harmonics and THD

- Harmonics are multiples of the input fundamental frequency
  - Created due to the nonlinearity of the system
- THD is the measure of total power in all harmonics

![Graph showing harmonic frequencies and THD](image)

**Fundamental frequency**

2\(^{nd}\) harmonic frequency

3\(^{rd}\) harmonic frequency

Output power (dBm)

Frequency
Basics of SNR

- SNR is an important factor for any signal
  - SNR for a known signal can be easily computed
  - SNR denotes the level of purity
  - For this sinusoid, SNR = 50 dB

\[ (-23) - (-73) = 50 \text{ dB} \]

- This notion can be extended to any known signal
Noise figure

- Noise figure measures the degradation of SNR of a signal when it passes through the DUT
  - Noise figure = $\frac{SNR_{in}}{SNR_{out}}$
  - This indicates the amount of noise added by the DUT
  - NF is usually measured in dB (it’s a ratio)

- NF is measured using NF meter
Noise figure (contd.)

- Formula to compute noise figure

\[ NF = N_{out} - (N_t + G) = N_{out} - (10\log(kTB) + G) \]

- Methods of computing noise figure
  - Noise figure meter
  - Gain method (using a spectrum analyzer)
  - Y-factor method
Using ENR to measure NF

- ENR → Excess noise ratio
- Y → Ratio of output power when a noise source is turned on and off, respectively

\[
Y = \frac{P_{on}}{P_{off}} \quad \text{and} \quad ENR = \frac{(N_{on} - N_{off})}{N_0}
\]

\[
N_{DUT} = \frac{ENR}{Y - 1}
\]

\[
NF = 10\log_{10}\left(\frac{ENR}{Y - 1}\right) = ENR_{dB} - 10\log_{10}(10^{\left(\frac{Y_{dB}}{10}\right)} - 1)
\]
NF of cascaded stages

- Noise figure measurement of cascaded stages

\[
N_{out} = N_{in} G_1 G_2 + N_1 G_2 + N_2 \quad \quad S_{out} = S_{in} \times G_1 \times G_2
\]

\[
F_{system} = \frac{S_{out}}{N_{in}} = \frac{S_{in} N_{out}}{N_{in} S_{out}} = 1 + \frac{N_1}{G_1 N_{in}} + \frac{N_2}{G_1 G_2 N_{in}}
\]

\[
F_{system} = 1 + \sum_{i=1}^{n} \left( \frac{F_i}{N_{in}} \frac{1}{N_{in} \prod_{j=i+1}^{n} G_j} \right)
\]

General form for cascaded systems

Stage 1: \( G_1, N_1 \)  \quad Stage 2: \( G_2, N_2 \)

\( N_{in} \rightarrow \quad \rightarrow N_{out} \)
System-level test: ACPR

- ACPR test provides an idea of the overall nonlinearity of a system
- Why is ACPR important?
  - In communication systems, information is transmitted in channels (a fixed span of frequencies)
  - Many devices communicate simultaneously in different channels
  - If power leaks from one channel to other, both channels may result in erroneous transmission

Power leakage to adjacent channels due to nonlinearity
ACPR Test

- Pseudo-random bitstream is transmitted from the DSP to test for ACPR
  - This ensures all frequencies within the channel are equally likely

- ACPR is the ratio of total power within the desired channel and the adjacent channel
  - Usually denoted in dB
ACPR test response

- Usually a multi-tone is used to measure ACPR

![ACPR test response diagram]

**Frequency**

**Output power (dBm)**

**In-band power**

**Out-of-band power – due to nonlinearity of the system**
Gain flatness

- This measures how well the device gain operates within its band of operation
  - Usually applicable for wideband devices

Diagram showing output power (dBm) vs. frequency with a peak labeled as Gain flatness.
RF systems employ modulation during transmission
  - Helps in protecting information from transmission channel noise

$$I(t) = A_I \cos(\omega t) \quad Q(t) = A_Q \sin(\omega t)$$ \hspace{1cm} \text{Ideal}

Inaccuracies in channel can cause
  - Amplitude and phase error
  - AM-PM or PM-AM modulation

$$I(t) = \alpha_I A \cos(\omega t) + \beta_I \quad Q(t) = A \sin(\omega t + \theta_Q) + \beta_Q$$ \hspace{1cm} \text{Non-ideal}

EVM is an aggregate measure of all the above effects
**EVM test**

- As done in ACPR, PR sequences are transmitted and received back during EVM test
- Use the demodulated data symbols to compute EVM
- EVM is the RMS of the received symbols compared to the actual symbols
  - Need to use a large number of symbols to obtain a statistically correct value
  - The amplitudes are normalized for systems employing phase-amplitude based modulation (e.g. 16-QAM, 64-QAM)
EVM measurement

- The symbols for phase modulated systems should lie on a circle
  - Deviations from the circle indicate presence of magnitude error + noise of the system
  - Rotation of the symbols indicate phase error
  - Non-uniform rotation indicates improper group delay present in the system (usually from passives)
EVM (contd.)

- EVM is calculated using the following formula

\[
EVM_{RMS} = \sqrt{\left( \frac{1}{N} \sum_{i=1}^{N} |V_{ideal,i} - V_{measured,i}|^2 \right) / \left( \frac{1}{N} \sum_{i=1}^{N} |V_{ideal,i}|^2 \right)}
\]

- EVM is a very good indicator of the overall system health
  - Typically, EVM is within 3-15 %
  - This figure shows EVM for a QPSK system
Using EVM to estimate system performance

- Amplitude imbalance
- Phase imbalance
- Both amplitude and phase imbalance + noise

- Ideal constellation point
- Actual constellation point
**Modulation error ratio**

- The signal to noise ratio of a digital signal is called the modulation error ratio
  - $I_{rj}$ and $I_{tj}$ are the received and transmitted in-phase components
  - $Q_{rj}$ and $Q_{tj}$ are the quadrature counterparts

$$MER = \frac{\sum_{j=1}^{N} (I_{rj}^2 + Q_{rj}^2)}{\sum_{j=1}^{N} [(I_{tj} - I_{rj})^2 + (Q_{tj} - Q_{rj})^2]}$$
Bit error rate (BER)

- Bit error rate indicates overall system performance level
  - Total bits transmitted = \( N \)
  - Total error bits received = \( N_{err} \)

- BER can be time-consuming to measure
  - To measure BER reliably, at least 100 error bits must be received
  - For BER = \( 10^{-12} \), this can be an extremely long test
Q-factor method for measuring BER

- The logic levels of ‘0’ and ‘1’ are measured and histograms constructed
  - From the histograms, the mean and std. deviations are computed

\[
Q = \frac{\mu_1 - \mu_2}{\sigma_1 + \sigma_2} \quad \Rightarrow \quad BER = \left[ \frac{1}{Q \sqrt{2\pi}} \right] e^{\left( -\frac{q^2}{2} \right)}
\]

- Pros: faster, requires much lesser bits
- Cons: cannot use a digital tester, requires measurement of analog level of signal
Architecture of a RF tester

Structure of a RF Tester

- User computer
- Tester computer
- Source memory
- AWG channels with *Force* and *Sense*
- Digital channels
- Digital power supply module
- RF channels
- Clock and synchronization
- Timing unit
- DIB
- Relay matrix
- Capture memory
- RF measurement unit
- Digitizers
- DC meter
- Time measurement unit
- DUT

Structure of a RF Tester
Probers

- Probers are used to manipulate wafer as the individual dies are tested by an ATE
  - Needlelike positioning probes are used to make contact to the devices pads for signal transfer to the DUT
  - Connected to the ATE through a Probe Interface Board (PIB)
Automatic test equipment (ATE)

- Major components of a Tester
  - Workstation
    - Interface for day to day operation of tester
    - Debug usage for engineers
  - Mainframe controller and DMA
    - Power supplies
    - Measurement instruments
    - Tester computer
  - Test head
    - Interface between Device Interface Board (DIB) to Device Under Test (DUT)
    - Usually contains sensitive measurement electronics such as RF signal sources
      - Benefit from short electrical path between the source and the DUT
**General-purpose voltage/current sources**

- Commonly referred to as *V/I sources* or *DC sources*.
- Programmable sources used to power up the DUT and stimulate its DC inputs.
- Can either force voltage or current.
- Kelvin connection

![Diagram of DAC and DC Source](image)

*Desired voltage* → *High force* → *Sense* → *Gnd* → *R_{LOAD}*

*Interconnect cabling, DIB, and DUT*
The closed feedback loop allows the instrument to force an accurate voltage on DUT \( R_{LOAD} \).

- Without the Kelvin connection, the small resistance in the force line \( R_{TRACE-H} \) and \( R_{TRACE-L} \) would cause a small IR voltage drop.

- The sense lines of a Kelvin connection are buffers and conduct no current. Hence, they are immune to errors caused by IR voltage drops.

- Ground sense lines are lumped into a single ground sense signal called DZ (device zero) or DGS (device ground sense) – this is the “golden zero reference”
**Precision voltage reference & calibration**

- **Precision voltage references**
  - High accuracy, low noise DC voltage references
  - Used to ensure the accuracy of the general purpose DC source
  - One such usage is in high resolution ADCs or DACs
    - DC error on the DC reference translates directly into gain error and increased noise

- **Calibration source**
  - The purpose of the calibration source is to provide standards conforming to NIST
  - The calibration source are recalibrated on a periodic basis
AC continuous wave source

- Simplest way to apply and measure AC waveforms
  - Continuous wave source (CWS)
  - RMS voltmeter

- Problem with simple voltmeters
  - Only measure a single frequency at a time
  - Voltmeter cannot distinguish between signal and distortion or noise

- Solution
  - Use Digital Signal Processing (DSP) based testing
  - It requires
    - Arbitrary Waveform Generator
    - Waveform Digitizer
Arbitrary waveform generator (AWG)

- Converts digital samples from tester source memory into continuous time waveforms
  - Consists of a bank of high-speed source memory
  - DAC which converts data into analog voltage levels
  - Programmable low pass filter to smoothen the waveform
  - PGA for output amplitude scaling
  - Differential outputs and/or DC offset cancellation circuits
Waveform digitizers

- Converts continuous time input waveforms into digitized samples
  - It consists of a programmable low pass filter (anti-aliasing)
  - Programmable gain stage
  - Differential to single ended conversion stage for measuring differential outputs from the DUT
  - Capture memory

Diagram:
- Noisy DUT signal
- Amplified DUT signal
- Filtered DUT signal
- Sampled DUT signal
- Waveform capture memory
- PGA
- Low-pass filter
- Range control
- ADC

Differential to Single-ended Instrumentation amplifier
Clocking and time measurement unit

- All sampling frequencies in the tester are set by a central frequency reference. Loss of synchronization would result in degradation of accuracy and repeatability.

- Time measurements:
  - Frequency, period, duty cycle, rise and fall time, jitter, skew and propagation delay
  - Accuracy – up to a few $ns$
    - Advanced testers can measure to a resolution of less than 1 $ps$

- Time Measurement Interconnects
  - The input and interconnect paths affect the shape of the waveform
    - It is impossible to accurately measure the rise time of 1 $ns$ if the shape of the waveform has been distorted by a non-50Ω interconnect
    - Equally futile to measure 100 $ps$ rising edge if the bandwidth of the TMU input is only 300 MHz
DC measurements – continuity

- Continuity testing
  - Ensures a reliable DUT & ATE interconnection
  - Forcing a voltage (typically, 1.3V or -1.3V) at the DUT pin and turning on the protection diodes
  - Measure diode drop

- Two types of continuity tests:
  - Serial continuity testing: tested one pin at a time.
  - Parallel continuity testing.
Leakage current testing

- A good design and a reliable fabrication of the DUT should result in very low leakage currents (typically, $\leq 10\mu$A).
  - Leakage currents can cause DC offsets, parametric shifts, or early failure (infant mortality).
- Force a small DC voltage on the DUT pins & measure the current flowing into or out of the pins.
  - For digital input pins: Apply positive (negative) power supply voltage $\rightarrow$ measure $I_{IH}$ ($I_{IL}$).
  - For analog input pins: Test at specific voltage level, usually 0.3V
  - For output pins: Set the device into a high-impedance state & measure in a manner similar to input pins.
Power supply current testing

- Purpose of supply current tests
  - To detect catastrophic defects
    - A low impedance path from one of the power supplies to ground.
  - To guarantee desired power consumption, specially for RF devices

- Set the power supply to the desired voltage & measure the current consumed by the DUT
  - Analog and digital supplies should be measured separately ($I_{qq}$ or $I_{dd}$)
  - Allow enough settling time
    - The supply current flowing into a DUT must settle to a stable value before it can be measured.
    - Any supply bypass capacitors must be charged before starting measurement
    - Same goes for the DUT output load capacitors
Accuracy and precision

- **Accuracy**
  - The difference between the average response measurements and the expected standard value
  - Usually expressed as %

- **Precision**
  - The variation in a measurement system obtained by repeating the measurement on the same setup under the same conditions.
  - Also known as “repeatability”.
**Systematic and Random Errors**

- **Systematic Error** are fixed errors that appear consistently from one measurement to next
  - Caused by measurement system offsets, caused by gain error and nonlinearity
  - Systematic errors can be reduced through **calibrations**

- **Random Errors**
  - Usually caused by a variety of sources of errors
    - Thermal noise, power supply noise, ADC resolution
  - Can be improved by a clean measurement environment
  - **Averaging** and **filtering** can significantly reduce effects of random errors
Quantization error

- Analog signals, when digitized, must be converted to specific digital levels usually, using analog-to-digital converters (ADCs)
  - This loss of information is called quantization error

- If a meter has N bits resolution, that means it can resolve a voltage to one part in $2^N - 1$
  - An ADC with 12 bits, full scale range = ± 2V → resolution ≈ 1mV
  - The ADC cannot resolve variations in $V_{in} < 1$ mV
  - This is not indicator of accuracy in step size
  - An instrument’s resolution can far exceed its accuracy.
Repeatability and Stability

- Repeatability
  - Caused by random noise or other external influences
  - If a test engineer gets the same value multiple times in a row, it should raise the question of incorrect test setup
    - Ex: Full scale range of an instrument has been set to low, resulting in a measurement clipped to max level

- Stability
  - The degree to which a series of identical measurements remains constant over time, temperature, humidity, and all other time varying factors is referred to as stability
  - Testers are equipped with temperature sensors to allow recalibration if a certain change in temperature occurs
Correlation and reproducibility

- **Correlation**
  - It is the ability to get the same measurement value using different test setups
  - Need debugging/calibration to achieve high correlation before production

- **Reproducibility**
  - Reproducibility is often incorrectly used interchangeably with repeatability.
    - **Repeatability**: the ability of a single test setup to get the same measurement multiple times as the test is repeatedly executed
    - **Reproducibility**: the statistical deviations between a particular measurement taken by any operator on any group of test setups (similar to correlation)
Calibration and Checkers

- **Traceability to standards**
  - Every tester and bench instrument must ultimately correlate to standards maintained by a central authority
    - e.g. National Institute of Standards and Technology (NIST), USA
  - Many testers have an internal reference, which is a thermally stabilized instrument in the tester mainframe

- **Hardware calibration**
  - A process of tweaking a physical parameter
  - Generally, it is not a convenient process since it requires
    - Manual adjustments, or
    - Elaborate robotic manipulations

- **Software calibration**
  - Change internal gains and offsets using a reference test setup
Accuracy

Sources of error:
- Systematic (offset, bias, etc.)
- Random (thermal noise, power supply noise)
- Resolution of DACs

Accuracy and Repeatability

Measurement issue (same result over consecutive measurement instances)

Outlier (discarded)

Mean of measured value

Expected value

Repeatability (random errors)

Accuracy (systematic variations)
Test Correlation and Reproducibility

Test Correlation:

- Variation in test results from different test setups (hardware and software)
- Determine test calibration needs for each setup
Concluding remarks

- RF test cost is on the rise
  - It is estimated that test cost can be up to 40% unless new techniques are developed
  - RF test is constantly gaining attention from industry and academia
  - RF testers are extremely expensive with limited functionalities compared to analog or digital testers
- In this light, innovative solutions are needed to overcome RF test challenges
Future trends

- Defect-based test of RF devices can provide a quick estimate in a production test environment
  - However, it does not provide any info about specifications
- Use of low-cost instrumentations/ATE to perform complex tests
  - Example, using a multi-tone signal to measure EVM (no transmitter needed)
- Use alternate measurements/BIST to facilitate test procedure
  - Can significantly reduce cost of testing + time required to test
  - Minimizes the requirements of the tester