WMC: Baseband Corrections for Precision Millimeter-Wave Signal Measurements

Kate A. Remley, Dylan Williams, Paul Hale, Jack Wang
National Institute of Standards and Technology (NIST)
Saeed Farsi, Dominique Schreurs
K.U. Leuven
Millimeter-Wave Wireless: Alignment of three critical factors

- Regulatory
  - Millimeter-wave spectrum recently allocated by FCC in the U.S. for commercial use

- Technology
  - Silicon devices now have adequate speed for integrated antennas, transmitters and receivers

- International need
  - Mobile broadband networks are hot
  - “Spectrum crunch”: a top telecommunications industry priority
What is the spectrum crunch?
What is the spectrum crunch?

Cisco Systems mobile forecast

- 3% of wireless smart-phone customers use 40% of total available wireless bandwidth
- 5000% growth in demand for wireless internet data in the last three years
- “The biggest threat to the future of mobile in America is the looming spectrum crisis.” (Julius Genachowski, Chair of the FCC)

Cellular Telecommunications Industry Association keynote talks, October 2009

* CAGR: Compound annual growth rate

Source: Cisco VNI Mobile, 2011
Technical enablers

• Attenuation not significant for paths under 1 km
  – Well-suited for cellular and mesh-networked architectures

• Transistor speed
  – Microwave industry ready to exploit its cutting edge high-speed technology

• Short wavelengths enable active, agile, integrated antennas
Technical challenge: Hardware verification

- Verifying sources and receivers of broadband digitally modulated signals at millimeter-wave frequencies
- Required measurement accuracy increases linearly with frequency
- Impedance, timing, nonlinearities: problematic at mm-wave

Lack of traceability for calibrations of commercial instruments inhibits knowledge of measurement accuracy
Wireless measurements:
hard at RF, harder at mm-wave

• Bandpass signals: Fast sampling for detail around carrier
• Multipath: Channel characterization, system equalization
• Effects of power amplifier: Nonlinear measurements
• Highly integrated systems: Free-field test
Errors in Sources and Receivers

- Need for accurate test of system response
- Characterized source needed to characterize system-measurement receiver
Vector Response of Sources and Receivers

- Characterized source
- Issue: many types of modulated signals
  - Modulation format: peak-to-average power ratio (PAPR) and bandwidth
  - Sources optimized for various formats, bandwidths
  - How to generalize the calibration?

Phase response of vector source: BW = 80 MHz
Calibration signals: Multisines

Multisines replicate various PAPRs, bandwidth, frequency spacing and sampling of digitally modulated signals.

**Top:** 9 frequency-offset sines

**Bottom:** vector addition of sines

**Detrending:** Phase alignment based on finding reference time

**Low PAPR Schroeder phases:**

\[ \phi_k = -k(k-1)\pi / F_k \]
Replicating waveform features

Four 65-tone multisines

- **input**
- **output**

QPSK signal with raised cosine filtering

Relative phase sets signal’s spectrum
Calibrating source and receiver

- Excite with multisines, measure imperfections
- Correct for imperfections before measuring system-under-test (with uncertainty)
- Reduce uncertainty with “best” measurement of source
Calibrated vector receiver: sampling oscilloscope

- Traceability: scope response
- Calibrated: time-base correction, mismatch correction
- Broadband: measure signal plus distortion
- Periodic signals: representative communication signals

* SINAD: Signal-to-interference-and-distortion ratio
Calibrating the oscilloscope

Calibrate a photodiode impulse source

Mode-locked laser → Photodetector → Electro-Optic Sampling (EOS) system (>1 THz BW)

Use calibrated source to correct oscilloscope

Mode-locked laser → Photodetector → Sampling oscilloscope
Vector sources are not ideal

Magnitude and phase distortion can affect error vector magnitude (EVM), bit error rate (BER), other metrics, especially for broadband signals.

Scope: 10 GHz Schroeder multisine with 1 GHz modulation bandwidth: Phase error up to 15 degrees
mm-wave sources are less so!

Verify source performance with calibrated sampling oscilloscope

Arbitrary waveform generator (AWG)  
Marker 1 clock in

Local oscillator

IF (5 GHz)

Mixer:
Input: 5 to 8.5 GHz  
LO: 10 GHz  
RF: 43 to 46.5 GHz

Amplifier

Modulated RF (45 GHz, 70+ GHz)

90 degree hybrid

0° 90°

Calibrated sampling scope

CH1 CH2 CH3 CH4

Trigger

Verify source performance with calibrated sampling oscilloscope.
Lab-based mm-wave source

- Mixer LO
- AWG clock
- Scope time-base correction

Calibrated vector receiver (oscilloscope)

Nonideal frequency conversion

Frequency converter and amplifier

Modulated RF (fc = 45 GHz)

Arbitrary waveform generator (IF = 5 GHz)

Baseband effects
Imperfect source response

Calibrated scope measurement characterizes source

Majority of error introduced at baseband frequency
Imperfect source response

How do baseband errors affect a measurement?

Baseband effects

EVM = 9.5 %

Baseband effects + nonideal frequency conversion

EVM = 11.9 %

16QAM signal with 1 GHz modulation bandwidth
Correct source output

- Predistort AWG-based source input signals
- Iterative predistortion: linear and nonlinear response

In-band magnitude and phase errors are reduced with predistortion
Quantization noise

- Nonlinearity of ADC
- Limits effective number of bits of AWG

Spurs

- Harmonics and mixing products caused by sampling
- Dithering improves AWG noise floor as much as 10 dB
Suppress in-band spurs

In-band spurs degrade generated baseband (IF) signal

Carrier offset moves spurs out of the passband of the signal, reduces in-band distortion and adjacent-channel power ratio
Good baseband signals give good mm-wave measurements.

1 GHz bandwidth BPSK signal at 45 GHz
Low-EVM 64 QAM waveform

EVM for 64 QAM

- Allows mm-wave vector receiver calibration, system characterization
- 45 GHz center frequency, 1.2 GHz modulation bandwidth, 512 symbols
Dithering to reduce ACPR

- Intentional addition of a special waveform to the input signal prior to the data conversion
  - Makes quantization noise less correlated to signal
  - Spreads quantization noise over frequency range
  - Reduces quantization noise

- Types:
  - Subtractive
  - Non-subtractive
Non-subtractive dithering

- Dithering signals are chosen so that by filtering, they can be efficiently removed after conversion.

- Ensemble dithering:
  - Record multiple periods of periodic waveform (multisine)
  - Add different dither to different ensemble member
  - Average over the whole ensemble to remove dither
Time-Domain Ensemble-Averaged Dithering

- Use self-subtractive dither
- Repeat the waveform with time-varying additive dither
Time-Domain Ensemble-Averaged Dithering

- The averaged waveform effectively lacks the dithering component
- This is a suitable technique for test and characterization with a high-resolution requirement
- The quantization noise is reduced in post-processing
Quantization noise reduced

11-tone multisine, $f_c = 4.5$ GHz, $BW = 160$ MHz

![Graph showing quantization noise reduced](image)
Improved dither signal

Use of larger dither signal to reduce non-idealities of signal generator in post processing
mm-wave ACPR improved

Baseband-frequency offset and dither improve mm-wave signal

Offset + Dithering
(ACPR 52 dB)
Looking forward

NIST EOS
On-wafer CPW
~1 THz BW
<< 1 ps FDHM

NIST Photodiode
1.0 mm connector
Calibrated to 110 GHz
100 GHz BW
~4 ps FDHM

PD

Impedance metrology,
mm-wave power

Meter, second, volt

Calibrated vector signal
sources

Calibrated vector signal
sources

Notches

NIST Oscilloscope
1.0 mm connector
Calibrated to 110 GHz

Large-signal
network analyzers

Vector
signal analyzers

Uncertainties established
Looking forward

Measurements for millimeter-wave wireless

- Baseband and frequency conversion:
  - mixing products, spurs
  - quantization noise
- Calibrated sources and receivers
  - Distortion characterization
  - Known EVM
  - Traceability
- Baseband effects can muddy the waters at millimeter-wave frequencies!