Software-based MIMO Channel Emulator

Fanny Mlinarsky
octoScope, Inc., Marlborough, MA, USA
fm@octoscope.com

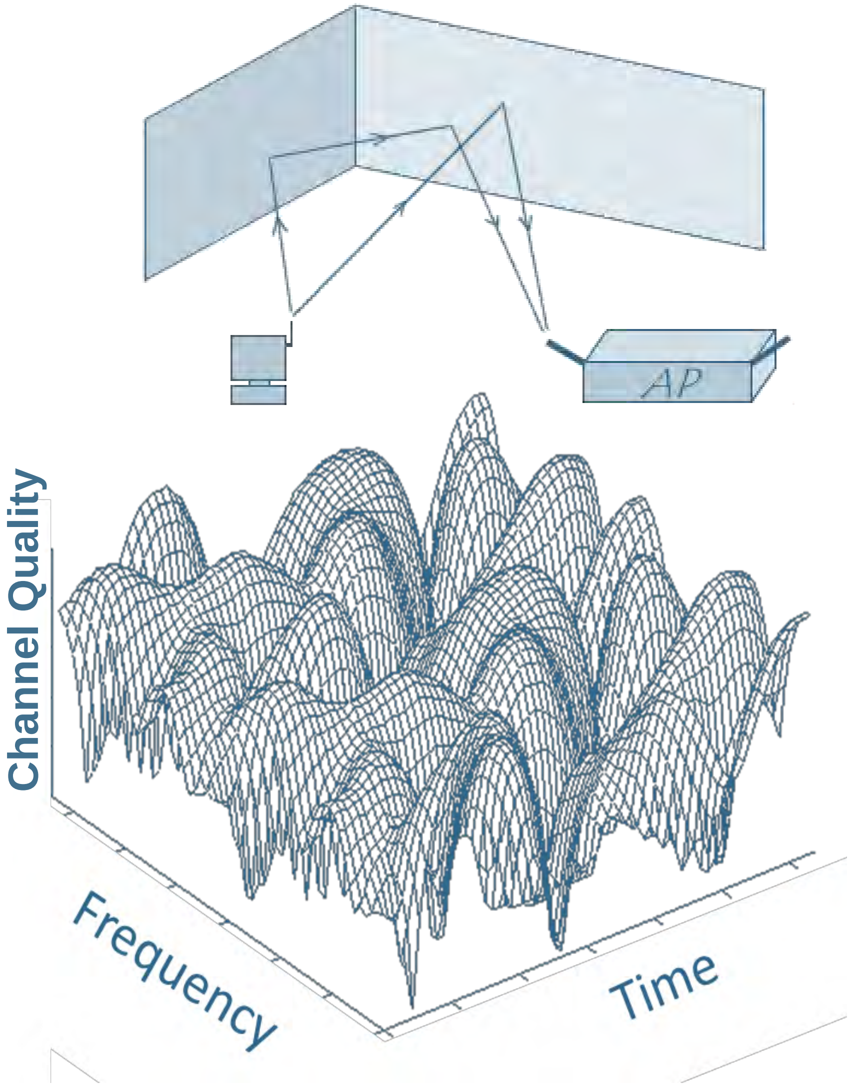
Samuel MacMullan, Ph.D.
ORB Analytics, Carlisle, MA, USA
sam.macmullan@orbanalytics.com

Outline

- What is channel emulation and why is it critical for MIMO systems?
- Channel modeling standards and technologies
- Channel model statistics
- Channel emulator implementation

Wireless Channel

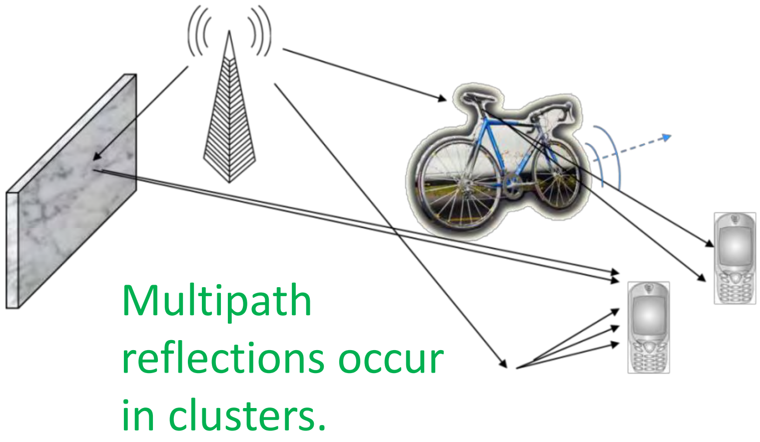
- Frequency and time variable wireless channel
- Multipath creates a sum of multiple versions of the TX signal at the RX
- Mobility of reflectors and wireless devices causes Doppler-based fading
- Multiple antenna techniques are used to optimize transmission in the presence of multipath and Doppler fading

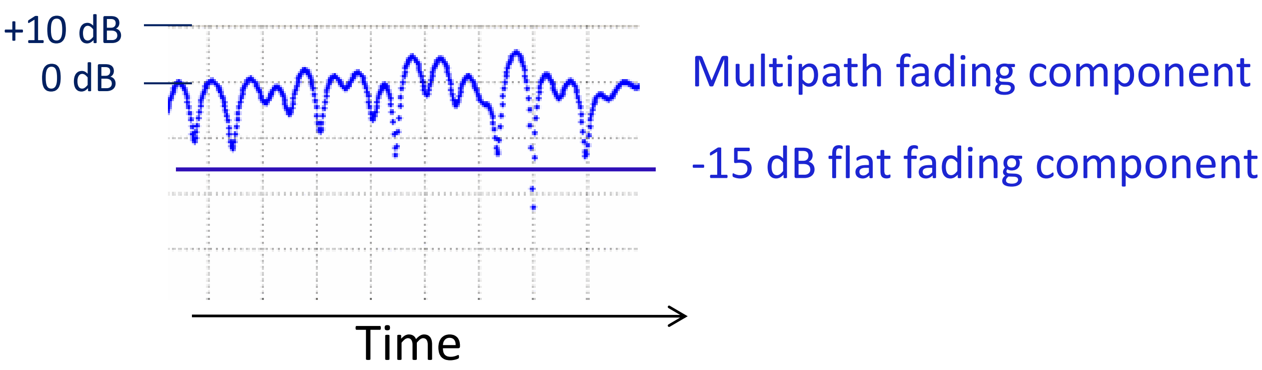


MIMO=multiple input multiple output

Multipath and Flat Fading

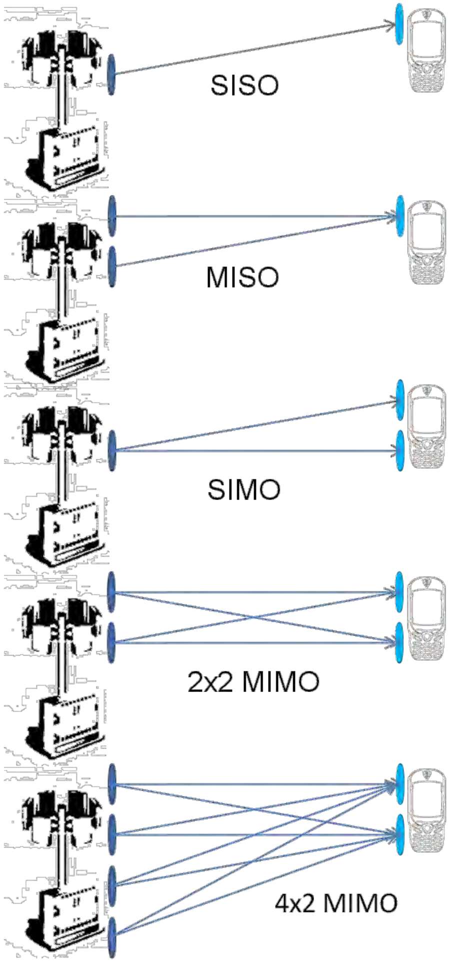
- In a wireless channel the signal propagating from TX to RX experiences
  - Flat fading
  - Multipath/Doppler fading





Multiple Antenna Techniques

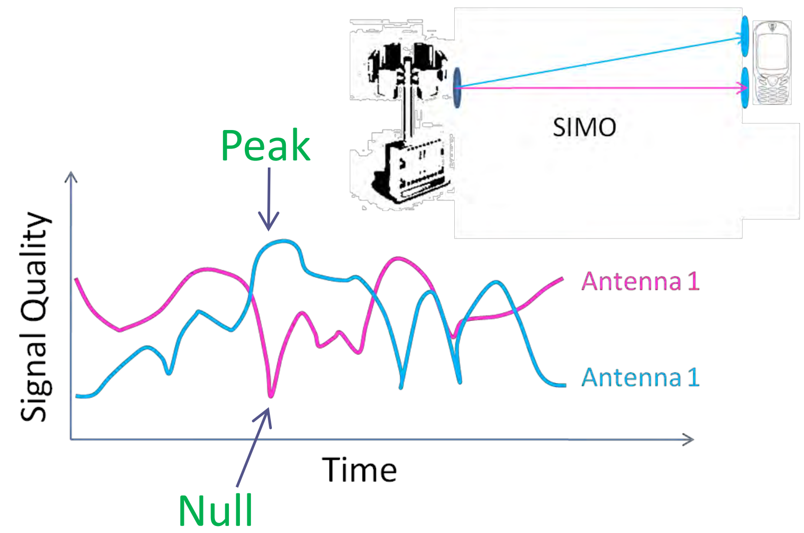
- SISO (Single Input Single Output)
  - Traditional radio
- MISO (Multiple Input Single Output)
  - Transmit diversity (STBC, SFBC, CDD)
- SIMO (Single Input Multiple Output)
  - Receive diversity, MRC
- MIMO (Multiple Input Multiple Output)
  - SM to transmit multiple streams simultaneously; can be used in conjunction with CDD; works best in high SNR environments and channels de-correlated by multipath
  - TX and RX diversity, used independently or together; used to enhance throughput in the presence of adverse channel conditions
- Beamforming



SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio

MIMO Based RX and TX Diversity

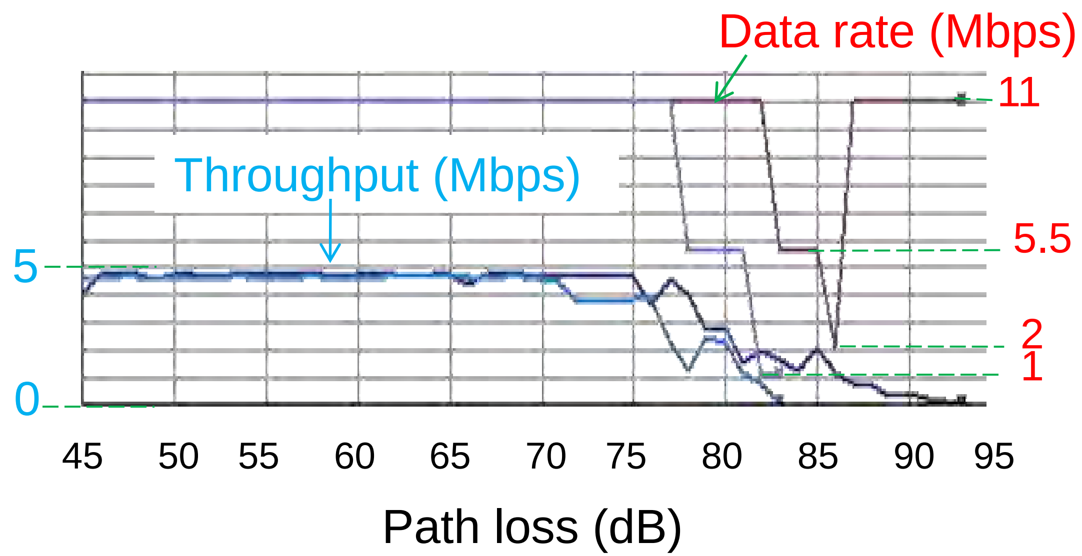
- When 2 receivers are available in a MIMO radio MRC can be used to combine signals from two or more antennas, improving SNR
- MIMO also enables transmit diversity techniques, including CDD, STBC, SFBC
- TX diversity spreads the signal creating artificial multipath to decorrelate signals from different transmitters so as to optimize signal reception



MIMO = multiple input multiple output
SIMO = single input multiple outputs
SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio

802.11 Modulation

- 11b (DSSS-CCK) – 1, 2, 5.5, 11 Mbps in 2.4 GHz band
- 11a (OFDM) – 6, 9, 12, 18, 24, 36, 48, 54 Mbps in 5 GHz band
- 11g – both 11b and 11a rates in 2.4 GHz band
- 802.11n – 6 to 600 Mbps in 2.4 and 5 GHz bands
    - MIMO introduces concept of Modulation and Coding Scheme (MCS)
    - Each MCS is determined by modulation, coding rate, # spatial streams, # FEC encoders



Data rate and MCS are automatically selected by the radio based on channel conditions. Above plot shows automatic adaptation of data rate as path loss increases.

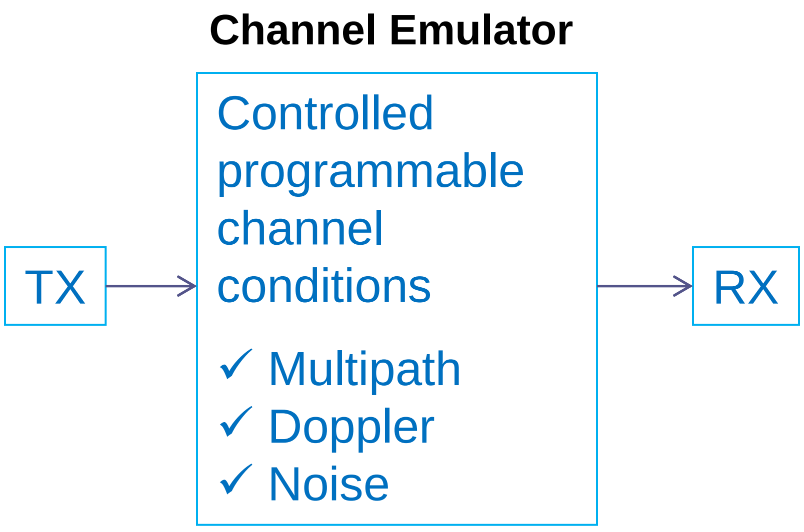
MIMO = multiple input multiple output
MCS = modulation coding scheme

IEEE 802.11a,b,g,n Data Rates

	20 MHz Channel				40 MHz Channel			
	1 stream	2 streams	3 streams	4 streams	1 stream	2 streams	3 streams	4 streams
	Data Rate, in Mbps							
802.11b 2.4 GHz	1, 2, 5.5, 11							
802.11a 5 GHz	6, 9, 12, 18, 24, 36, 48, 54							
802.11g 2.4 GHz	1, 2, 6, 9, 12, 18, 24, 36, 48, 54							
802.11n 2.4 and 5 GHz	6.5, 13, 19.5, 26, 39, 52, 58.5, 65	13, 26, 39, 52, 78, 104, 117, 130	19.5, 39, 58.5, 78, 117, 156, 175.5, 195	26, 52, 78, 104, 156, 208, 234, 260	13.5, 27, 40.5, 54, 81, 108, 121.5, 135	27, 54, 81, 108, 162, 216, 243, 270	40.5, 81, 121.5, 162, 243, 324, 364.5, 405	54, 108, 162, 216, 324, 432, 486, 540
802.11n, SGI enabled 2.4 and 5 GHz	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	14.4, 28.9, 43.3, 57.8, 86.7, 115.6, 130, 144.4	21.7, 43.3, 65, 86.7, 130, 173.3, 195, 216.7	28.9, 57.8, 86.7, 115.6, 173.3, 231.1, 260, 288.9	15, 30, 45, 60, 90, 120, 135, 150	30, 60, 90, 120, 180, 240, 270, 300	45, 90, 135, 180, 270, 360, 405, 450	60, 120, 180, 240, 360, 480, 540, **600**

Validating Radio DSP

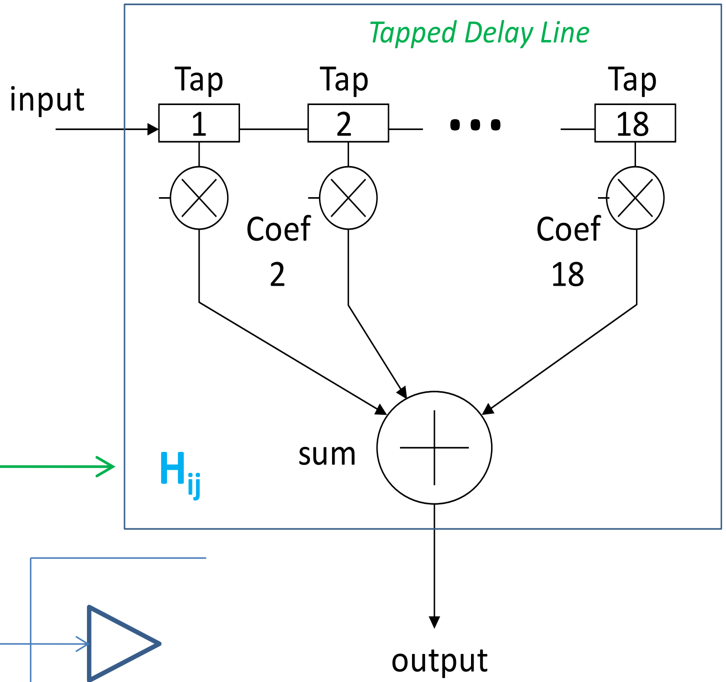
- A variety of channel conditions and complex multiple-antenna algorithms for adapting to these conditions make a channel emulator necessary for developing and testing radio DSP

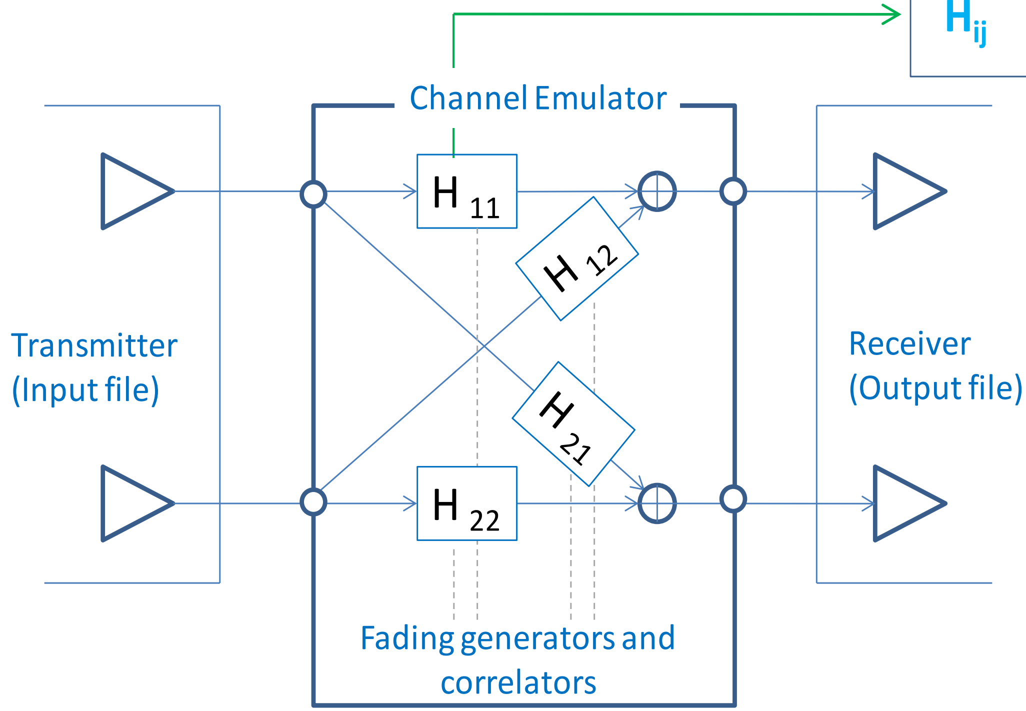


Channel Modeling

A SISO channel is modeled by a TDL

A MIMO channel is modeled by multiple TDLs with spatially correlated coefficients, each representing a MIMO path

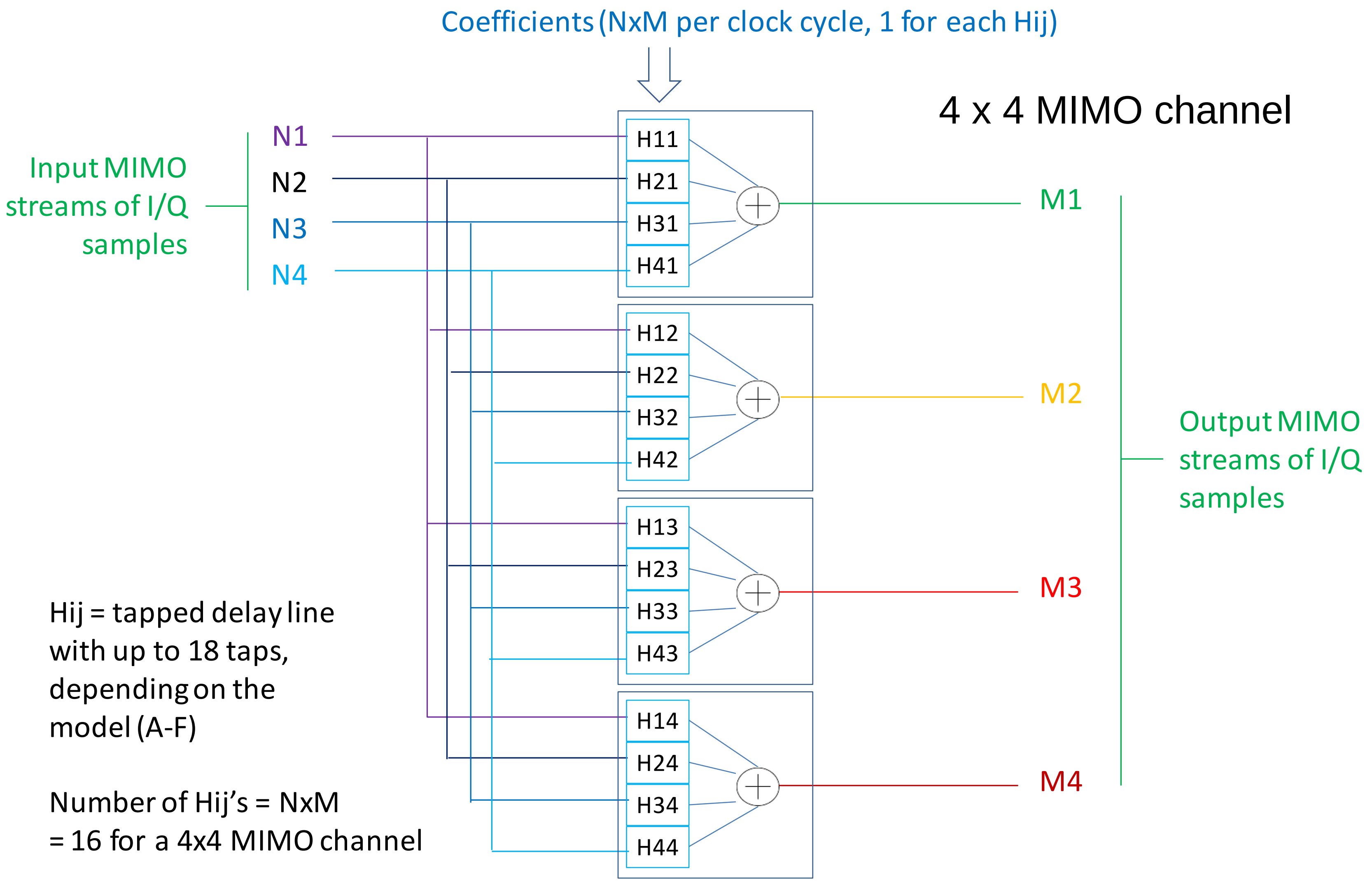




2 x 2 MIMO channel

TDL = tapped delay line

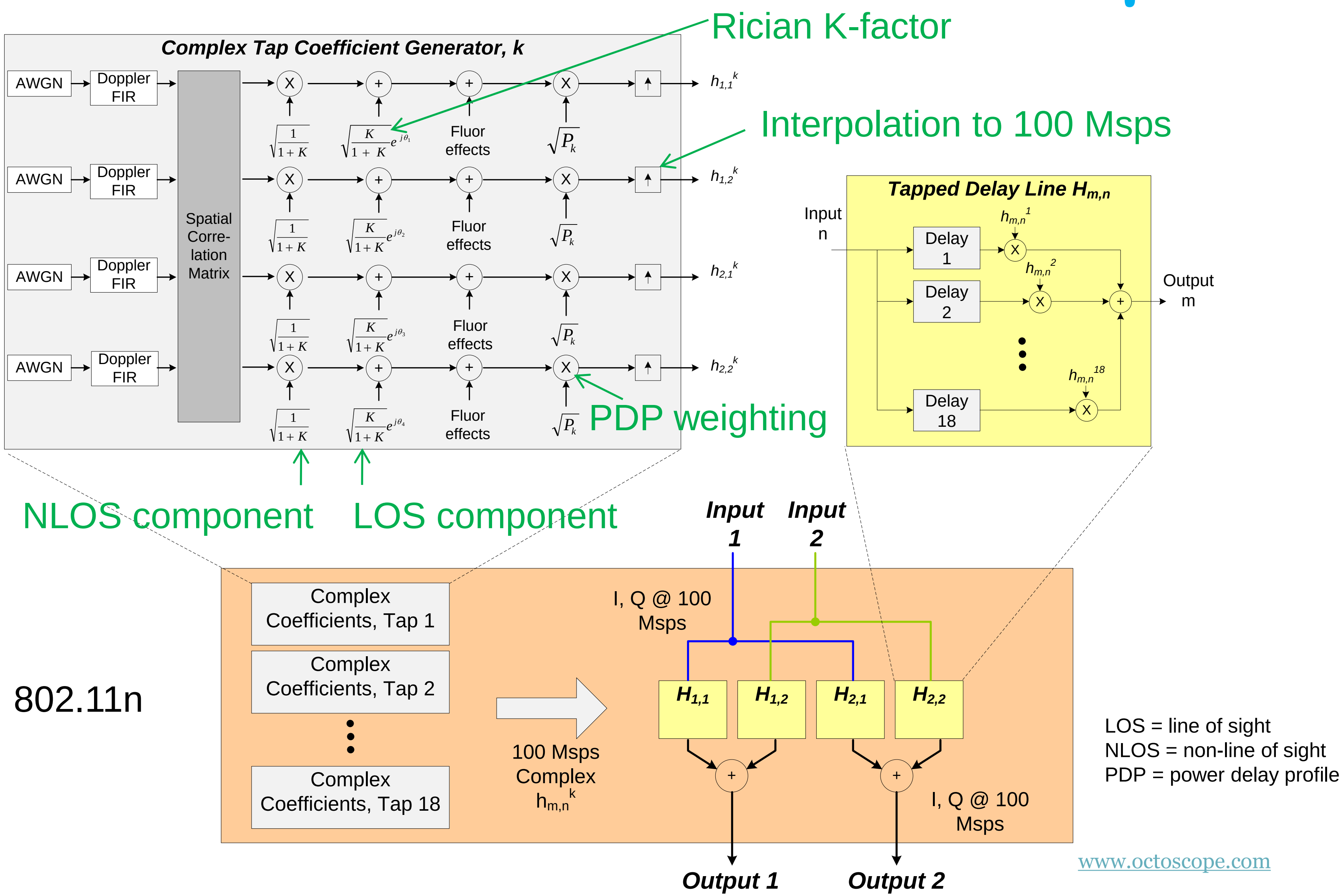
Data Flow Through Emulator



Hij = tapped delay line with up to 18 taps, depending on the model (A-F)

Number of Hij's = NxM
= 16 for a 4x4 MIMO channel

2 x 2 Channel Emulator Example



802.11n

LOS = line of sight
NLOS = non-line of sight
PDP = power delay profile

Outline

- What is channel emulation and why is it critical for MIMO systems?
- Channel modeling standards and technologies
- Channel model statistics
- Channel emulator implementation

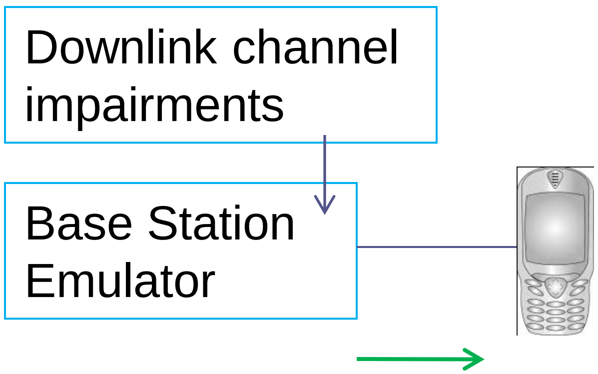
802.11n Chanel Models A through F

Model		Distance to 1st wall (avg)	# taps	Delay spread (rms)	Max delay	# clusters
A*	test model		1	0 ns	0 ns	
B	Residential	5 m	9	15 ns	80 ns	2
C	small office	5 m	14	30 ns	200 ns	2
D	typical office	10 m	18	50 ns	390 ns	3
E	large office	20 m	18	100 ns	730 ns	4
F	large space (indoor or outdoor)	30 m	18	150 ns	1050 ns	6

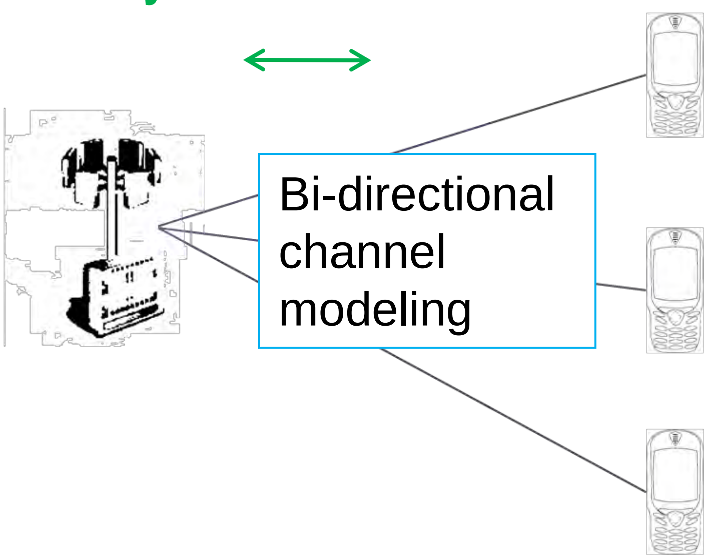
* Model A is a flat fading model; no delay spread and no multipath

Test Scenarios

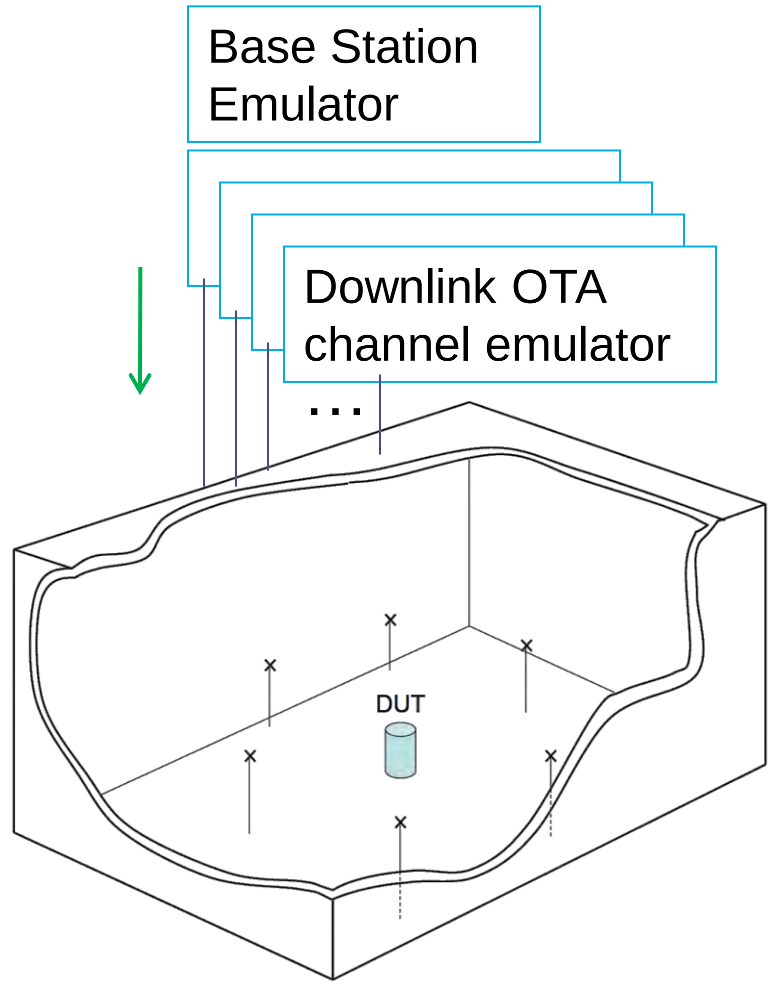
Certification



2-way test with 2 or more DUTs



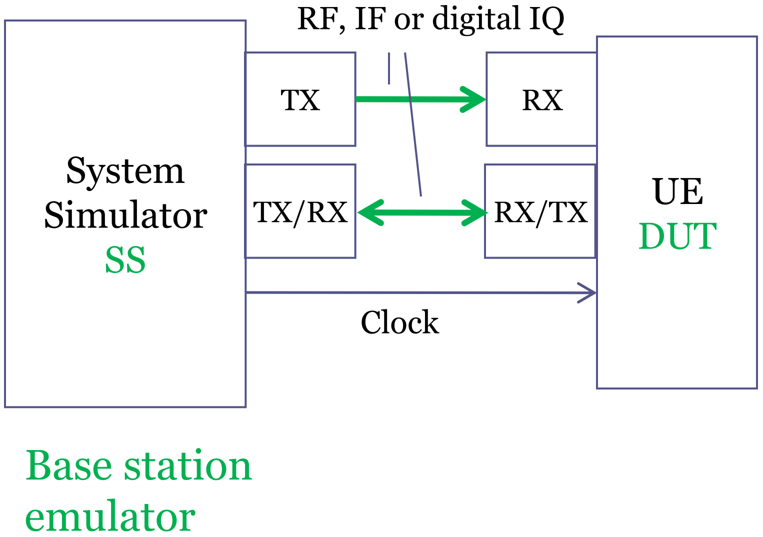
MIMO OTA (over the air) test

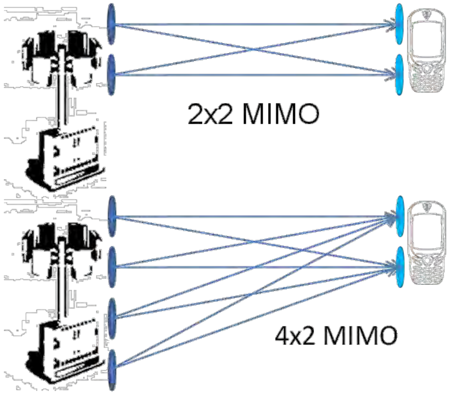


OTA = over the air
DUT = device under test

LTE Test Configuration Example

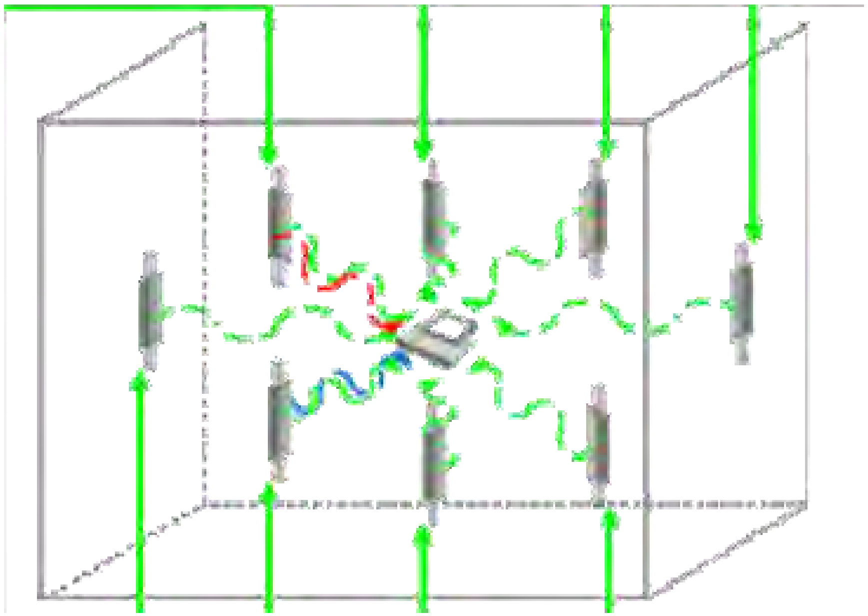
- Primary antenna for transmit and receive functions
- Secondary antenna for MIMO and receive diversity functions
- Downlink 2x2 and 4x2 transmit diversity
- Downlink 2x2 and 4x2 spatial multiplexing



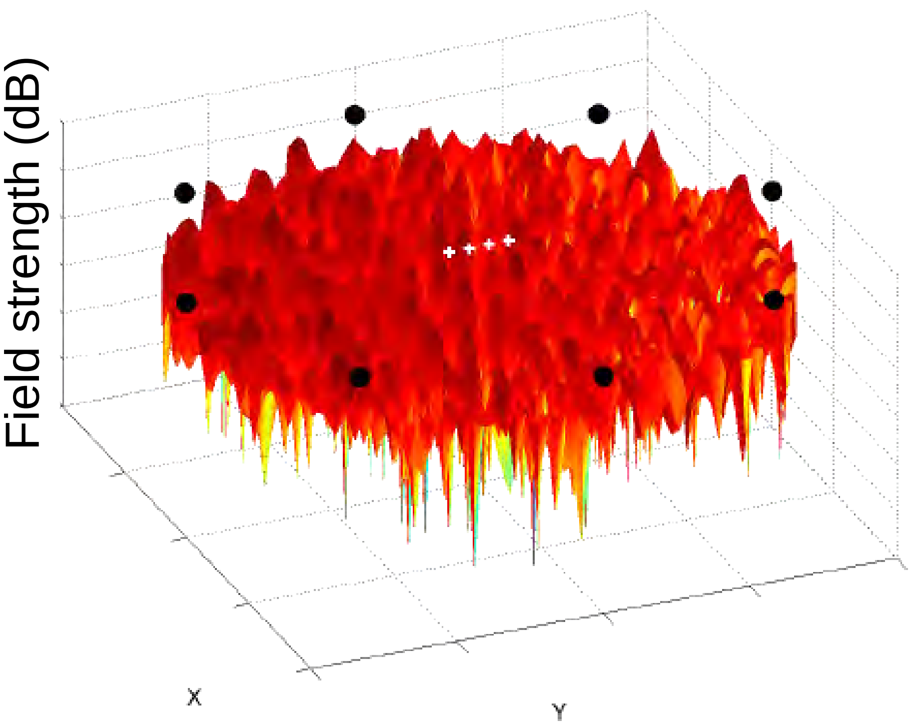


UE = user equipment

Geometry Based Stochastic Models



Source: 3GPP R4-103856



Work being done by

- 3GPP – RAN 4
- COST 2100 - Sub Working Group 2.2
- CTIA

Outdoor Channel Models from 3GPP/3GPP2

Source: 3GPP TR 25.996 V9.0.0 (2009-12)

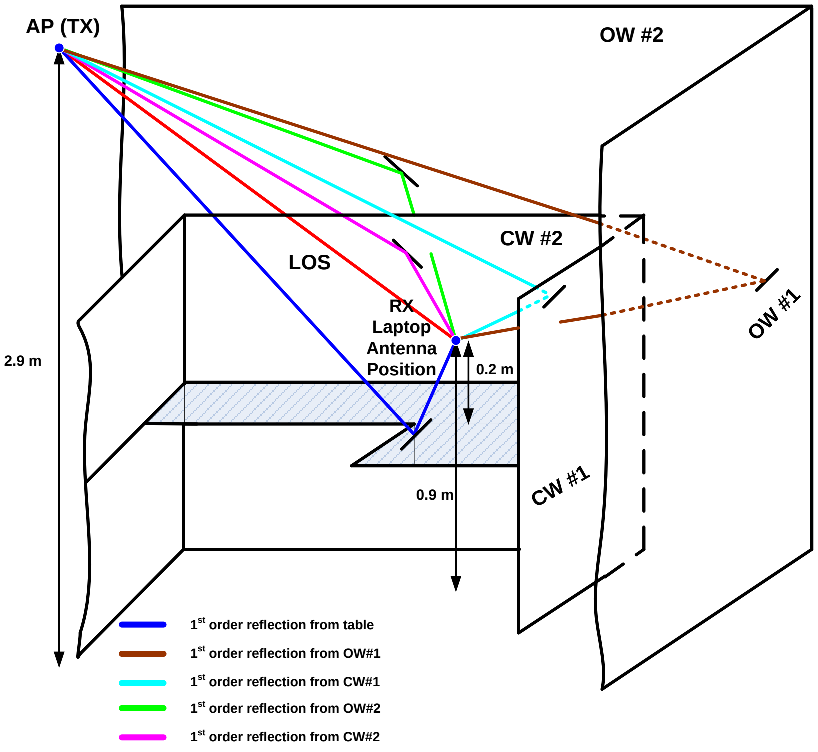
Model	Case I	Case II	Case III	Case IV
Corresponding 3GPP Designator*	Case B	Case C	Case D	Case A
Corresponding 3GPP2 Designator*	Model A, D, E	Model C	Model B	Model F
PDP	Modified Pedestrian A	Vehicular A	Pedestrian B	Single Path
# of Paths	1) 4+1 (LOS on, K = 6dB) 2) 4 (LOS off)	6	6	1

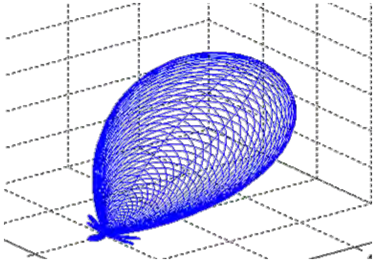
⋮

- Spatial Channel Models (SCM)
- Fewer taps (paths), but faster Doppler speeds to model high speed trains and other transport

60 GHz IEEE 802.11ad Channel Models

- Living room, conference room, office cubicles
- 60 GHz channel models incorporate
  - Path loss
  - Human-induced shadowing
  - LOS and NLOS environments
  - Clustering, Beamforming, Polarization



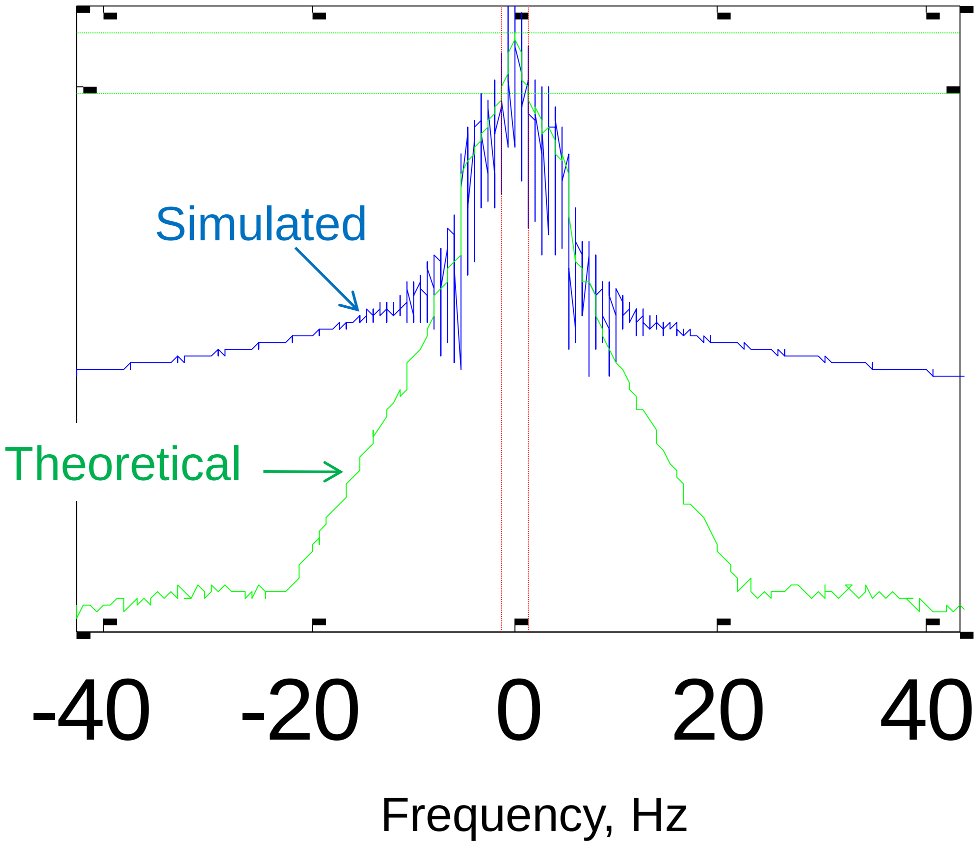


Source: IEEE 11-09-0334-08-00ad-channel-models-for-60-ghz-wlan-systems

Outline

- What is channel emulation and why is it critical for MIMO systems?
- Channel modeling standards and technologies
- Channel model statistics
- Channel emulator implementation

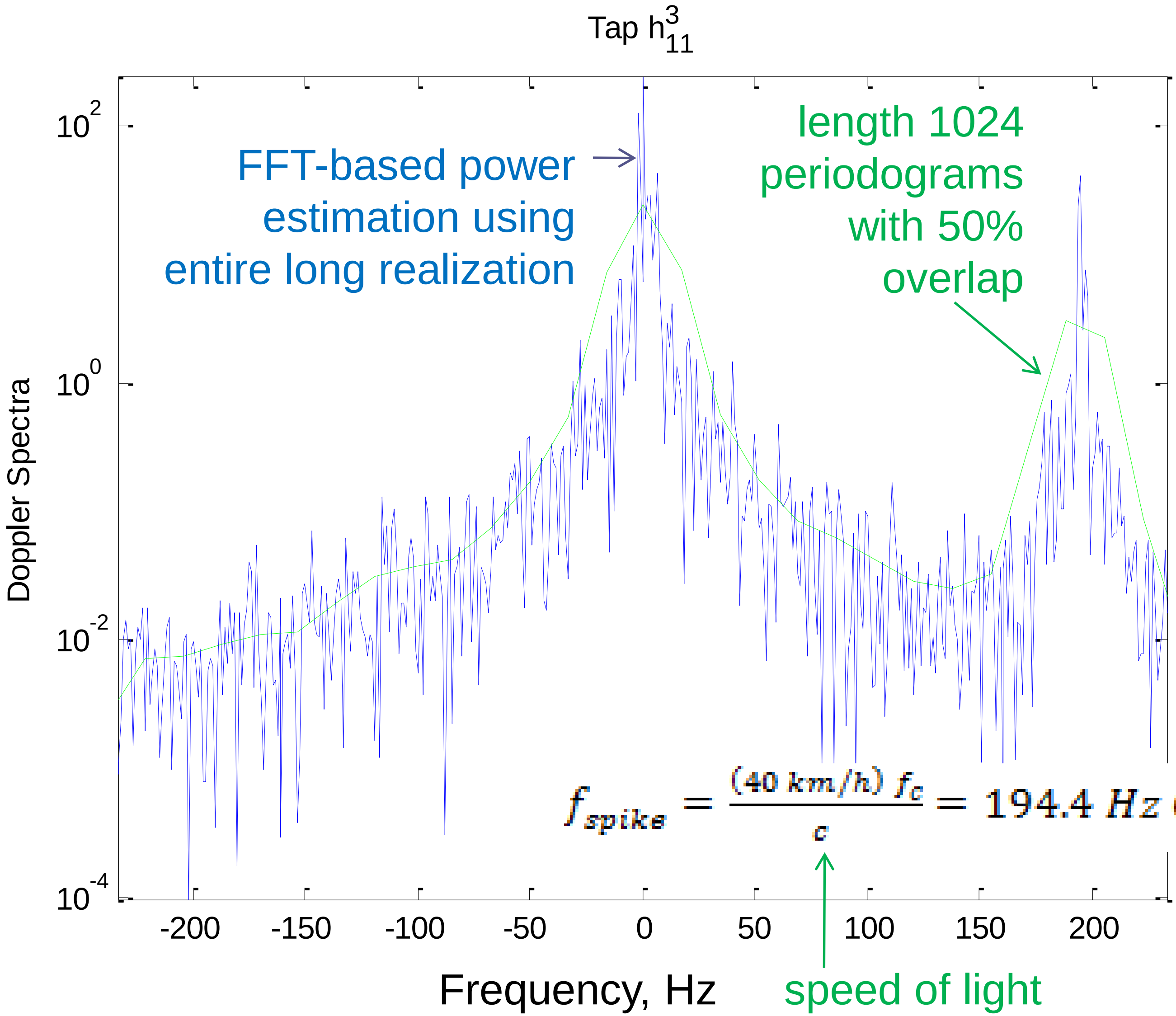
Doppler Spectrum – Model F



The Doppler spread is 3 Hz at 2.4 and 6 Hz at 5.25 GHz for environment speed of 1.2 km/h

- Example of Doppler spectrrum plots for IEEE 802.11n model F
  - Environment velocity is 1.2 km/hr and is modeled on all taps for all models
  - Tap 3 for model F includes automotive velocity spike at 40 km/hr

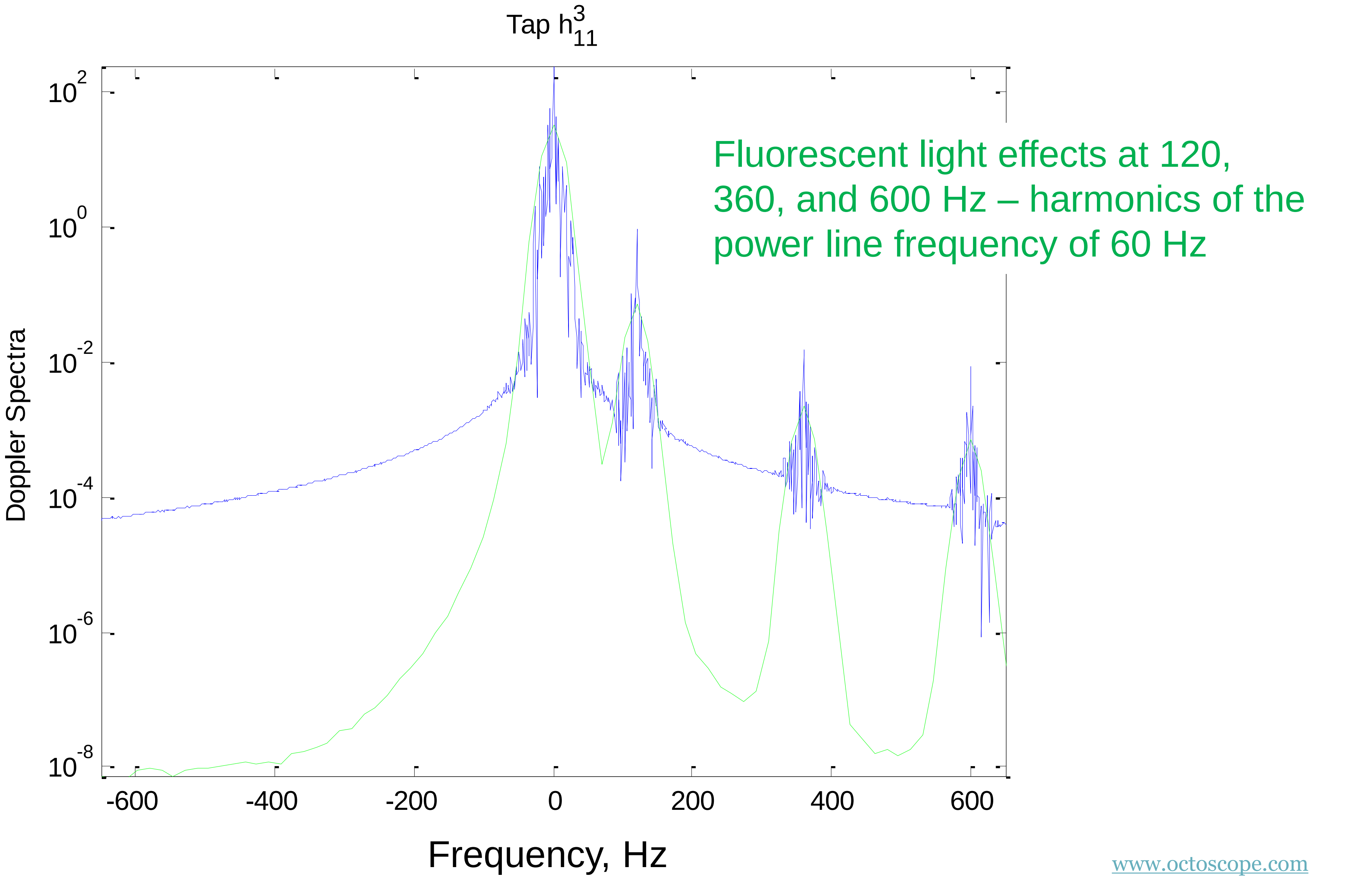
Doppler Spectrum – Model F, Tap 3



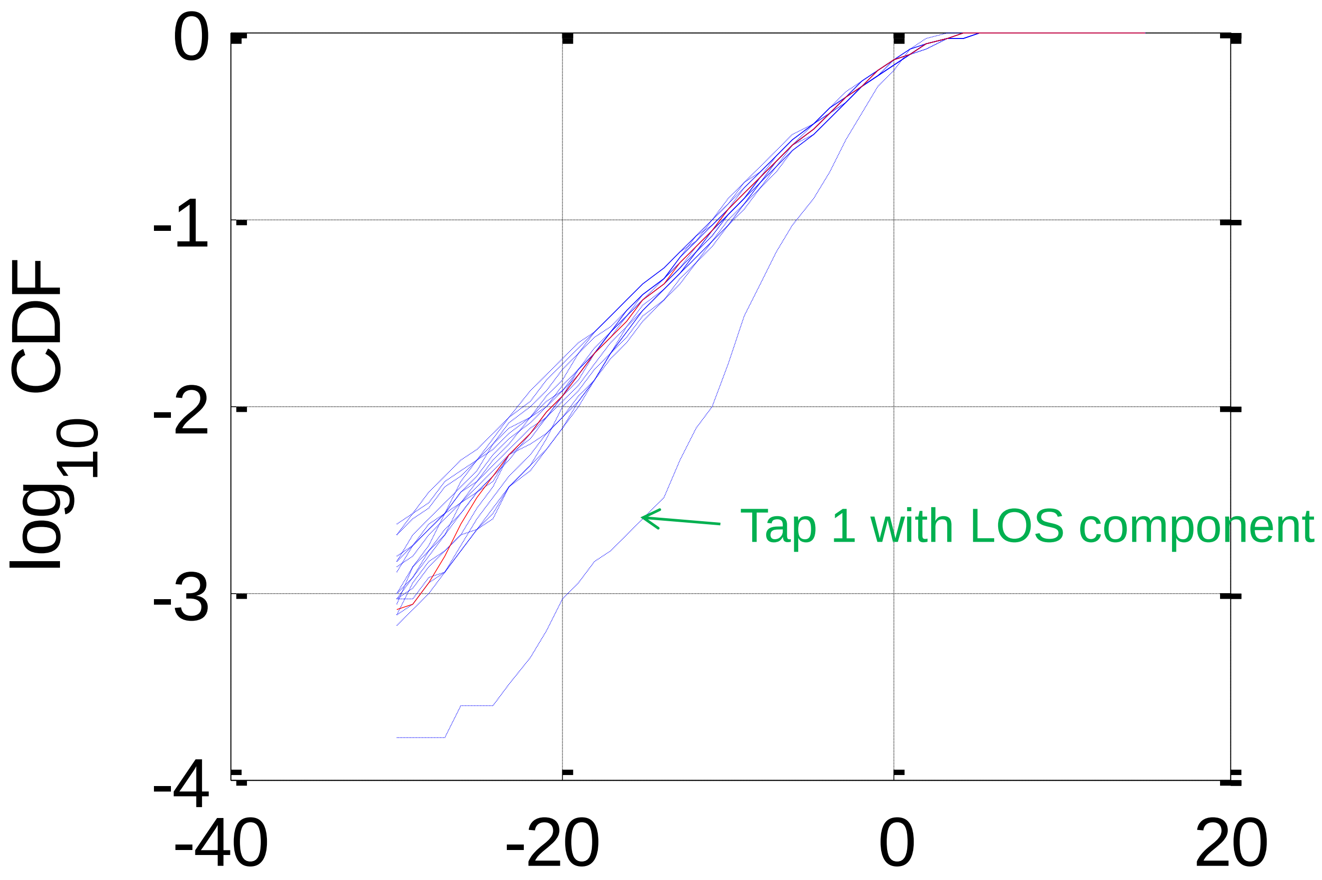
$$f_{spike} = \frac{(40\ km/h)\ f_c}{c} = 194.4\ Hz\ @\ f_c = 5.25\ GHz$$

speed of light

Doppler Spectrum – Model E, Tap 3

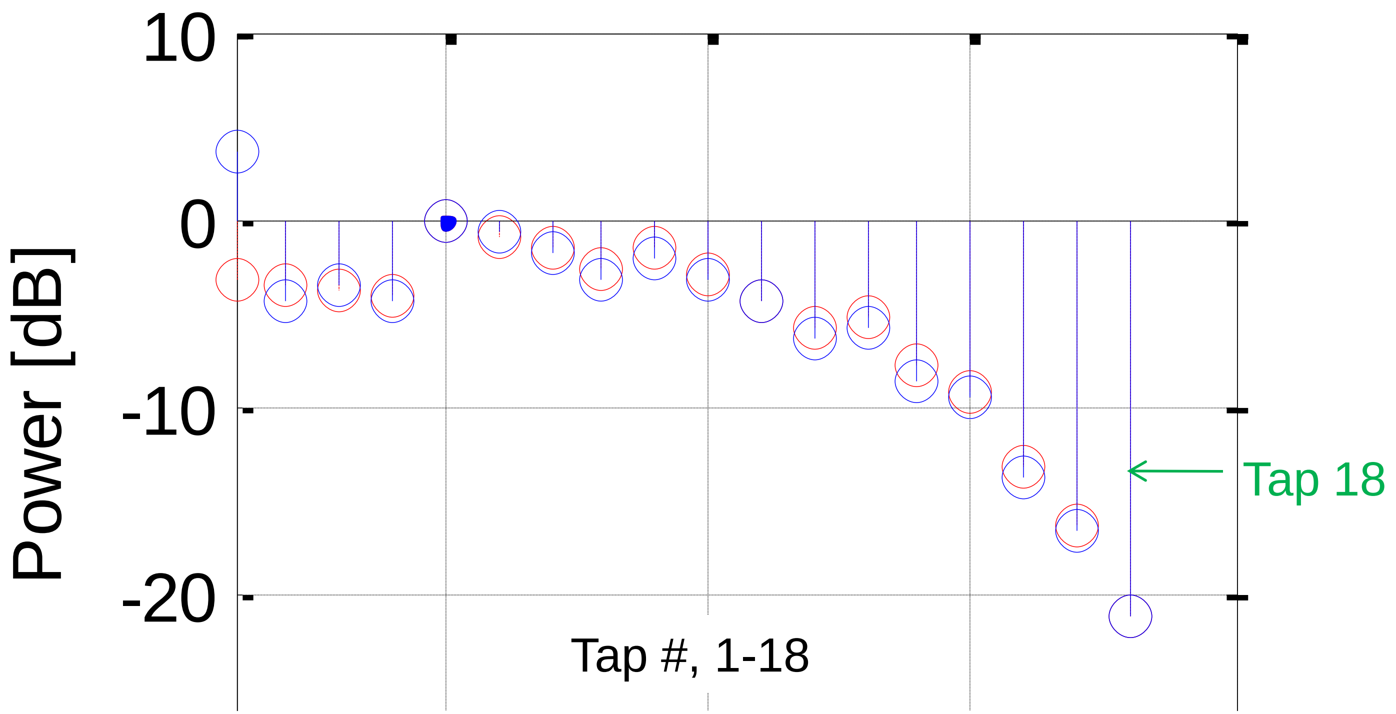


Cumulative Distribution Function (CDF)



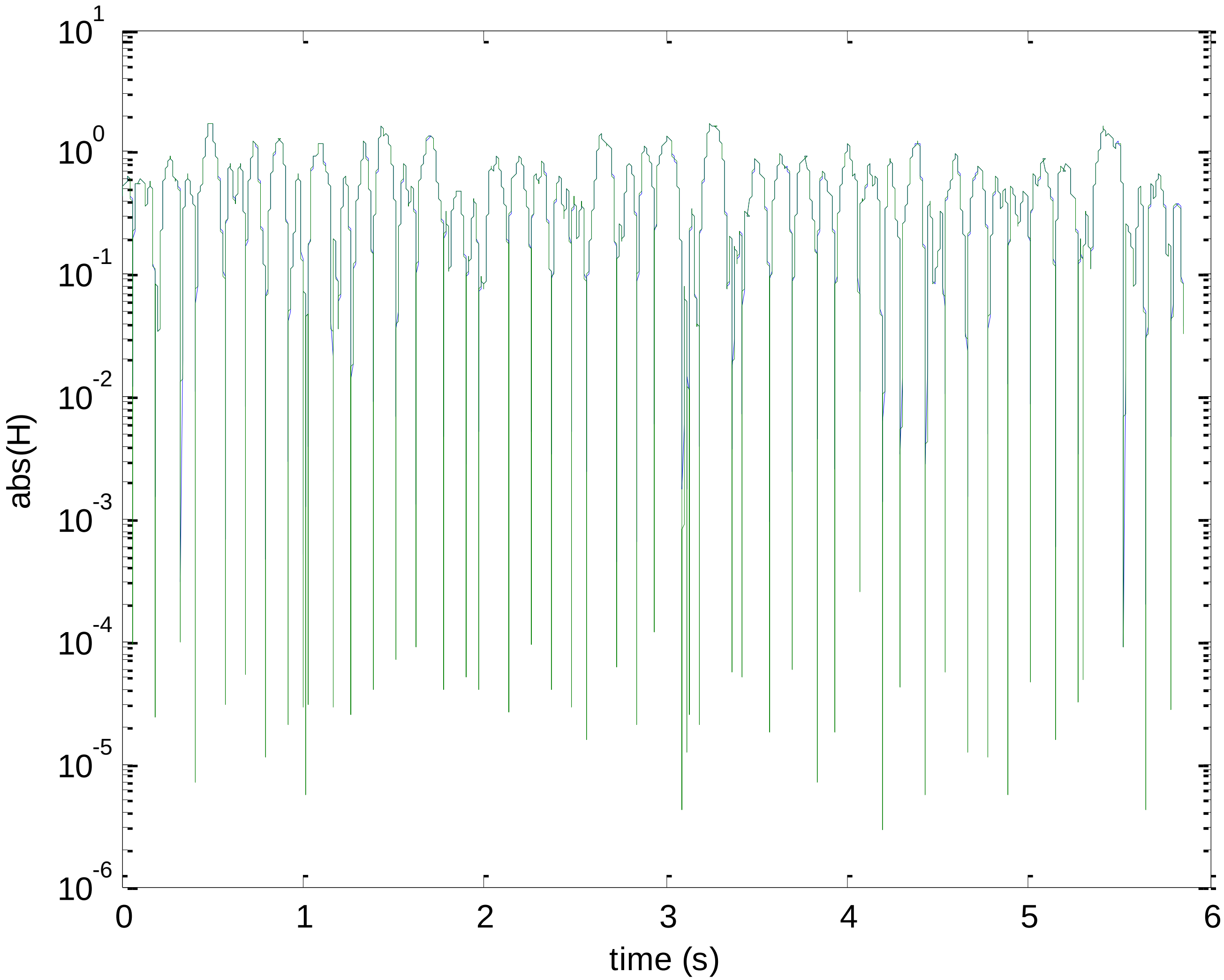
- IEEE 802.11n, Model F, CDF for 18 taps

Power Delay Profile (PDP) – Model F



- Power decreases with increasing tap delay.
- Red points are for the normalized PDP under NLOS conditions. Blue points are simulated normalized PDP under LOS conditions.

Channel Impulse Response

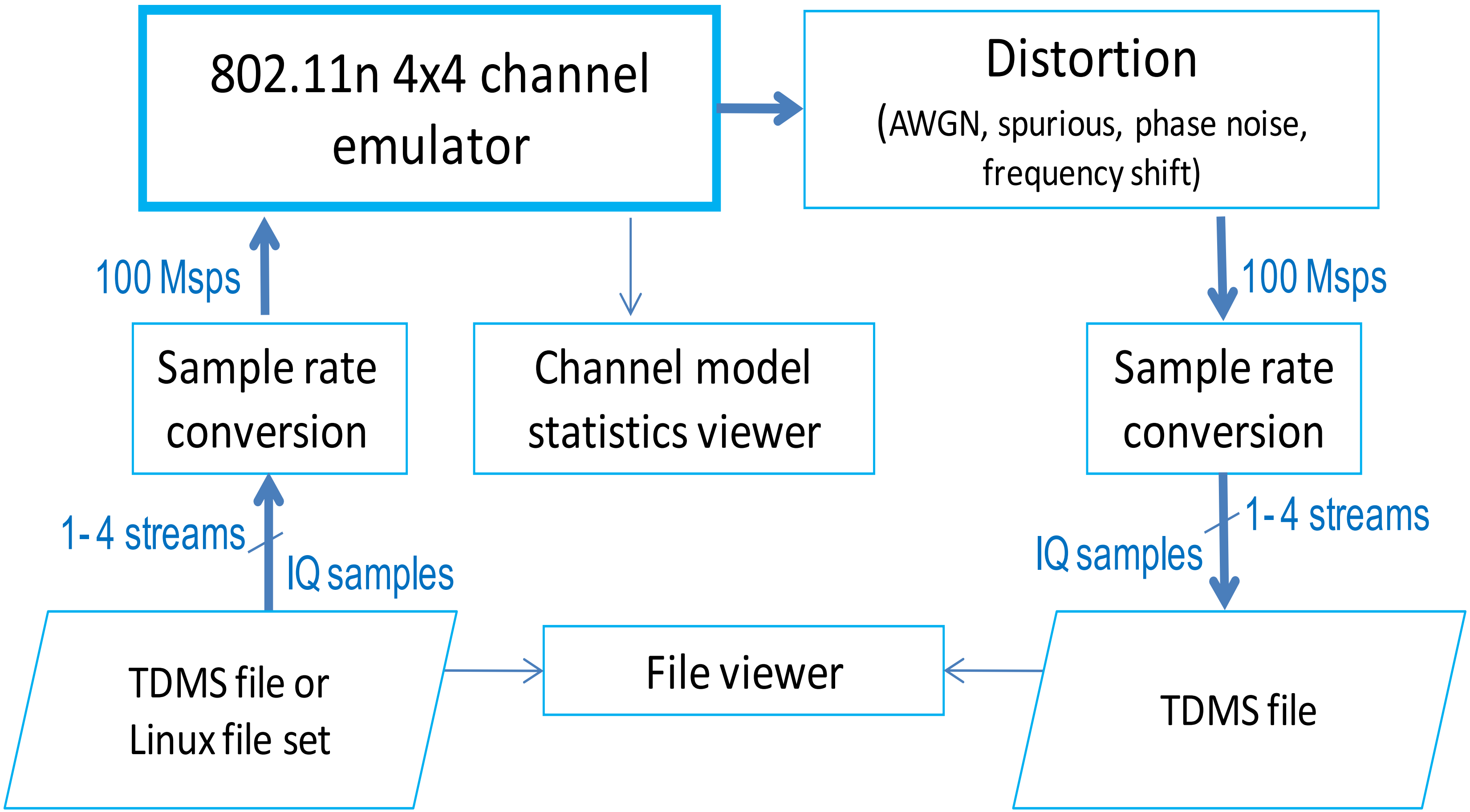


- Impulse response, IEEE 802.11n model F

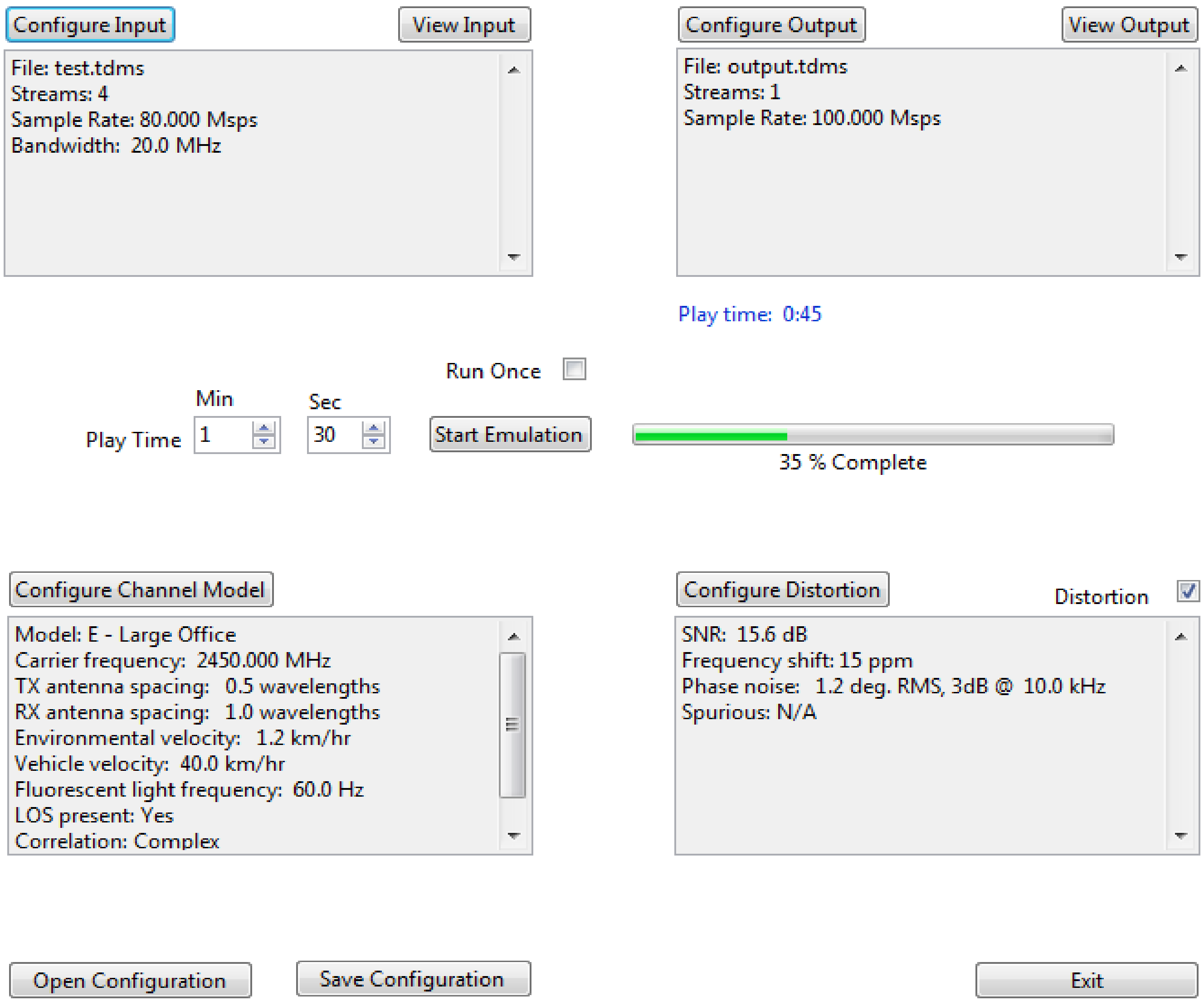
Outline

- What is channel emulation and why is it critical for MIMO systems?
- Channel modeling standards and technologies
- Channel model statistics
- Channel emulator implementation

Software-based Channel Emulator



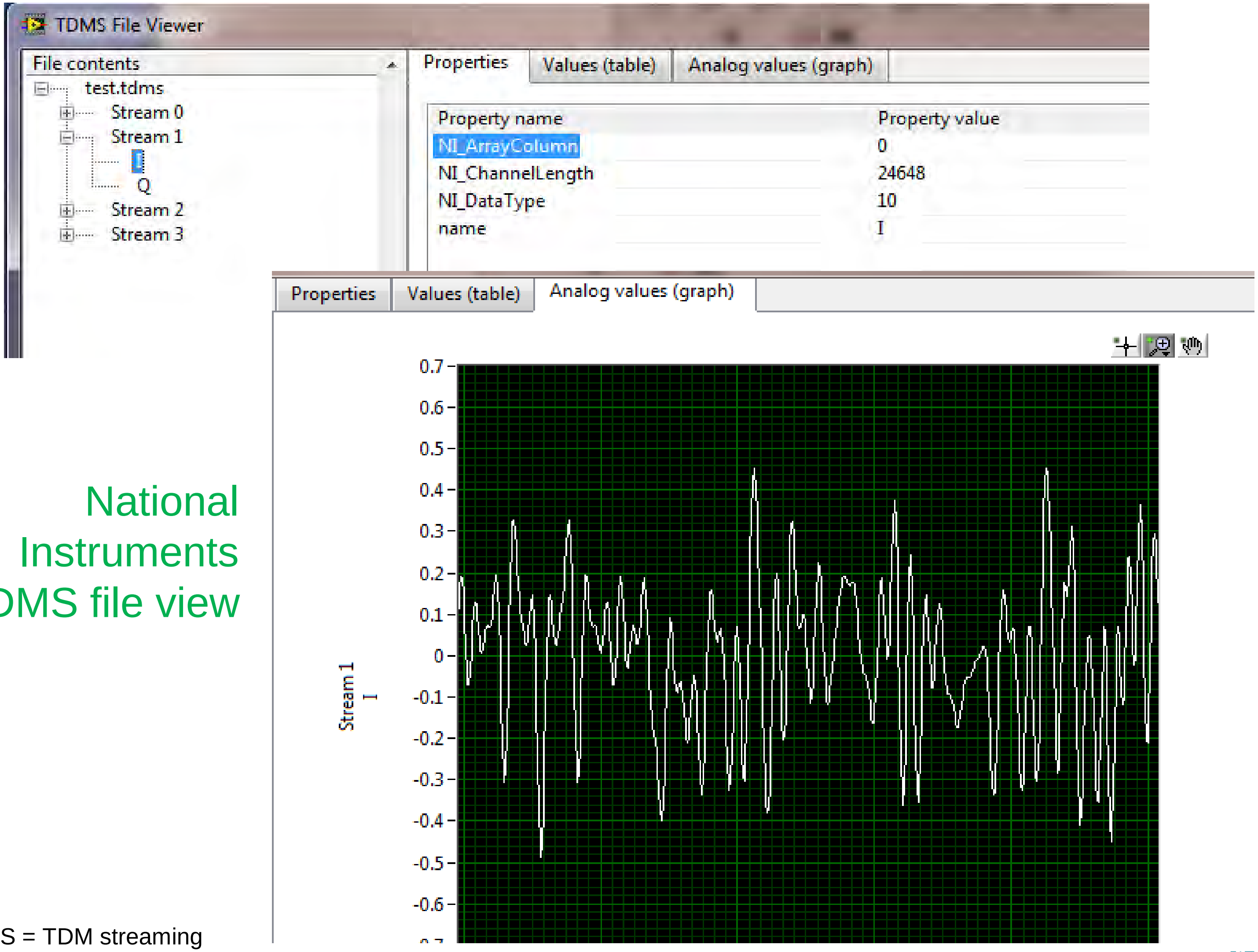
Channel Emulator Console



National Instruments LabVIEW application

Graphical programming environment

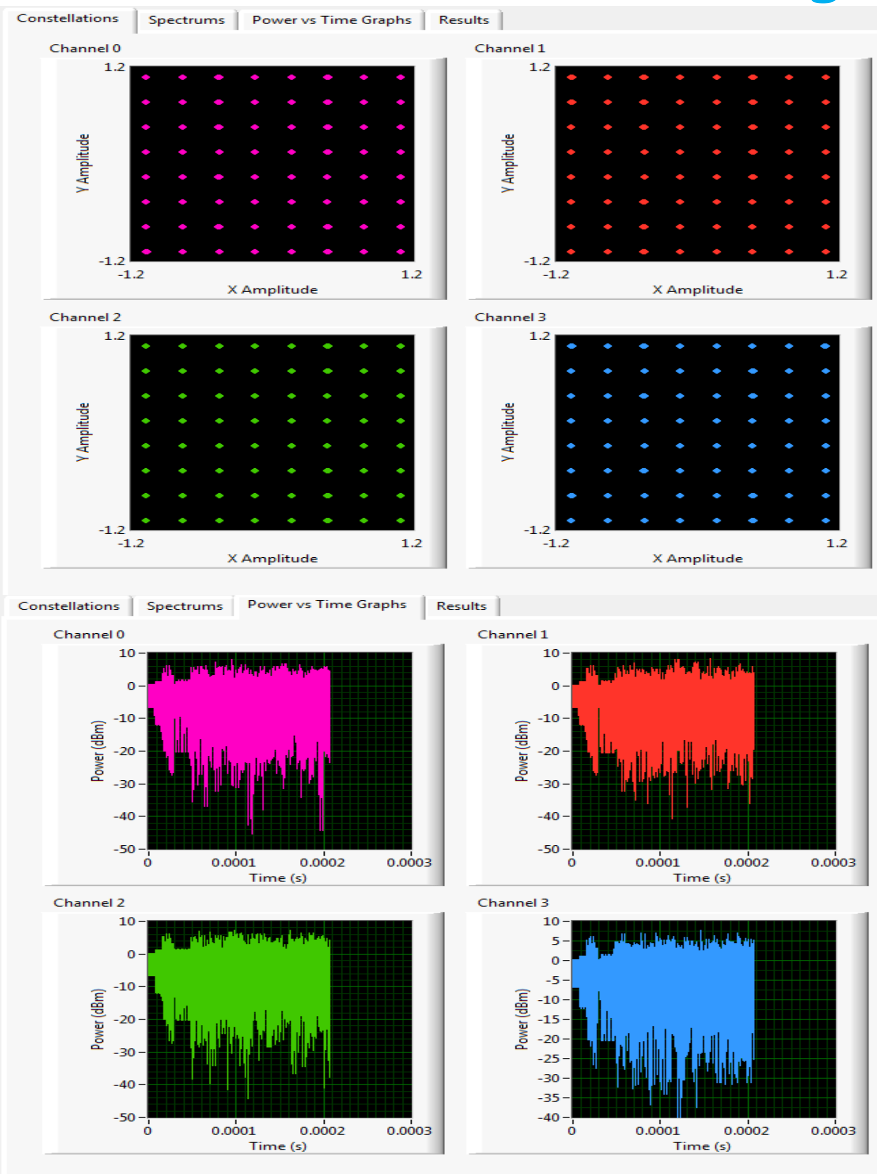
Viewing Input and Output Streams

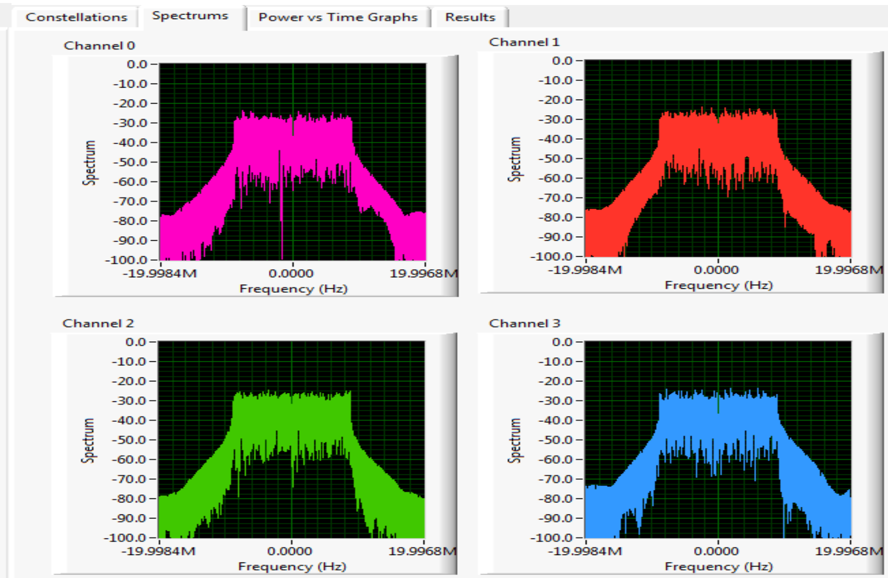


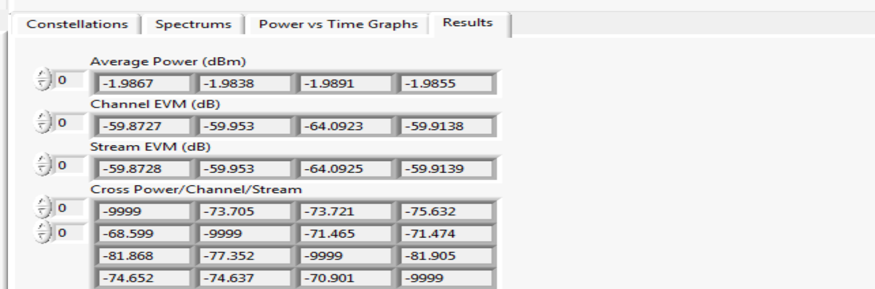
National Instruments TDMS file view

TDMS = TDM streaming
TDM = technical data management

Waveform Analysis







National Instruments WLAN Toolkit

Channel and Distortion Settings

Channel Model Configuration

Protocol: 802.11n

Channel Model: E - Large Office

LOS present ☑

Carrier frequency, MHz (2000 - 6000): 2450

Antenna Spacing (wavelengths)

TX: 0.5 (2.9 cm) RX: 1.0 (5.8 cm)

Correlation: Complex

Fluorescent Light Frequency, Hz: 60

Keep seed fixed ☐ Seed (0 - 2^32): 2355

Return

Distortion Configuration

Es/No (SNR), dB (-30.0 to +80): 15.6

Frequency Shift, ppm (-50 to +50): 15

Phase Noise ☑

Phase noise 3dB BW, kHz (? to ?): 10

RMS phase noise, deg (? to ?): 1.2

IQ imbalance ☑

Amplitude, dB (? to ?): 2

Phase, deg (? to ?): 3.5

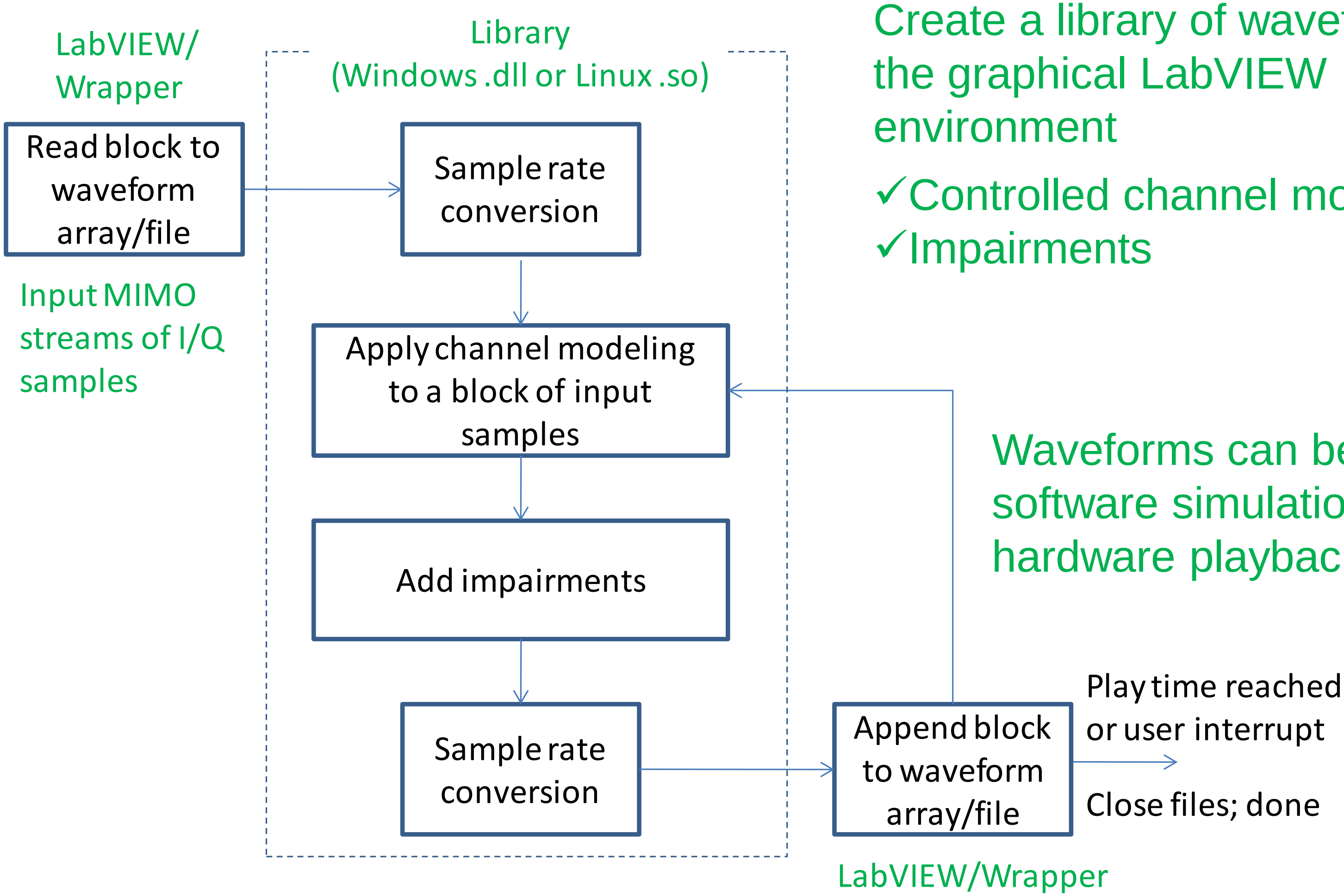
Spurious ☐

# of Spurs (0 to 40): 10

Spur Frequencies, MHz (-20.0 to +20.0)	Spur Levels, dBc (-90.0 to +20.0)
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0
0	0

Return

Software Operation



Create a library of waveforms in the graphical LabVIEW environment

✓Controlled channel modeling
✓Impairments

Waveforms can be used for software simulation or hardware playback

References

- IEEE, 802.11-03/940r4: TGn Channel Models; May 10, 2004
- Schumacher et al, "Description of a MATLAB® implementation of the Indoor MIMO WLAN channel model proposed by the IEEE 802.11 TGn Channel Model Special Committee", May 2004
- Schumacher et al, "From antenna spacings to theoretical capacities - guidelines for simulating MIMO systems"
- Schumacher reference software for implementing and verifying 802.11n models - http://www.info.fundp.ac.be/~lsc/Research/IEEE_80211_HTSG_CMSC/distribution_terms.html
- 3GPP 36-521, UE Conformance Specification, Annex B
- 3GPP TR 25.996, "3rd Generation Partnership Project; technical specification group radio access networks; Spatial channel model for MIMO simulations"
- IST-WINNER II Deliverable 1.1.2 v.1.2, "WINNER II Channel Models", IST-WINNER2, Tech. Rep., 2008 (http://projects.celtic-initiative.org/winner+/deliverables.html)
- 3GPP TR37.976, MIMO OTA channel models
- IEEE, 11-09-0334-08-00ad-channel-models-for-60-ghz-wlan-systems