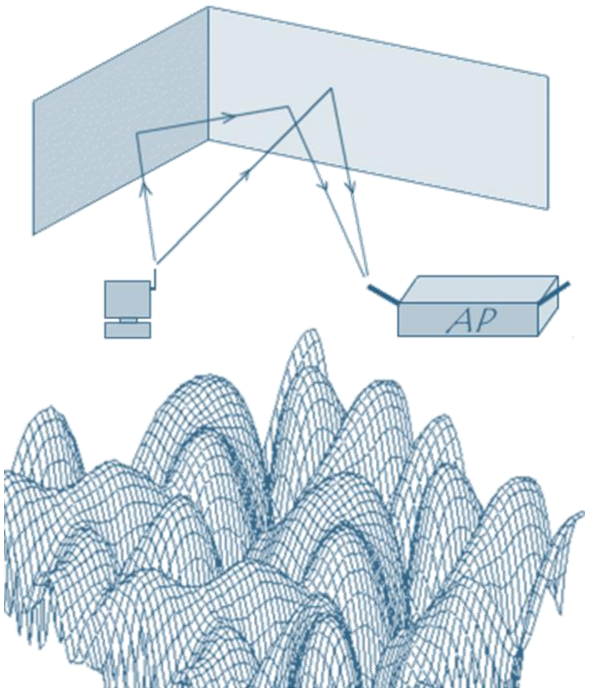
Fundamentals of Wireless Channel Emulation



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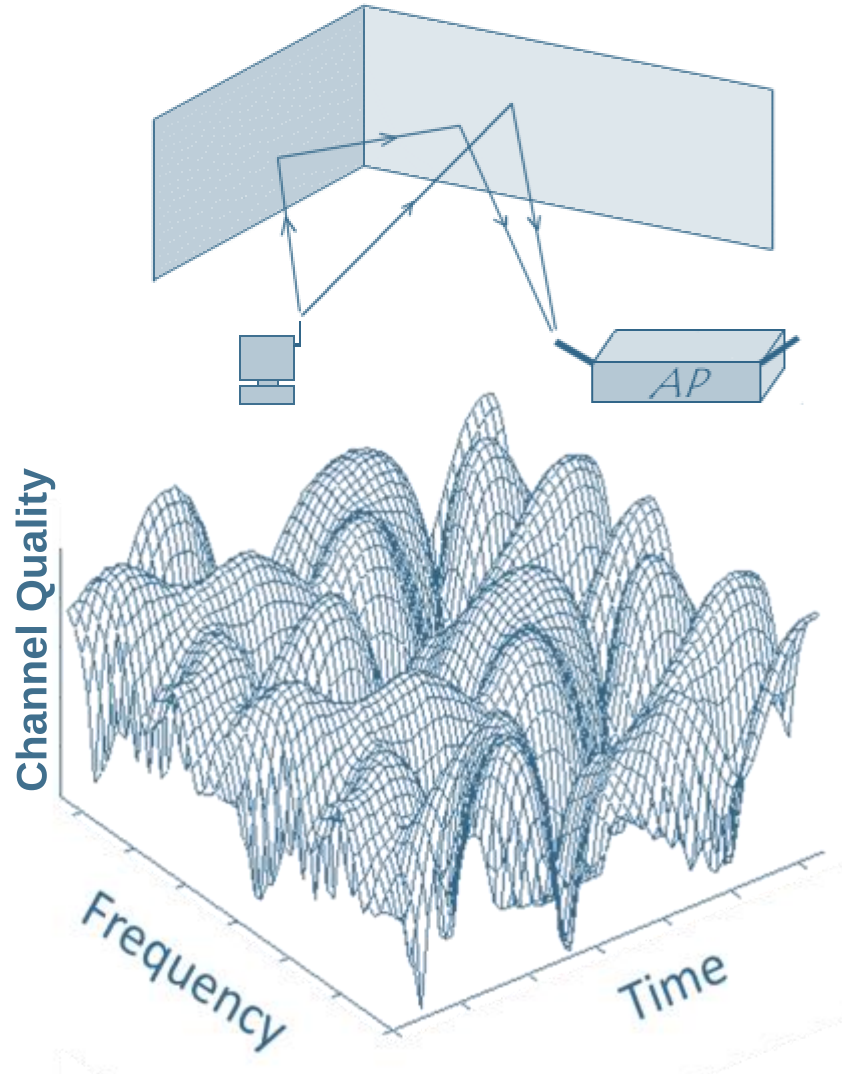
Outline

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

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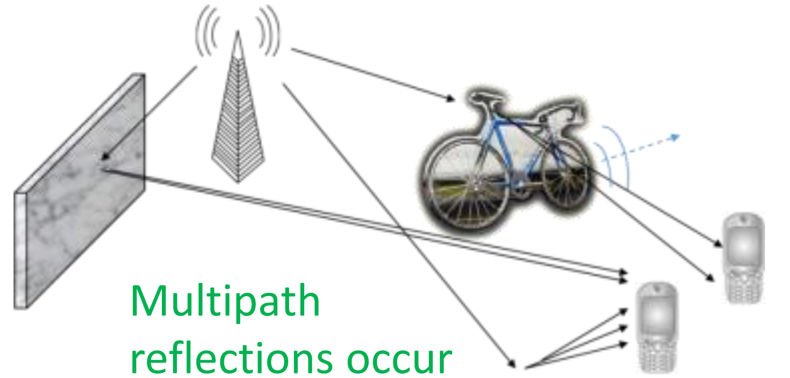
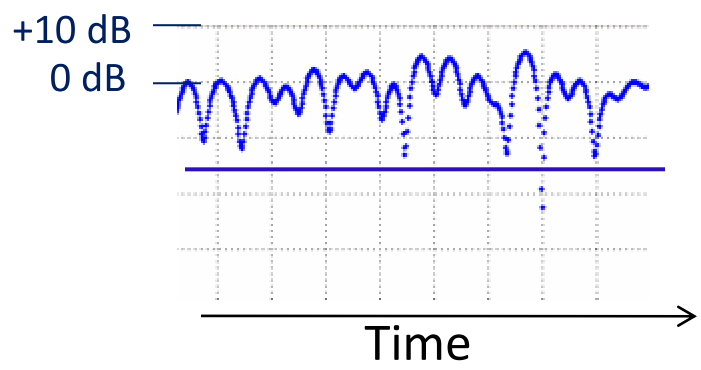
Multipath and Flat Fading

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



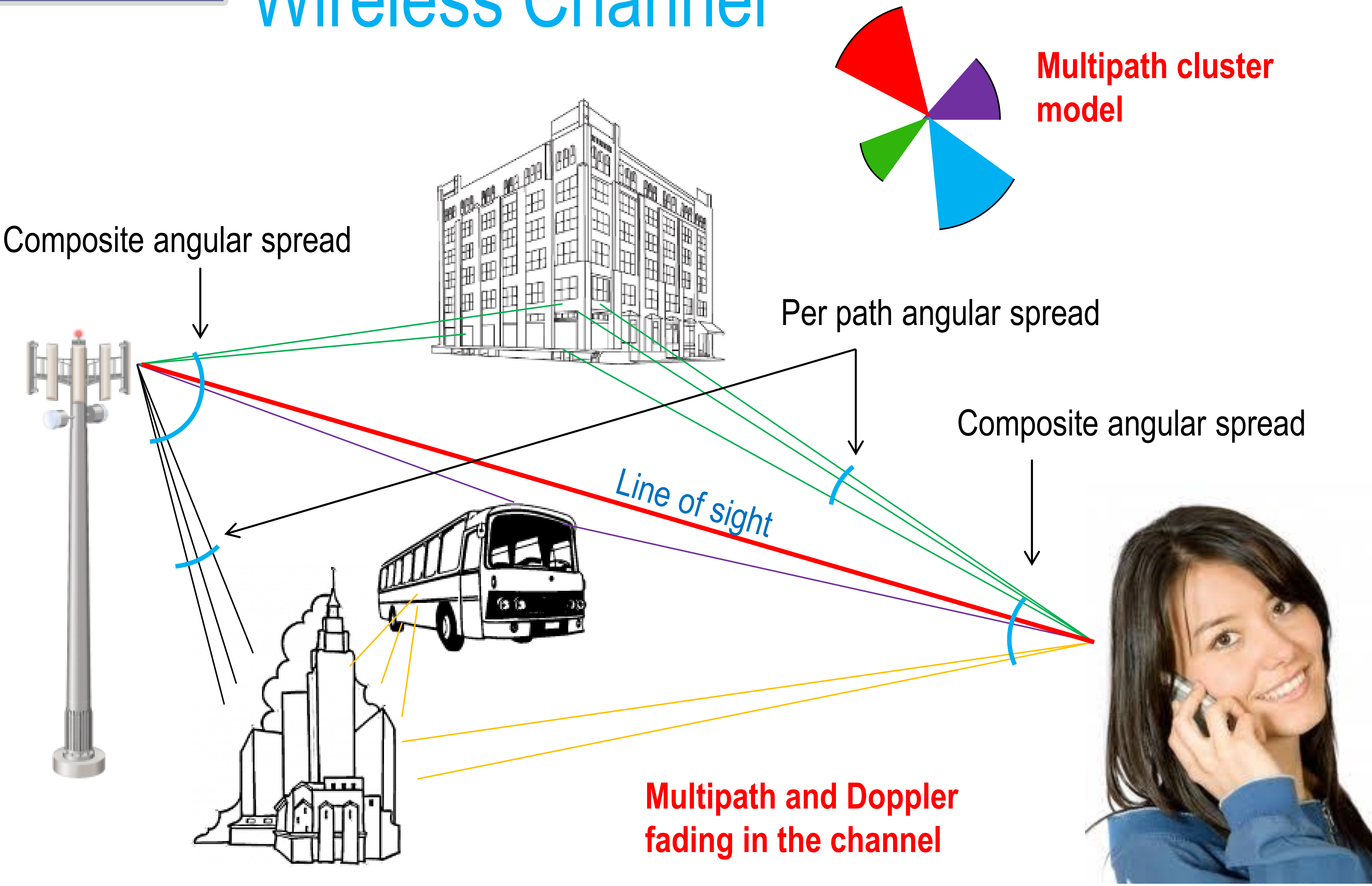
Multipath reflections occur in clusters.



Multipath fading component

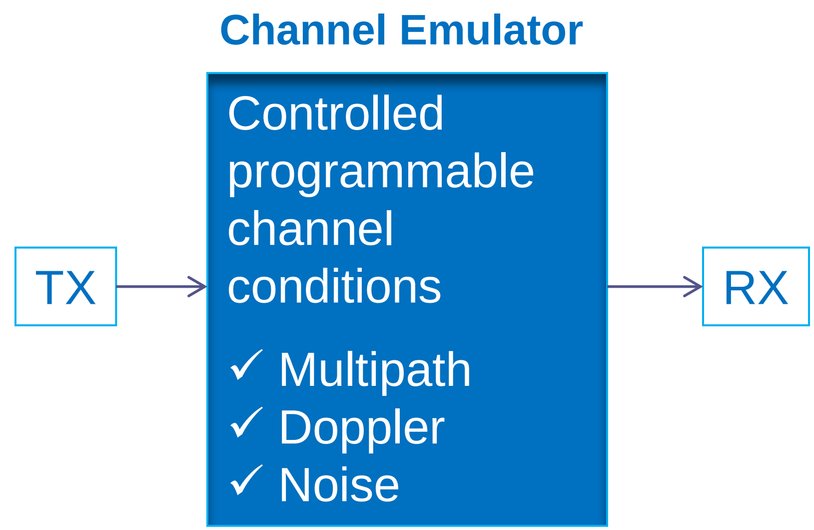
-15 dB flat fading component

Wireless Channel



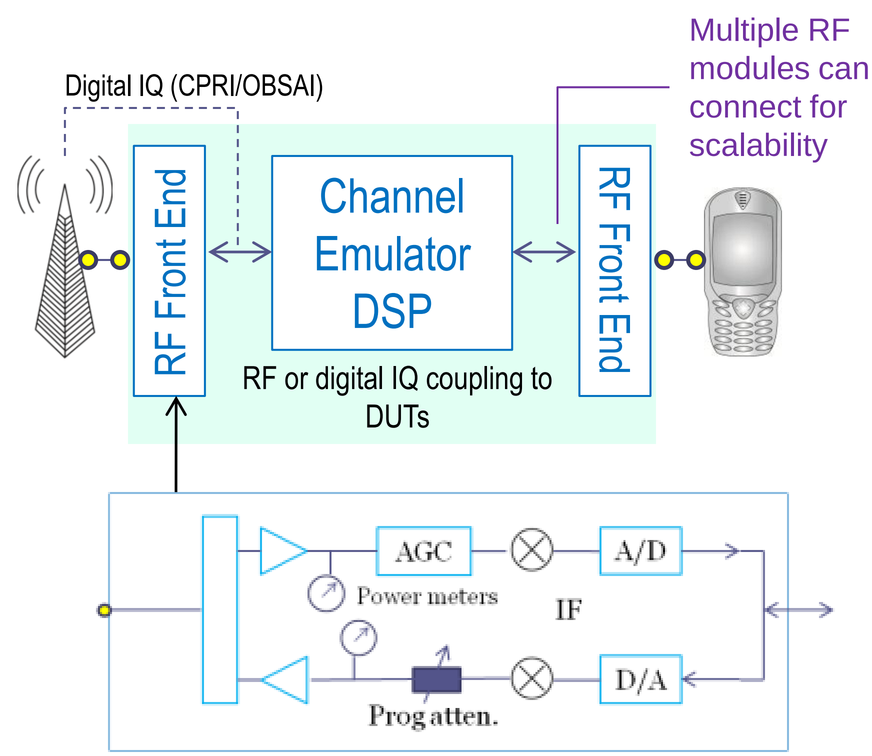
Validating Radio DSP

- 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



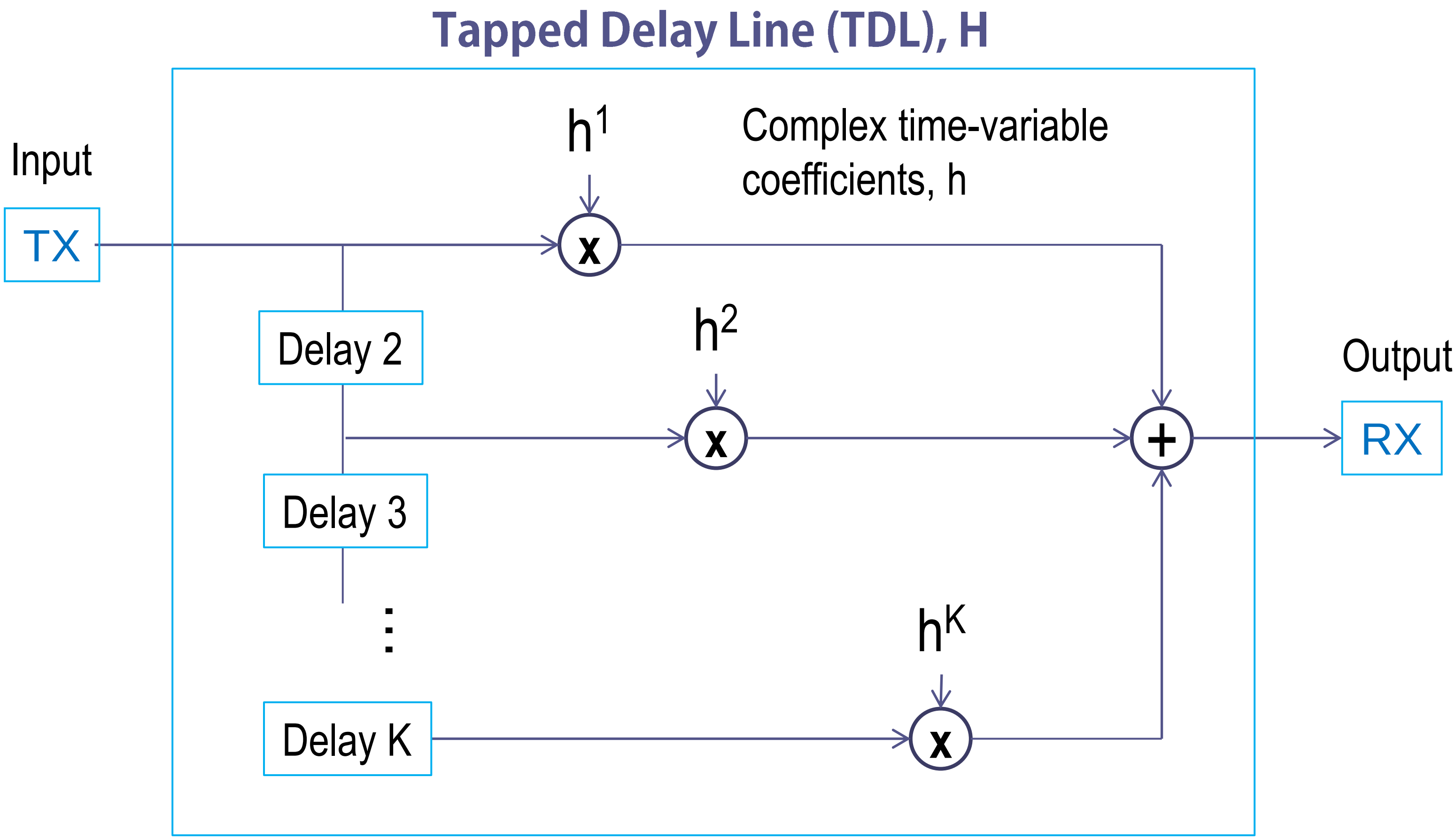
Development and Test of MIMO

- Development and test of MIMO systems requires a channel emulator to emulate multipath and Doppler fading in a variety of wireless channels.
- Adaptive multiple antenna techniques, including TX and RX diversity, spatial multiplexing and beamforming involve sophisticated open and closed loop algorithms that must be tested under a range of controlled (emulated) channel conditions.



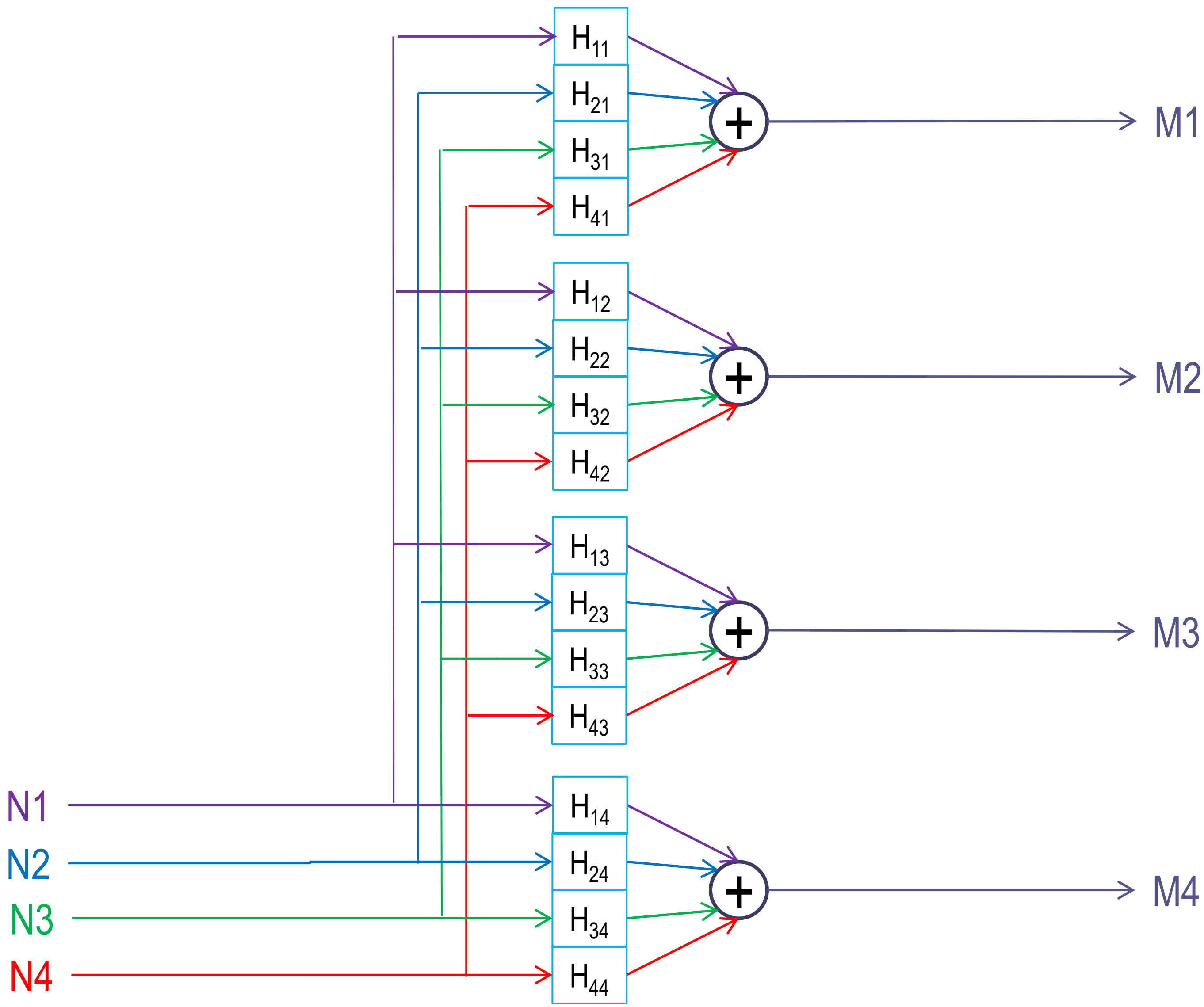
Typical channel emulator block diagram
MIMO emulators have multiple RF ports

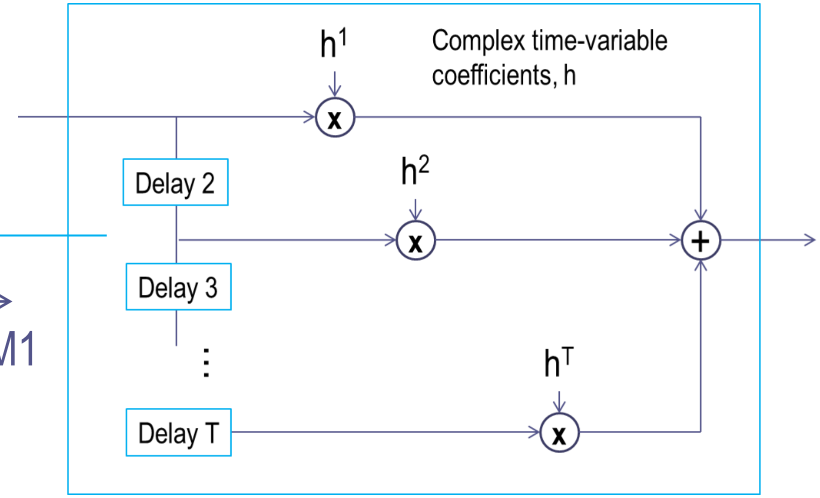
SISO Channel Emulator Block Diagram



where **K** is the number of taps in the TDL

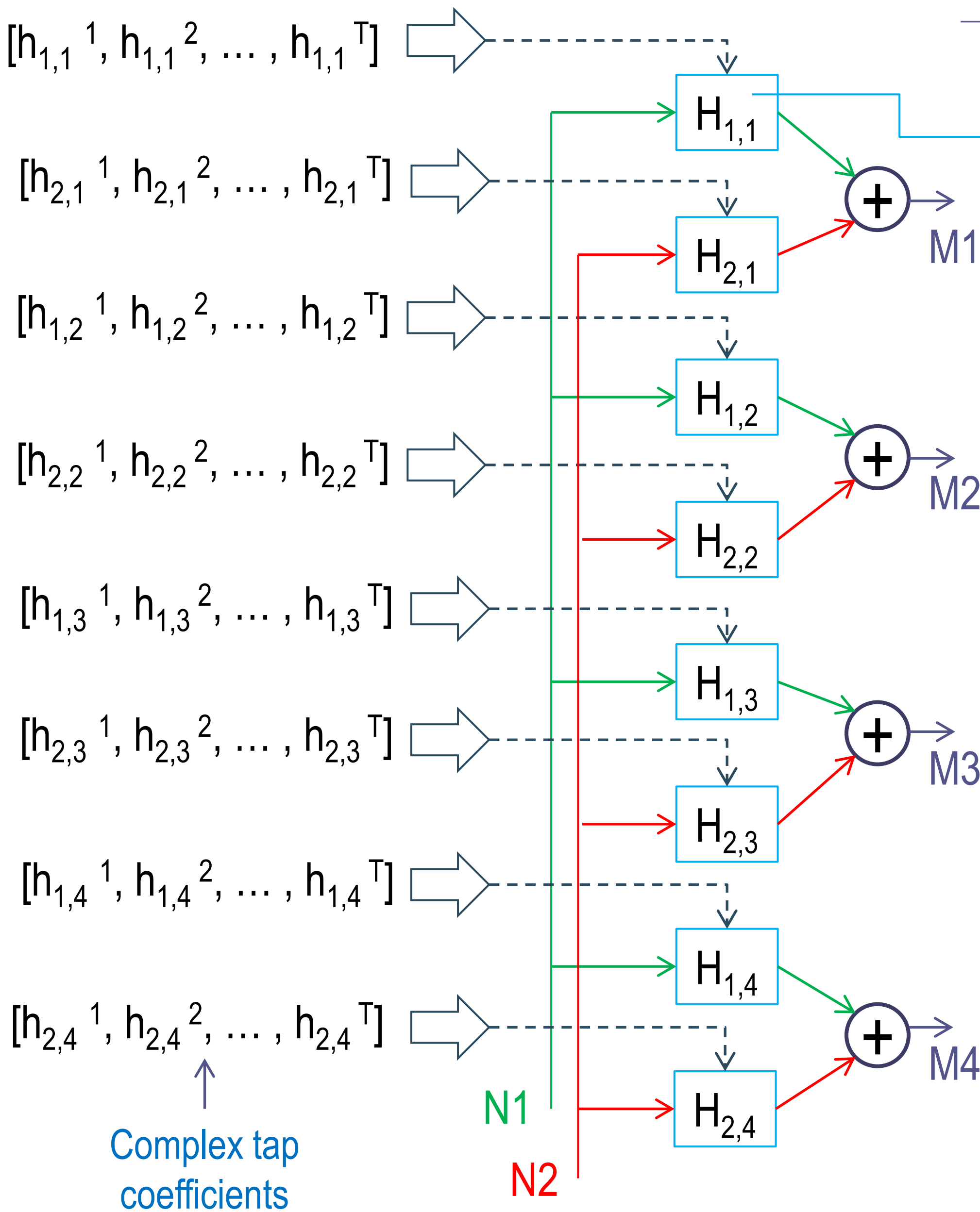
4x4 MIMO Channel Emulator Logic



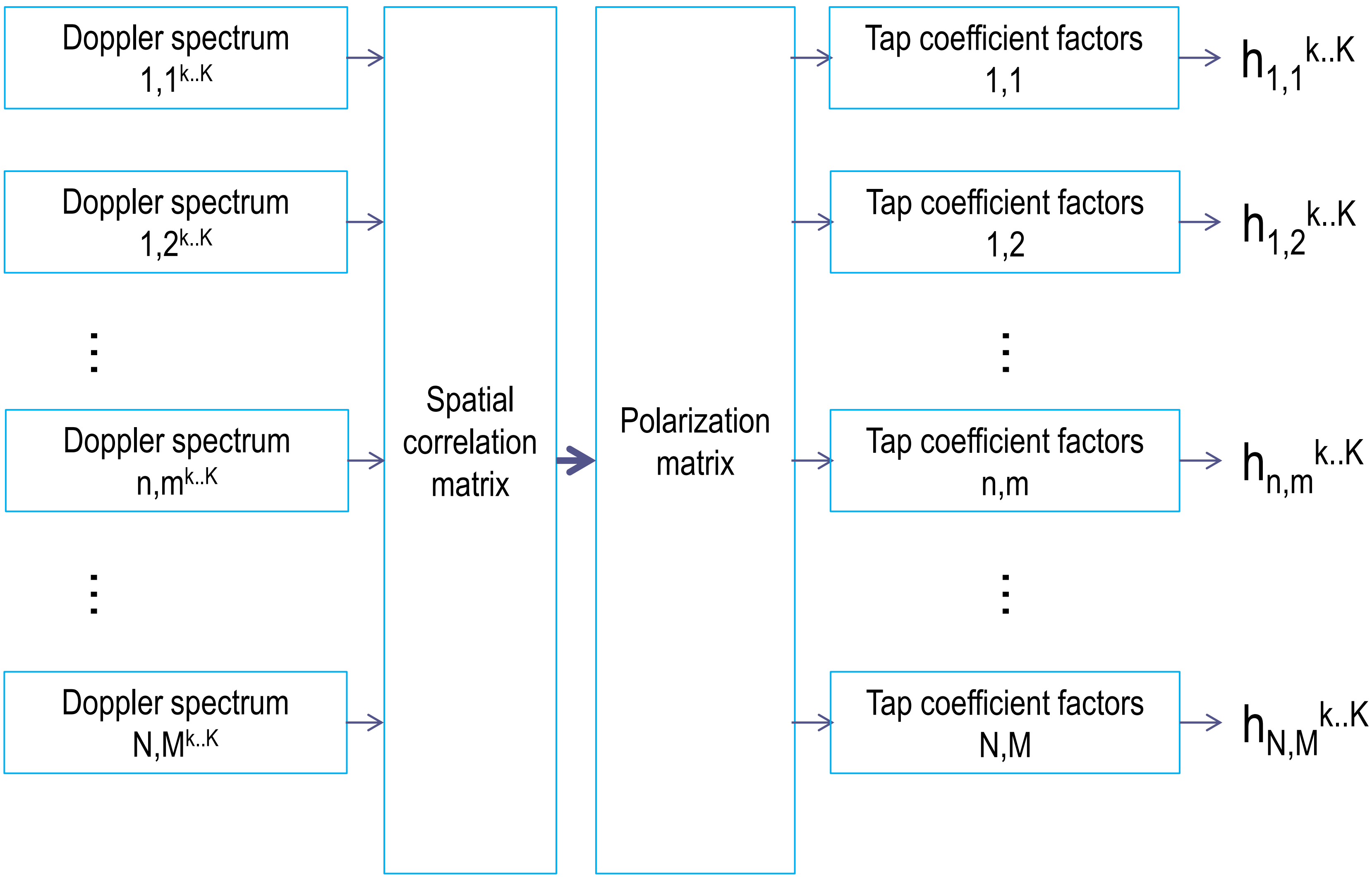


Tapped Delay Line, $H_{n,m}$

MIMO Channel Emulation Logic 2 x 4 Example

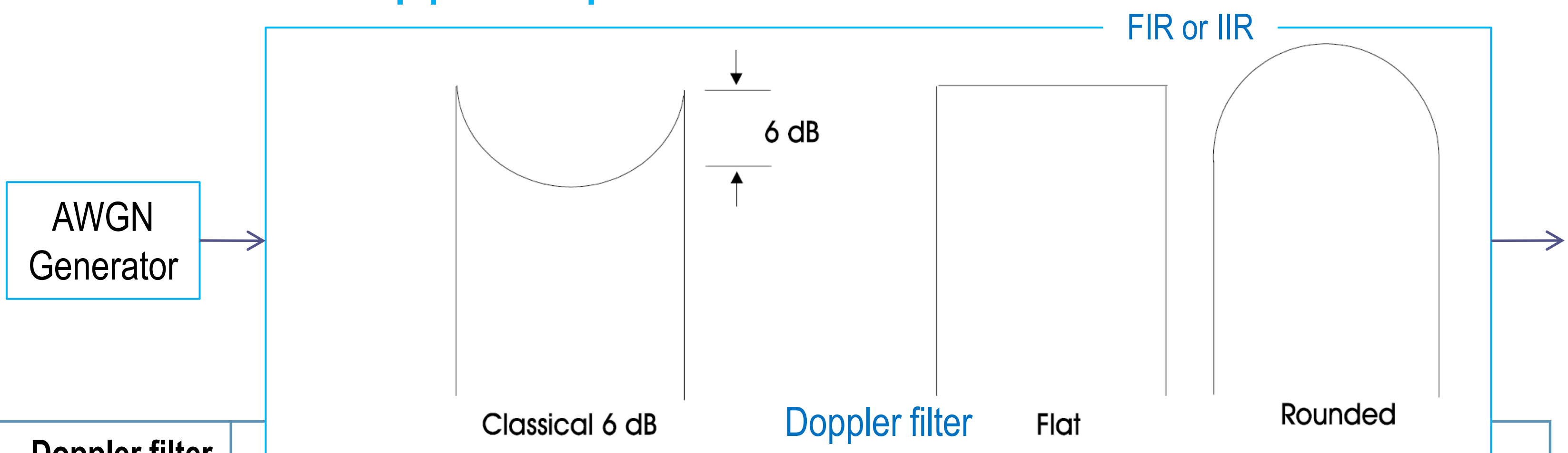


Complex Tap Coefficient Generator



where **k** is the tap number, K is the maximum number of taps and **h** is the time-variable coefficient

Doppler Spectrum Block

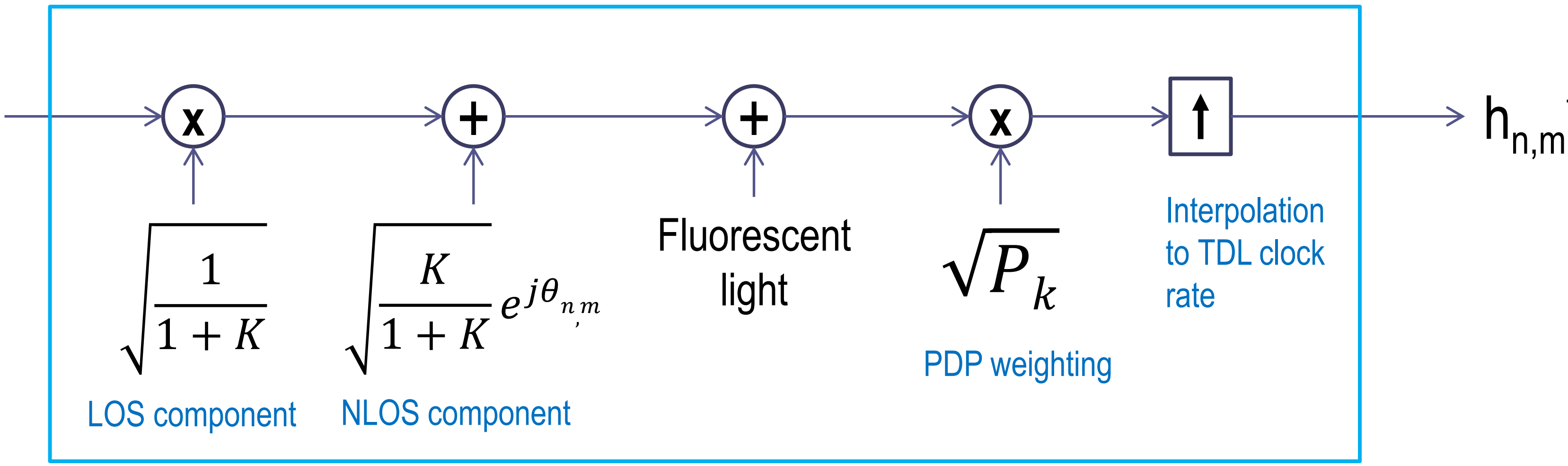


Doppler filter	
Classical	Specified for most 3GPP channel models; Classical = Jakes; Classical 3 dB and 6 dB
Bell	Specified for 802.11n channel models; variations of this filter include Bell-spike, which is used by 802.11 model F to model a 40 km/hour spike in the spectrum
Static	Models LOS on first tap; used in custom channel modeling
Flat	Can also be implemented using RF attenuators via an identity matrix (i.e. connecting inputs to outputs through attenuators)
Rounded	Variations of this filter include Rounded 12 dB
Gaussian	
Constant phase	
Butterworth	
Pure Doppler	Rician LOS component only, no Reilly

Notes on Doppler Filter Implementation

- AWGN sources are connected to Doppler filters that provide the desired spectral shape of the fading. The Doppler filter is IIR in the octoFade implementation.
- For 802.11n models, the filter is Bell-shaped for models A through F and Bell-Spike for model F. The Bell spectrum models fading due to walking-speed motion in the environment at an average speed of 1.2 km/hr. The spike in the Bell-Spike spectrum adds the effect of a vehicle moving at an average speed of 40 km/hr.
- For 3GPP models, the Doppler spectrum is Classical.

Tap Coefficient Factors



Tap coefficient factors
n,m

where **t** is the tap number, **h** is the time-variable complex coefficient, **K** is Rician K-factor

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Notes on Tap Coefficient Factors

- The parameter K (Rician K-factor) determines the relative strength of the LOS and NLOS components and is set based on the chosen model.
- The $\sqrt{\frac{K}{1+K}}$ term models the LOS component. The $\sqrt{\frac{1}{1+K}}$ term models the NLOS component.
- The LOS component can only be present on the 1st tap. If the distance between the transmitter and the receiver is greater than the distance to 1st reflector (typically a wall in the indoor environment) then LOS component is not present. The presence of LOS is a configuration parameter that can be enabled or disabled.
- The first tap's LOS component isn't Doppler filtered. Thus, if LOS is present, the power spectrum on the first tap deviates from the Bell spectrum since it includes both the LOS and the NLOS components. If LOS is present, the PDF and CDF of the 1st tap are Rician. If LOS is not present the PDF and CDF on the 1st tap are Rayleigh. On all other taps the PDF and CDF are always Rayleigh.
- $\sqrt{P_t}$ represents the Power Delay Profile (PDP) weighting, summed over all the clusters that contribute power for the t_{th} tap. It reflects how strong the total power is at tap t.

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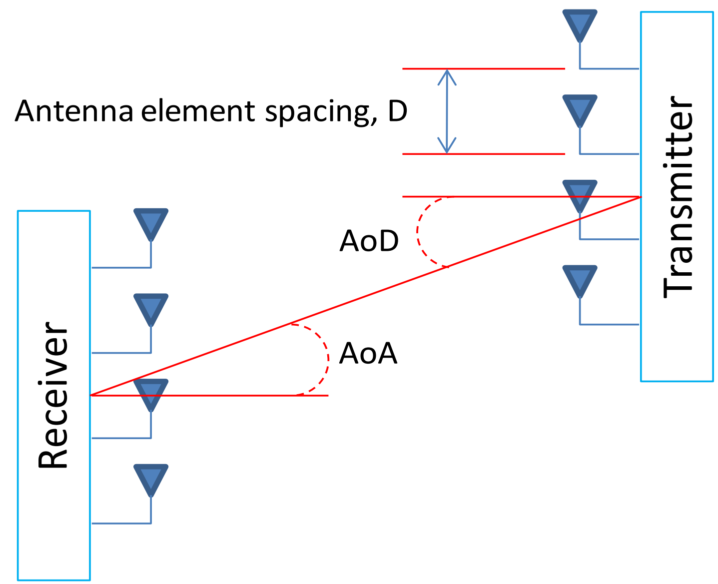
802.11n/ac Correlation Matrix

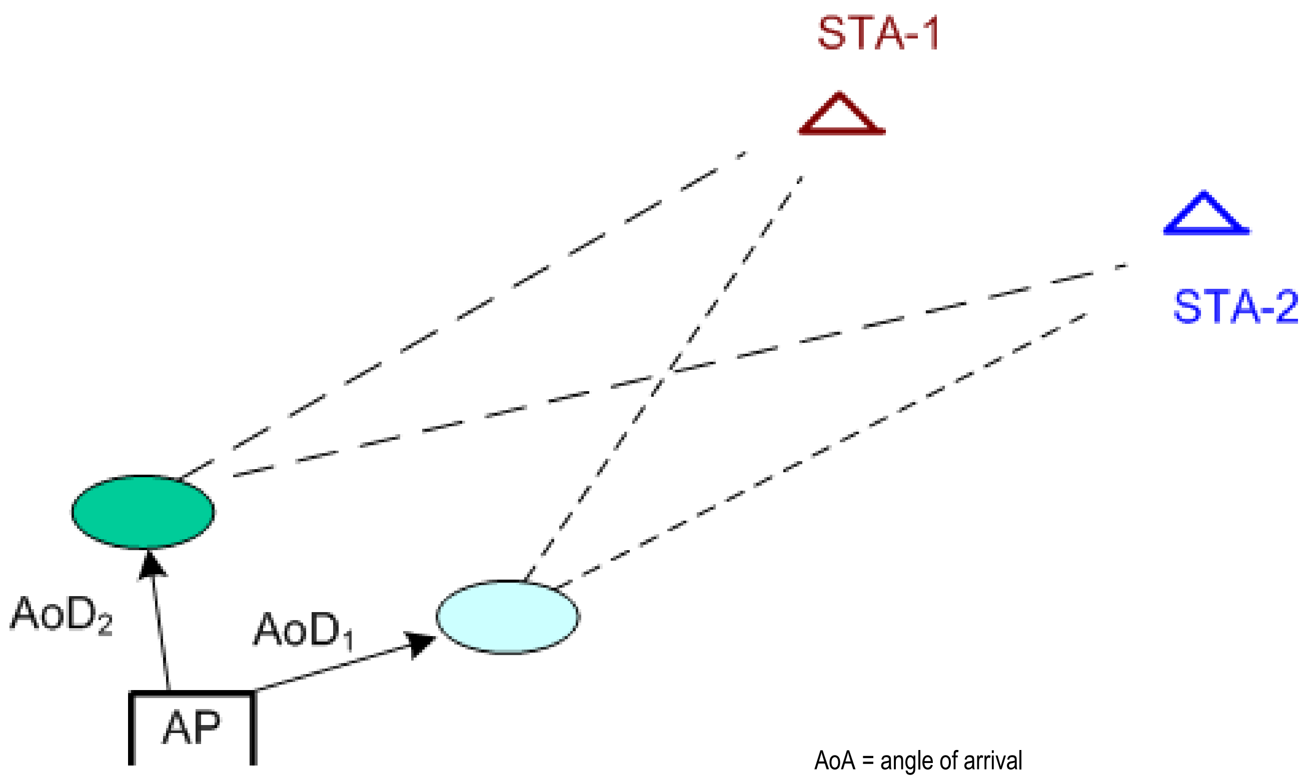
- The spatial correlation matrix is a function of the angular spread of each cluster, angle of arrival (AoA) and angle of departure (AoD). 802.11n models assume that RX and TX antenna systems are uniform linear arrays with equally spaced antenna elements.
- Spatial correlation is implemented using the Kronecker product of the transmit and receive correlation matrices, R_{tx} and R_{rx}, respectively. These matrices are comprised of correlation coefficient terms,ρ, that depend on the PAS, AoA, AoD, tap powers and distance D between antenna elements. Fox computes the real and imaginary parts, $R_{XX}(D)$ and $R_{XY}(D)$, respectively, for each ρ. This allows spatial correlation based on the complex field (i.e., using $\rho = R_{XX}(D) + jR_{XY}(D)$) or real power (i.e., using $\rho = R_{XX}^2(D) + R_{XY}^2(D)$).

Angle of arrival (AoA),
Angle of departure (AoD)
Antenna spacing, D



802.11ac Correlation and Polarization

- MU-MIMO modeled for AoD and AoA
- Polarization matrix added since 802.11ac devices are expected to have cross-polarized antennas



AoA = angle of arrival
AoD = angle of departure

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802.11n Channel Models - Summary

Model [1]		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

The LOS component is not present if the distance between the transmitter and the receiver is greater than the distance to 1st wall. The presence of LOS is a configuration parameter that can be enabled or disabled.

802.11ac Channel Models

- 802.11ac channel models are an extension of 802.11n models [2]

System Bandwidth W	Channel Sampling Rate Expansion Factor	Channel Tap Spacing
W ≤ 40 MHz	1	10 ns
40 MHz < W ≤ 80 MHz	2	5 ns
80 MHz < W ≤ 160 MHz	4	2.5 ns
W > 160 MHz	8	1.25 ns

3GPP Channel Models

Parameter	*Specification*
LTE models	EPA 5Hz; EVA 5Hz;EVA 70Hz; ETU 70Hz; ETU 300Hz; MBSFN
GSM models	RAx; HTx; TUx; EQx; TIx
WCDMA models	PA3; PB3; VA30; VA120; MBSFN
Special models	Moving propagation, birth-death, high-speed train
Custom models	Arbitrary fading profiles can be implemented in software and loaded into the FPGA via register interface.
AWGN	SNR: -10 to +25dB; 0.1dB resolution Bandwidth: Up to 20MHz, per 3GPP standard requirements
Fading	Types: Rician/Rayleigh Spectrum: Classical Doppler Shift: 0.1 – 1000Hz; 1Hz resolution

Channel Emulation – Requirements Summary

	802.11n	802.11ac		LTE (36-521 Annex B)
		80 MHz	160 MHz	
RF bandwidth (no channel aggregation)	40 MHz	80 MHz	160 MHz	20 MHz
EVM (avg down-fading is -40 dB)	-28 dBm (64QAM)	-32 dBm (256QAM)	-32 dBm (256QAM)	-22 dBm (8% 64QAM)
TDL Taps	18	35	69	9
Delay resolution	10 ns	5 ns	2.5 ns	10 ns

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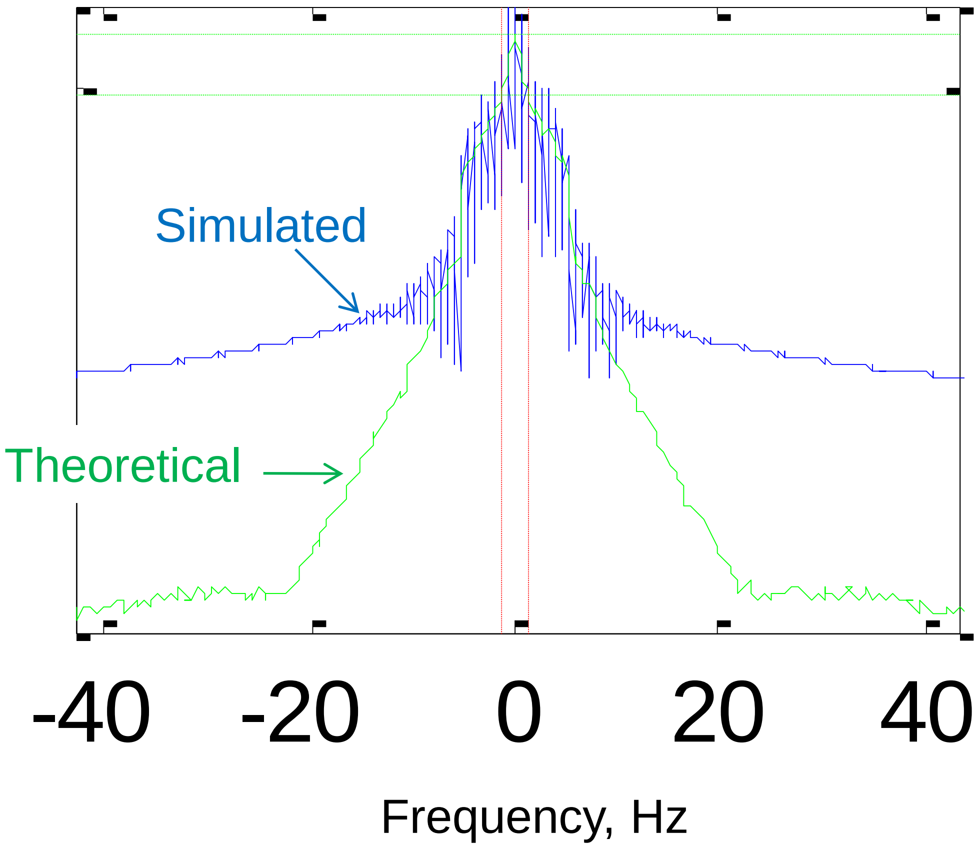
Doppler Spectrum – 802.11n Model F



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

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

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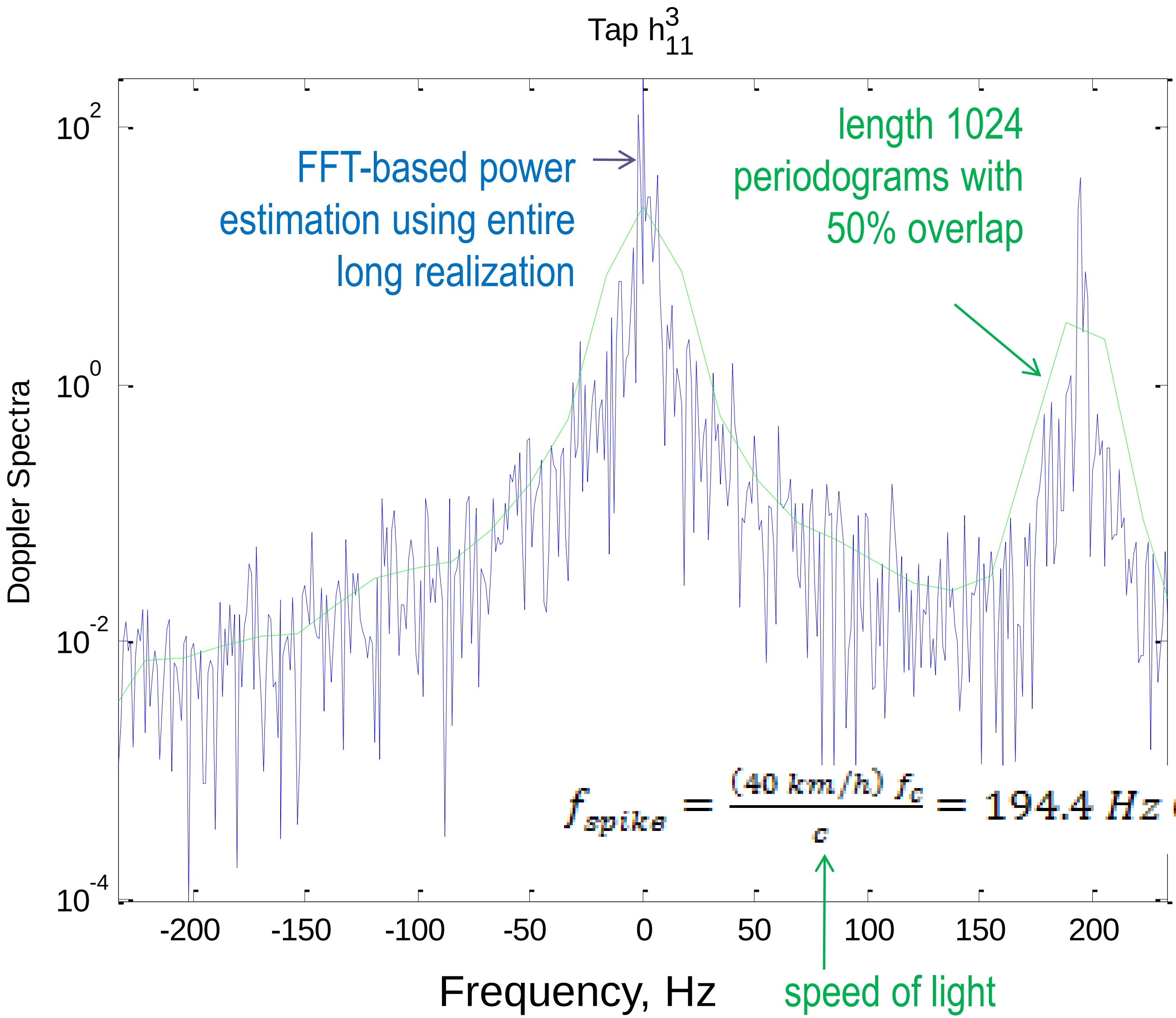
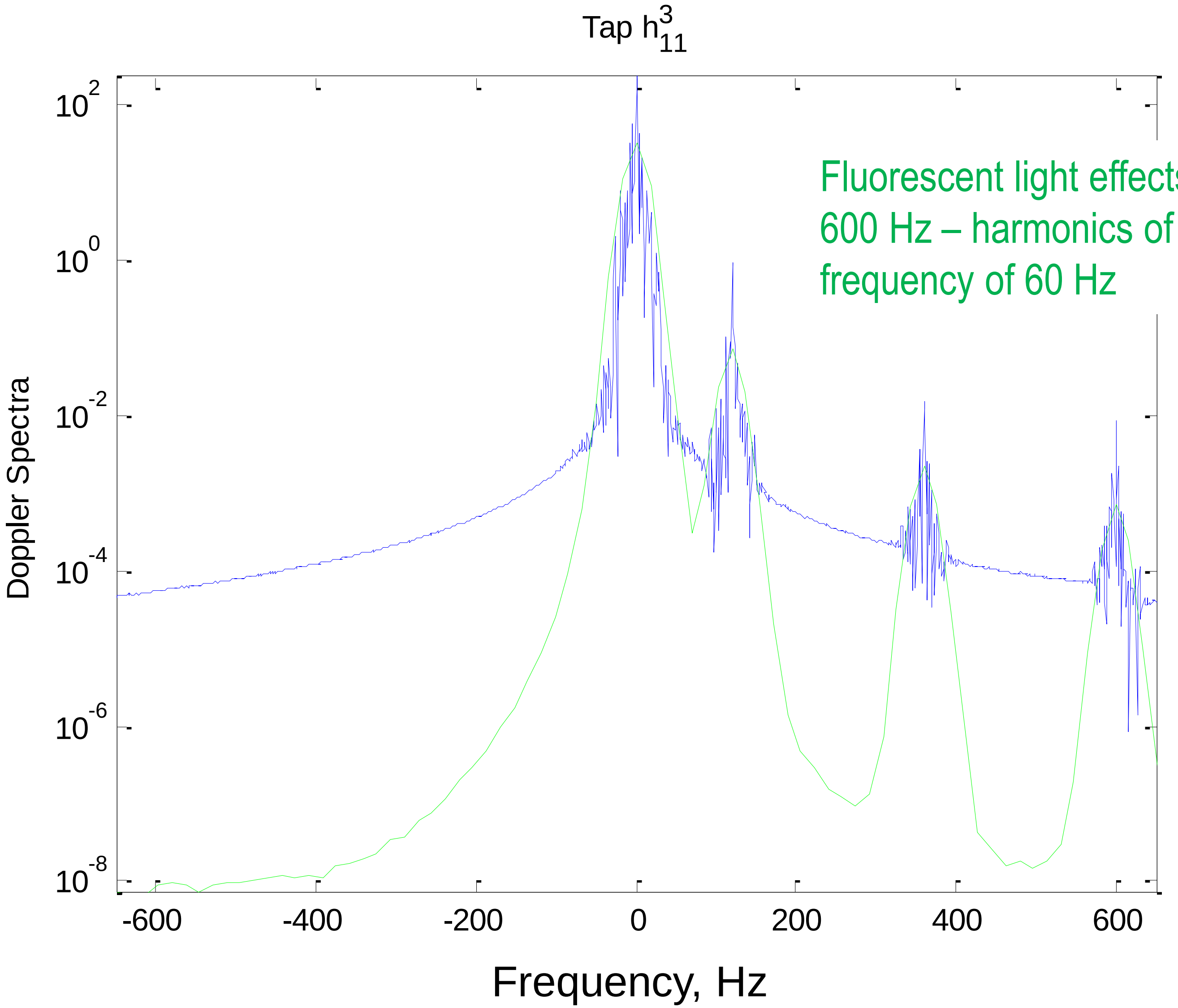
Doppler Spectrum – 802.11n Model F, Tap 3



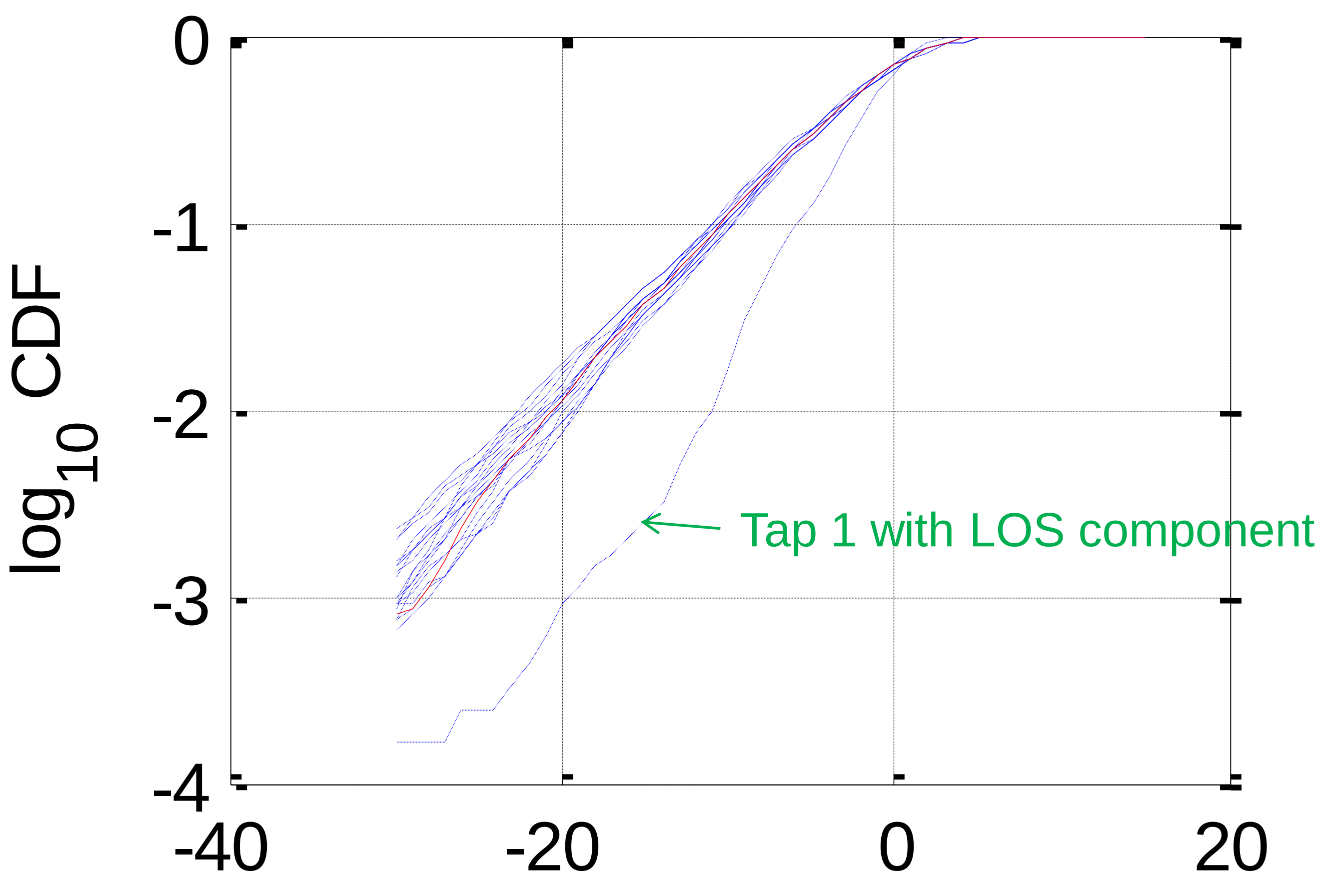
$$f_{spike} = \frac{(40\ km/h)\ f_c}{c} = 194.4\ Hz\ @\ f_c = 5.25\ GHz$$

Doppler Spectrum – 802.11n Model E, Tap 3



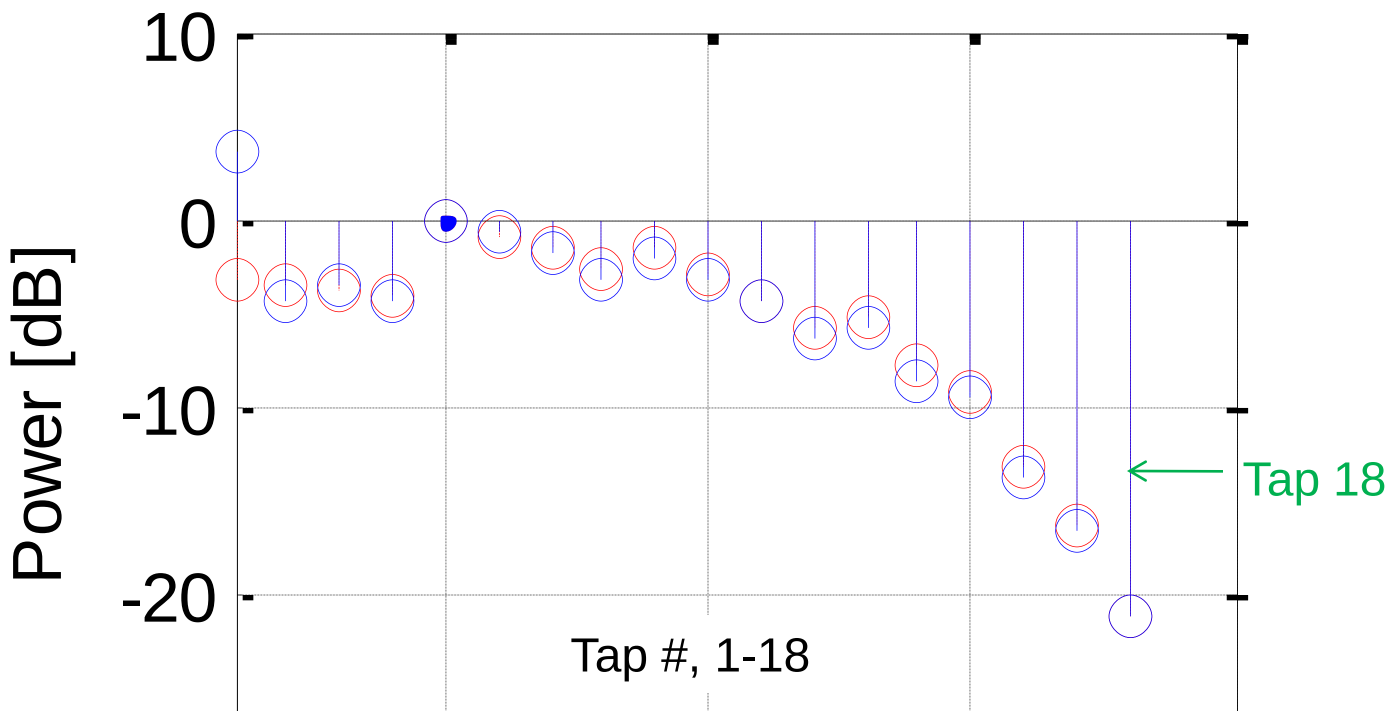
Fluorescent light effects at 120, 360, and 600 Hz – harmonics of the power line frequency of 60 Hz

Cumulative Distribution Function (CDF)



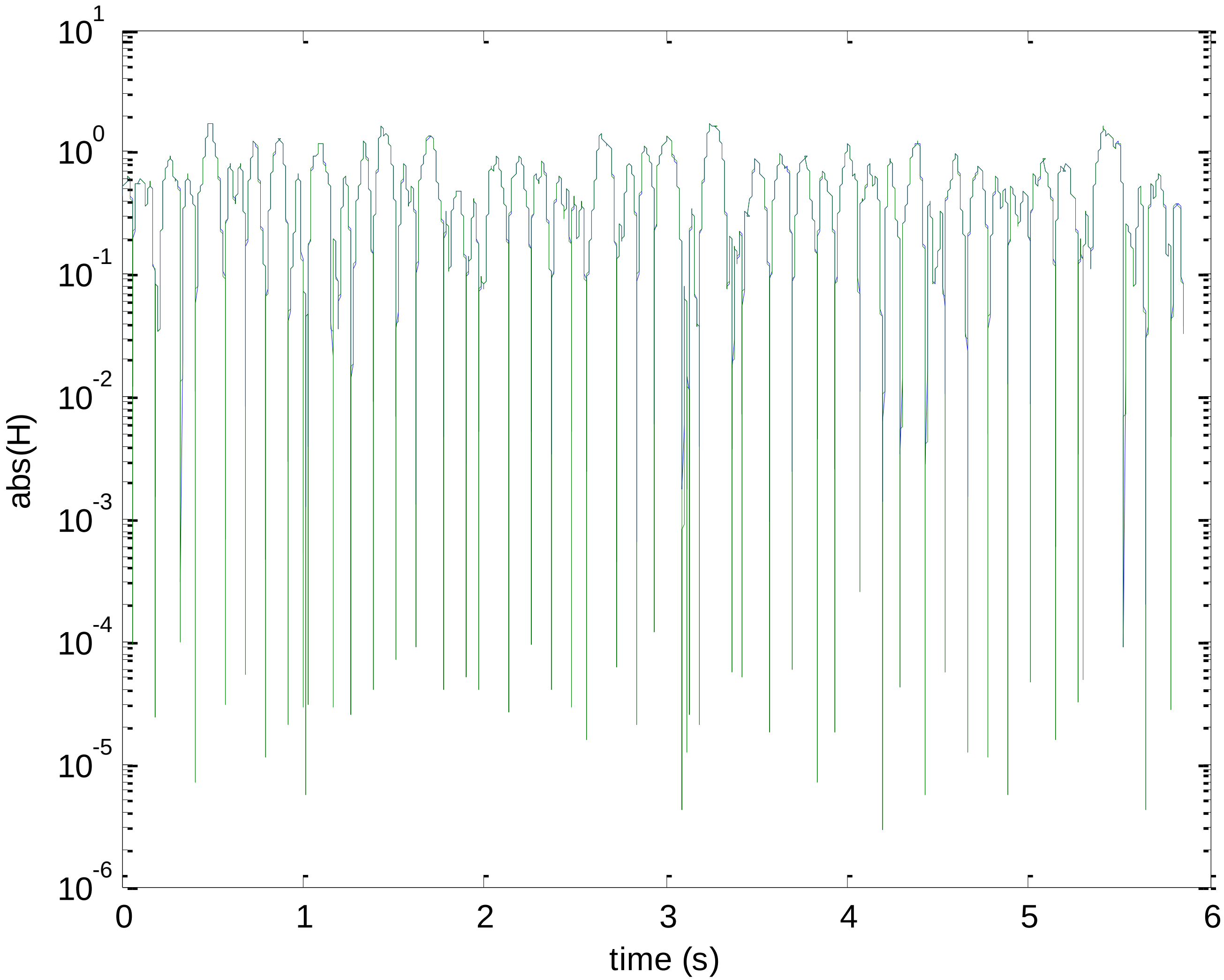
- IEEE 802.11n, Model F, CDF for 18 taps

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

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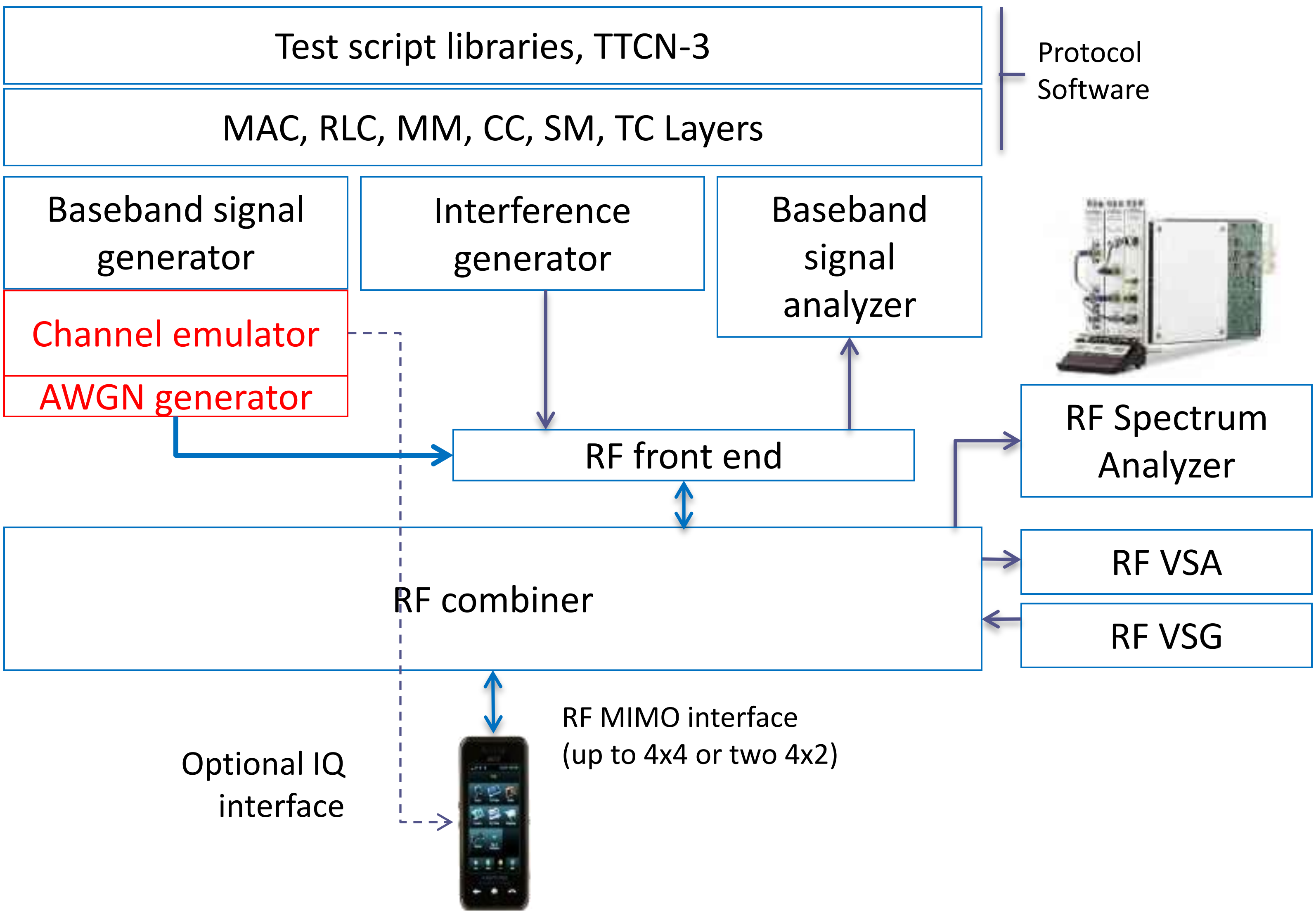
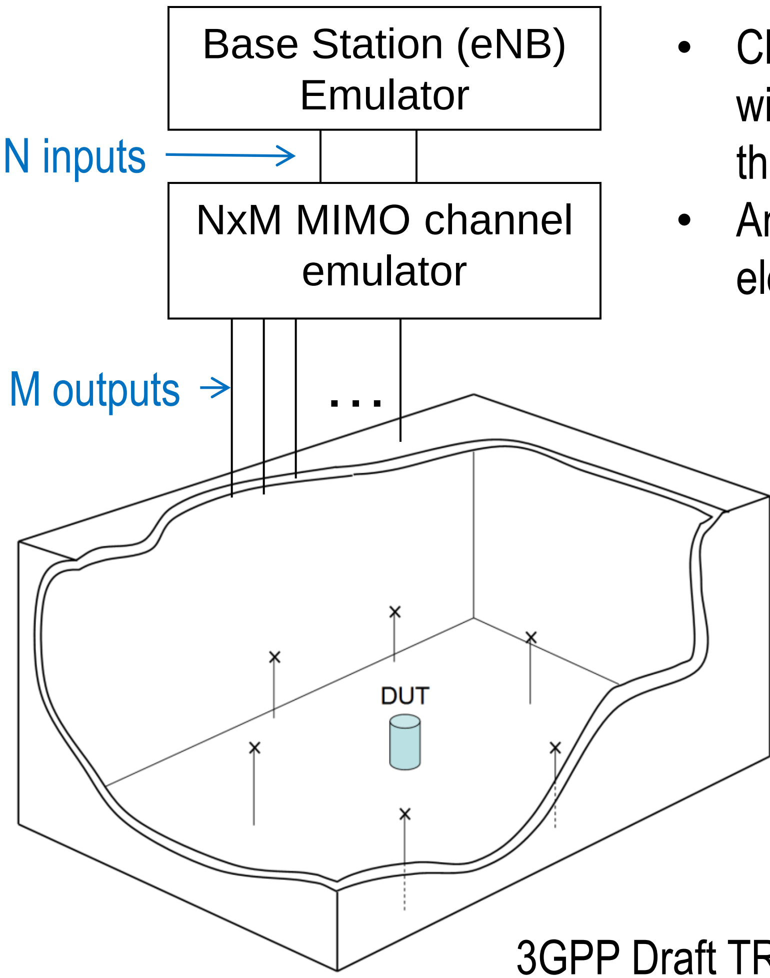
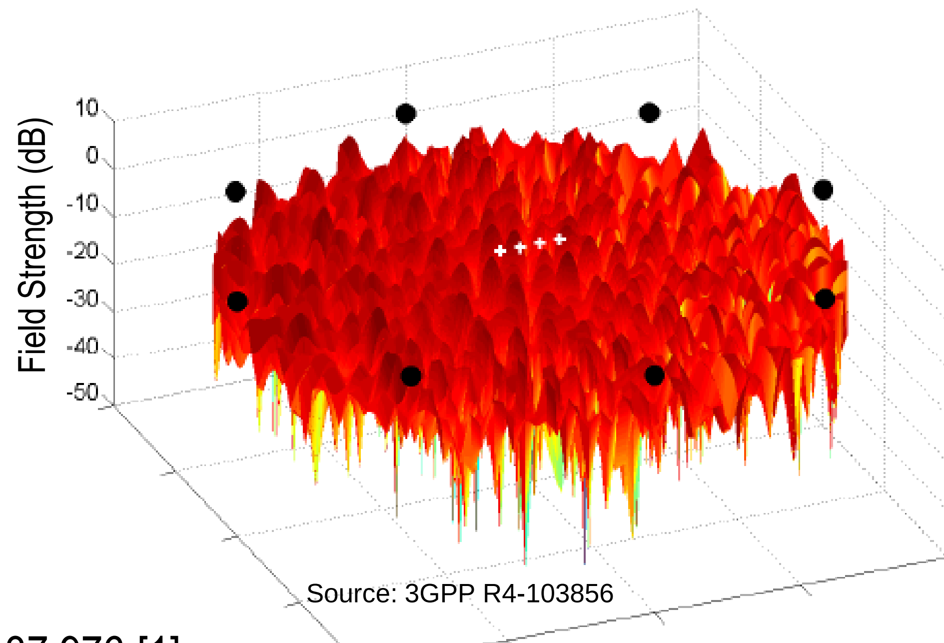
Typical LTE Certification Configuration



MIMO/OTA Standardization Efforts

- Channel emulator performs NxM DL emulation with N typically being 2 and M being equal to the number of probe antennas
- Antennas are typically cross polarized (with 2 elements each: vertical and horizontal)





Source: 3GPP R4-103856

3GPP Draft TR 37.976 [1]

OTA = over the air

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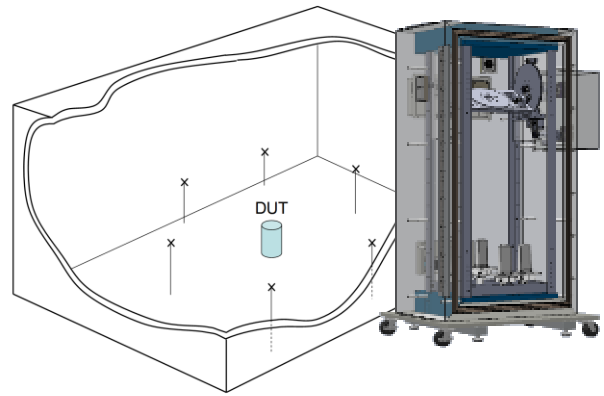
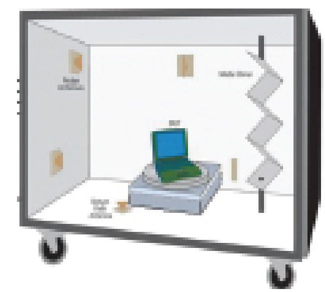
MIMO/OTA Standards Organizations

- 3GPP (International)
  - MIMO/OTA specification development [1]
  - Driven by TSG RAN WG4 in collaboration with CTIA & COST
- CTIA (US)
  - SISO OTA certification standard [13]
  - Recently formed MIMO/OTA Sub-Working Group (MOSG) is driving effort to update current standard for MIMO/diversity
- COST (Europe)
  - Recently formed ICT COST IC1004 Action: "Cooperative Radio Communications for Green Smart Environments"; Formerly COST 2100 Action: "Pervasive Mobile & Ambient Wireless Communications"
  - Contributions driven by SWG2.2: "Compact Antenna Systems for Terminals"

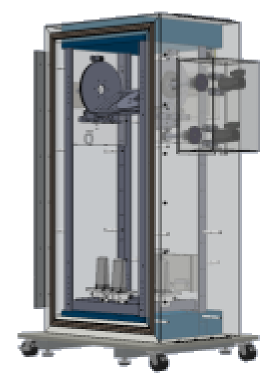
Proposed MIMO OTA Test Methods



- Anechoic chamber
  - DUT is surround by multiple antenna elements inside the chamber in conjunction with external channel emulator/fader and a BS emulator
  - Various antenna numbers/positions and model permutations are being evaluated
- Reverberation chamber
  - Mode-stirrer(s) within DUT chamber are used to generate channel fading environment in conjunction with an external BS emulator
  - An external channel emulator can be added to provide higher power delay profiles, faster Doppler shifts and multipath fading correlation

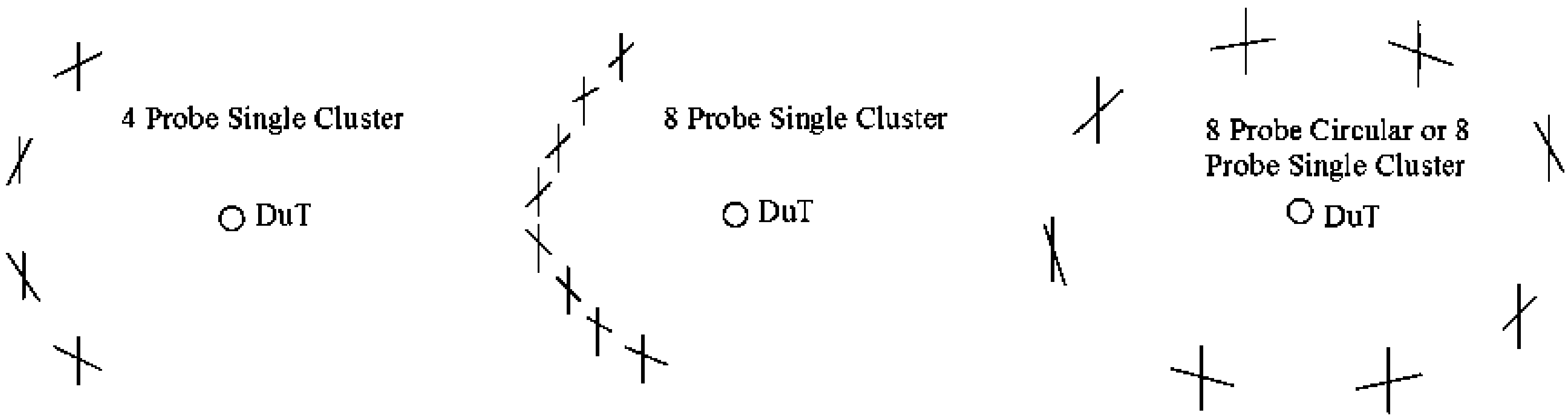


- Two-stage method
  - 3-D far-field patterns for the DUT's antenna array are measured OTA in an anechoic chamber (w/ VNA or w/BS emulator & on-DUT measurements)
  - Antenna patterns are mathematically incorporated into the channel models
  - DUT is then tested in a conducted fashion with BS and channel emulators



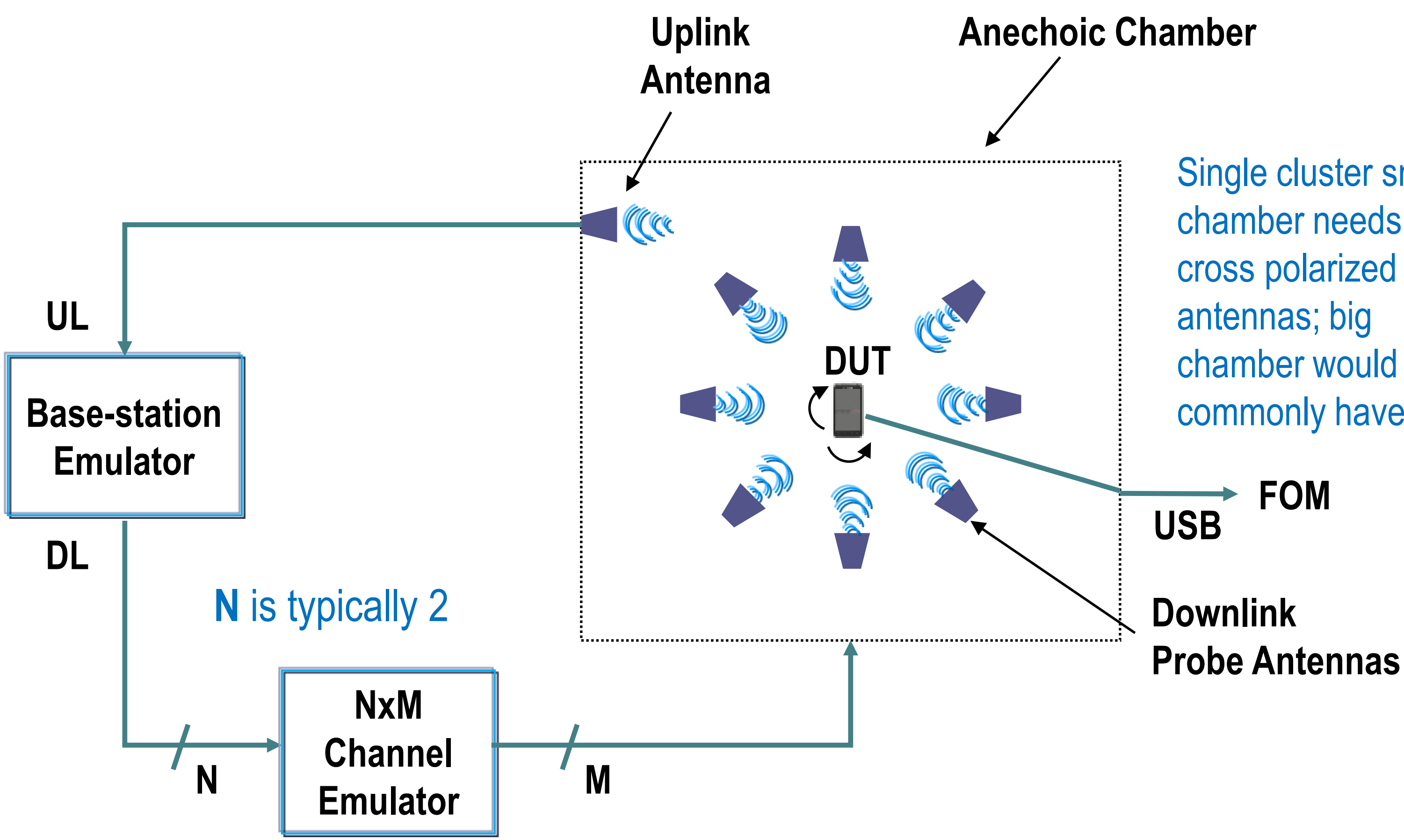
LTE channel models in the draft [1]: SCME Urban Macro (UMa), Urban Micro (UMi), WINNER II Outdoor-to-indoor and EPA.

Anechoic Chamber - Cluster Modeling



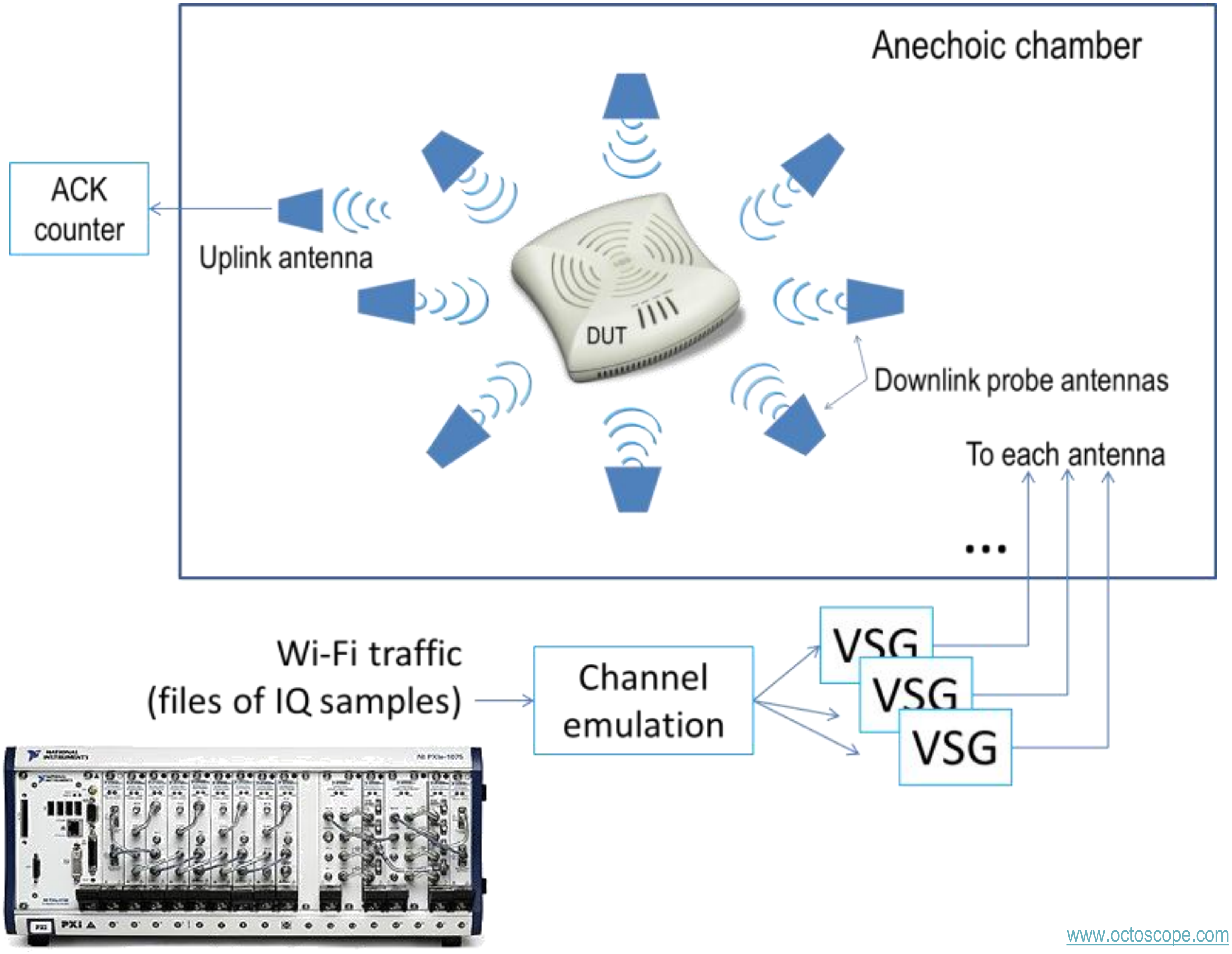
- MIMO/OTA modeling can be done in a large anechoic chamber with probes surrounding the DUT or in a small chamber modeling a single cluster
- 8 channel emulator DL RF ports are needed for 4 cross polarized probes modeling a cluster (configuration on left)

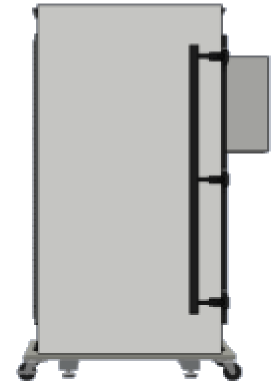
Anechoic Chamber Setup

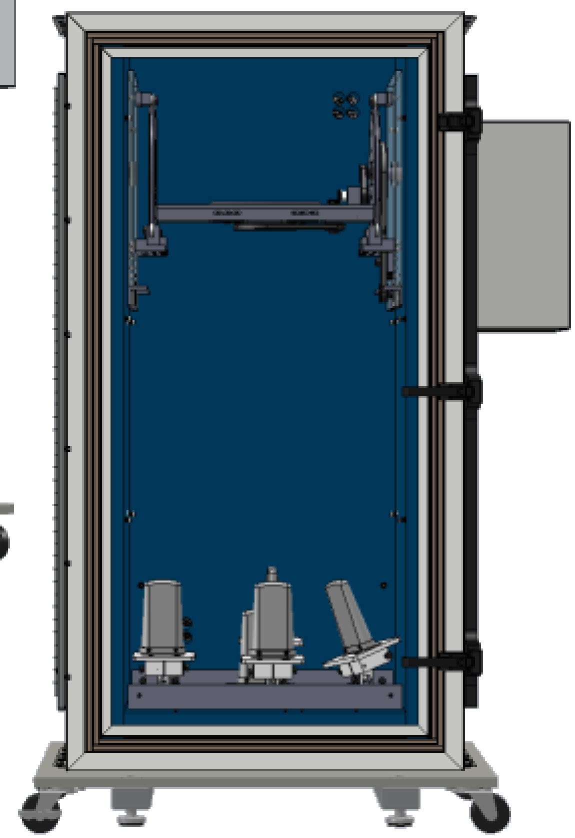


Single cluster small chamber needs 4 cross polarized antennas; big chamber would commonly have 8

Possible Wi-Fi Anechoic Chamber Setup





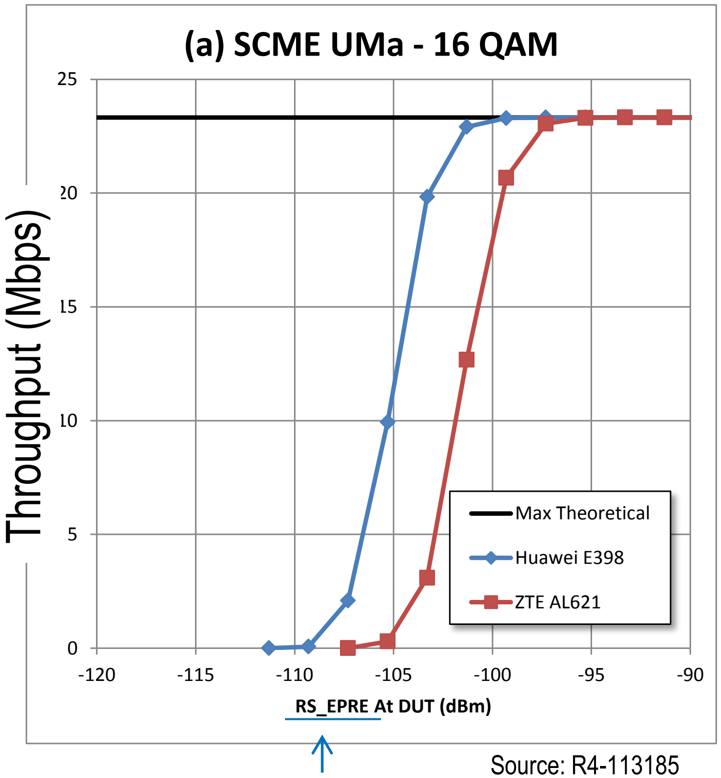


Single Cluster Setup Using octoBox II

MIMO/OTA Test Figure of Merit (FOM)

- Predominant MIMO/OTA FOM is averaged MIMO OTA throughput
  - Indicator of end-to-end link capacity
  - Measured actively with a BS emulator in a fading environment
  - Measured at top of UE LTE/HSPA physical layers
  - Performed with fixed or variable RCs (reference channels)
  - Typically measured while varying RX input power (sensitivity), SNR (co-channel interference), channel models and DUT orientation

Example MIMO/OTA Measurement



Source: R4-113185

Energy at DUT per LTE subcarrier
(i.e. per 15 kHz)

SCME = spatial channel model enhances
UMa = Urban Macro
Umi = Urban Micro

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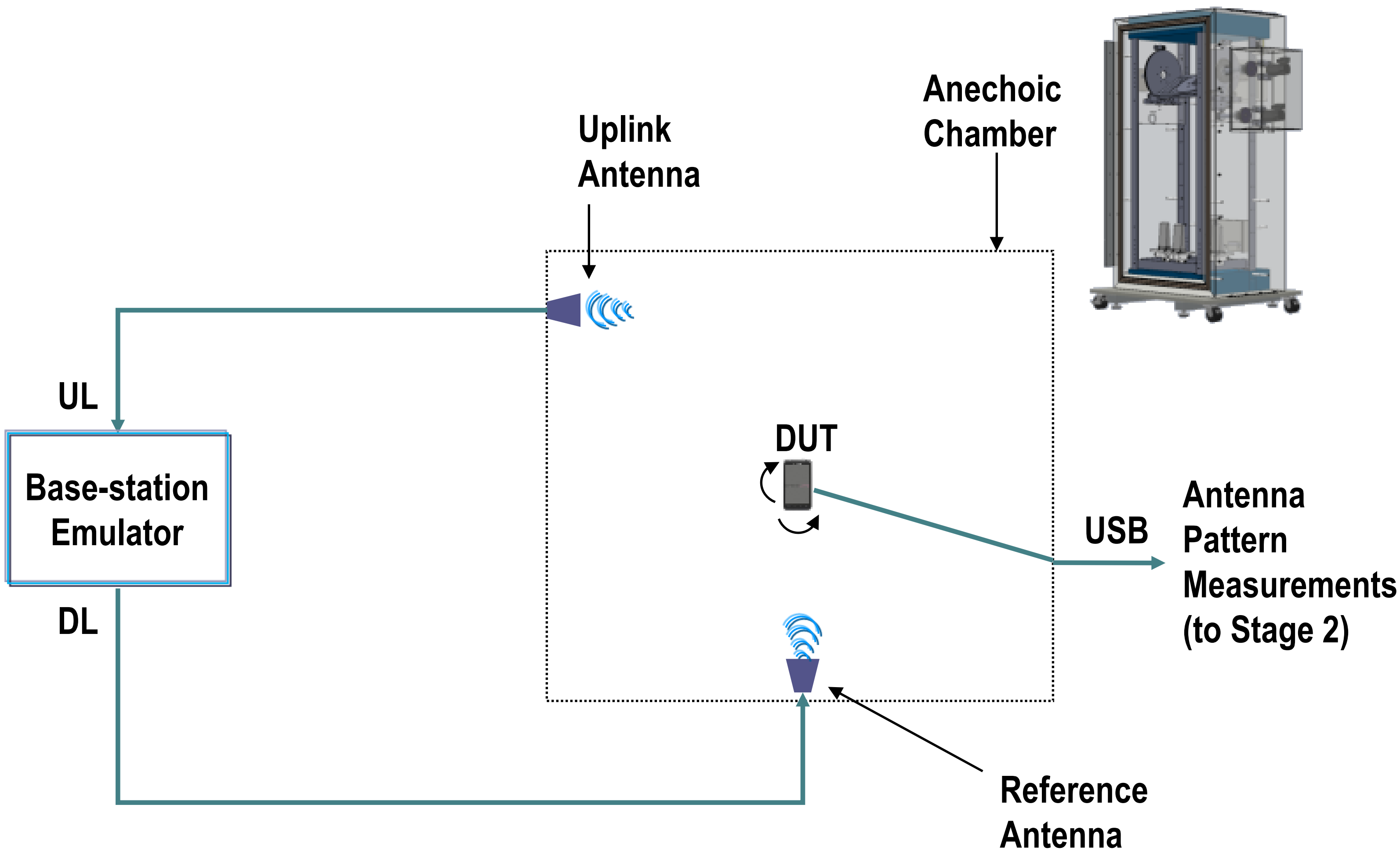
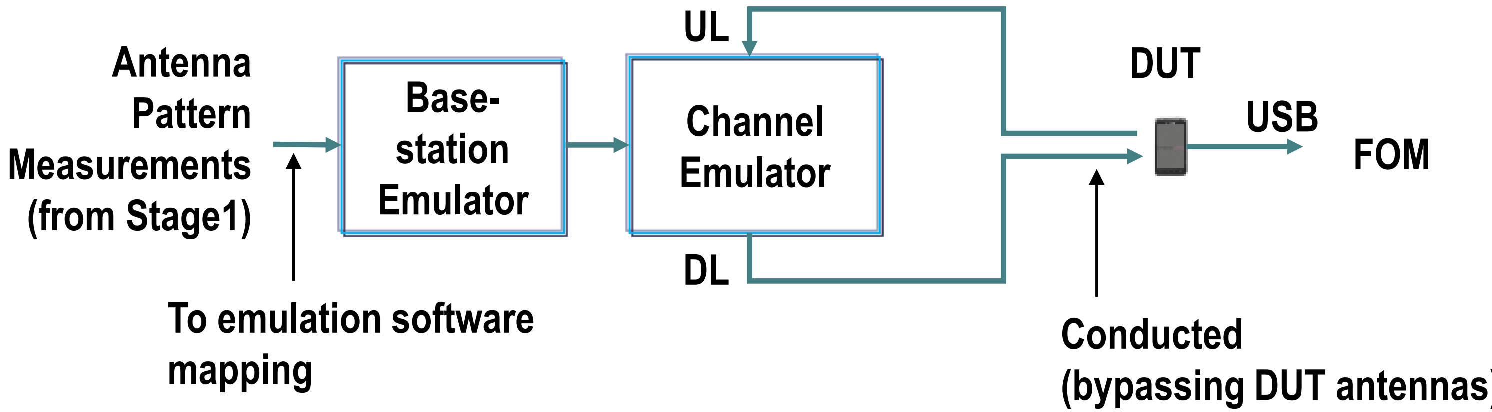
Two-Stage Method Setup (Stage 1)

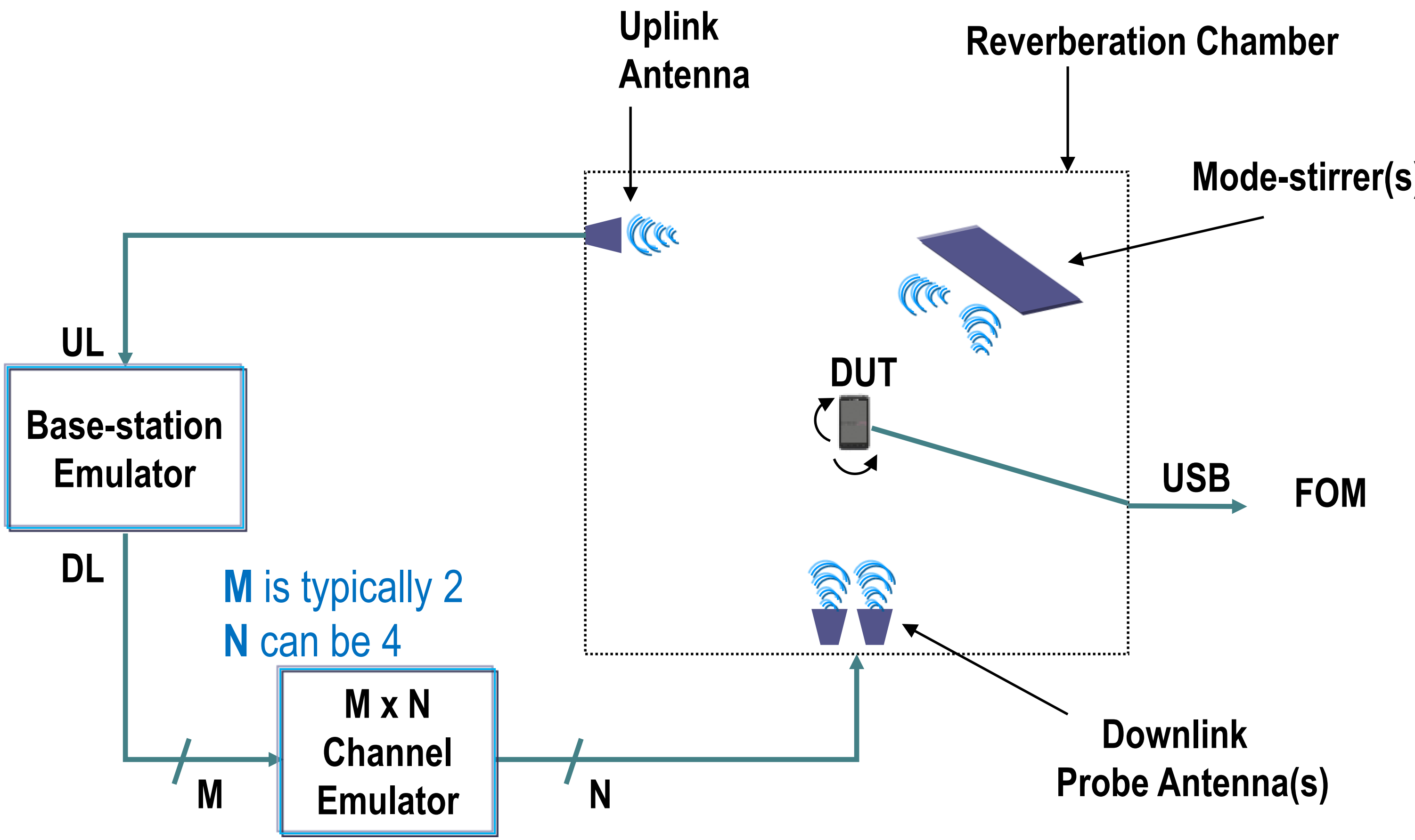


Two-Stage Method Setup (Stage 2)



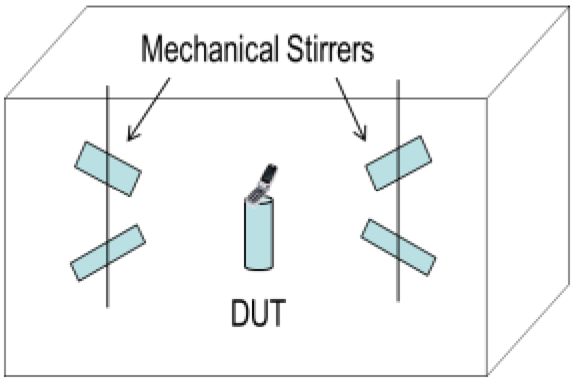
FOM = figure of merit

Reverberation Chamber Setup



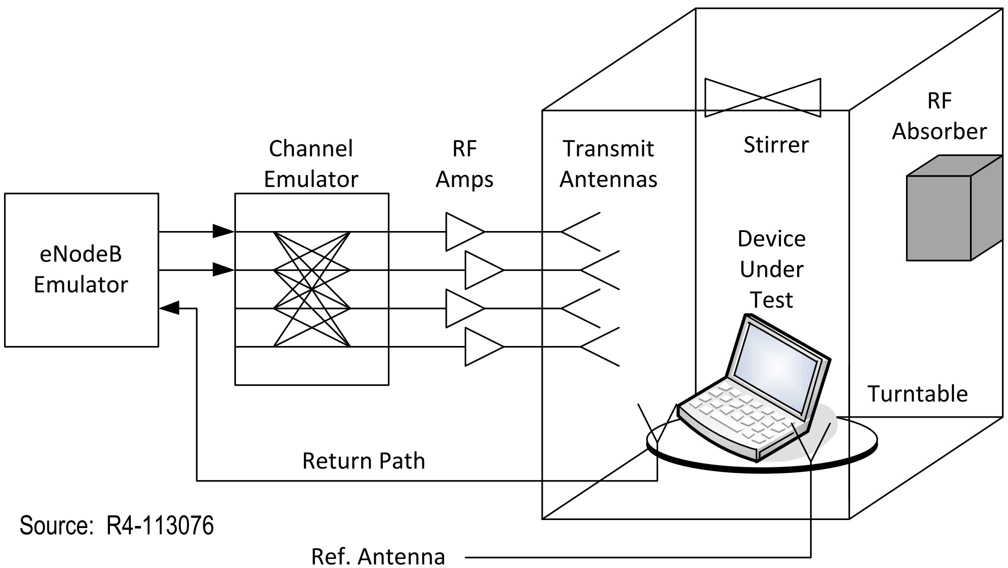
FOM = figure of merit

Reverberation Chamber Setup Example



Traditional reverb configuration
Doppler effects are modeled by stirrers

Uniform angular spread; difficult to reproduce a standards based model



Source: R4-113076

3GPP MIMO/OTA proposal
Doppler effects are modeled by stirrers; channel emulator provides more realistic Doppler

One of the 3GPP RAN4 round-robin test DUTs

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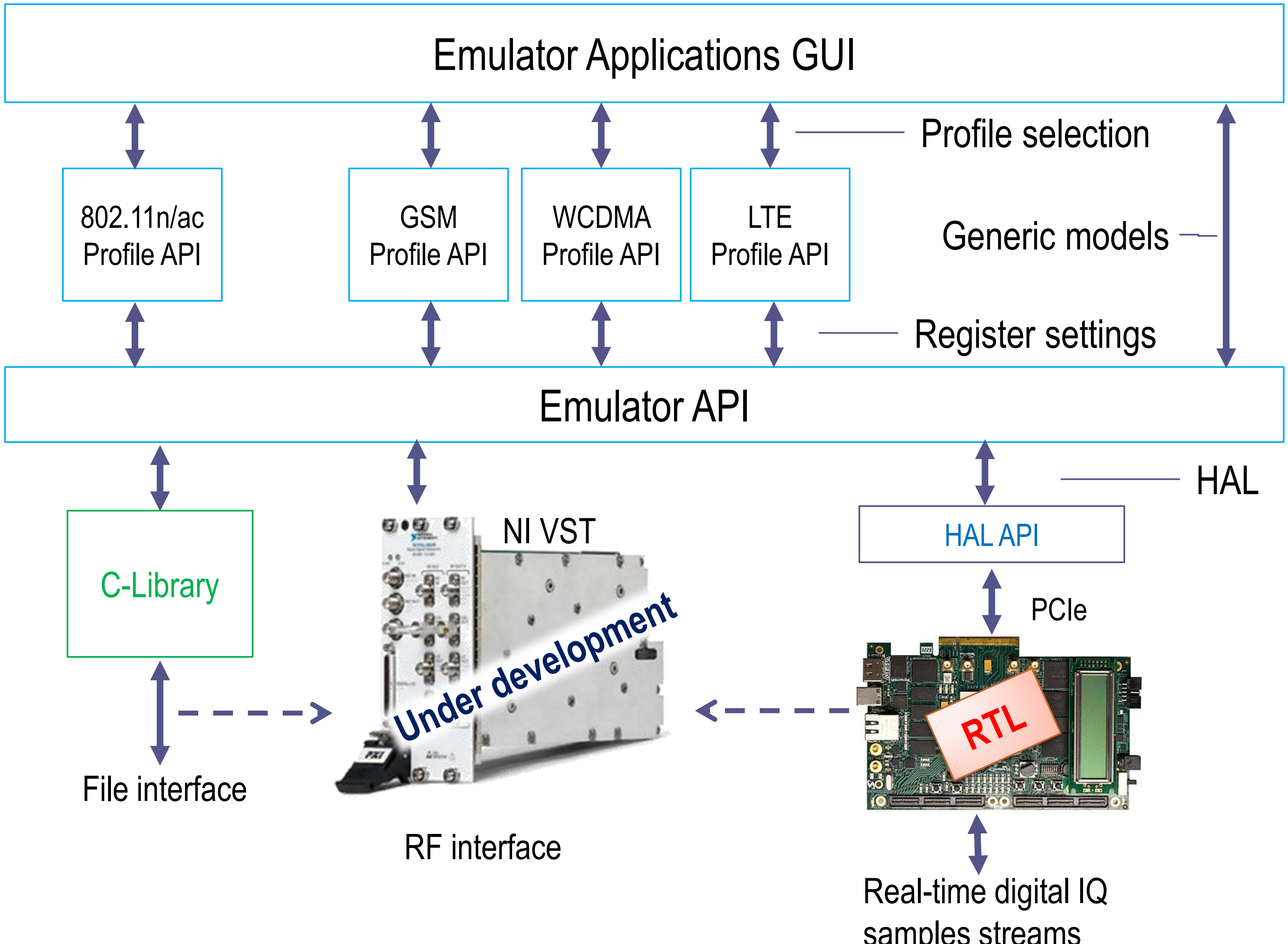
octoFade System Architecture



HAL = hardware abstraction layer
VST = vector signal transceiver

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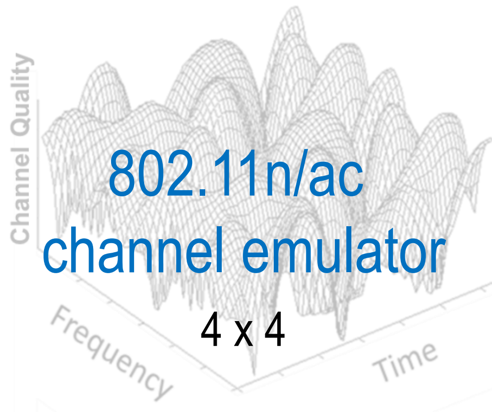
octoFade Software

Up to 4x4 MIMO configuration



802.11n/ac channel emulator

4 x 4

Impairments: AWGN, spurious, phase noise, IQ imbalance, frequency shift

4 streams

4 streams

Sample rate conversion

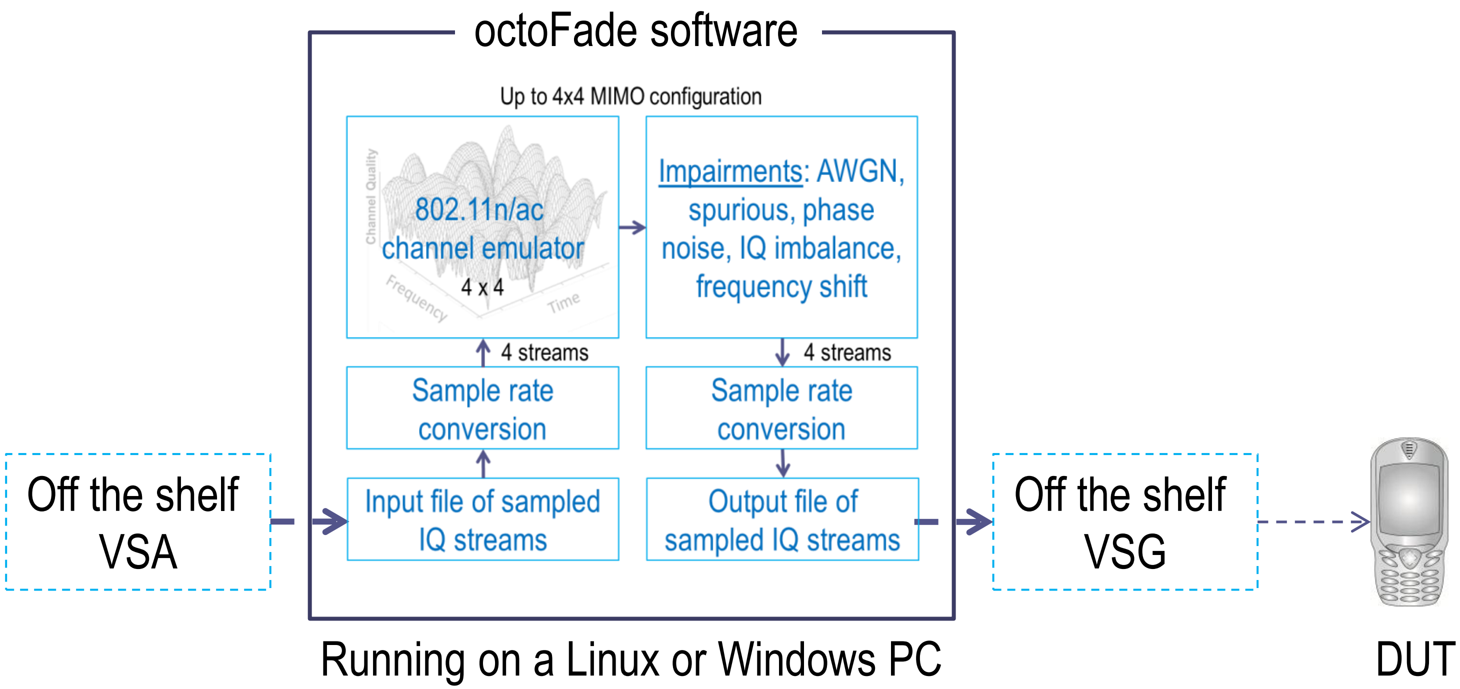
Sample rate conversion

Input file of sampled IQ streams

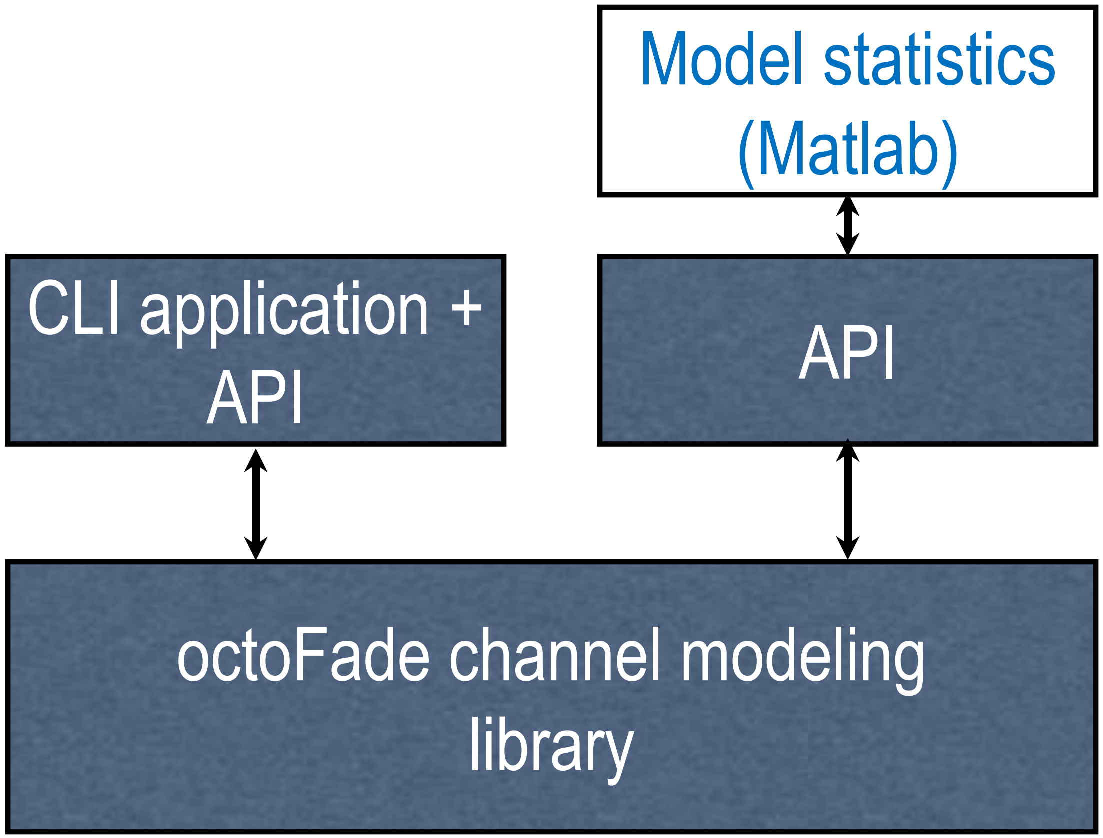
Output file of sampled IQ streams

AWGN = average white Gaussian noise

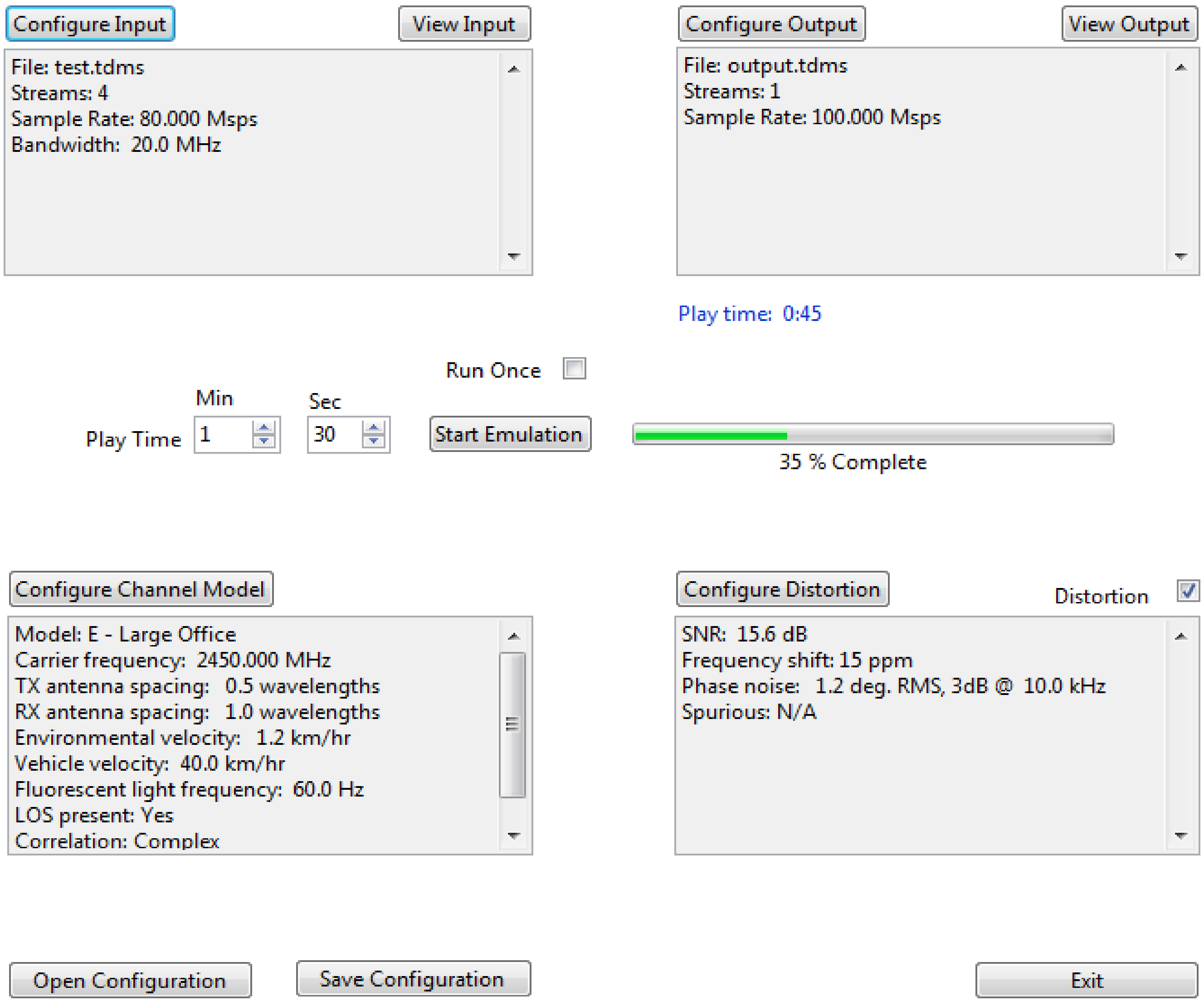
Use octoFade Software with Off-the-shelf Equipment



octoFade Software Architecture



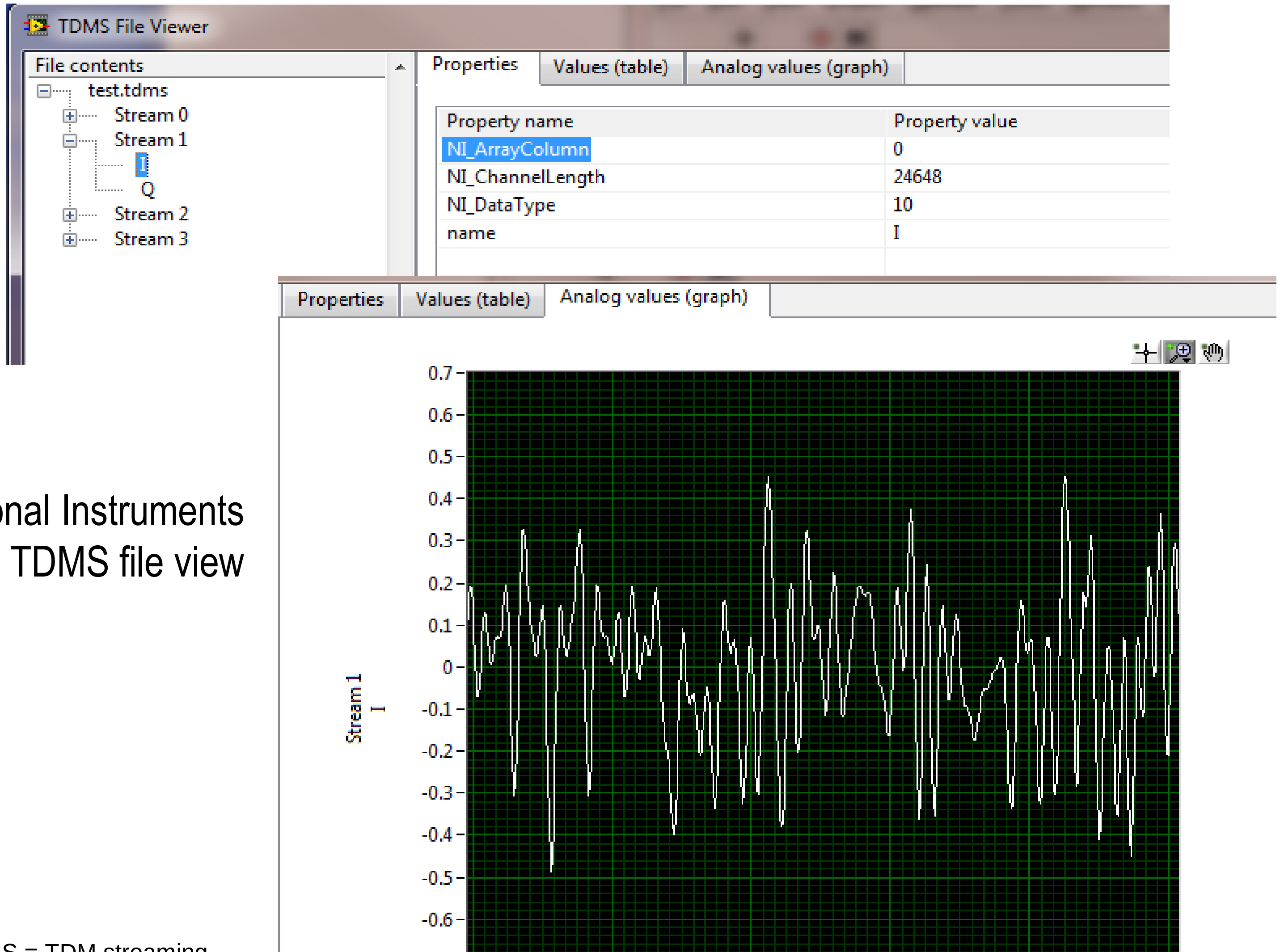
National Instruments LabVIEW Console



National Instruments LabVIEW application

Graphical programming environment

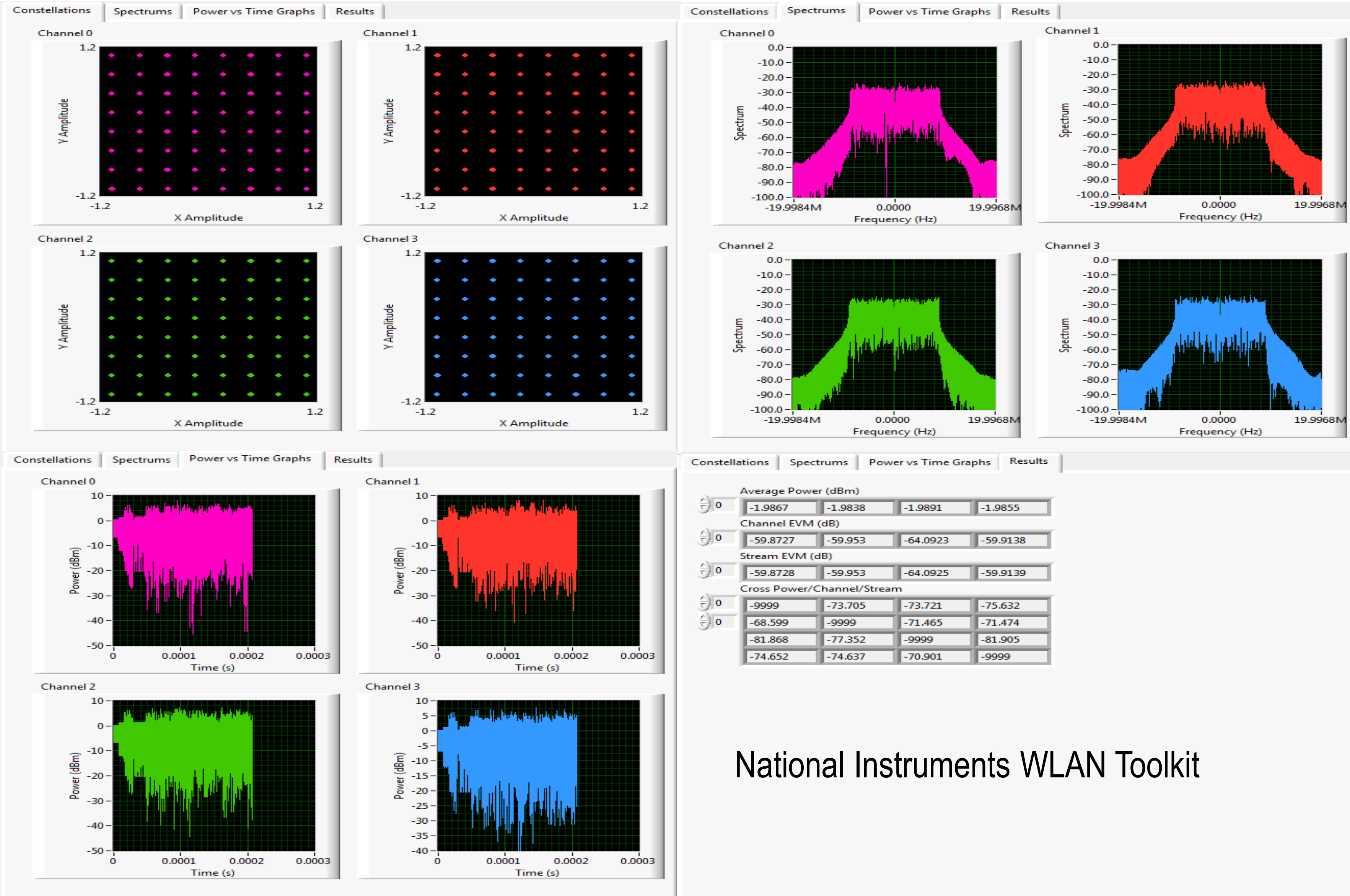
Viewing Input and Output Streams



National Instruments
TDMS file view

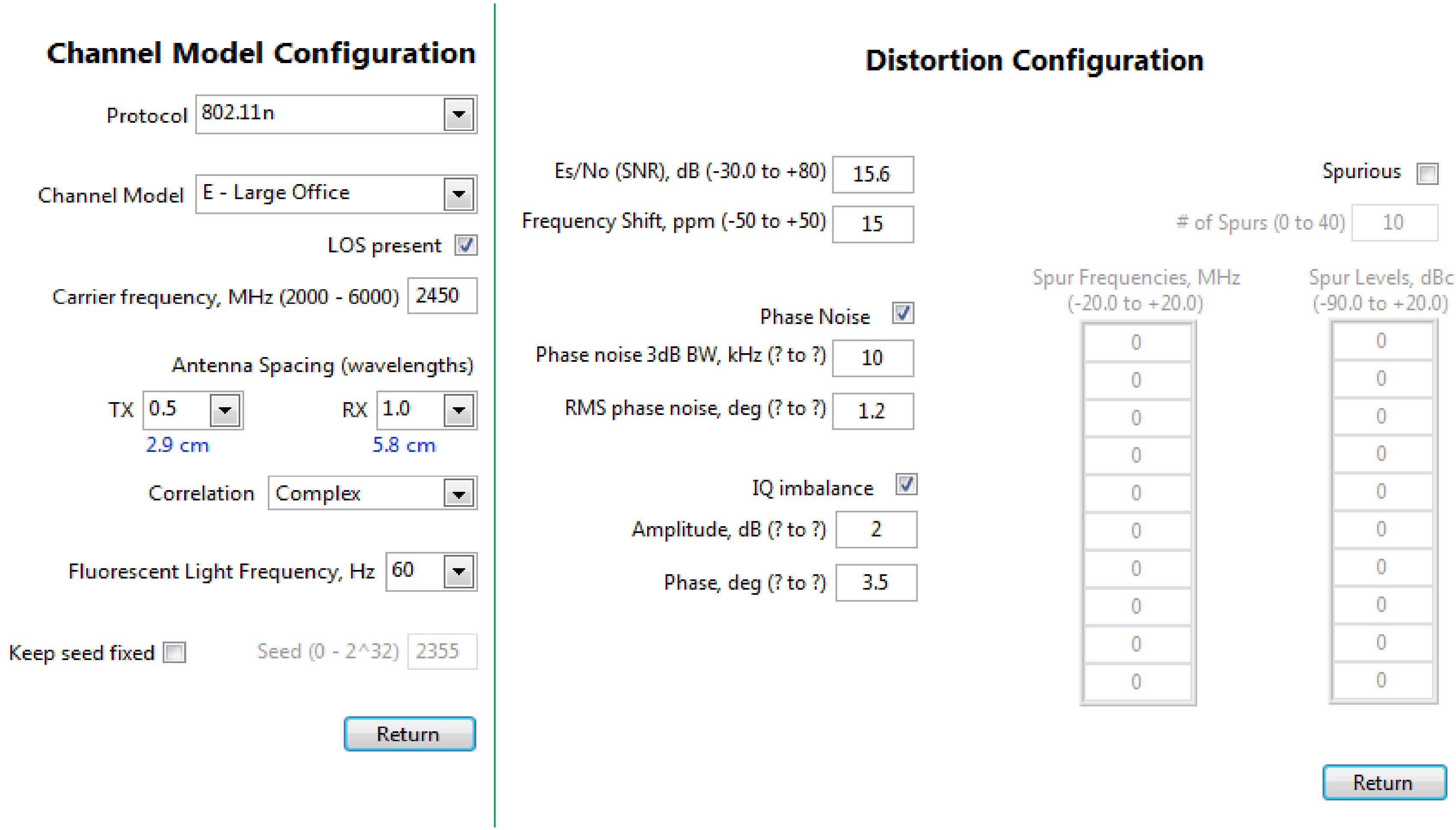
TDMS = TDM streaming
TDM = technical data management

Waveform Analysis



National Instruments WLAN Toolkit

Channel and Distortion Settings



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Supported Models and Building Blocks

Parameter	Model Name	References and Notes
3GPP Models (RTL)	**LTE:** EPA 5Hz; EVA 5Hz; EVA 70Hz; ETU 70Hz; ETU 300Hz; High speed train; MBSFN	3GPP TS 36.521-1 V10.0.0 (2011-12) Annex B 3GPP TS 36.101 V10.5.0 (2011-12) Annex B
	GSM: RAx; HTx; TUx; EQx; TIx	3GPP TS 45.005 V10.3.0 (2011-11) Annex C
	3G: PA3; PB3; VA30; VA120; High speed train; Birth-Death propagation; Moving propagation; MBSFN	3GPP TS 25.101 V11.0.0 (2011-12) Annex B 3GPP TS 25.104 V11.0.0 (2011-12) Annex B
IEEE 802.11n/ac Models (software)	A, B, C, D, E, F	IEEE 802.11-03/940r4; IEEE 11-09-0569
Static Models (software and RTL)	Identity matrix	Static bypass
	Butler matrix	Static, minimum correlation
Channel modelling building blocks (RTL)	Tap: delay, Doppler, PDP weight Path: list of taps System: NxM, correlation matrix	

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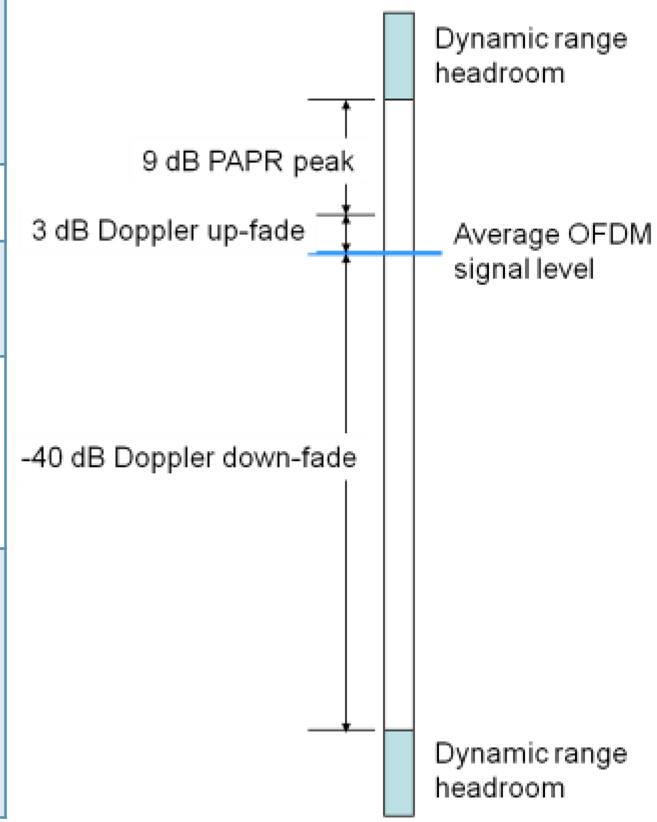
RTL DSP Specifications

Parameter	Specification	Notes
Number of IQ input paths	1-8	Unused inputs disabled where applicable
IQ input data format	18-bit	
Number of IQ output paths	1-8	Unused outputs set to zero where applicable
IQ output data format	18-bit	
Input/output sample rate	Up to 400 MHz	Current capability: 100 MHz
Channel bandwidth	Up to 160 MHz	Current capability: 40 MHz
Maximum number of total taps	FPGA resources-dependent	N x M x taps_per_TDL
Number of TDL blocks	Up to 64	
Number of taps per TDL block	FPGA resources-dependent	
Tap delay range	FPGA resources-dependent	Current capability: 30 usec
Minimum tap delay resolution	2.5 ns	Current capability: 10 ns
Tap weight range	0 to -50 dB	
Tap weight resolution	0.1dB	
Doppler shift	2 kHz	To support high speed train
SNR setting	-10 to +35 dB, average +/- 0.1 dB accuracy	
Noise filter bandwidth	Up to 160 MHz	Equal to preconfigured channel bandwidth

Subject to the availability of FPGA resources, octoScope can customize any of these specifications.

RF Front End Considerations

Parameter	Specification	Notes
MIMO configuration	8 x 8	To support emerging 802.11ac and LTE beamforming configurations
Bidirectionality	Important	To support beamforming
Bandwidth	160 MHz	To support emerging 802.11ac
Dynamic range (RF dynamic range, converter and DSP resolution)	Accommodate 52 dB of output signal dynamic range with little distortion	Signal fluctuation: +9 dB for PAPR +3 dB for up-fade -40 dB for down-fade
EVM	About 6 dB higher than EVM required for RF signal	For example, channel emulator's EVM should be at least 36 dB over the entire dynamic range to minimize distortion of a 30 dB EVM 802.11n signal



Outline

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

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References

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2. IEEE, 11-09-0569 , “TGac Channel Model Addendum Supporting Material”, May 2009
3. 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
4. IEEE 802.11-09/0308r12, “TGac Channel Model Addendum”, March 18, 2010
5. IEEE, 11-09-0334-08-00ad-channel-models-for-60-ghz-wlan-systems
6. Schumacher et al, "From antenna spacings to theoretical capacities - guidelines for simulating MIMO systems"
7. 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
8. 3GPP 36-521, UE Conformance Specification, Annex B
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10. 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)
11. 3GPP TR37.976, MIMO OTA channel models
12. 3GPP TS 34.114: “User Equipment (UE) / Mobile Station (MS) Over The Air (OTA) Antenna Performance Conformance Testing”
13. CTIA, “Test Plan for Mobile Station Over the Air Performance - Method of Measurement for Radiated RF Power and Receiver Performance”, Revision 3.1, January 2011

Thank you!

For additional information, please visit our website
articles, white papers and test reports

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