NASCTN Project Out-brief
Characterizing User Equipment Emissions – Sponsored by DSO
May 13th, 2021

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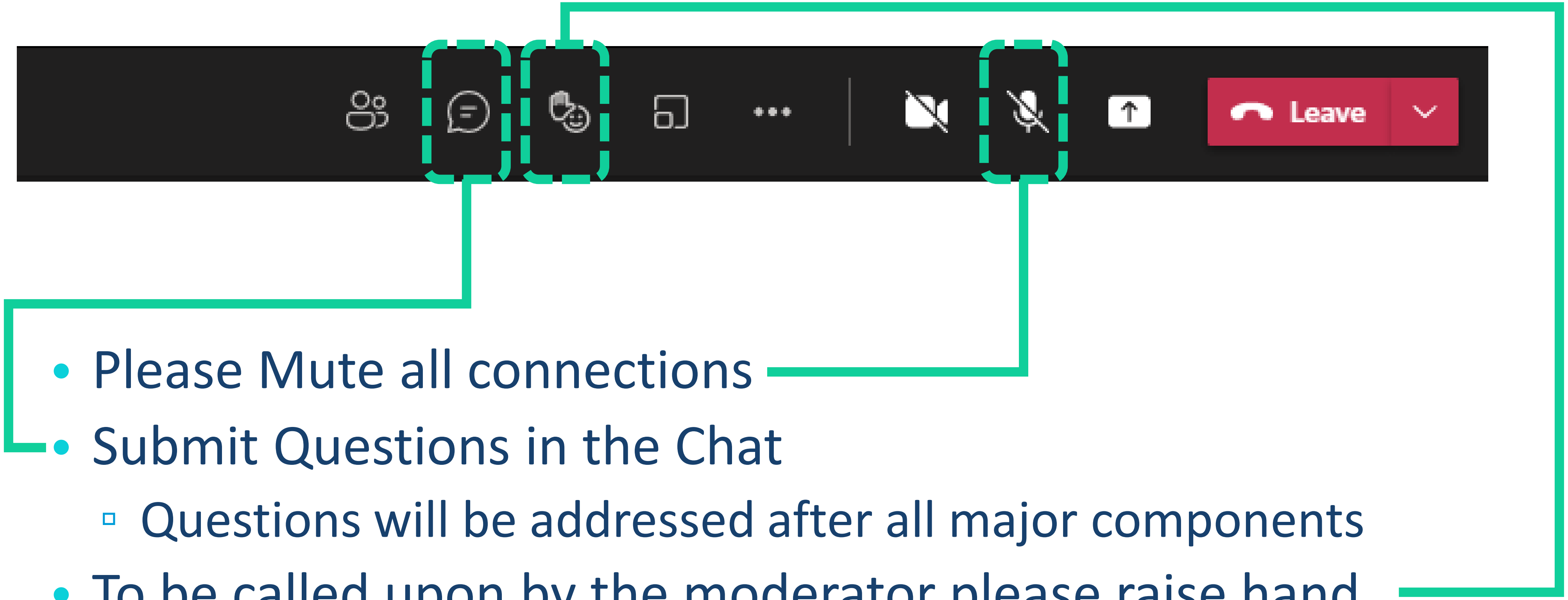
Audience Instructions

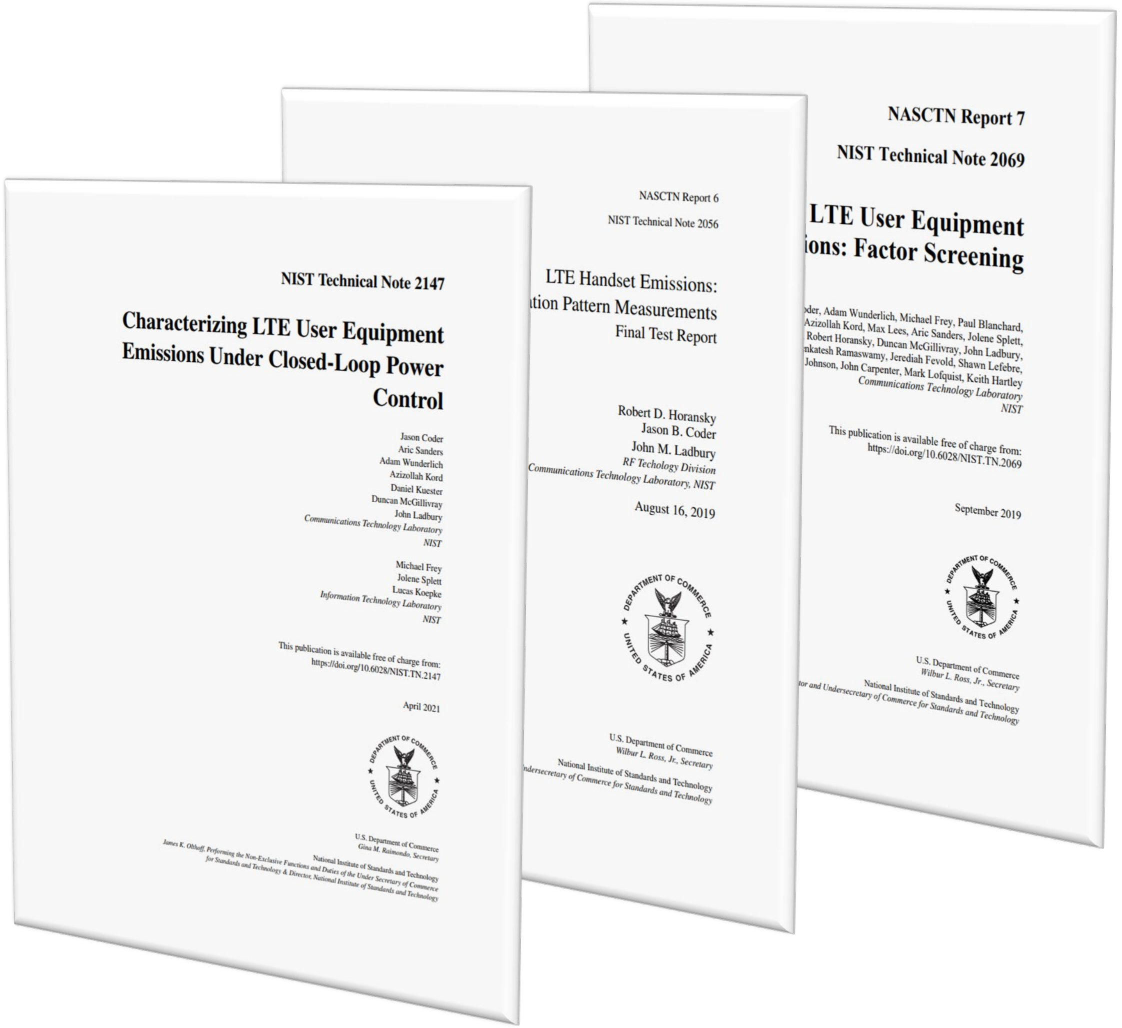


- Please Mute all connections
- Submit Questions in the Chat
  - Questions will be addressed after all major components
- To be called upon by the moderator please raise hand

NASCTN
National Advanced Spectrum
and Communications Test Network

Outline

- Project Overview
    - Background & Problem Statement
- Part I: Factor Screening (TN 2069)
    - Identification of Factors and Testbed Setup
    - Design of Experiment
    - Statistical Analysis & Results
    - Engineering Interpretation
- Part II: Closed-Loop Power Control (TN 2147)
    - Background, objective
    - Measurements
    - Statistical Analysis
- Engineering Analysis
    - UE Antenna Pattern Measurements (TN 2056)
    - UE Measured vs. Reported Power
    - Scheduling Dynamics in Negative Power Headroom
    - UE's Measurement of Path Loss
- Conclusions and Q&A
    - (30 minutes)



NIST Technical Note 2147

Characterizing LTE User Equipment
Emissions Under Closed-Loop Power
Control

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April 2021

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
James K. Olthoff, Performing the Non-Exclusive Functions and Duties of the Under Secretary of Commerce
for Standards and Technology & Director, National Institute of Standards and Technology

NASCTN Report 6

NIST Technical Note 2056

LTE Handset Emissions:
tion Pattern Measurements
Final Test Report

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August 16, 2019

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
ndersecretary of Commerce for Standards and Technology

NASCTN Report 7

NIST Technical Note 2069

LTE User Equipment
ions: Factor Screening

der, Adam Wunderlich, Michael Frey, Paul Blanchard,
Azizollah Kord, Max Lees, Aric Sanders, Jolene Splett,
Robert Horansky, Duncan McGillivray, John Ladbury,
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This publication is available free of charge from:
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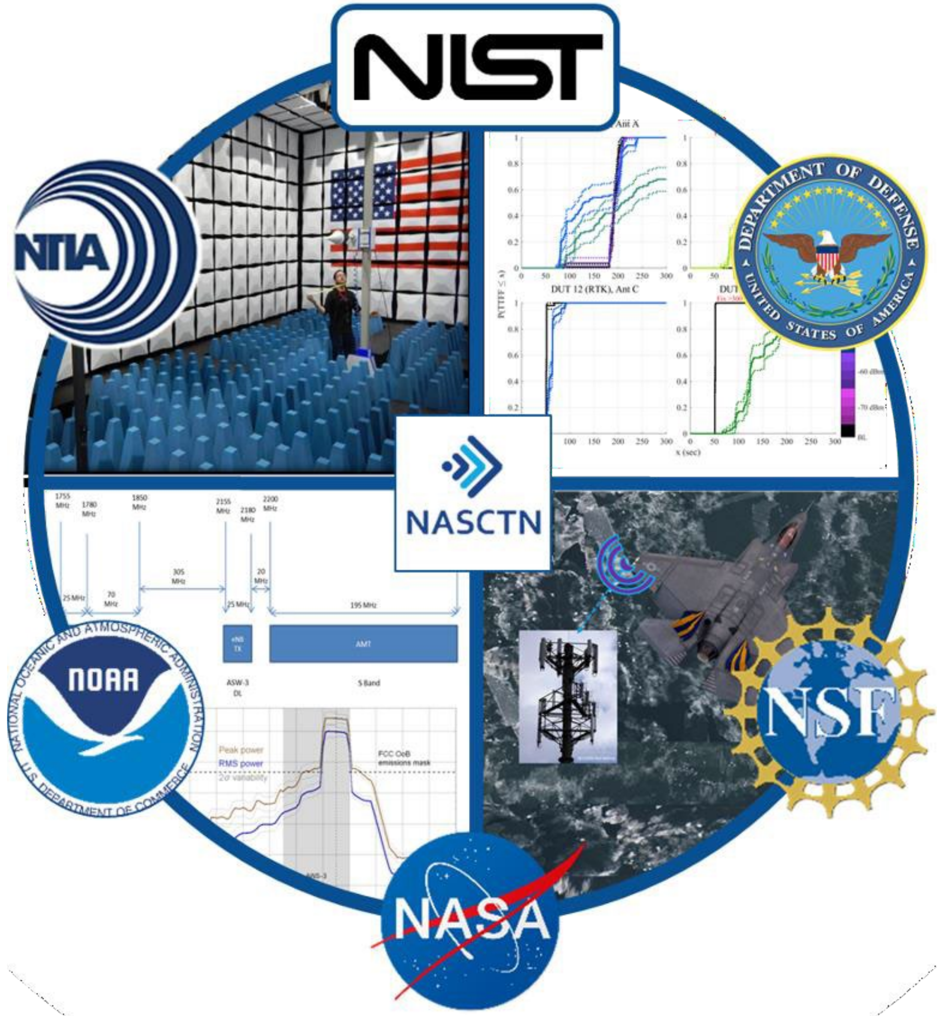
September 2019

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
tor and Undersecretary of Commerce for Standards and Technology

Note: clickable links to reports included above

National Advanced Spectrum and Communications Test Network (NASCTN)



- Established in 2015 by NIST, the U.S. DoD, and NTIA. In 2018, added NOAA, NSF, and NASA.
- Organizes a national network of federal, academic, and commercial test facilities
- Provides trusted spectrum testing, modeling, and analysis to develop and deploy spectrum-sharing technologies and inform future spectrum policy and regulations.

NASCTN MISSION

To provide, through its members, **robust test processes** and **validated measurement data** necessary to develop, evaluate and deploy spectrum sharing technologies that can **improve access to the spectrum** by both federal agencies and non-federal spectrum users.

- Develop scientifically rigorous test plans and new methodologies with independent experts
- Access to key test facilities, and commercial and federal equipment and capabilities
- Provide validated data and models for use within the spectrum sharing community

Operates as a trusted agent and protect proprietary, sensitive, and classified information

Test Team and Collaborators

Testbed

Jason Coder*

Technical Lead

Dan Kuester

Data Acquisition and Testbed Automation

Aziz Kord

LTE Engineering

John Ladbury

RF Metrology and Uncertainty Characterization

Rob Horansky*

Radiation Pattern Measurements

Duncan McGillivray

Final Testbed Construction

Shane Allman

Testbed Automation

*Speaker

Experimental Design, Data Processing & Analysis

Adam Wunderlich*

Technical Lead

Aric Sanders*

Data Analysis

Paul Blanchard

Data Parsing

Max Lees

Data Analysis

Michael Frey*, Jolene Splett, Lucas Koepke

Statistics

Programmatic Support

Melissa Midzor*, Matt Briel, Amanda Hyman, Fabio Da Silva, Michael Janezic, Linda Derr – NIST; Joe Mruk, Keith Hartley, Mark Lofquist - MITRE

External Technical Experts

Jeff Correia, Venki Ramaswamy - MITRE

JD Fevold, Shawn Lefebre, Jacob Johnson - MITRE

Arnab Das – JHU APL

Project Overview - Objective

- Design, demonstrate, & validate a test methodology to measure LTE UE emissions for use in aggregate interference calculations.
  - Key Elements:
    - Collect measurements in a controlled laboratory setting
      - Control or mitigate uncontrolled variables present in field measurements
      - Test a wide range of network configurations/morphologies
    - Rigorous uncertainty assessment and statistical analyses
    - Ensure the results are repeatable

Background

- Develop a better understanding of LTE UE emissions for use in aggregate interference calculations.
    - Ideally, everyone would like a perfect, predictive model that explains emissions in a variety of circumstances. Not easy!
- NASCTN's approach: Controlled measurement of LTE equipment emissions in a laboratory environment
    - Cover a wide range of network configurations/morphologies
    - Publish the measurement method, data, and results
- Specific case
    - AWS-3 Frequency Band Auction in 2015. ~$41B in net proceeds. Coordination with incumbent users required in certain geographic areas.
        - **Uplink: 1710 MHz – 1780 MHz**
        - Downlink: 2110 MHz – 2200 MHz
- Project divided into two phases:
    - Factor Screening: "What factors influence the amount of energy a UE radiates?"
    - Closed-Loop Power Control (CLPC): "Assuming CLPC is used, how well can we describe emissions behavior?"

Project Deliverables

Primary

1. Distribution of EIRP from a UE in an active resource block, over an appropriate range of path loss values, UE settings, and LTE network settings
2. Comparison of UE-reported and measured power distributions
3. UE beam pattern measurements and TRP calculations

Secondary

1. Engineering Analysis and Interpretation
   a) UE's measurement of path loss
   b) Scheduling dynamics
2. Ideas for future measurements (both laboratory and in-field)

Part I: Factor Screening

What factors influence the amount of energy a UE radiates?

Factor Selection

- Brainstorm factors that may impact UE uplink emissions
  - Based on LTE expertise, prior literature, and public comment
- Which factors have a statistically significant impact?
  - “Engineering judgement” may be necessary in some cases
- 28 total factors:

  8 non-eNB, 20 eNB

Identifer	Testbed Component	Factor
A	Variable Attenuator	Path Loss (Simulated DUT UE Position)
B	UTG	Spatial Size of Cell
C	UTG	Number of Loading UEs in Serving Cell (Cell A)
D	UTG	Number of Loading UEs in Adjacent Cell (Cell B)
E	UTG	Spatial Distribution of Loading UEs in Cell A
F	UTG	QCI Value of Loading UEs
G	DUT UE/UTG	Traffic Data Rate
H	DUT UE/UTG	Traffic Type (UDP/TCP)
I	eNB	UL Scheduling Algorithm Type
J	eNB	UL Scheduler FD Type
K	eNB	Power Control Type (Closed Loop/Open Loop)
L	eNB	SRS Config
M	eNB	SRS Offset
N	eNB	PUCCH Power Control: P_0
O	eNB	PUSCH Power Control: P_0
P	eNB	Power Control: α
Q	eNB	Receive Diversity
R	eNB	Filter coefficient for RSRP measurements
S	eNB	Maximum uplink transmission power (own cell)
T	eNB	Minimum PRB allocation for power-limited UEs
U	eNB	UL Improved Latency Timer Reaction
V	eNB	Initial Max # of Resource Blocks
W	eNB	Outer Loop Link Adaptation
X	eNB	Uplink link adaptation
Y	eNB	Cell Scheduling Request Periodicity
Z	eNB	Scheduling Weight UL for SRS
a	eNB	Blanked PUCCH Resources
b	eNB	Target UL Outer Scheduling

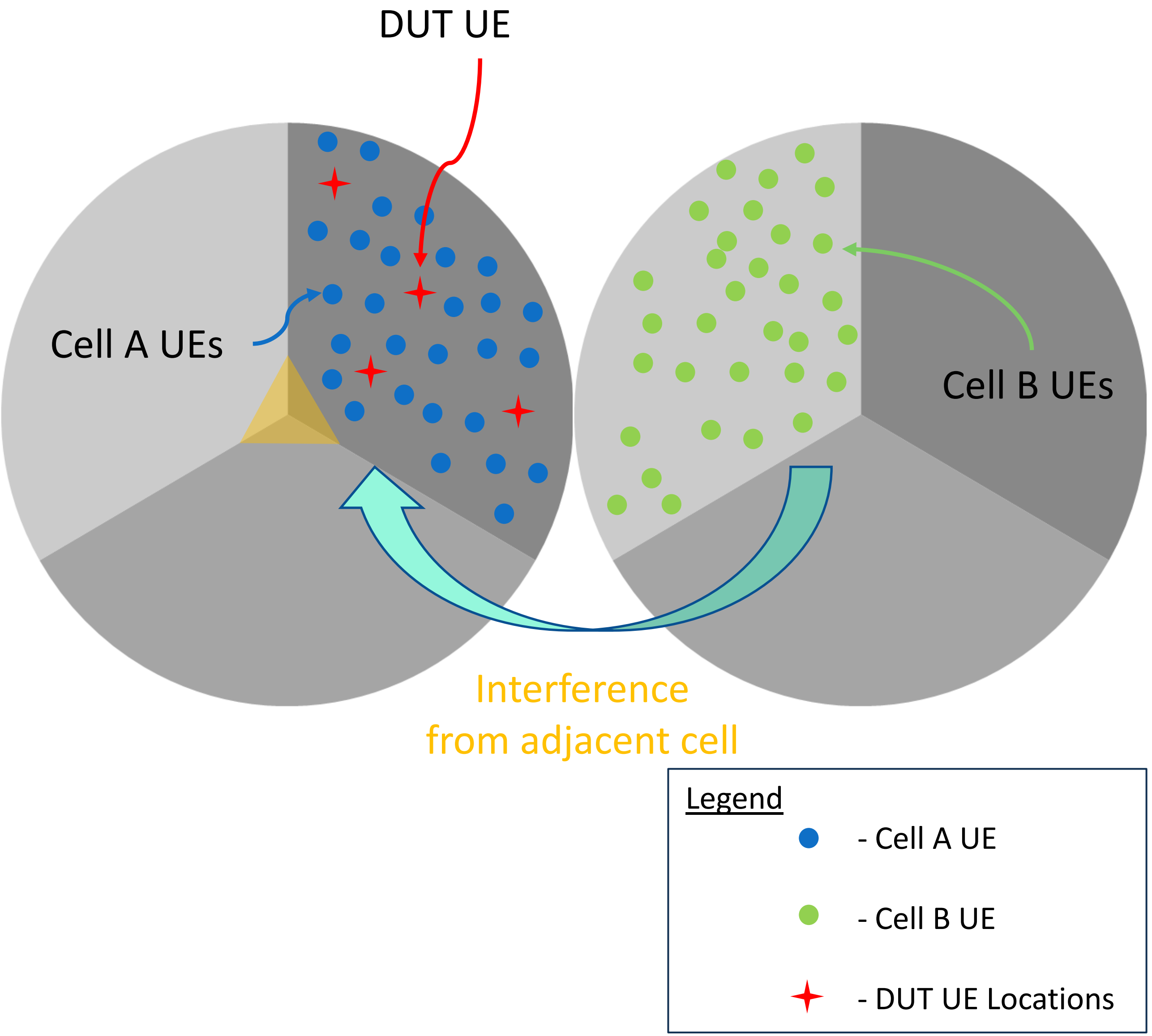
Measurement Concept

1) Cell A and Cell B are loaded with UEs
2) Cell A UEs load eNB scheduler
3) Cell B UEs increase noise at eNB

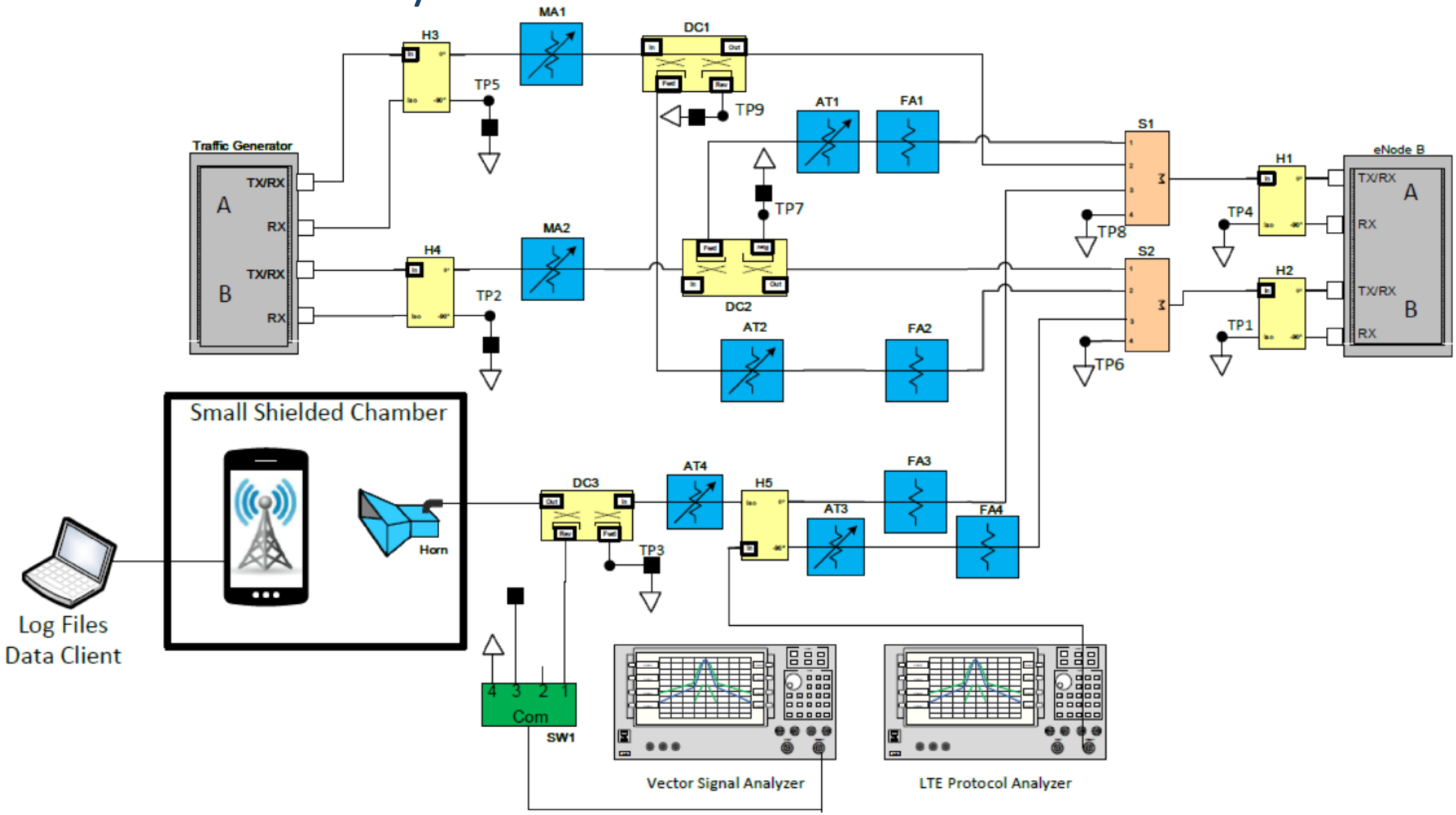
At different positions of DUT UE

1) Measure DUT UE emitted power
2) Measure DUT UE emitted spectrum
3) …and many other parameters for analysis, error checking, and troubleshooting

DUT UE = Commercial-off-the-shelf phone



Measurement System



Data Sources

- Collecting, parsing and synchronizing data from three sources:

1) Vector Signal Analyzer (VSA) Spectrograms
    - 1 ms time-resolution – Raw spectrograms processed to remove noise and blurring
    - Two consecutive 5 second captures for each test configuration
    - Power in each physical resource block (PRB)

2) UE Traffic Generator (UTG) logs
    - 0.5 sec time-resolution
    - Number of UEs signaled per transmit time interval (TTI), distribution of PRB allocations across loading UEs

3) UE diagnostic software logs
    - 1 ms time-resolution
    - Active PRBs (PUSCH, PUCCH, SRS), UE-Reported Tx Power, Power Headroom Report (PHR), Modulation and Coding Scheme (MCS) Index, Buffer Status Report (BSR), …

- Data used for test verification and deliverables

Factor Screening:
- Design of Experiment -

Speaker: Adam Wunderlich

Factor List

Identifer	Testbed Component	Factor	# Levels
A	Variable Attenuator	Path Loss (Simulated DUT UE Position)	2
B	UTG	Spatial Size of Cell	2
C	UTG	Number of Loading UEs in Serving Cell (Cell A)	2
D	UTG	Number of Loading UEs in Adjacent Cell (Cell B)	2
E	UTG	Spatial Distribution of Loading UEs in Cell A	2
F	UTG	QCI Value of Loading UEs	2
G	DUT UE/UTG	Traffic Data Rate	2
H	DUT UE/UTG	Traffic Type (UDP/TCP)	2
I	eNB	UL Scheduling Algorithm Type	3
J	eNB	UL Scheduler FD Type	3
K	eNB	Power Control Type (Closed Loop/Open Loop)	2
L	eNB	SRS Config	2
M	eNB	SRS Offset	2
N	eNB	PUCCH Power Control: P_0	2
O	eNB	PUSCH Power Control: P_0	2
P	eNB	Power Control: α	2
Q	eNB	Receive Diversity	2
R	eNB	Filter coefficient for RSRP measurements	2
S	eNB	Maximum uplink transmission power (own cell)	2
T	eNB	Minimum PRB allocation for power-limited UEs	2
U	eNB	UL Improved Latency Timer Reaction	2
V	eNB	Initial Max # of Resource Blocks	2
W	eNB	Outer Loop Link Adaptation	2
X	eNB	Uplink link adaptation	2
Y	eNB	Cell Scheduling Request Periodicity	2
Z	eNB	Scheduling Weight UL for SRS	2
a	eNB	Blanked PUCCH Resources	2
b	eNB	Target UL Outer Scheduling	2

Abbreviations:

DUT = Device Under Test
UE = User Equipment (cell phone)
UTG = UE Traffic Generator
eNB = evolved node B (base station)
QCI = quality of service class ID
PUSCH = uplink shared channel
PUCCH = uplink control channel
SRS = Sounding reference signal

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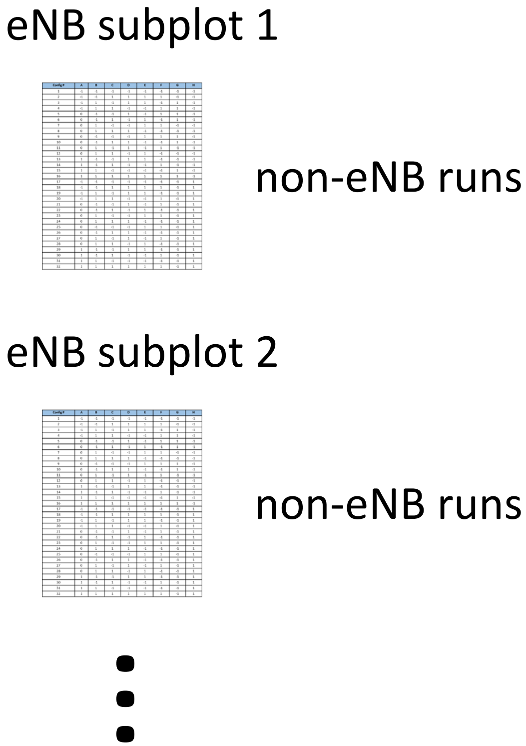
Design Considerations

- 28 factors: 8 non-eNB and 20 for the eNB. Two 3-level factors
- Constraints on factors (I, J, L, M, X) – scheduler & SRS
  - not all combinations of eNB settings are possible
- Design Goals:
  - Minimize number of eNB factor changes
  - Ensure that main effects are not confounded by other main effects
    - i.e., estimates of main effects are uncorrelated

Experimental Design Overview

- 32-run design for eNB factors crossed with a 32-run for non-eNB factors
  - eNB design: resolution III orthogonal array
    - (I, J, L, M, X) combined into one 16-level factor
  - Non-eNB design: resolution IV fractional factorial
- To minimize eNB factor changes, change eNB and non-eNB factors in two nested loops
  - Outer loop: 32 eNB configurations
  - Inner loop: 32 non-eNB configurations
- Known as a “split-plot” design in the experimental design literature



eNB subplot 1

non-eNB runs

eNB subplot 2

non-eNB runs

⋮

Implementation Details

- Randomization
  - Test the 32 eNB configurations in random order
  - Test each block of 32 non-eNB configurations in random order
- Physically change DUT UE every 4 eNB configs
  - Interchange with another UE of same model (2 UEs of same model used)
  - Enables estimates of variability across test conditions
- Test a reference eNB configuration every day
  - Provides a baseline that can be tracked with time
  - Same UEs used for Rounds 1 & 3 and 2 & 4, respectively
- Valid test time for full design + baselines ≈ 54 hours
- Repeat 4 times to maximize chance of conclusive findings
  - Total valid test time ≈ 216 hours

Factor Screening Experiment
- Statistical Analysis & Results -

Speaker: Mike Frey

Factor screening experiment

Purpose: Vary experiment factors among their different levels to discover which factors have statistically discernible, important effects on a measured variable called the response.

- The response, measured PUSCH power, is a distribution; we represent it by its 99 percentiles $C_1, C_2, \ldots, C_{99}$ and work with

$$C_{50}, \quad C_S = C_{95} - C_5, \quad C_Q = (C_{95} - C_{50}) - (C_{50} - C_5).$$

- 22 two-level factors plus 1 sixteen-level factor Ω.
- The factor Ω is a combination of 5 two- and three-level factors.

What is a p-value?

A p-value is the probability, under a null condition, that a test statistic is more extreme than observed in experiment.

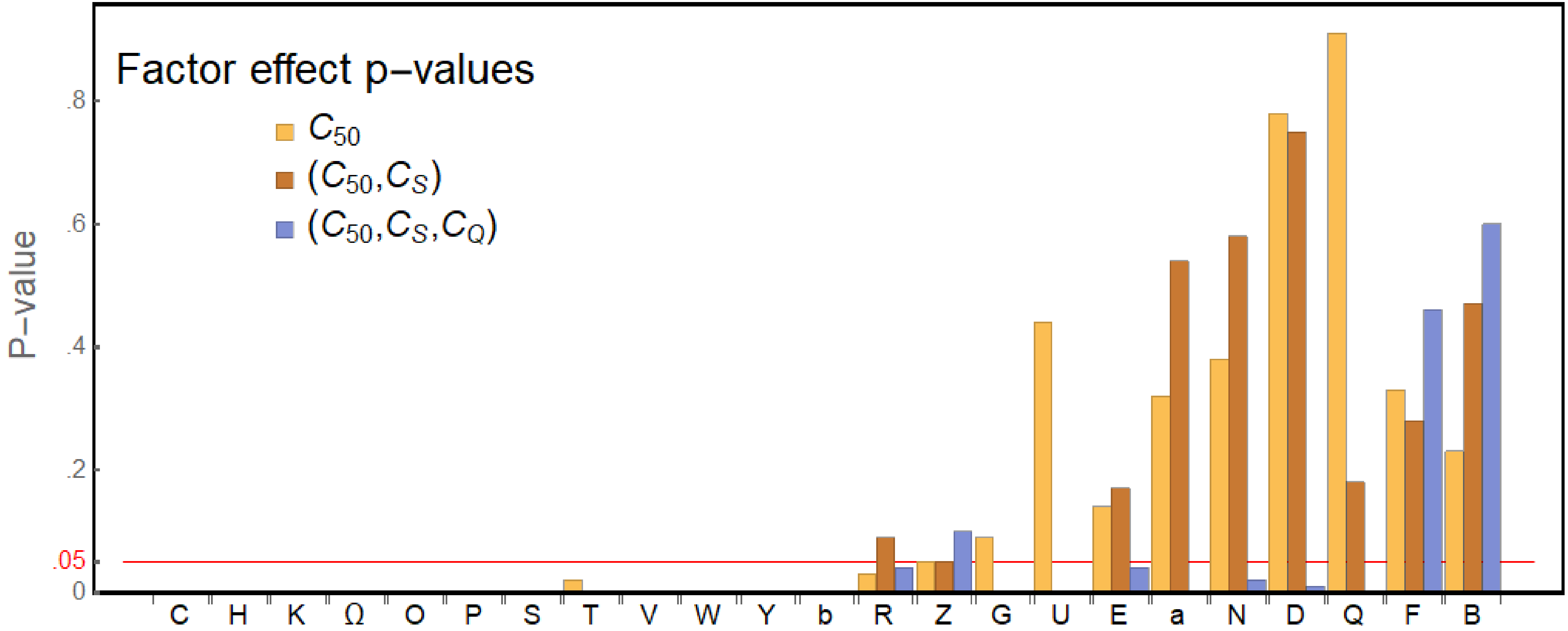
Intuition: A p-value is the strength of the evidence that an observed factor effect is not just random variation.

Range: A p-value is a number between 0 and 1.

Caution: The *smaller* the p-value, the *stronger* the evidence for a discernible factor effect.

Decision rule: P-value $\leq \alpha\ (= 0.05) \Longrightarrow$ factor has a discernible effect on the response. α is called the significance level; it is our standard of evidence.

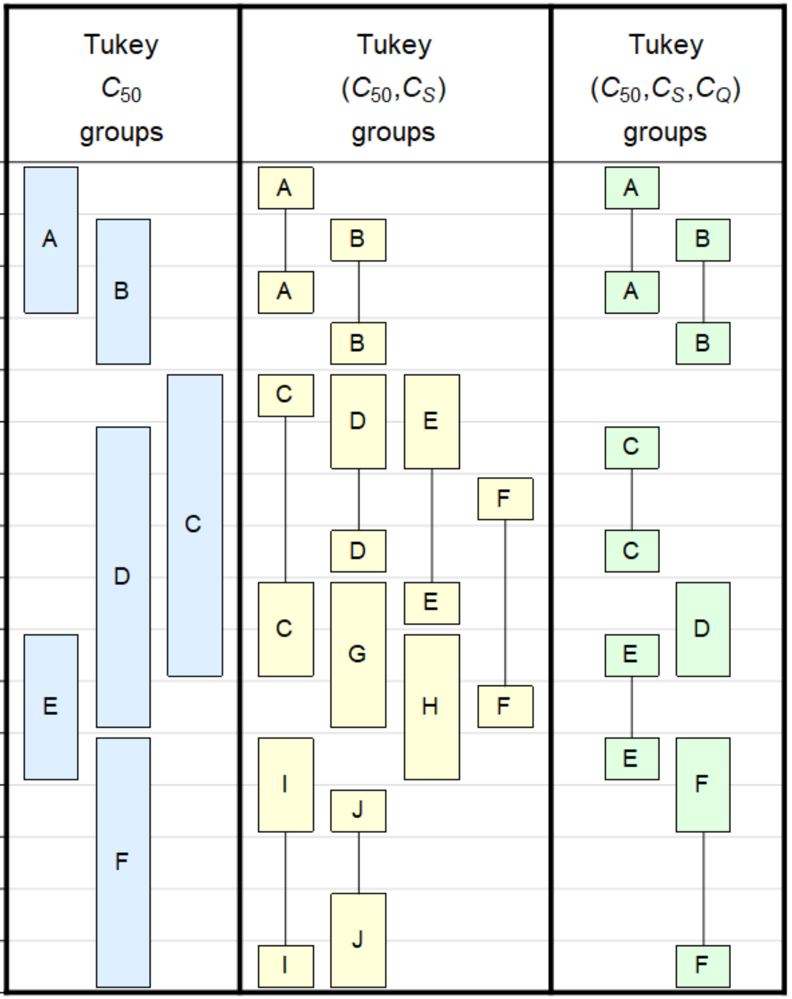
ANOVA and MANOVA p-values for factor effects



The sixteen-level factor Ω is significant

(statistically significant ⇔ p-value ≤ α ⇔ *some* discernible effect)

16 levels of Ω	Subfactors I	J	L	M	X	C_{50} (dB)	C_S (dB)	C_Q (dB)
4	1	1	1	−1	1	4.6	2.55	0.35
11	0	−1	1	1	1	7.0	1.40	−0.01
7	1	1	1	1	1	8.4	2.73	−0.24
8	0	−1	−1	na	−1	10.1	1.36	0.02
12	0	0	−1	na	−1	16.7	4.53	2.57
5	−1	1	1	1	1	17.2	4.27	1.09
15	0	0	1	1	1	18.1	6.00	0.97
1	−1	1	−1	na	1	19.5	4.10	0.60
2	−1	1	1	−1	1	19.6	5.05	0.03
6	1	1	1	1	−1	21.2	5.03	−0.22
13	0	0	−1	na	1	21.9	5.40	1.90
14	0	0	1	−1	1	26.1	5.54	0.31
3	1	1	1	−1	−1	28.2	5.67	0.81
9	0	−1	−1	na	1	28.7	7.38	0.23
0	−1	1	−1	na	−1	29.0	6.34	−0.46
10	0	−1	1	−1	1	30.0	5.85	1.06



Permutation-based Multivariate Tukey Analysis

Changes between levels of Ω in the *same* group have *no* statistically discernible effect.

Factor List

No discernable statistically significant impact on PUSCH power in mean, spread, or skew

Identifer	Testbed Component	Factor	# Levels
A	Variable Attenuator	Path Loss (Simulated DUT UE Position)	2
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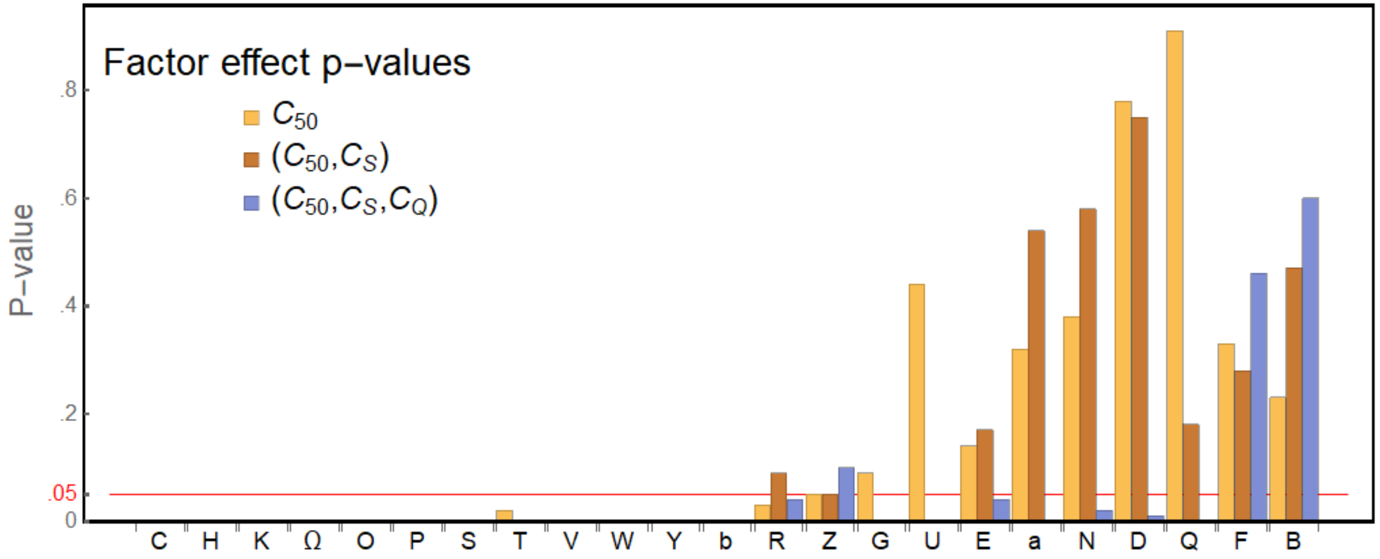
Factor Screening Experiment
- Engineering Analysis -

Speaker: Jason Coder

What are the practical implications?

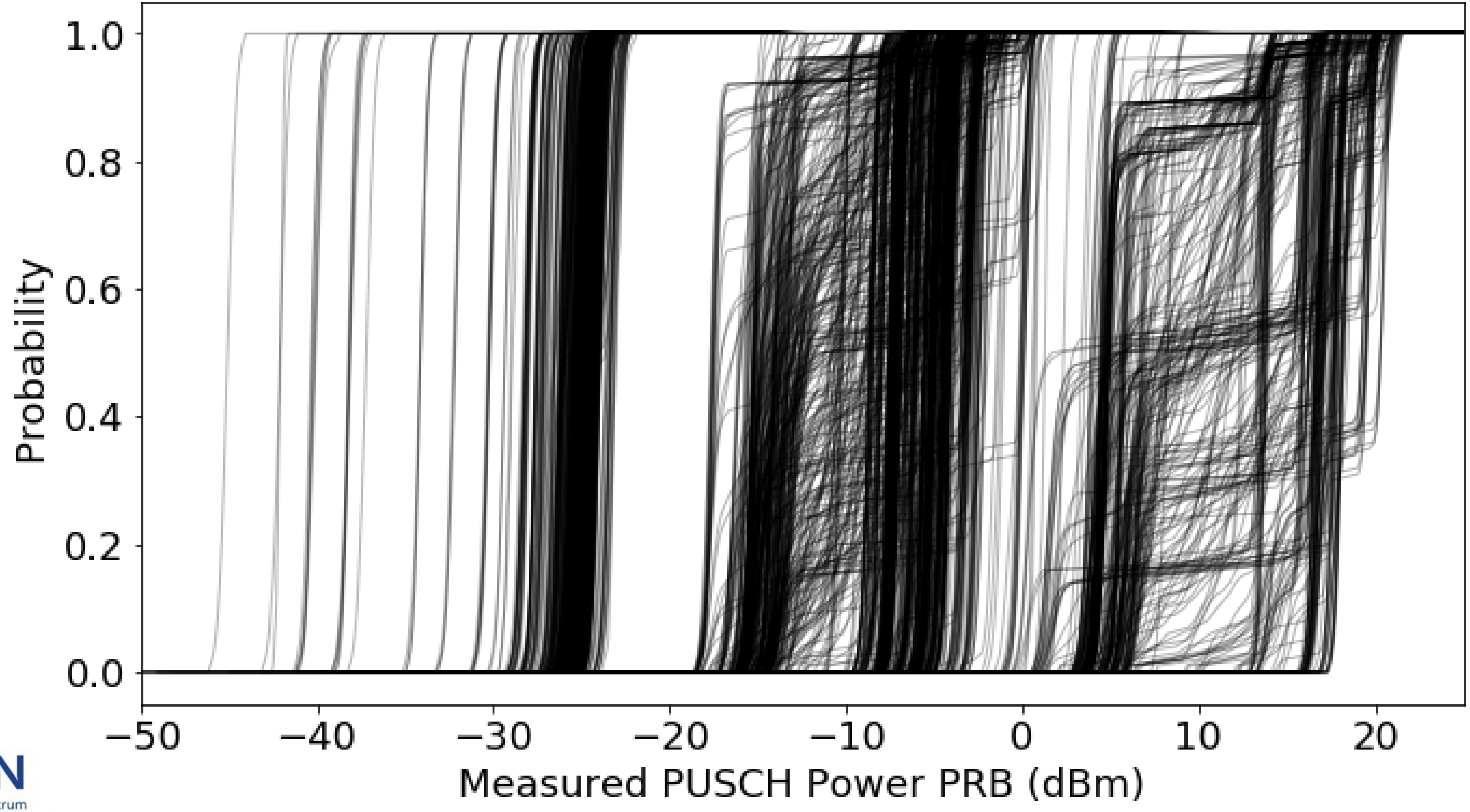
- Almost all factors shown to be significant in at least one dimension
  - How does that ***statistical*** significance translate into ***practical*** significance?
  - How likely is it that some of these features are actually used?
  - How large of a change in median, spread, or skew is necessary before a factor needs to be accounted for in modeling/simulation/analysis?
- We have done a limited number of experiments to confirm the results of the analysis
  - Results indicate good agreement with the analysis…the results are real
  - There may be false alarms and/or missed detections in the analysis….and other unknowns



Unknowns

- What is the influence of second order effects?
  - Additional side experiments indicate that some of these factors may be influenced by others
    - Open/Closed loop power control – when closed loop power control is activated, effect sizes may be different
    - Path loss – effect sizes may scale with path loss – in combination with other factors
- How applicable are these results to other UEs?
  - Initial tests indicate that other UEs of the same generation may behave the same way
    - Older UEs may not have newer features implemented – thus they don’t respond
- How applicable are these results to other eNBs?
- What eNB configuration are carriers actually using?

Empirical CDFs for all Factor Screening Tests



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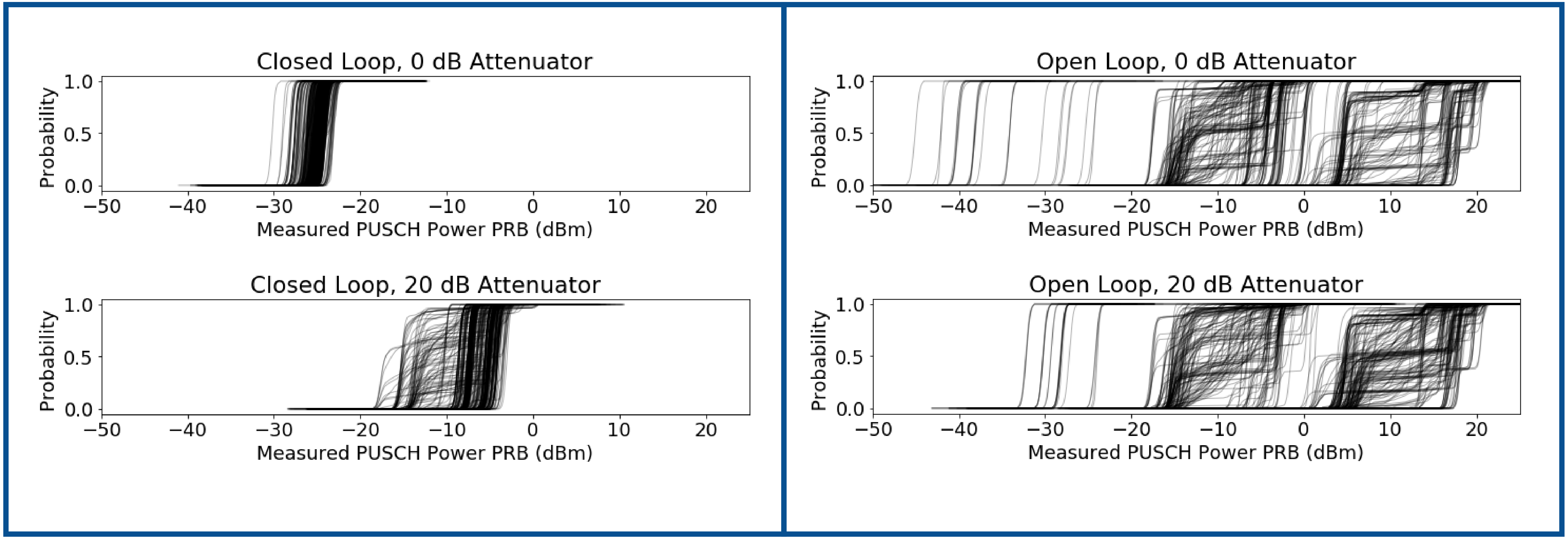
Empirical CDFs – Closed Loop vs. Open Loop Power Control



- Closed loop power control is much more tightly grouped
  - May be easier to describe mathematically

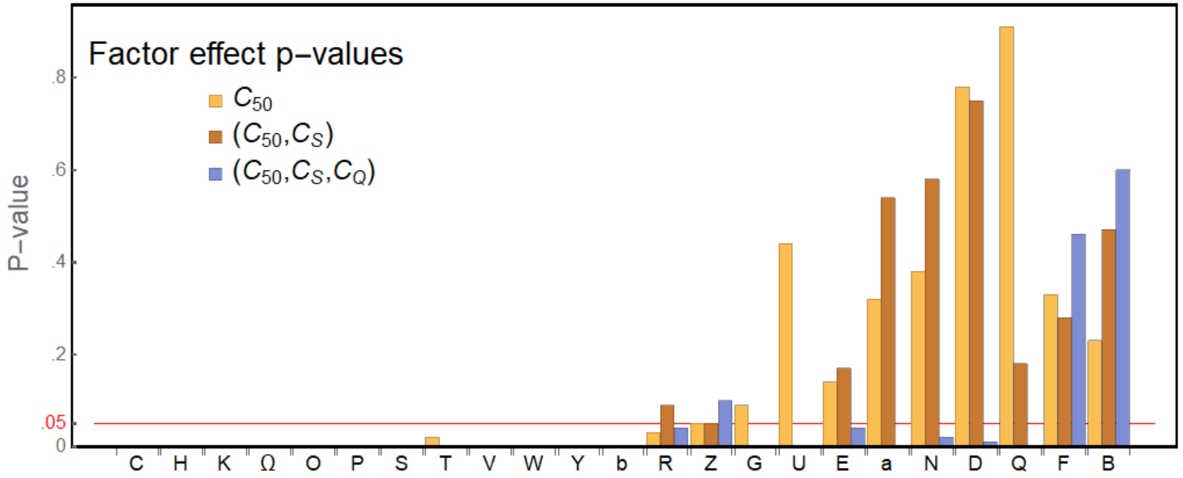
Part II: Closed-Loop Power Control

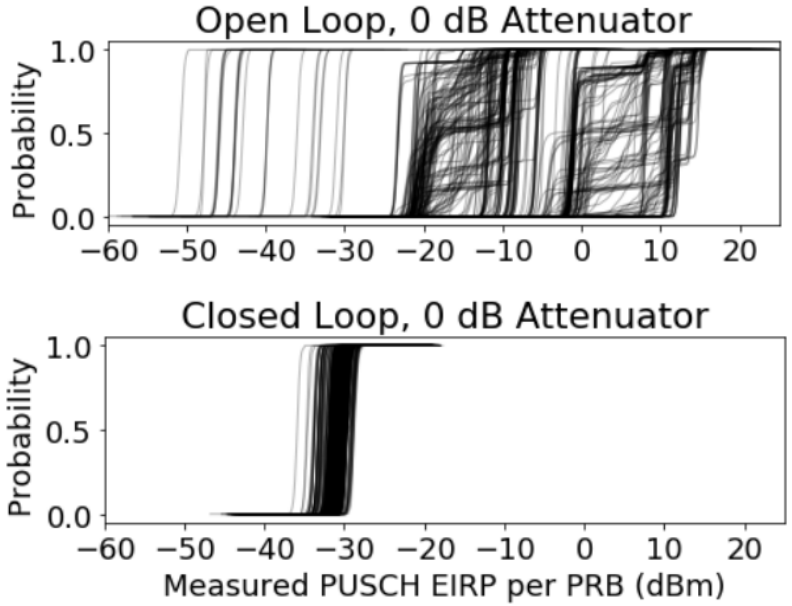
When Closed-Loop Power Control is enabled, what factors influence UE emissions? How well can we describe UE behavior?

Speaker: Jason Coder

Part II: Closed-Loop Power Control

- Part I: Ideas for future work
  - 14 ideas in tech note
- What smaller set of experiments will have a large impact?
- Emissions with closed loop power control enabled appear to be much more predictable
  - What factors are significant in this case?
- Difference from Factor Screening:
  - Focus on realistic conditions





Closed-Loop Power Control: Objective

Objective: Characterize PUSCH power variations in closed-loop mode over a range of realistic conditions.

Description: For closed-loop power control, investigate how PUSCH emissions are impacted over a range of realistic settings for path loss and P_0. Evaluate magnitude of possible factor interactions. (Not possible in factor screening experiment)

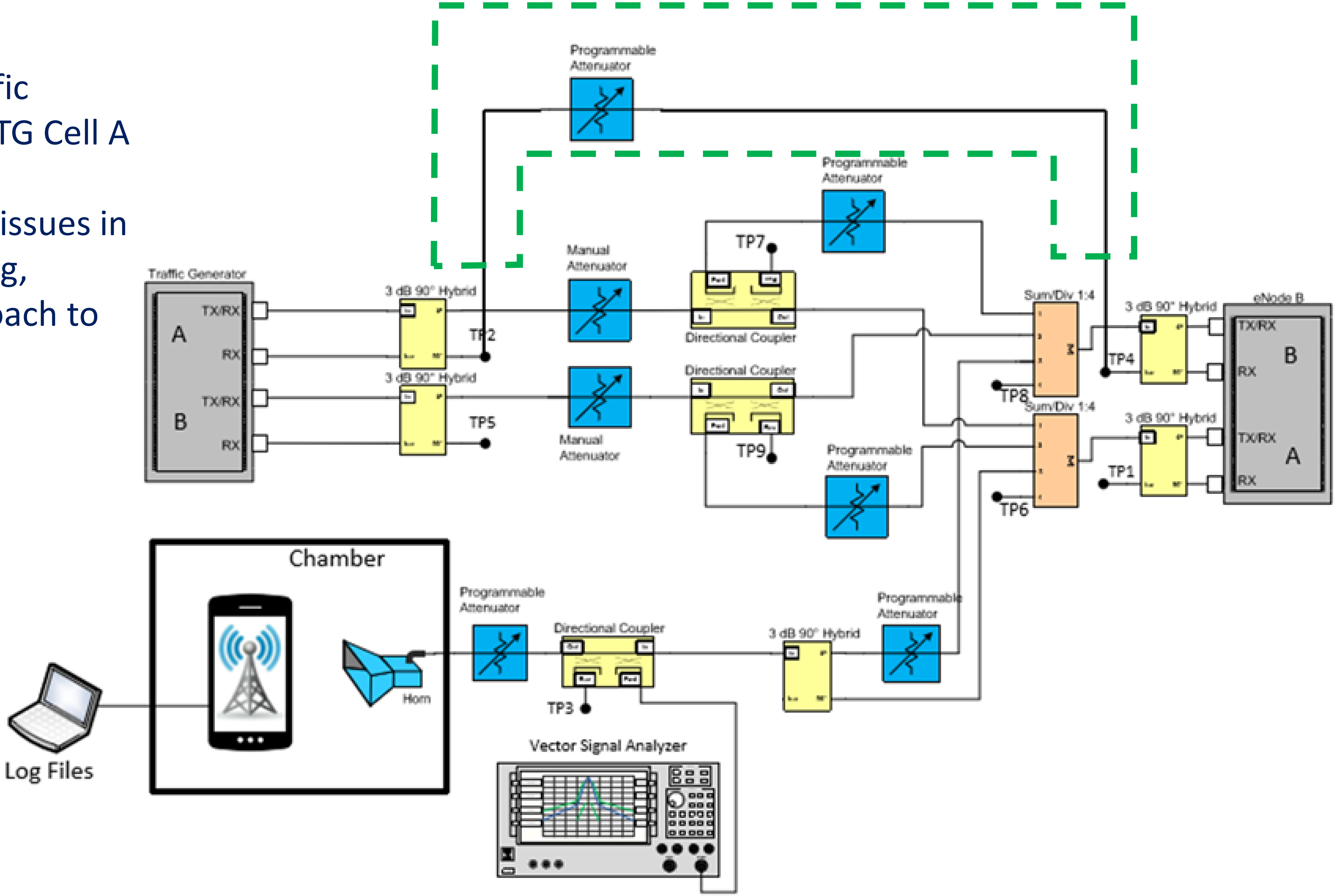
Risk/Reward: Low risk/High reward. If closed loop power control is predominantly used, this experiment would clarify the variability that can be expected under realistic conditions.

Type of Experiment: Confirmation/Characterization

Bonus: Additional insight into information on UE behavior (measured vs. reported values)

Test Circuit

- eNB Cell B traffic imposing on UTG Cell A
- In response to issues in factor screening, different approach to cross-talk



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Closed-Loop Power Control
- Experimental Design -

Speaker: Adam Wunderlich

Experimental Design Overview

Two complementary experiments executed in parallel: modeling and monitoring

Modeling Experiment

Primary Objective: Develop descriptive model(s) for PUSCH EIRP per PRB under closed-loop power control over range of realistic conditions.

Secondary Objectives: Assess negative power headroom conditions and differences between measured and UE-reported power.

Monitoring Experiment

Objectives: Assess testbed stability, gauge the impact of different UEs, and explore negative power headroom in fuller detail than in the modeling experiment.

Modeling Experiment

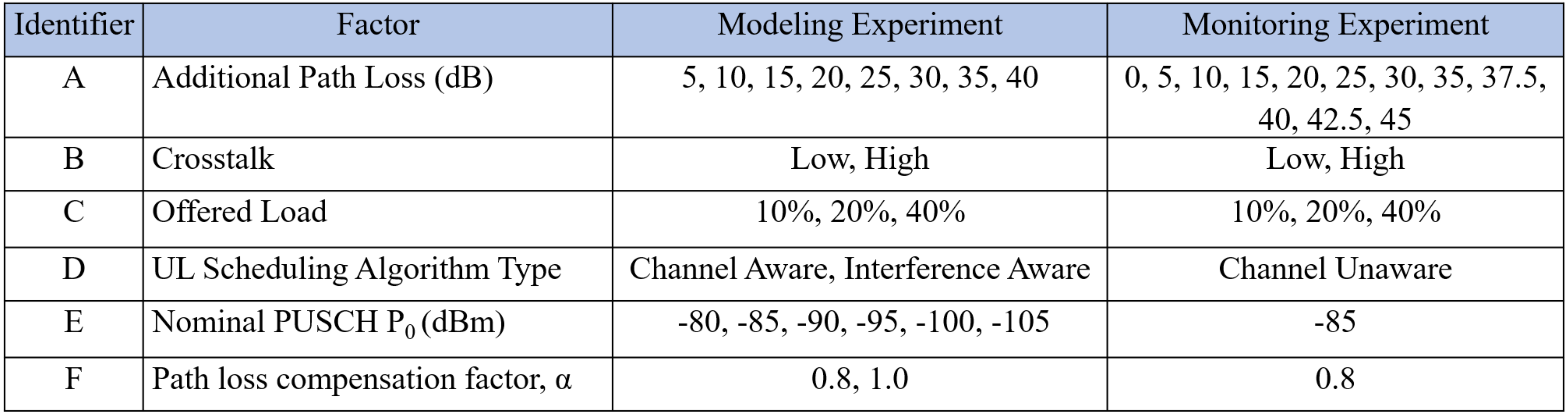
Identifier	Testbed Component	Factor	# Levels
A	Variable Attenuator	Path Loss	8
B	UTG	Crosstalk (variable attenuator & adjacent cell UEs)	2
C	UTG	Offered Load (number of loading UEs)	3
D	eNB	UL Scheduling Algorithm Type	2
E	eNB	Power Control: Nominal PUSCH P_0	6
F	eNB	Power Control: Path loss compensation factor, α	2

- Six factors: 3 non-eNB and 3 eNB
- Execute four rounds of testing, where each round uses a split-plot design
    - 12 configurations for eNB factors
    - 48 configurations for non-eNB factors
    - Full factorial designs for eNB and non-eNB factors → All factor interactions resolved
- To test more settings of P_0, use staggered values for Rounds 1&3 and 2&4
- Test four copies of same UE model, different phone used for each round

Monitoring Experiment

- Fixed “default” eNB configuration
- Three non-eNB factors: Path Loss, Crosstalk, Offered Load
- Increase number of Path Loss levels from 8 to 12 to better characterize emissions in negative power headroom conditions
  - ➢ 12x2x3= 72 non-eNB configurations
- Monitoring design retested periodically during Modeling Experiment
  - ▫ Repeated at start of every block of 4 eNB configurations and before any retests
    - Fourteen repetitions executed over the course of testing
  - ▫ Four UEs changed systematically between replications in the following order: 1,2,3,4,1,2,3,4,1,2,3,4,2,3

Settings & Implementation Details



Identifier	Factor	Modeling Experiment	Monitoring Experiment
A	Additional Path Loss (dB)	5, 10, 15, 20, 25, 30, 35, 40	0, 5, 10, 15, 20, 25, 30, 35, 37.5, 40, 42.5, 45
B	Crosstalk	Low, High	Low, High
C	Offered Load	10%, 20%, 40%	10%, 20%, 40%
D	UL Scheduling Algorithm Type	Channel Aware, Interference Aware	Channel Unaware
E	Nominal PUSCH P_0 (dBm)	-80, -85, -90, -95, -100, -105	-85
F	Path loss compensation factor, α	0.8, 1.0	0.8

- Path loss only adjusted for DUT UE
  - Additional PL values from 0 dB to 45 dB yield DUT RSRP from -72 dBm to -117 dBm
  - Loading UEs have constant RSRP (-95 dBm)
- Constant data rate for all UEs (500 kbps)
- Offered Load: adjust number of loading UEs (4, 8, 16)
- Cross-talk implemented with variable attenuator and number of UEs in cell B
  - High crosstalk yields ≈10 dB change in eNB-reported SINR
- Scheduling algorithm type impacts both cells
  - Collateral setting adjustments required, e.g., enable/disable SRS

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Closed-Loop Power Control Experiment
- Statistical Analysis & Results -

Speaker: Mike Frey

NASCTN CLPC Study Goal

Descriptive model(s) of measured PUSCH EIRP per PRB power percentiles in terms of 6 study factors

Descriptive model

- Identify relationship
- Assess explanatory power
- Simple, easy-to-interpret
- Need not fit all the data

Predictive model

- Point predictions *with* uncertainties
- Assess prediction error
- Can be a "black box"
- Should fit all the data

Illustration: Radar equation - descriptive

$$P_{rcv} = \frac{P_{xmt} G_t \sigma A_e}{(4\pi)^2 R^4}$$

A descriptive model is a useful roadmap for creating a predictive model.

CLPC Study – two parallel experiments

	Modeling experiment	Monitoring experiment
Goal	• Descriptive model(s)	• Assess testbed stability • Estimate UE-contributed variability • Descriptive model for default conditions
Response	99 centiles of measured PUSCH EIRP per PRB power	99 centiles of measured PUSCH EIRP per PRB power
Factors		
A: Path loss (dB)	5, 10, 15, 20, 25, 30, 35, 40	0, 5, 10, 15, 20, 25, 30, 35, 37.5, 40, 42.5, 45
B: Crosstalk	Low, High	Low, High
C: Network loading (%)	10, 20, 40	10, 20, 40
D: Scheduler type	Channel aware, Interference aware	Channel unaware
E: Nominal power, P_o (dB)	–105, –100, –95, –90, –85, –80	–85
F: Power fraction, α	0.8, 1.0	0.8
Replicates	1,2,3,4	1,2,3,4, 1,2,3,4, 1,2,3,4, 2,3

Key findings

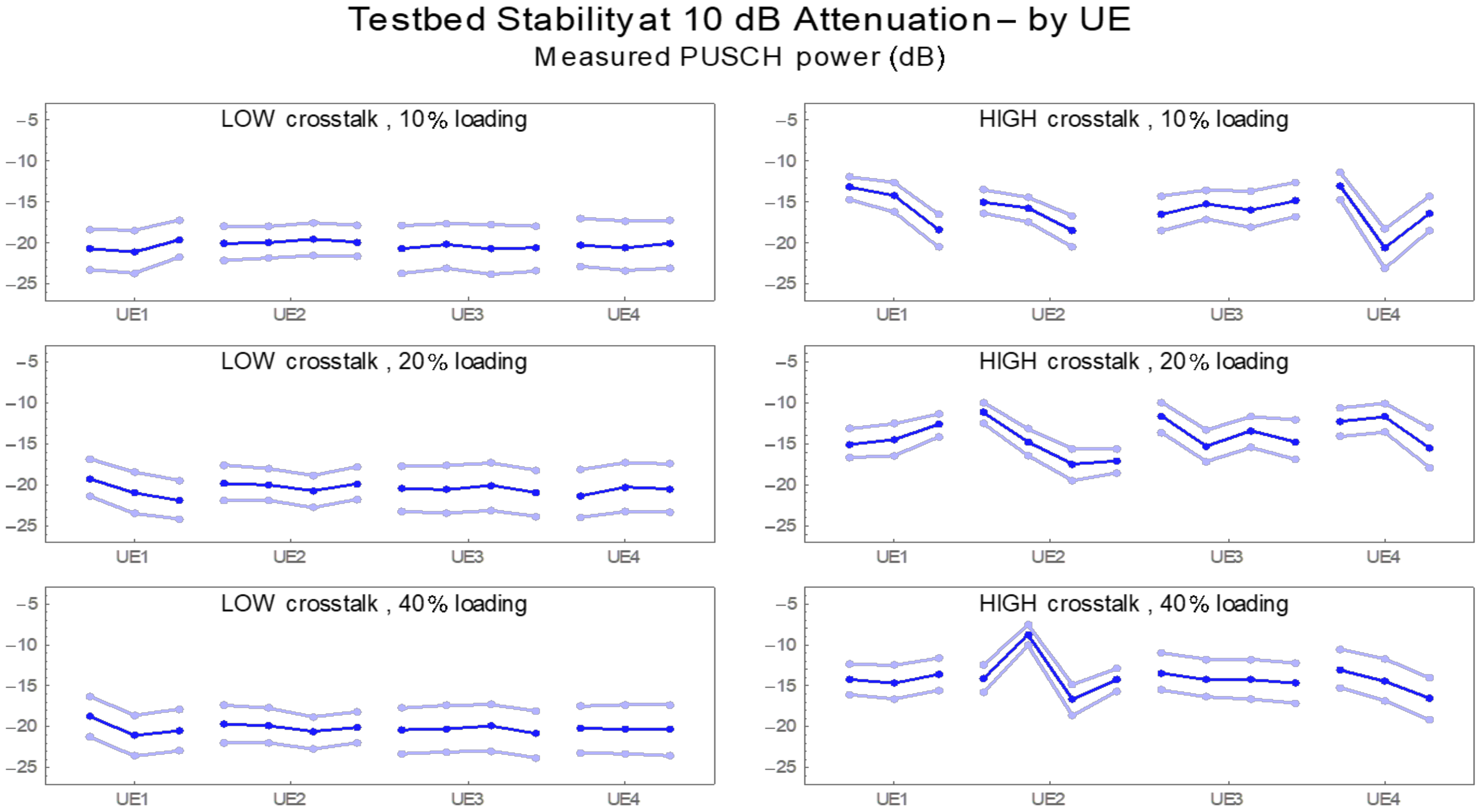
F1: The testbed was stable (over nearly 2 months).

F2: UE-contributed variability is very low (≤ 1 dB, not discernible)

F3: Only factors A and E have meaningful, statistically discernible effects on the measured PUSCH EIRP per PRB power distribution. Factors C, D, and F do not.

F4: Models for percentiles of the measured PUSCH EIRP per PRB power distribution

F1: Stable testbed



Unanticipated phenomenon operating at HIGH crosstalk.

F2: No discernible UE-contributed variability

Model: $Y = \mu + \beta A + \mathrm{UE} + \varepsilon$ (for six B-C setting combinations)

50th centile (dB)		
Network loading	Crosstalk	
	B = LOW	B = HIGH
C = 10%	0.2 0.19	0.0 1.00
C = 20%	0.1 0.47	0.9 0.15
C = 40%	0.0 1.00	1.5 0.14

90th centile (dB)		
Network loading	Crosstalk	
	B = LOW	B = HIGH
C = 10%	0.1 0.29	0.3 0.37
C = 20%	0.0 1.00	0.9 0.15
C = 40%	0.1 0.42	1.3 0.14

Large numbers in red are estimated standard deviations (in dB).

Small numbers are the associated p-values for $H_o: \sigma_{bc} = 0$

F3: Factors with important,discernible effects

ANCOVA model:

$$Y = \gamma_0 + \gamma_1 A + \gamma_2 E + \ \gamma_3 AE$$
$$+\gamma_4 C + \gamma_5 D + \gamma_6 F + \gamma_7 CD + \gamma_8 DF + \gamma_9 CF + \delta + \kappa$$

Effect	P-value (50th percentile)	P-value (90th percentile)
A	0.00	0.00
E	0.42	0.17
$A \times E$	0.00	0.00
C	0.34	0.00
D	0.15	0.83
F	0.26	0.07
$C \times D$	0.02	0.11
$D \times F$	0.88	0.88
$C \times F$	0.15	0.15

For the 50th power percentile, only A and the interactions A×E and C×D are discernible (green). But C×D is not practically important (max. abs. dev. = 0.54 dB).

For the 90th power percentile, only A and the interactions A×E and C are discernible (green). But C is not practically important (max. abs. dev. = 0.37 dB).

So, only factors A and E have statistically discernible, important effects.

F4: Descriptive model of power percentiles

Model: $Y = f(A, E) + \varepsilon$

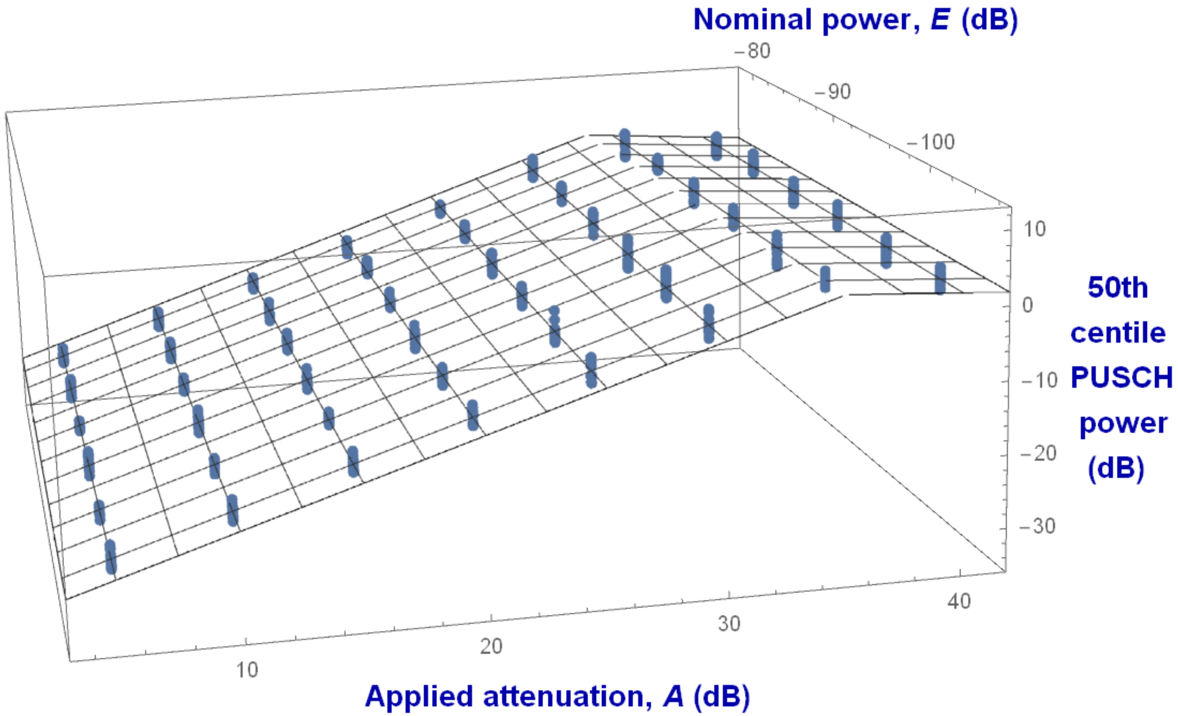
Y is a percentile of the measured PUSCH EIRP per PRB power.

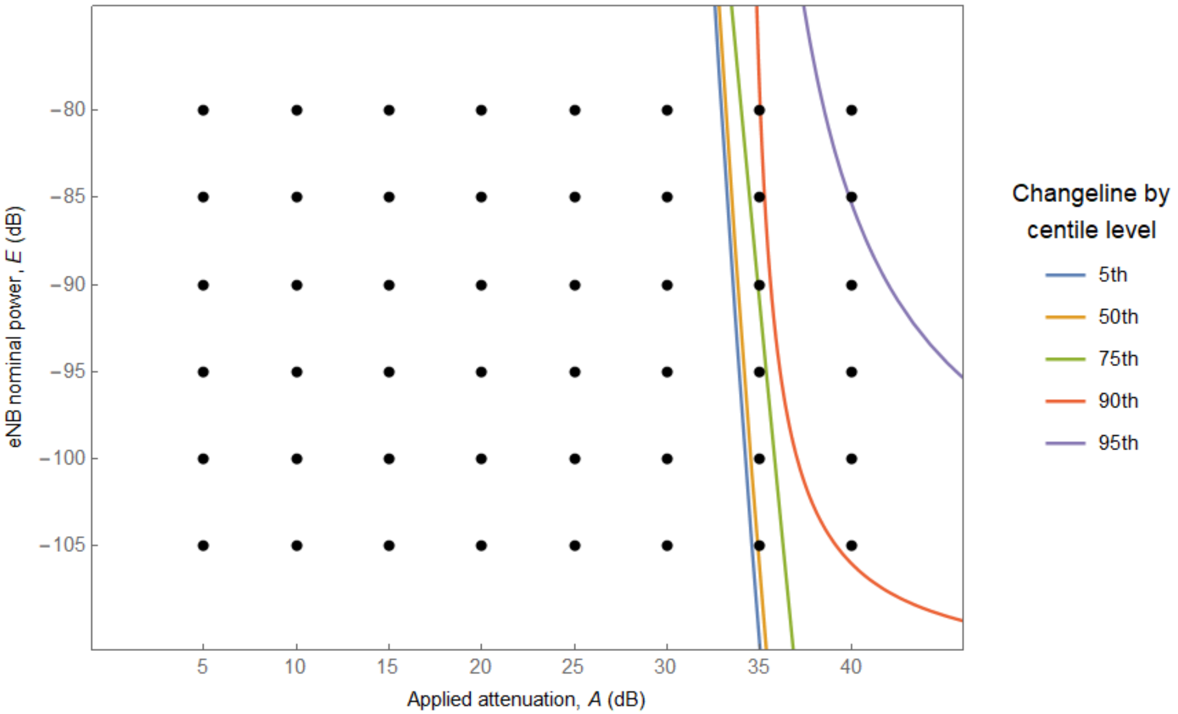
ε is additive random variation.

A is path loss (dB) and E is nominal power (dB).

$f(A, E)$ is a two-region hyperbolic paraboloid
with parametric changeline.

Region of NPH – Descriptive model





Entry of the top of the PUSCH power distribution into NPH is delayed relative to the center of the distribution.

Engineering Analysis
- Insight into Additional Questions -

Speaker: Rob Horansky & Aric Sanders

Engineering Analysis
- Antenna Pattern Measurements -

Speaker: Rob Horansky

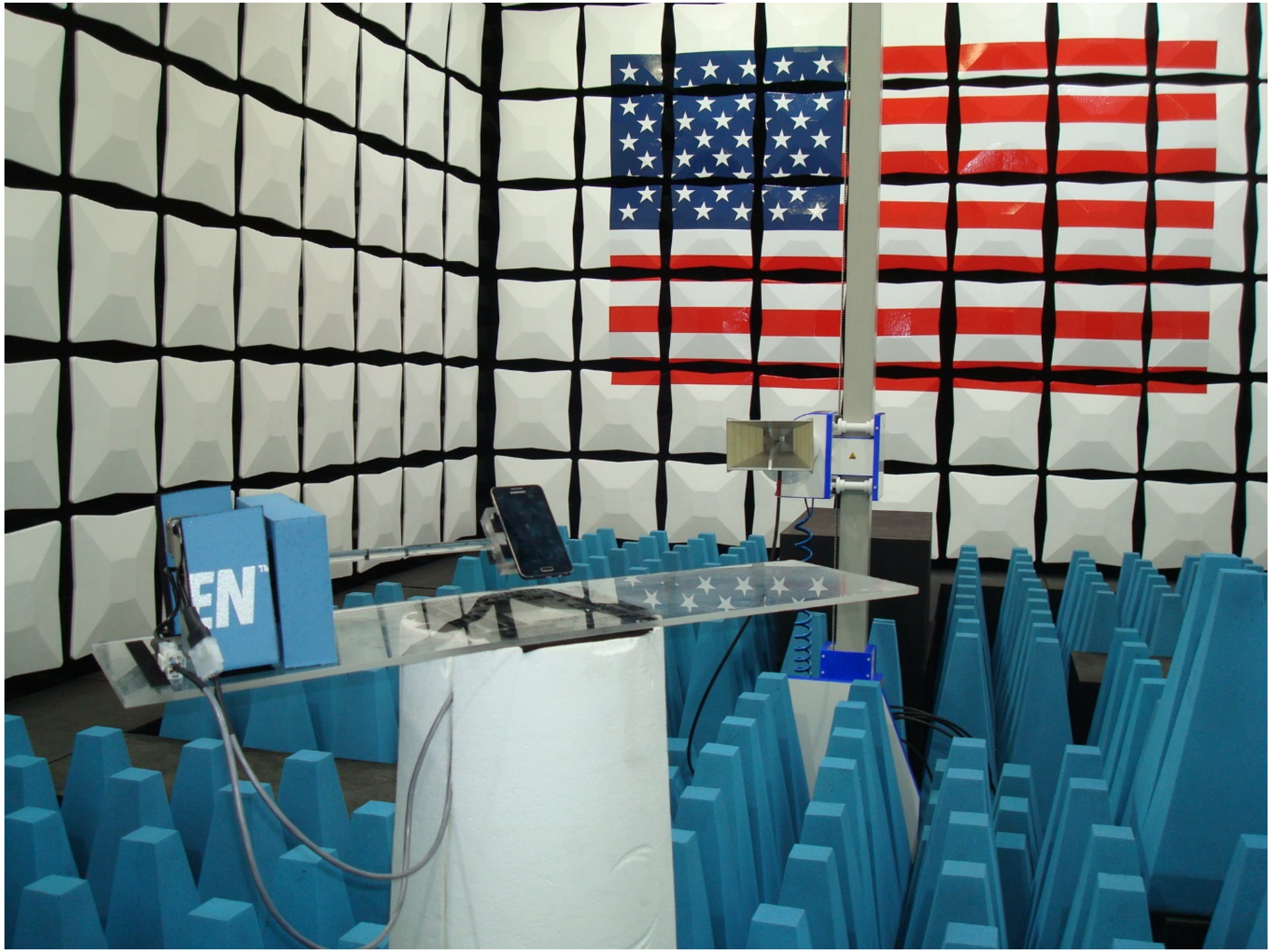
Results of this work

- UE Antenna Pattern
  - Large nulls
  - Consistent polarization along top of phones
- Total Radiated Power (TRP)
  - Distributions for LOS power
- UE Orientation Uncertainty
  - Dominated by range loss and cable placement

5 Types of Phones

Covering two OS types, slight variation in form factor for antenna design

1. Phone A
   16cm x 7.8 cm (x2)
2. Phone B
   16 cm x 7.5 cm (x2)
3. Phone C
   13 cm x 6.55 cm
4. Phone D
   13.8 cm x 6.7 cm
5. Phone E
   15.8 cm x 7.8 cm



NIST Broadband Interoperability Testbed (NBIT) facility

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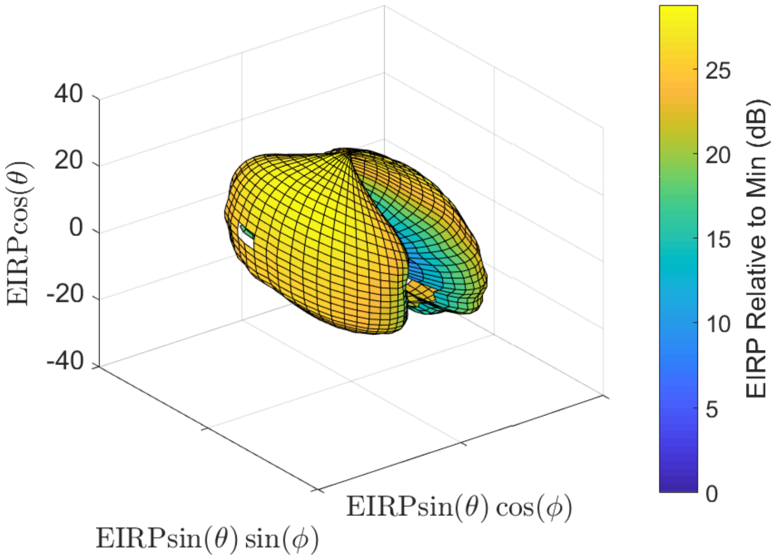
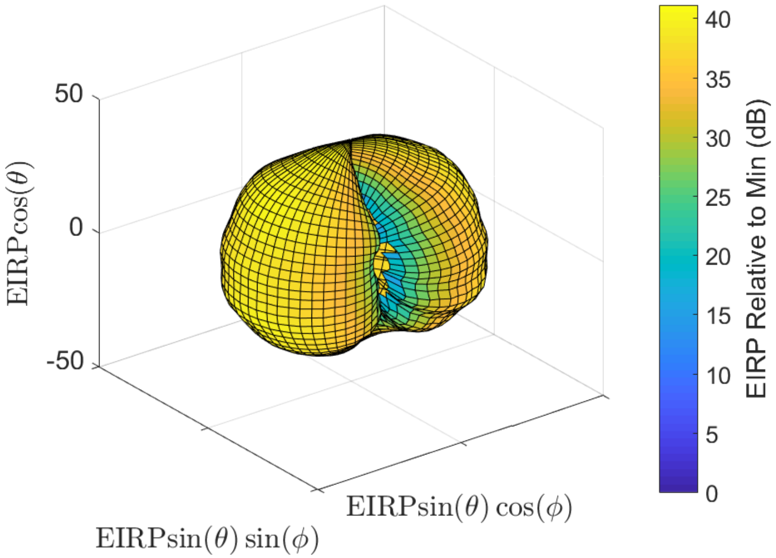
Patterns – Vertical Polarization

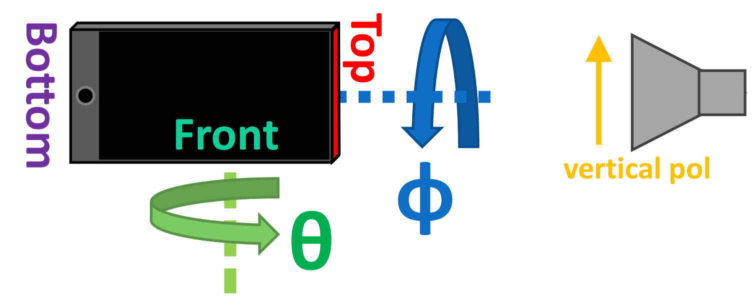
Phone A



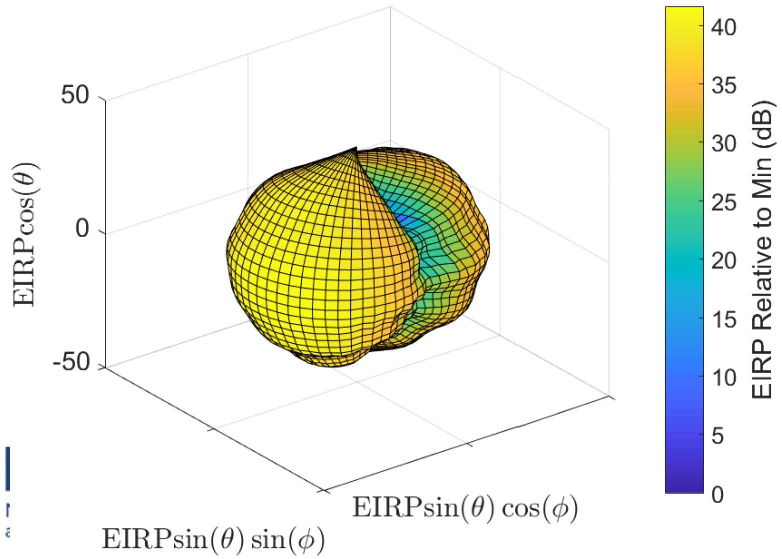
Phone B



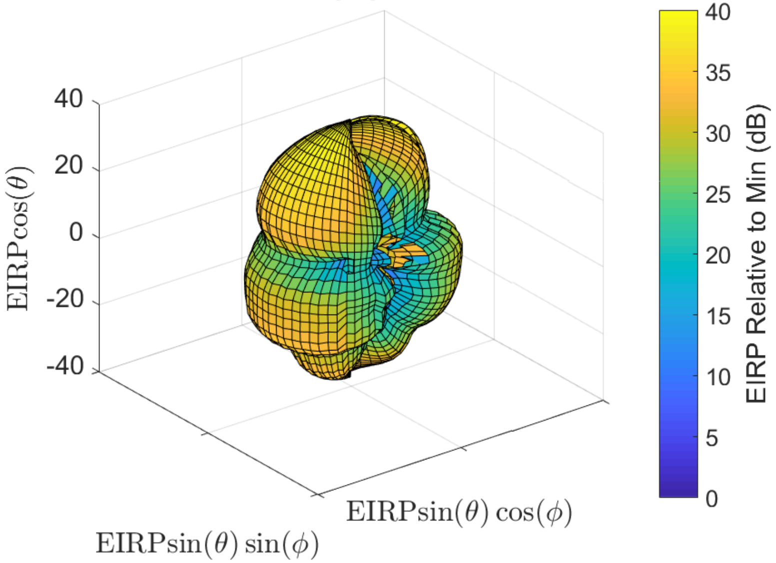
Drawing: ϕ = 0; θ = 0



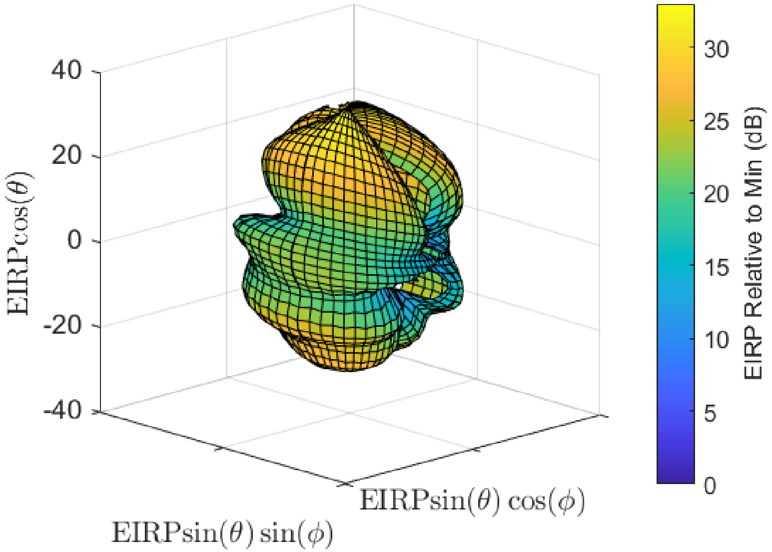
Phone C



Phone D

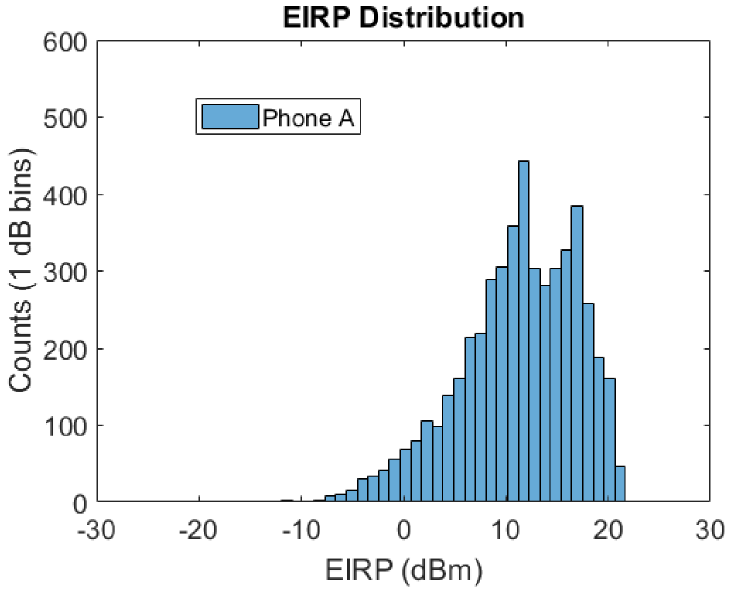


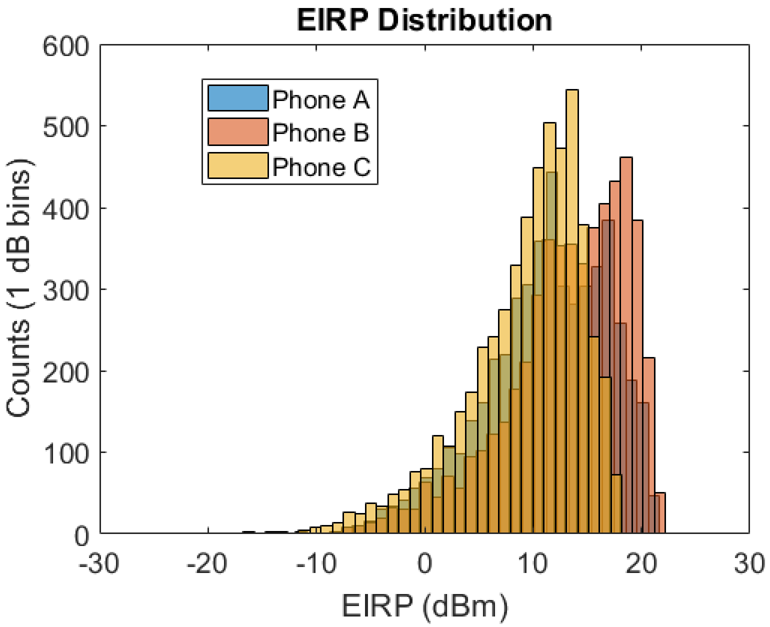
Phone E

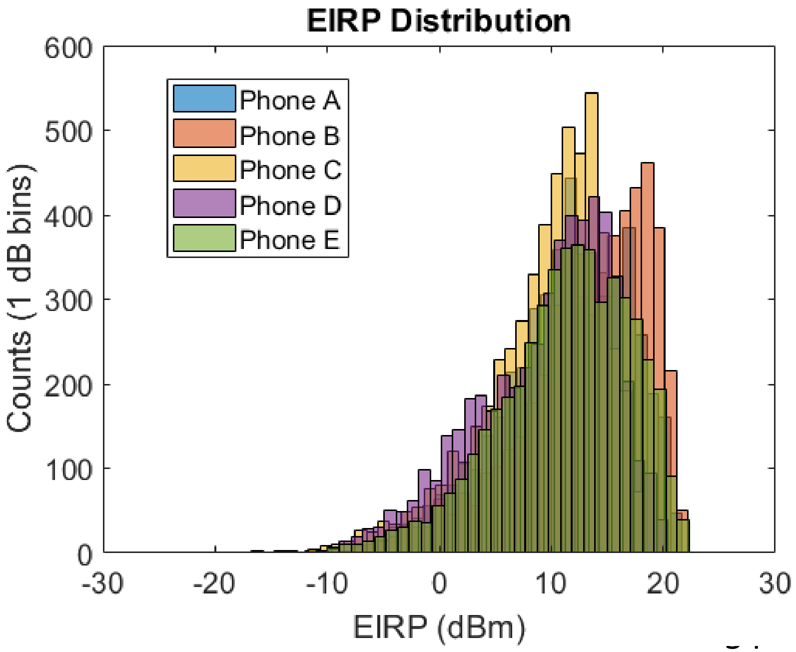


EIRP Distributions and Total Radiated Power (TRP)

Phone	TRP (dBm)	Uncertainty (dB)
A	19.6	1.5
B	21.6	1.5
C	17.5	1.5
D	17.3	1.5
E	18.7	1.5







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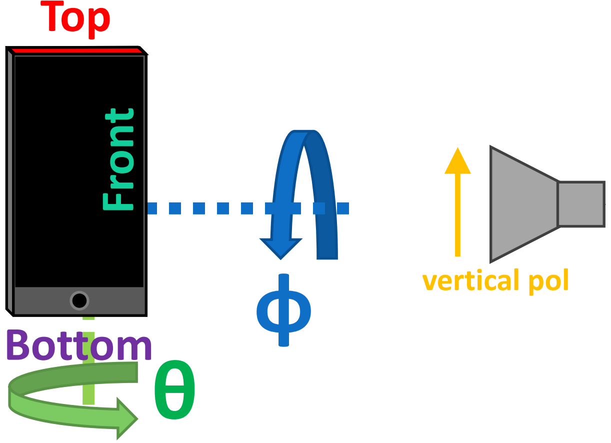
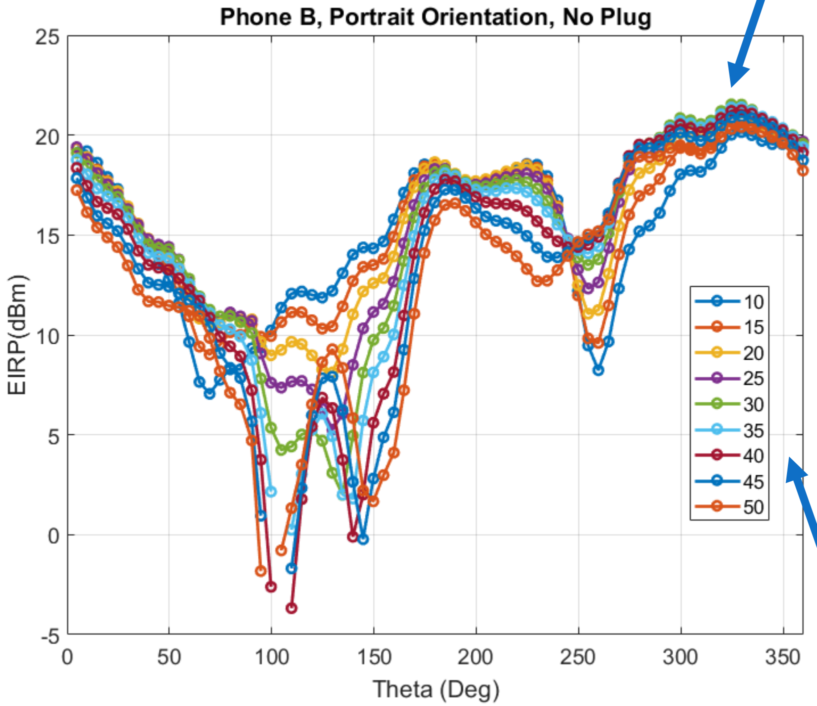
Plug Alters Pattern Significantly

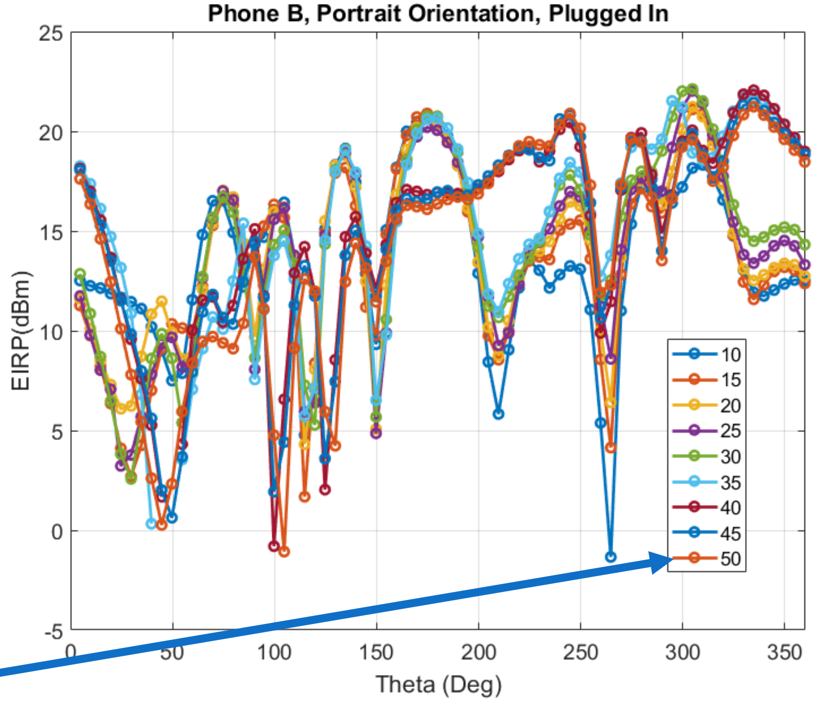
Drawing: ϕ = 0; θ = 0



Pattern Change = larger uncertainty due to UE orientation

Unplugged: Defined Peak

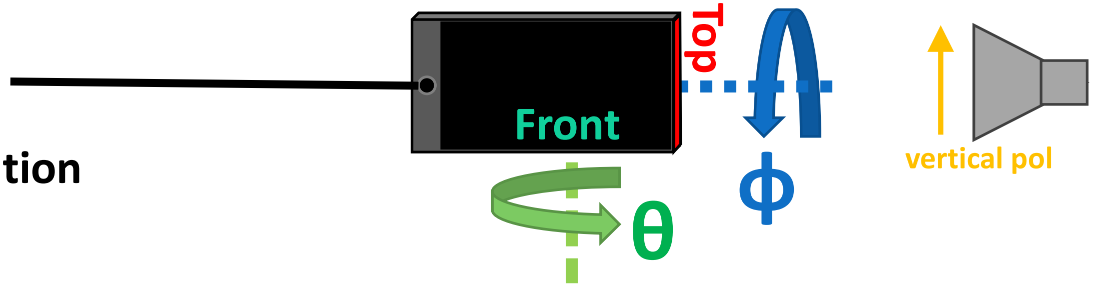




Phi Angles

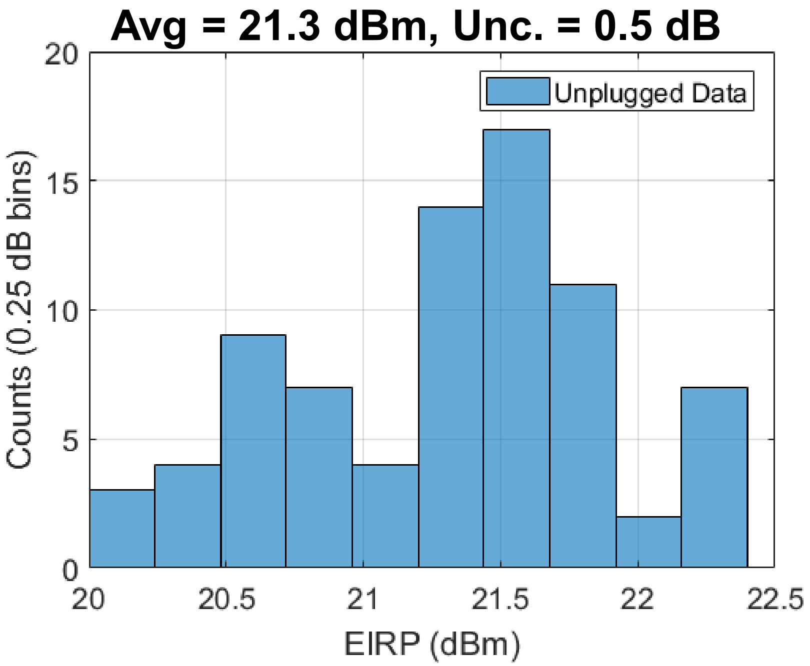
Cable Uncertainty > Phone Uncertainty

Drawing: ϕ = 0; θ = 0

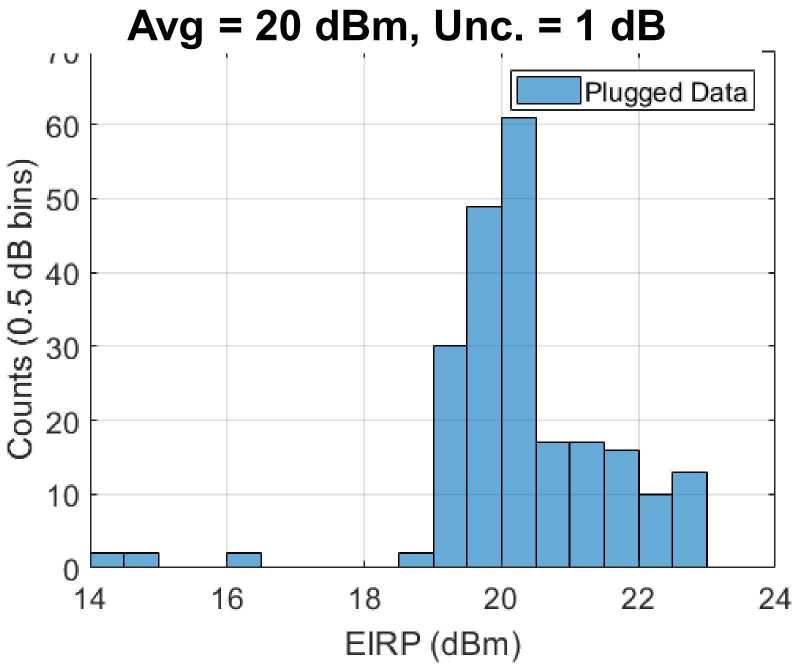


Solution: **Cable Perpendicular to Antenna Polarization**

Phone Variation Uncertainty = 0.5 dB



Cable and Phone Var Uncertainty = 1 dB,
Not a Normal Distribution

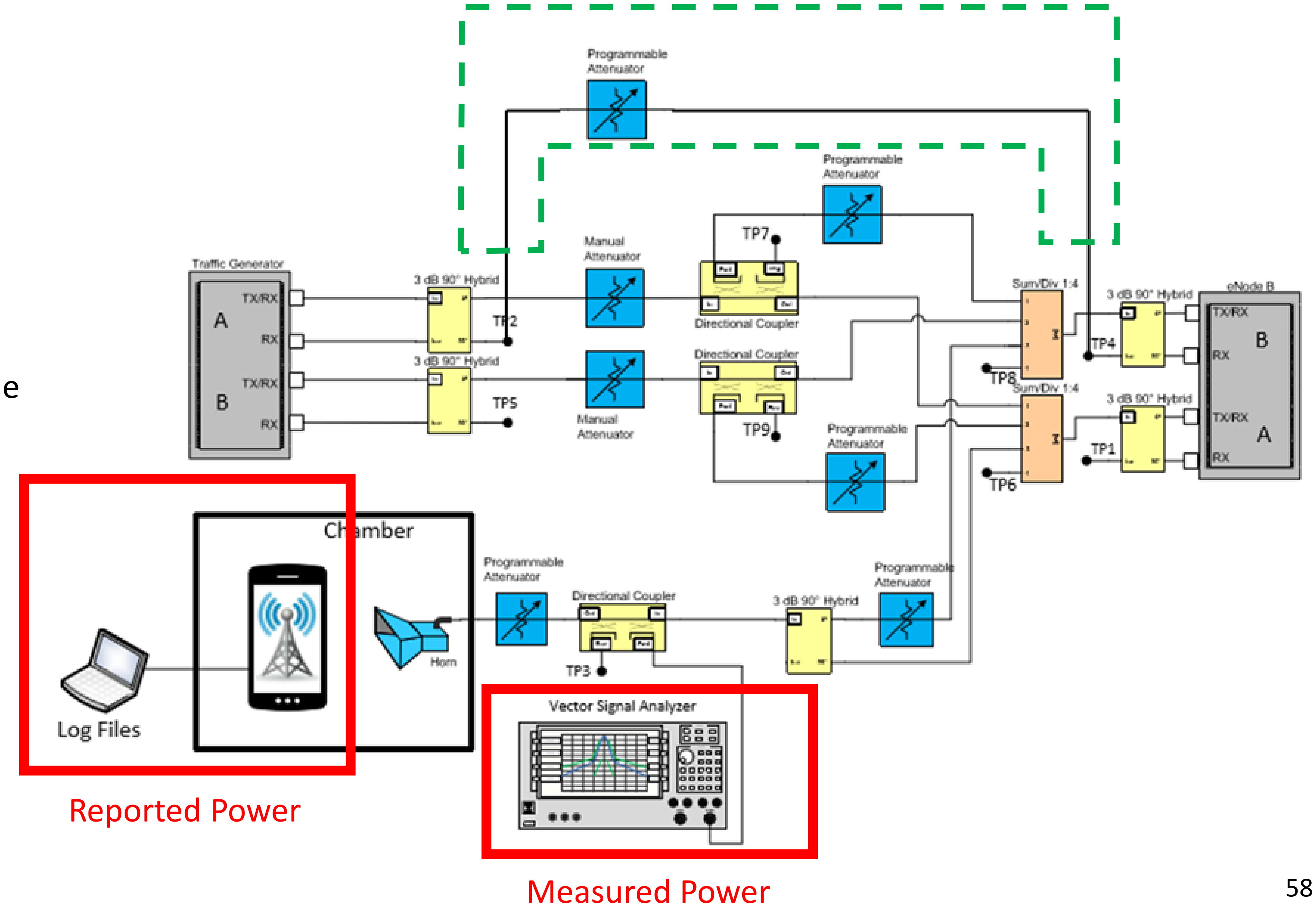


Engineering Analysis
- Measured vs. Reported Values -

Speaker: Aric Sanders

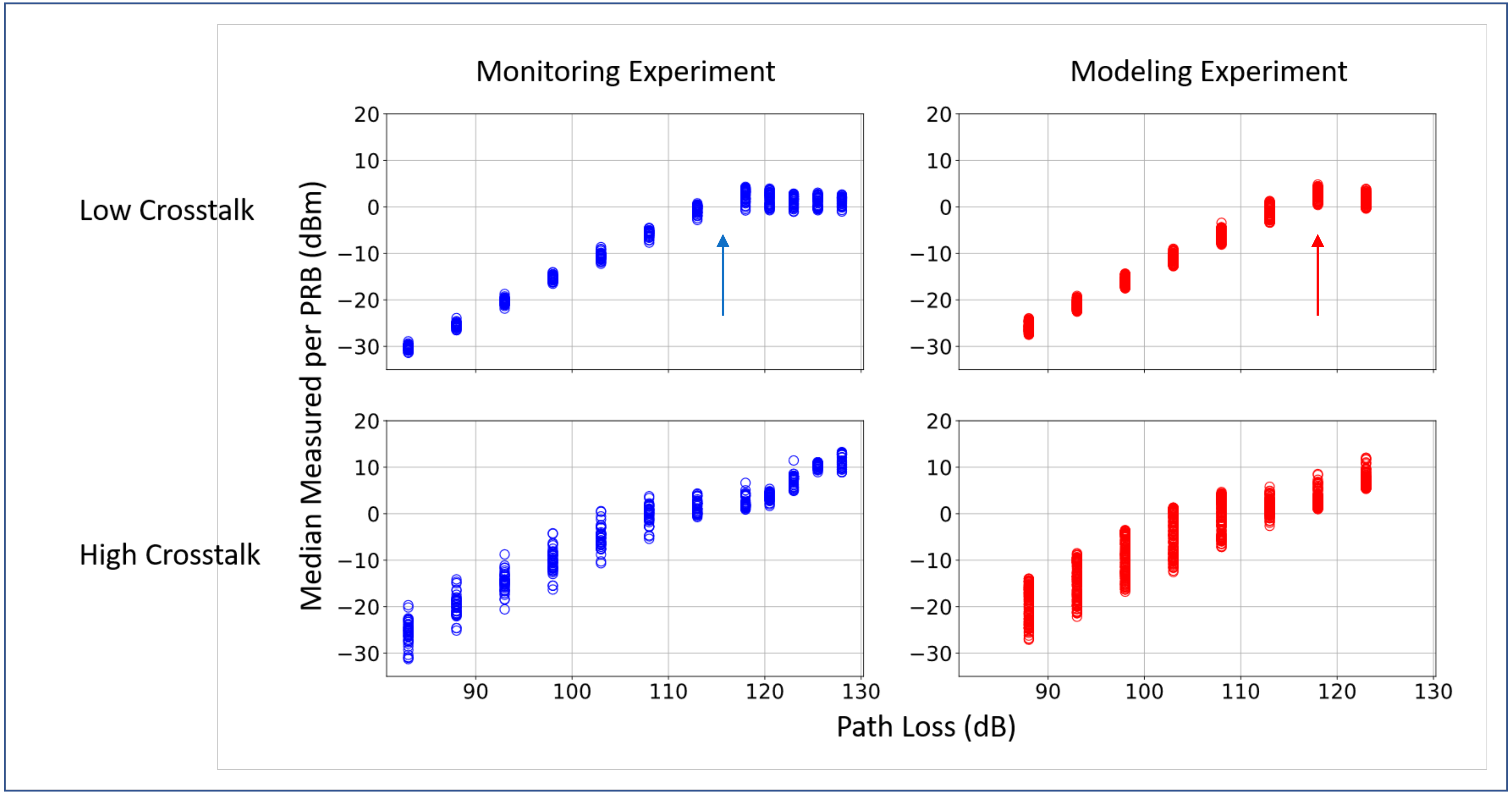
Test Circuit

- Reported power originates from UE diagnostics and is frequently used in interference models.
- Measured power is independent and corrected for losses directly outside the UE to the measurement device.
- Reported power is greater than measured power by approximately 3 dB per PRB or 7 dB per TTI.



Reported vs. Measured (Measured per PRB)

- Statistical analysis was on measured power per PRB.
- These plots use VSA-calibrated pathloss (78.1 dB added to attenuator value)



Just Median Power

PRB –Physical Resource Block
VSA – Vector Signal Analyzer

Quantitative Differences (Monitoring per PRB)

Path Loss (dB)*	Applied Attenuation (dB)	Low Cross Talk Measured (dBm/PRB)	Low Cross Talk Reported (dBm/PRB)	High Crosstalk Measured (dBm/PRB)	High Crosstalk Reported (dBm/PRB)
78.1 ± 1.6	0 ± 0.5	-30.3 ± 1.1	-26.0 ± 1.1	-25.3 ± 5.3	-21.0 ± 5.9
83.1 ± 1.6	5 ± 0.5	-25.4 ± 1.1	-22.0 ± 1.1	-20.1 ± 4.8	-16 ± 5.4
88.1 ± 1.7	10 ± 0.5	-20.3 ± 1.1	-17.0 ± 1.1	-14.7 ± 4.3	-11 . 0 ± 4.7
107.2 ± 4.2	30 ± 0.5	-0.3 ± 1.7	3.0 ± 1.7	1.7 ± 2.9	7.0 ± 3.4
112.5 ± 3.0	35 ± 0.5	3.1 ± 2.7	9.0 ± 2.7	1.9 ± 2.6	8.0 ± 4.1
117.9 ± 2.6	40 ± 0.5	1.5 ± 1.8	8.2 ± 2.1	7.6 ± 2.5	12.0 ± 2.3

- Measured power is ~ 3-4 dB/PRB lower than reported power at path loss <110 dB

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Quantitative Differences (Monitoring per PRB)

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- High crosstalk is ~ 5-6 dB/PRB higher than low crosstalk at path loss <110 dB

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- Measured power is ~ 3-4 dB/PRB lower than reported power at path loss <110 dB
- High crosstalk is ~ 5-6 dB/PRB higher than low crosstalk at path loss <110 dB
- High crosstalk has a higher variance

Quantitative Differences (Monitoring per PRB)

Path Loss (dB)*	Applied Attenuation (dB)	Low Cross Talk Measured (dBm/PRB)	Low Cross Talk Reported (dBm/PRB)	High Crosstalk Measured (dBm/PRB)	High Crosstalk Reported (dBm/PRB)
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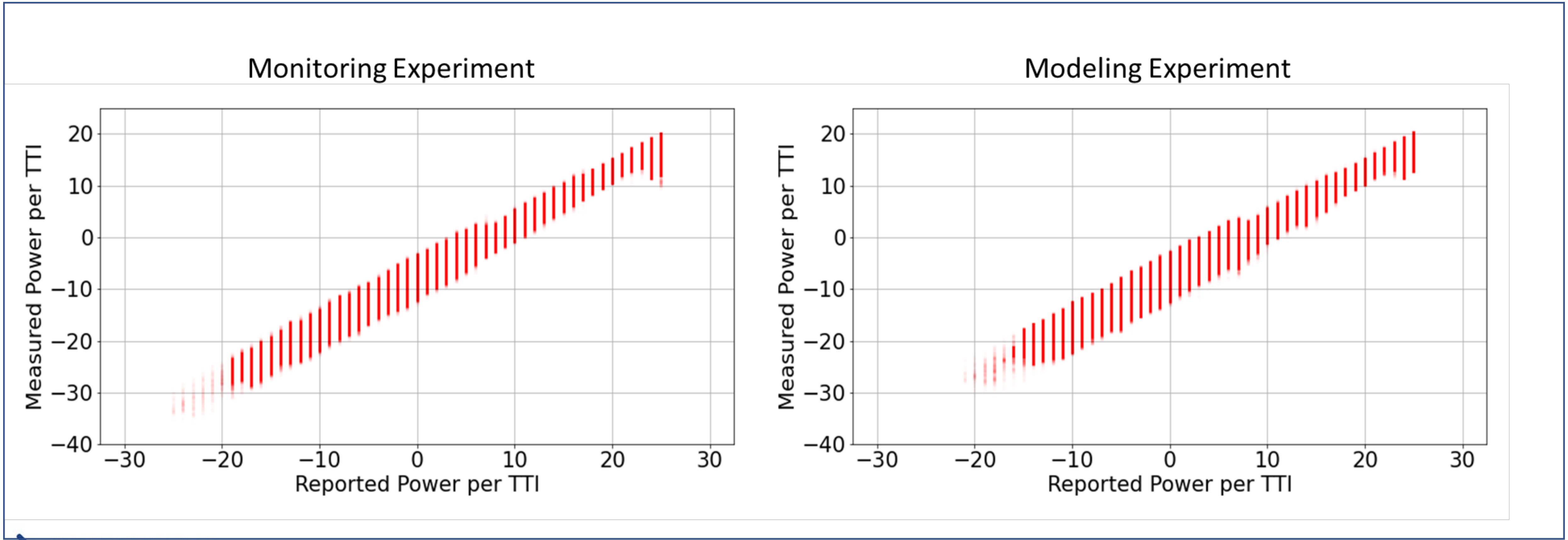
- Measured power is ~ 3-4 dB/PRB lower than reported power at path loss <110 dB
- High crosstalk is ~ 5-6 dB/PRB higher than low crosstalk at path loss <110 dB
- High crosstalk has a higher variance
- Low crosstalk saturates and high crosstalk continues to increase

Reported vs. Measured (per TTI)

- Large span of reported power due to range of path loss values
- If UE reports 0 dBm, measured EIRP ≈ -7 ± 2 dBm
- Reflects instantaneous differences in reported and measured total power

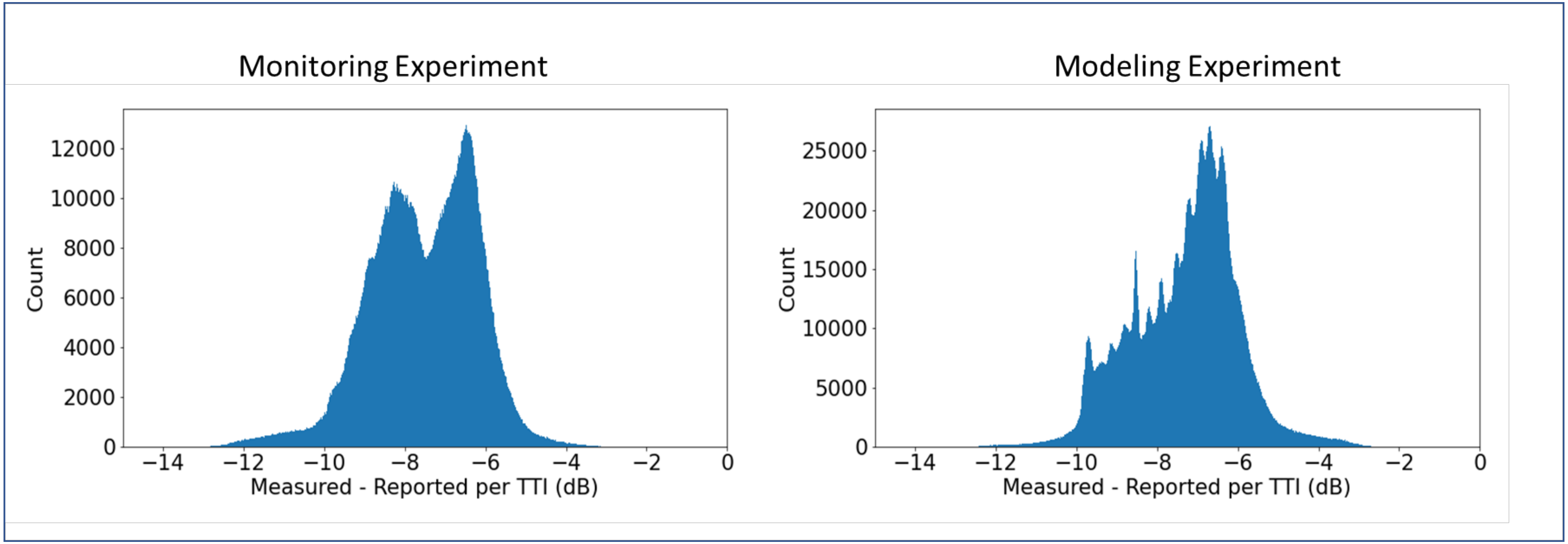


Monitoring Experiment

Modeling Experiment

TTI – Transmission Time Interval

Combined histogram of experimental results – all active TTIs



Details:

Monitoring Experiment: 2.8 Million Points, Mean: -7.5 dB, Standard Deviation: 1.3 dB

Modelling Experiment: 5.0 Million Points, Mean: -7.3 dB, Standard Deviation: 1.3 dB

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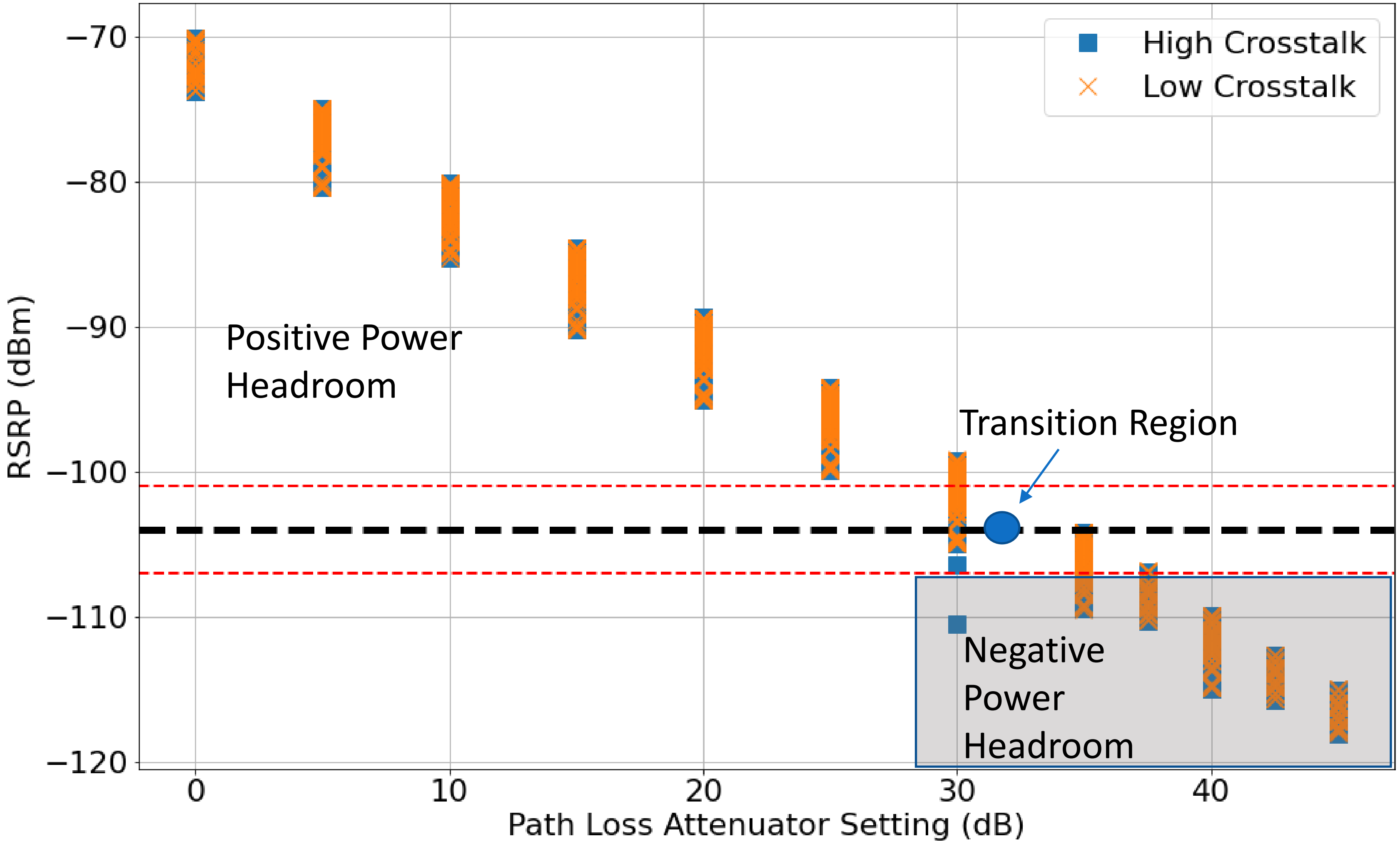
Negative Power Headroom and Path Loss

- UEs are frequently broadcasting at maximum power, or in negative power headroom conditions.
- In our experiment, there is a decrease in MCS index and an increase in PRB grant size when the UE is in negative power headroom.
- Different measurement techniques produce significantly different path loss.
- This difference in path loss explains UE reported power behavior.

Negative Power Headroom

- Attenuator setting controls RSRP
- RSRP is estimated on DL
- RSRP reflects small variations



RSRP – Reference Signal Received Power

DL - Downlink

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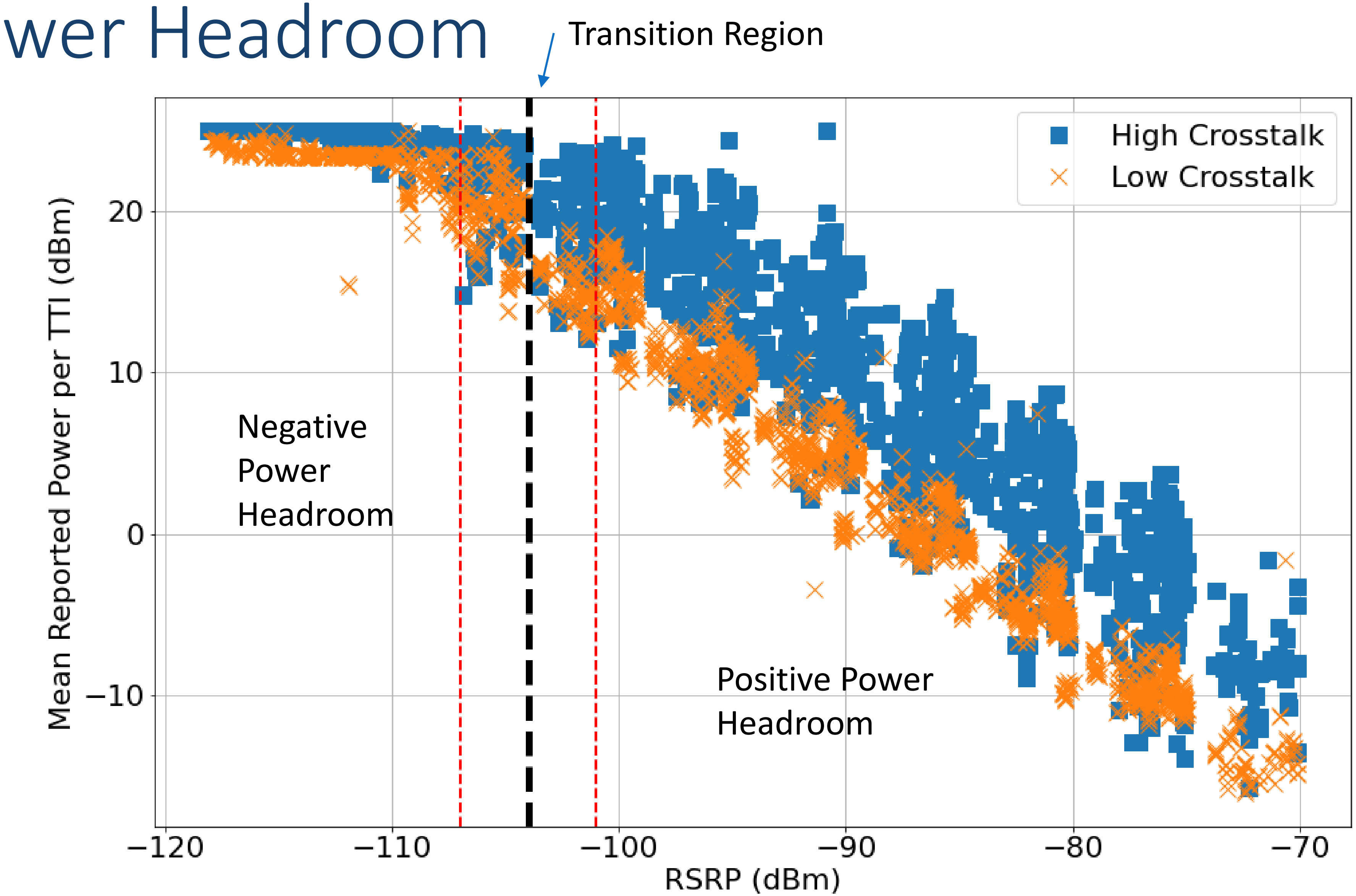
Negative Power Headroom

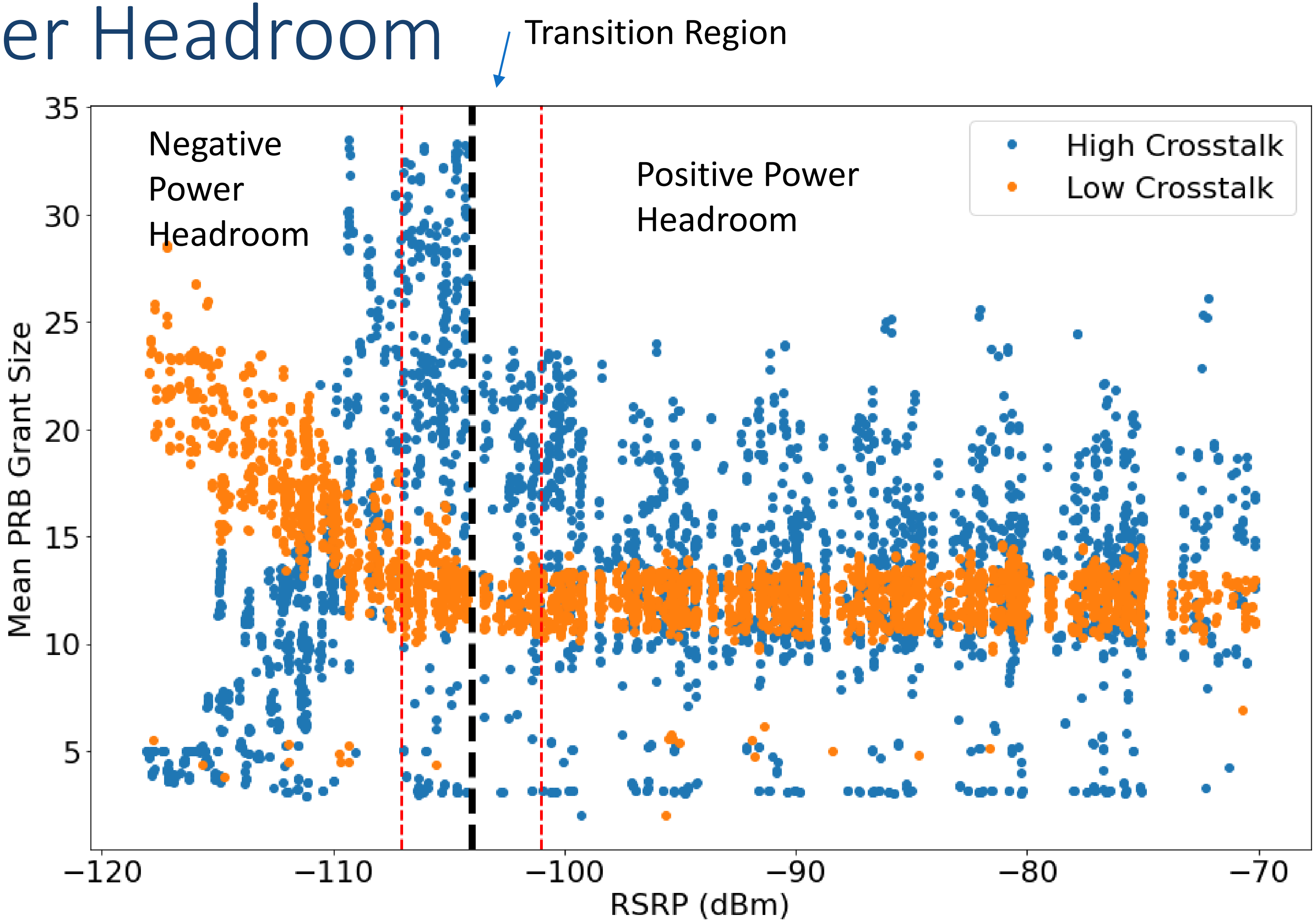
- There is a strong dependence on crosstalk.


Transition Region

Negative Power Headroom

Positive Power Headroom

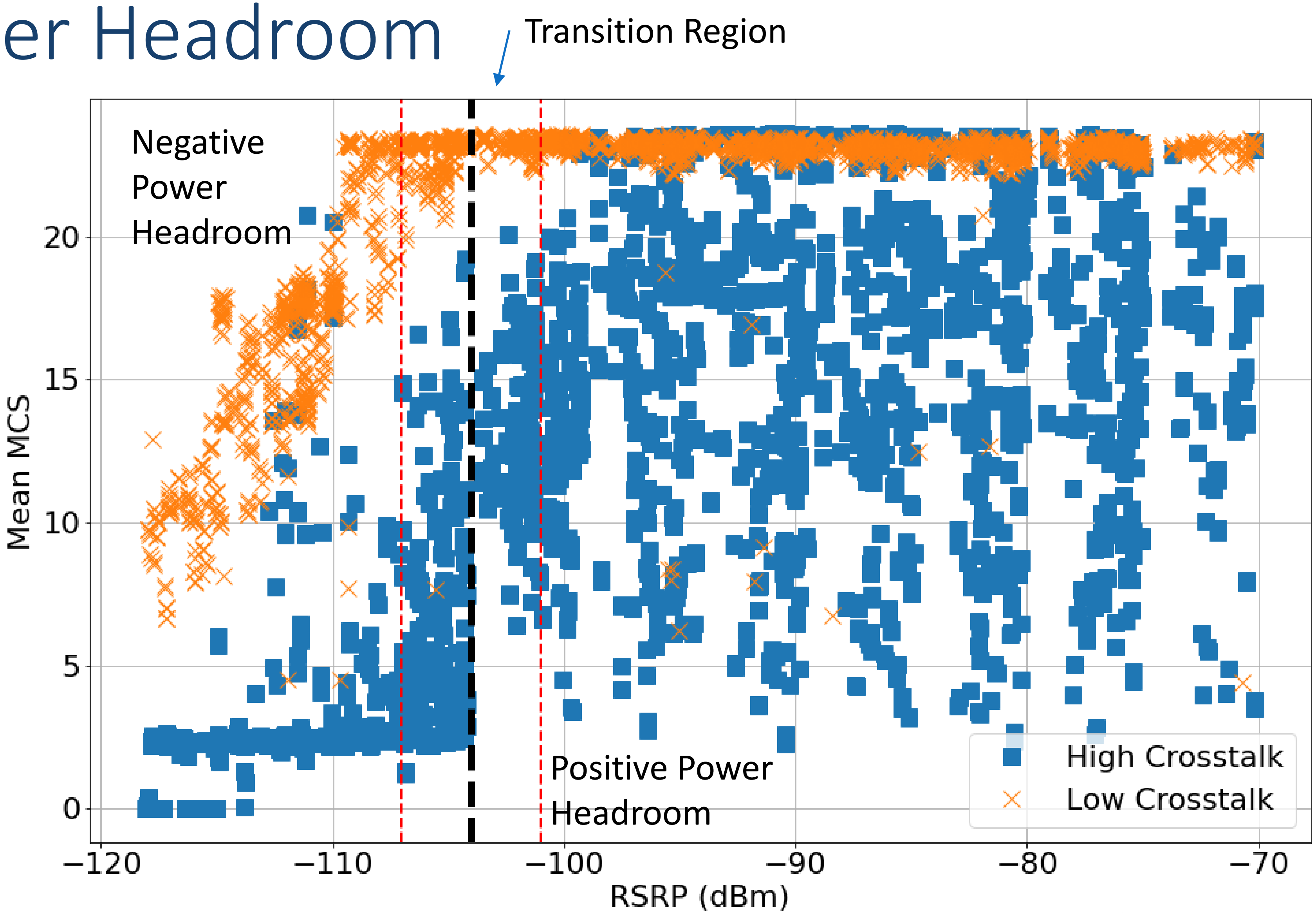
Negative Power Headroom



- We see a general increase in the grant size as the UE moves into the negative power headroom region.

Negative Power Headroom

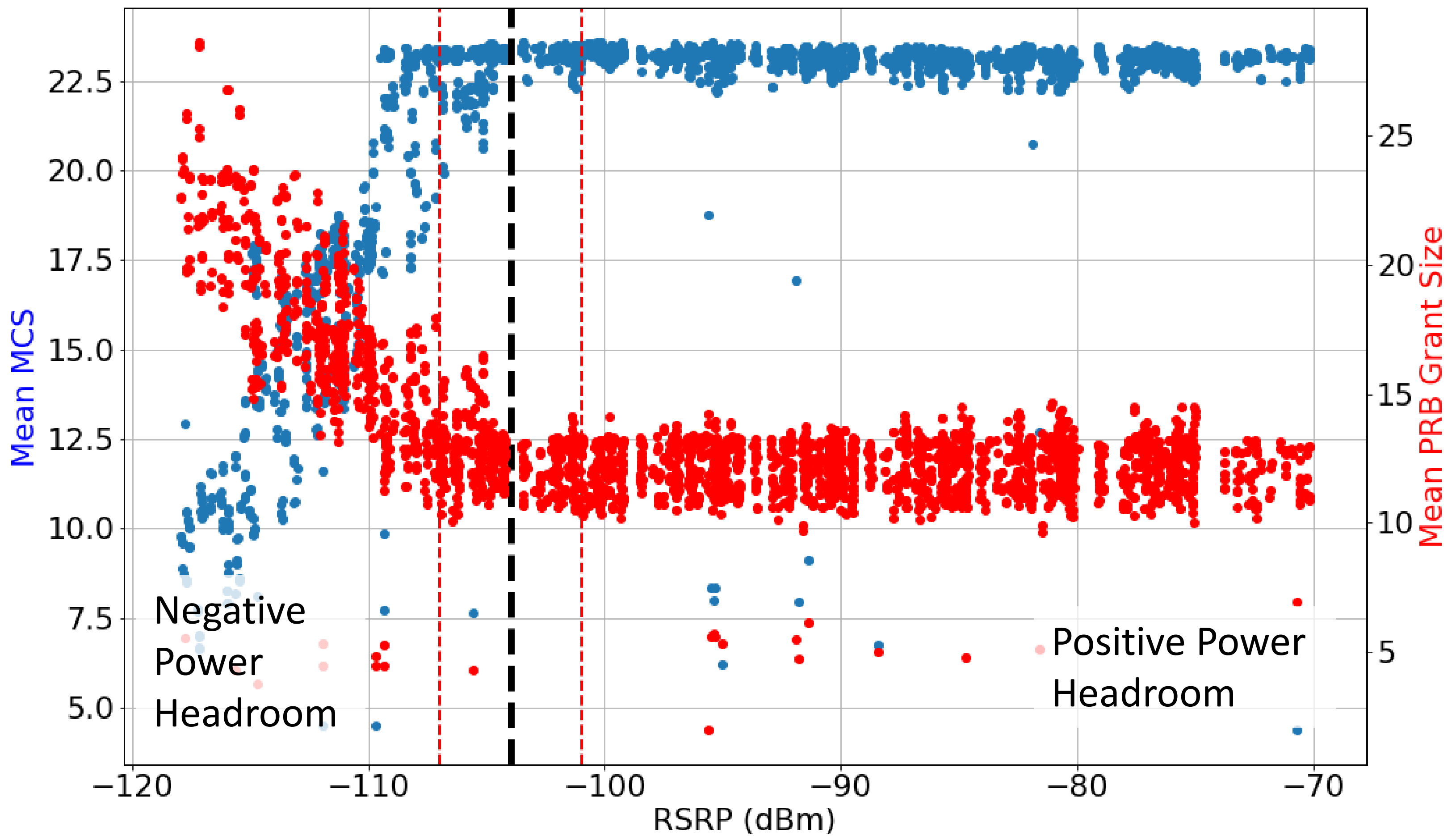
- In the negative power headroom region, we observe a mean MCS that decreases.



MCS – Modulation Coding Scheme

Negative Power Headroom

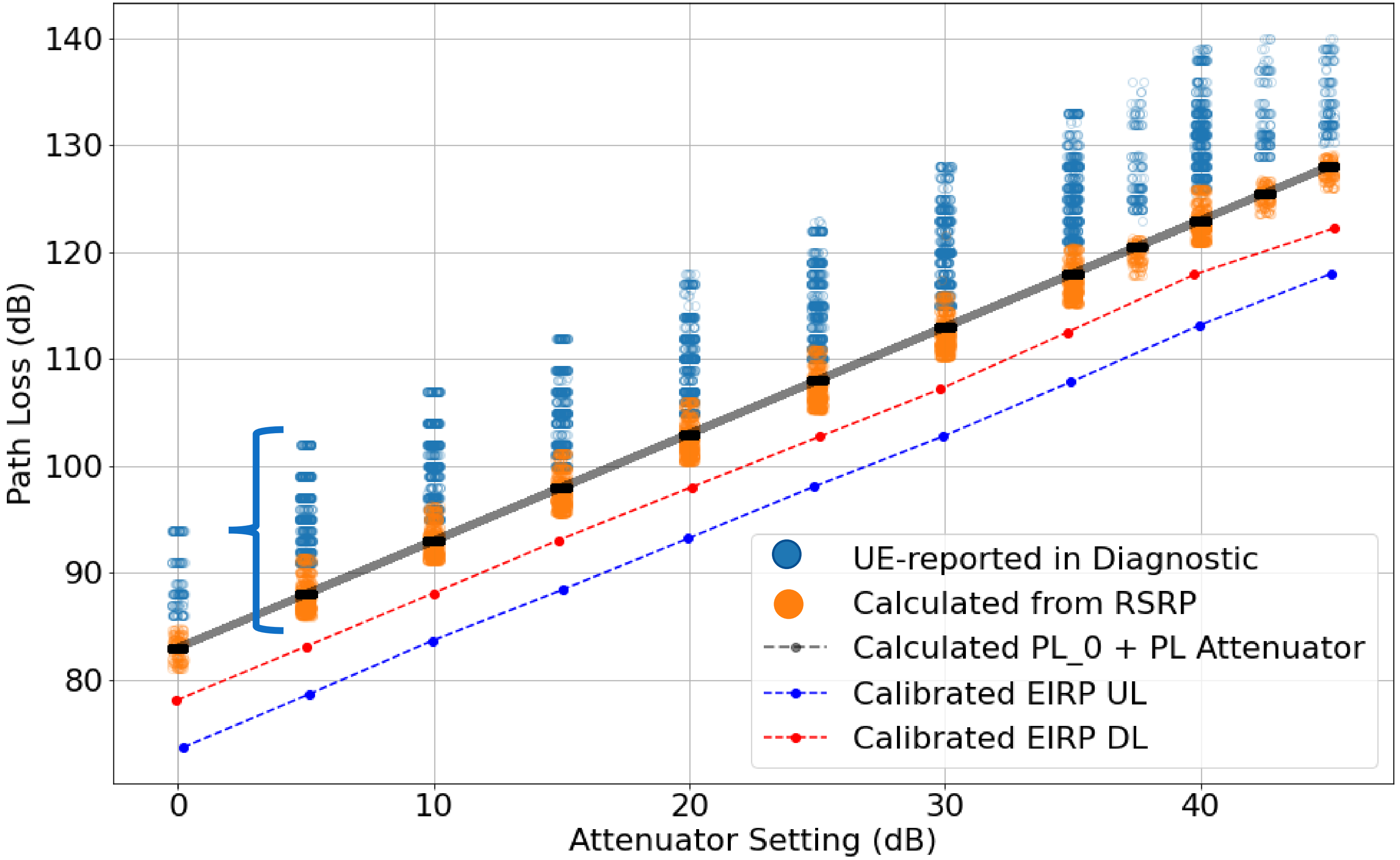
- Without crosstalk, negative power headroom causes a decrease in mean MCS and an increase in grant size.



Transition Region

Five Ways to Assess Path Loss - Calibrated measurements vs UE-reporting

- UE-reported DL path loss in power control packet



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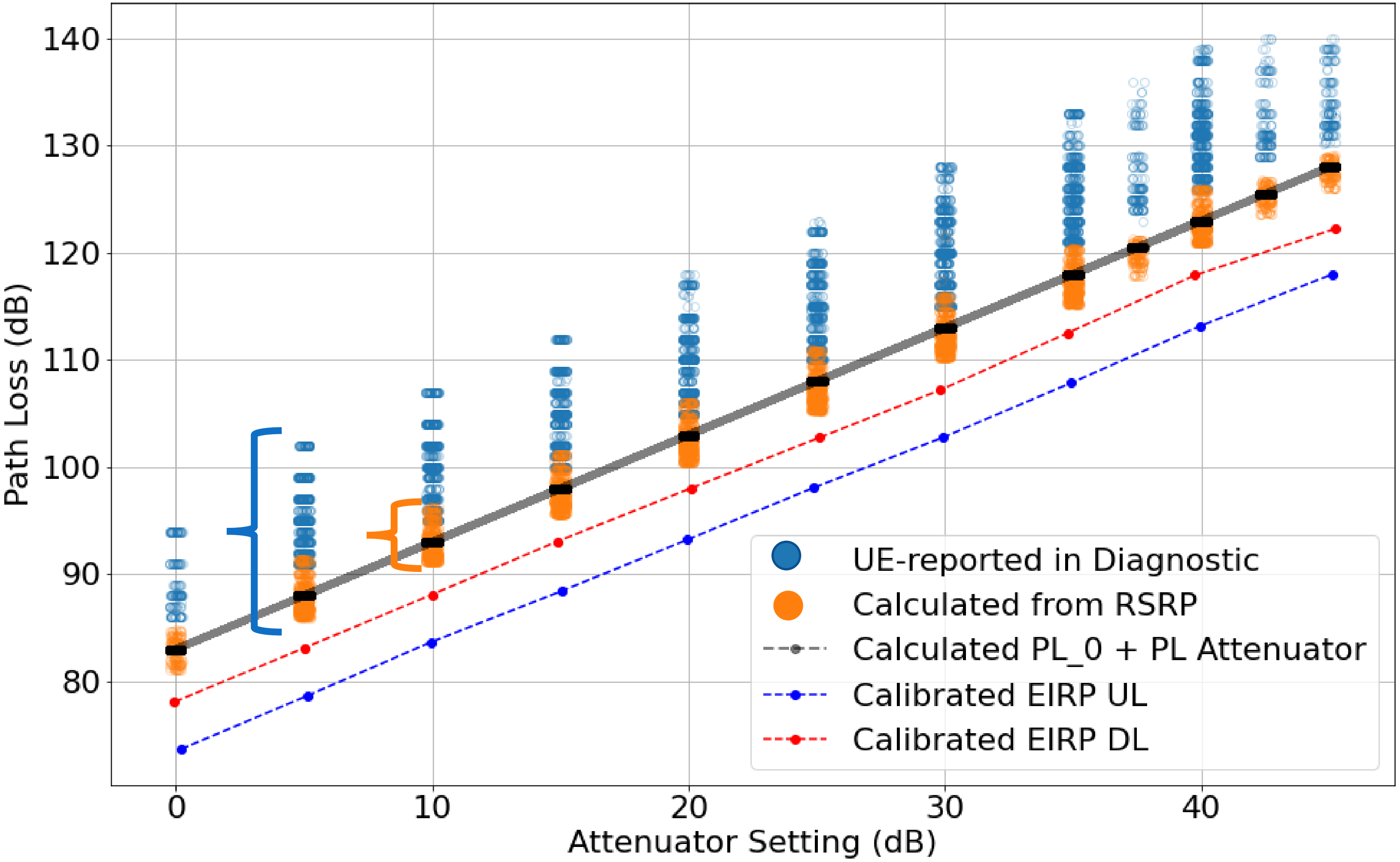
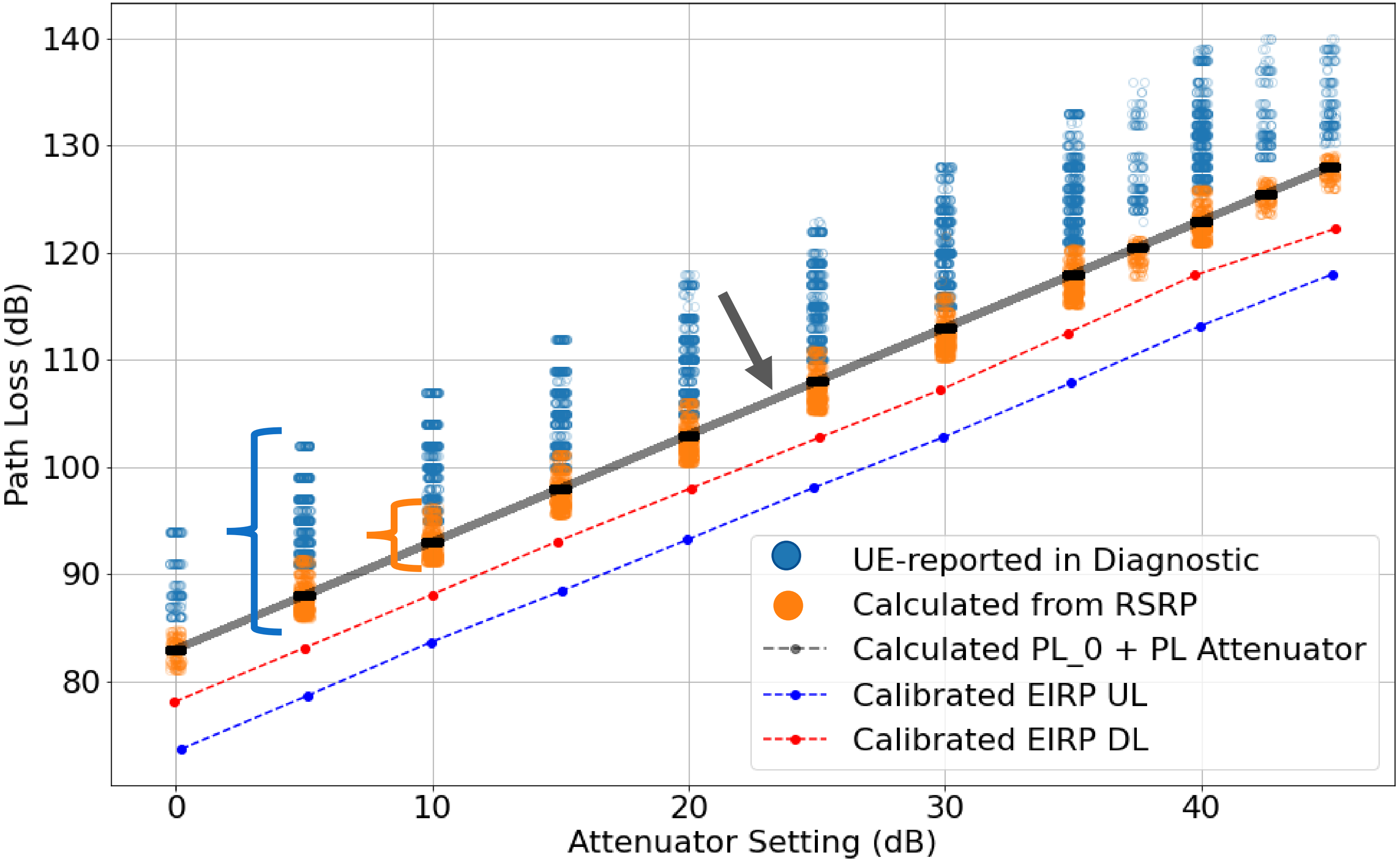
Five Ways to Assess Path Loss - Calibrated measurements vs UE-reporting

- UE-reported DL path loss in power control packet
- DL path loss calculated from RSRP (3GPP standard)



Five Ways to Assess Path Loss - Calibrated measurements vs UE-reporting

- UE-reported DL path loss in power control packet
- DL path loss calculated from RSRP (3GPP standard)
- DL path loss calculated from RSRP with zero excess attenuation plus excess attenuator value



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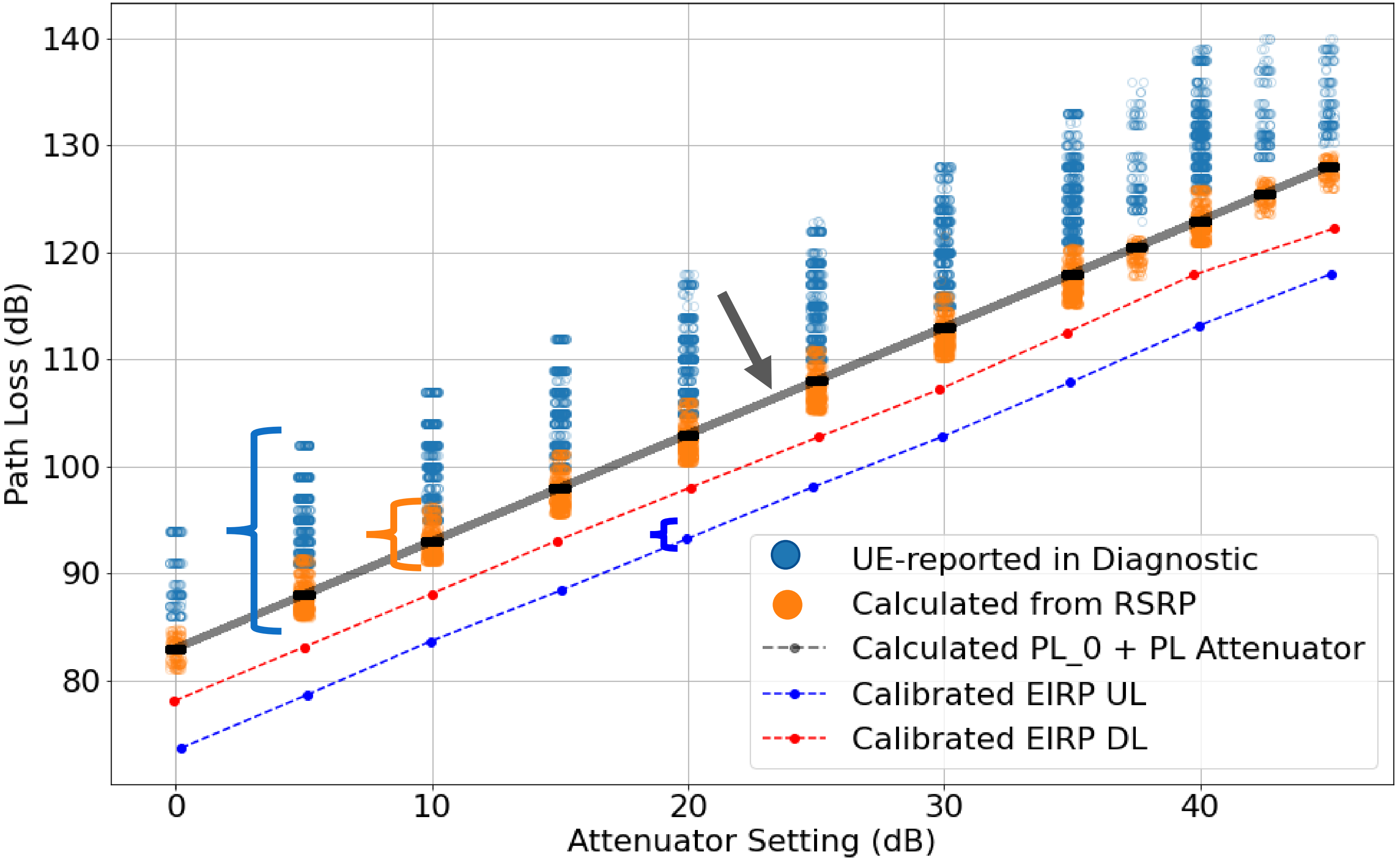
Five Ways to Assess Path Loss - Calibrated measurements vs UE-reporting

- UE-reported DL path loss in power control packet
- DL path loss calculated from RSRP (3GPP standard)
- DL path loss calculated from RSRP with zero excess attenuation plus excess attenuator value
- UL path loss measured with calibrated VNA

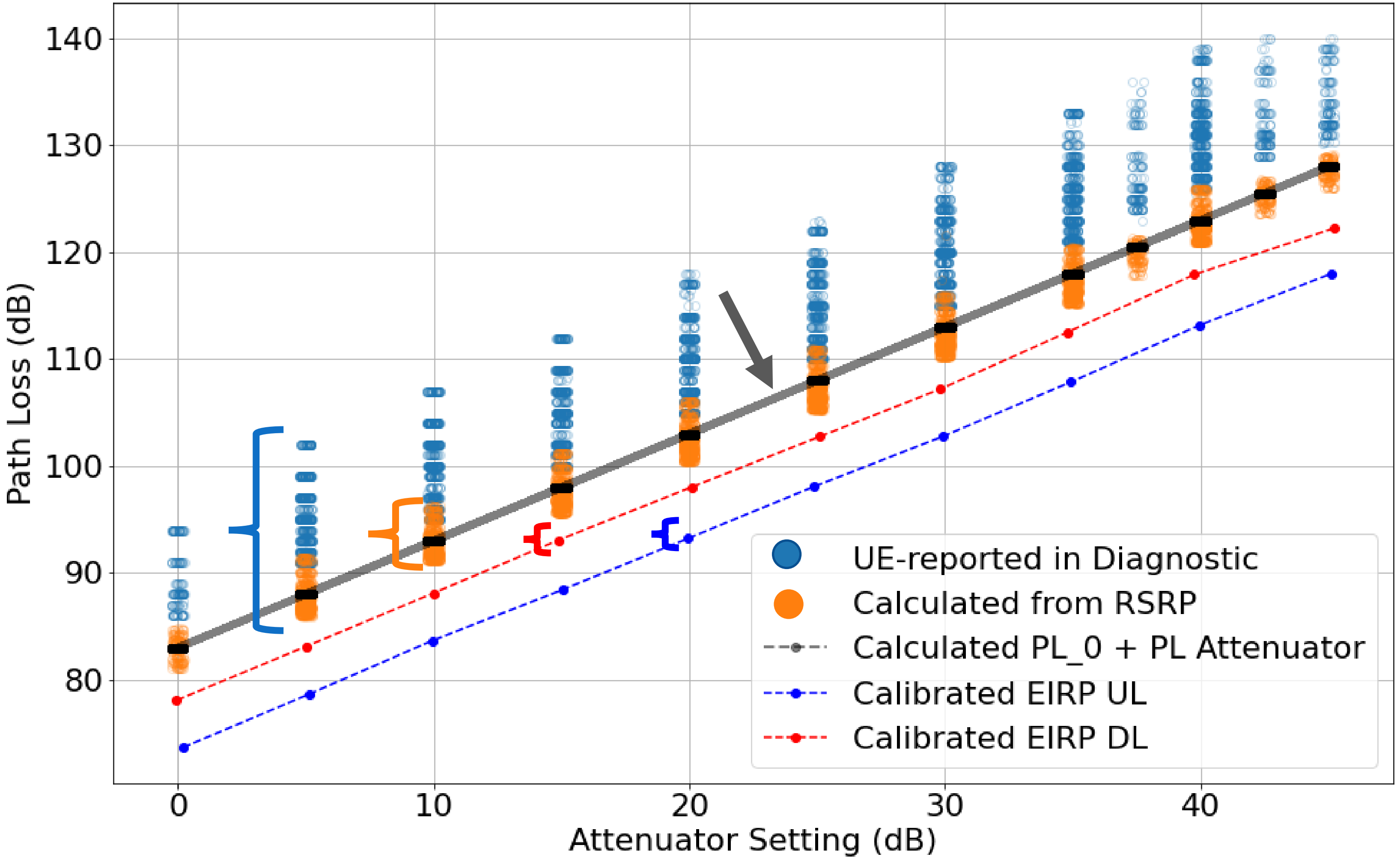


VNA – Vector Network Analyzer

UL - Uplink

Five Ways to Assess Path Loss - Calibrated measurements vs UE-reporting

- UE-reported DL path loss in power control packet
- DL path loss calculated from RSRP (3GPP standard)
- DL path loss calculated from RSRP with zero excess attenuation plus excess attenuator value
- UL path loss measured with calibrated VNA
- DL path loss measured with calibrated VNA



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Path Loss

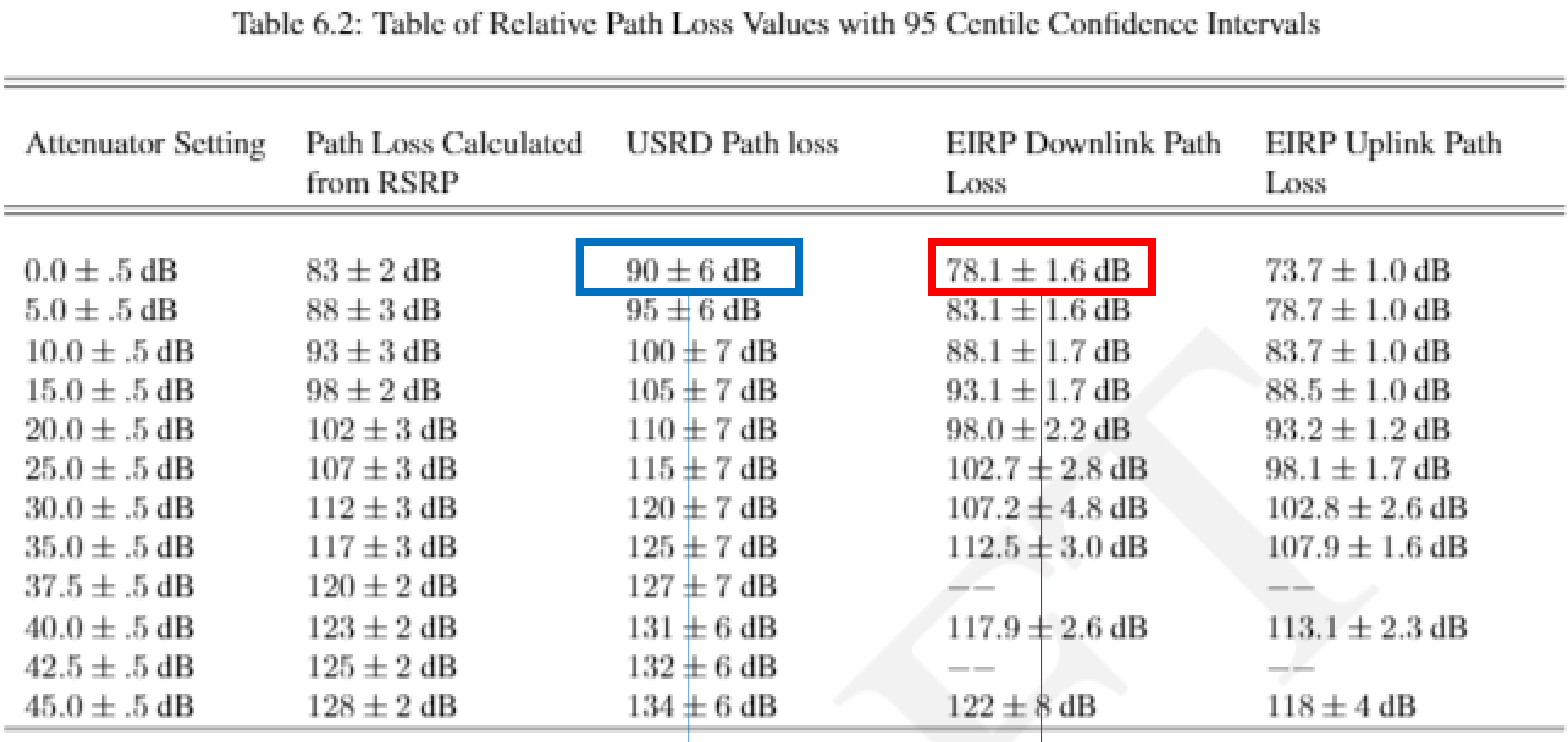


Table 6.2: Table of Relative Path Loss Values with 95 Centile Confidence Intervals

Attenuator Setting	Path Loss Calculated from RSRP	USRD Path loss	EIRP Downlink Path Loss	EIRP Uplink Path Loss
0.0 ± .5 dB	83 ± 2 dB	90 ± 6 dB	78.1 ± 1.6 dB	73.7 ± 1.0 dB
5.0 ± .5 dB	88 ± 3 dB	95 ± 6 dB	83.1 ± 1.6 dB	78.7 ± 1.0 dB
10.0 ± .5 dB	93 ± 3 dB	100 ± 7 dB	88.1 ± 1.7 dB	83.7 ± 1.0 dB
15.0 ± .5 dB	98 ± 2 dB	105 ± 7 dB	93.1 ± 1.7 dB	88.5 ± 1.0 dB
20.0 ± .5 dB	102 ± 3 dB	110 ± 7 dB	98.0 ± 2.2 dB	93.2 ± 1.2 dB
25.0 ± .5 dB	107 ± 3 dB	115 ± 7 dB	102.7 ± 2.8 dB	98.1 ± 1.7 dB
30.0 ± .5 dB	112 ± 3 dB	120 ± 7 dB	107.2 ± 4.8 dB	102.8 ± 2.6 dB
35.0 ± .5 dB	117 ± 3 dB	125 ± 7 dB	112.5 ± 3.0 dB	107.9 ± 1.6 dB
37.5 ± .5 dB	120 ± 2 dB	127 ± 7 dB	−−	−−
40.0 ± .5 dB	123 ± 2 dB	131 ± 6 dB	117.9 ± 2.6 dB	113.1 ± 2.3 dB
42.5 ± .5 dB	125 ± 2 dB	132 ± 6 dB	−−	−−
45.0 ± .5 dB	128 ± 2 dB	134 ± 6 dB	122 ± 8 dB	118 ± 4 dB

UE Estimation

Independent Measurement

Conclusions
- Challenges & Key Findings -

Speaker: Jason Coder

Challenges (Parts I & II)

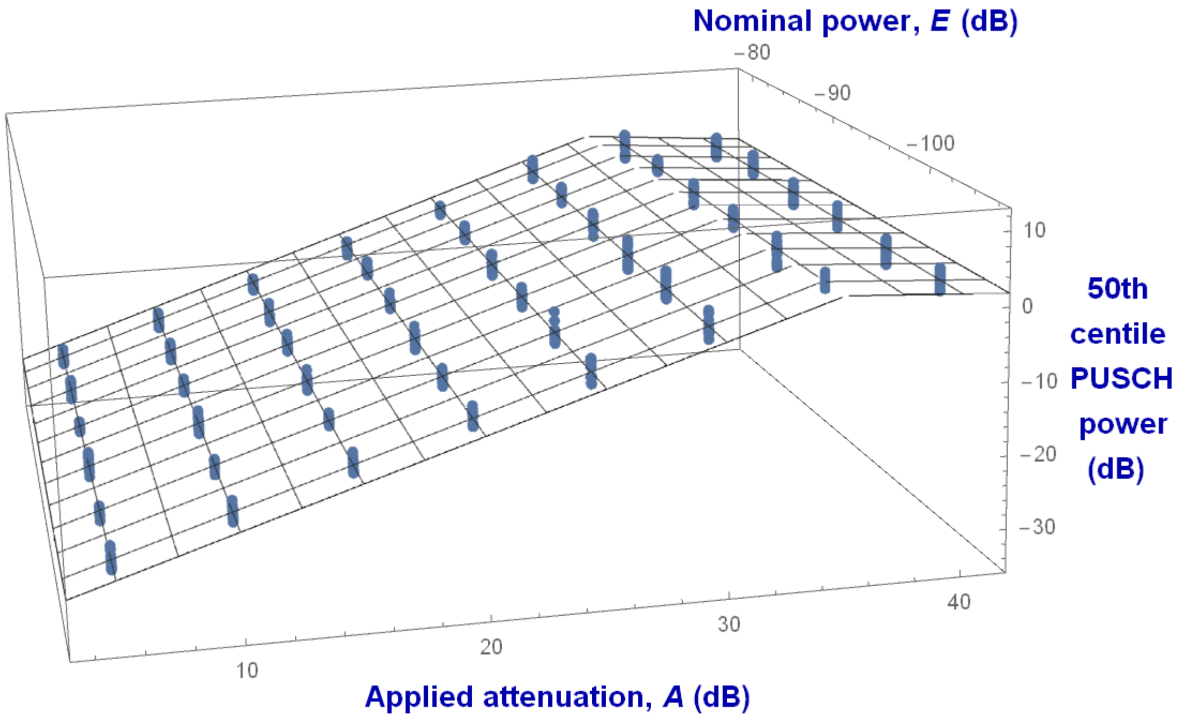
- Statistical Analysis - The response variable is a distribution, not a scalar or vector.
  - PUSCH power per PRB distributions are frequently multimodal. Not a textbook problem.
- Commercial equipment - Limited technical documentation, not intended for automated laboratory testing (e.g., frequent setting changes, time-alignment).
- Automation - Makes testing a large number of equipment configurations practical, providing sufficient data for rigorous uncertainty assessment and statistical analysis.
  - Acquisition + parsing + summary statistics → ~52,000 lines of code
  - Parts I & II: 1,696 unique measurement configurations; 8,825 total configurations measured
- Data verification - 28 different automated checks during parsing and time alignment.
  - Each 80 min test block auto-generated 294 pages of data verification plots for manual inspection.
- Estimating real-world configurations
  - What configuration are carriers using?

Key Findings (Parts I & II)

- PUSCH &PUCCH power per PRB distributions with OLPC spanned a much larger range than distributions with CLPC.
  - Closed-loop power control could enable better prediction of UE behavior.
- In some scenarios, the UE reported power was a poor metric of the actual radiated power.
  - UE never transmitted more power than it reported.
- In both the open-loop and closed-loop power control cases, the open-loop component of the power control equation was found to have little predictive utility.
  - Additional investigation is necessary.
- Performed 3-D radiation pattern measurements of several common LTE
  - The UE radiation patterns were not isotropic.
- MITRE used an independent testbed to test configurations similar to some of those used in the screening experiment.
  - The power distributions observed in the MITRE tests were consistent with the NASCTN laboratory measurements.

Key Findings (Parts I & II)

- CLPC - Statistical analysis
  - Descriptive model with two different regions
    - No significant impact due to UE variation or network loading/offered load
- Engineering analysis
  - When using UE-reported path loss, UE-reported power follows the power control equation.
    - UE-reported path loss often differs substantially (up to 15 dB) from calibrated measurements of path loss.
  - UE-reported power per TTI is on average 7 dBm greater than the measured EIRP.
  - In negative power headroom, UE has more scheduled PRBs and a lower MCS index.



Summary

- Effort produced three publications and sets of data:
  - NIST Technical Note 2056: Antenna Pattern Measurements
  - NIST Technical Note 2069: Factor Screening Experiment
  - NIST Technical Note 2147: Closed-Loop Power Control Experiment
  - All available free-of-charge: nist.gov; each publication contains a link to the data (data.nist.gov)
- Findings summarized in an Appendix of TN 2147
  - Designed to make it easy to use and apply NASCTN findings
- Statistical analysis provides a starting point, should the community be interested in extending this work to a predictive model
- Provided insight into UE emissions behavior, which could be used to inform next generation interference models/assessments
- Provided insight into additional questions via the engineering analysis
  - Results in the context of power control equation
  - Measured vs. reported power
  - Scheduling dynamics in negative power headroom

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Note: Clickable links to the reports included above

Questions?

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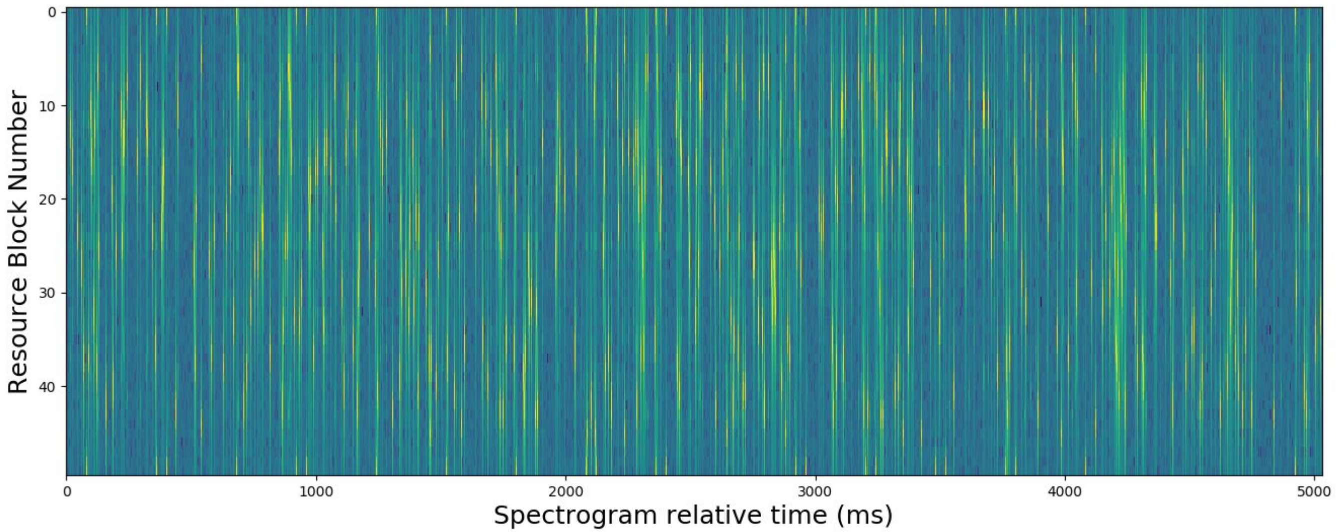
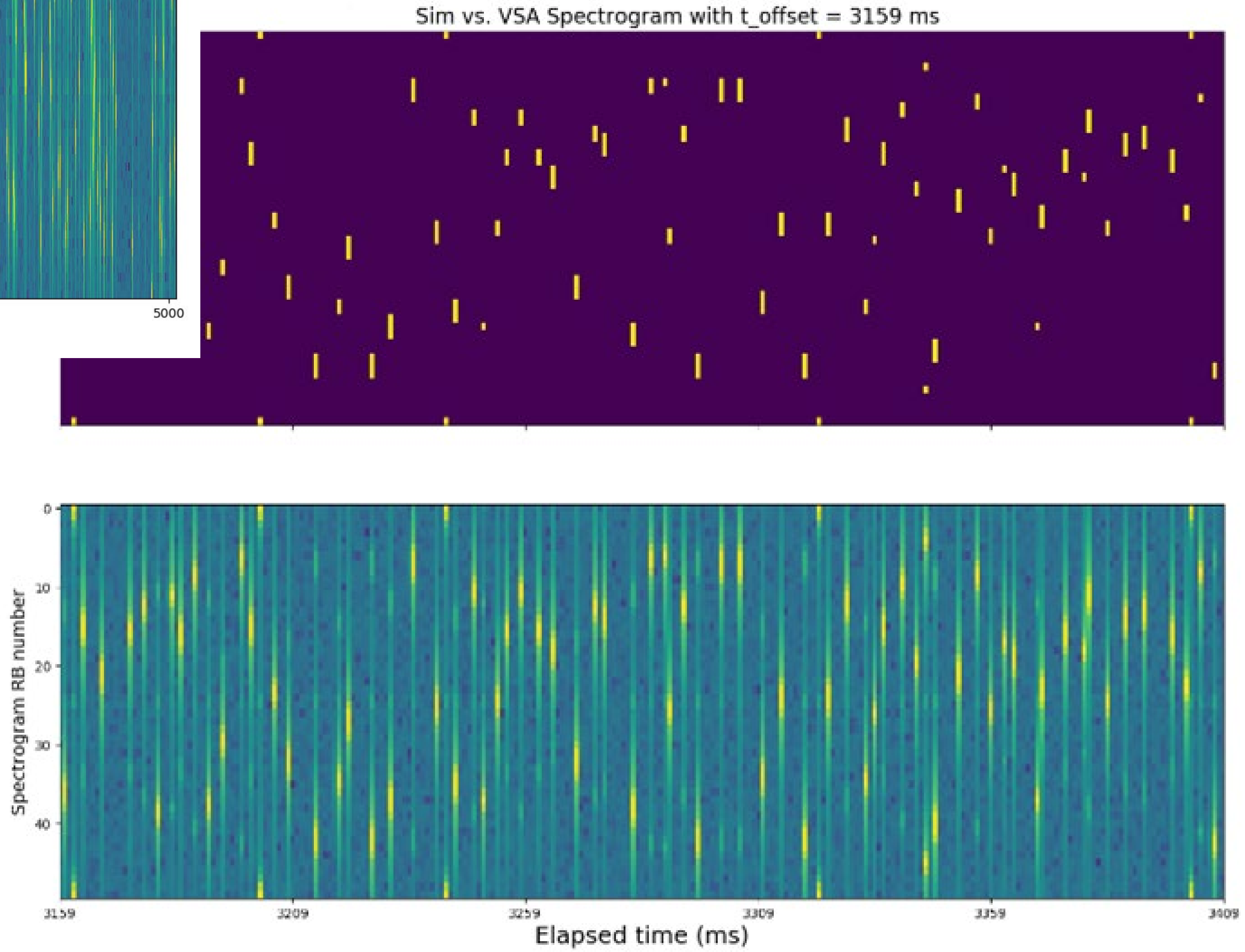
Back-up Material

Parsing/Alignment

- Developed an automated process to time align and parse the raw data files
  - Time-domain cross correlation between self-reported and measured power
    - RB allocations from diagnostic monitoring software compared with spectrogram
  - Parsed data from each of the three sources
  - Performed preliminary statistical analysis → "summary packets"
- Data are scrutinized during parsing to aid in identifying testbed issues
  - 28 different checks during the time alignment process
    - RACH attempts
    - Time alignment errors
    - Sequence of acquisition errors
    - ….



1) Extract RB allocation from diagnostic monitoring software
2) Time align the reported and measured data



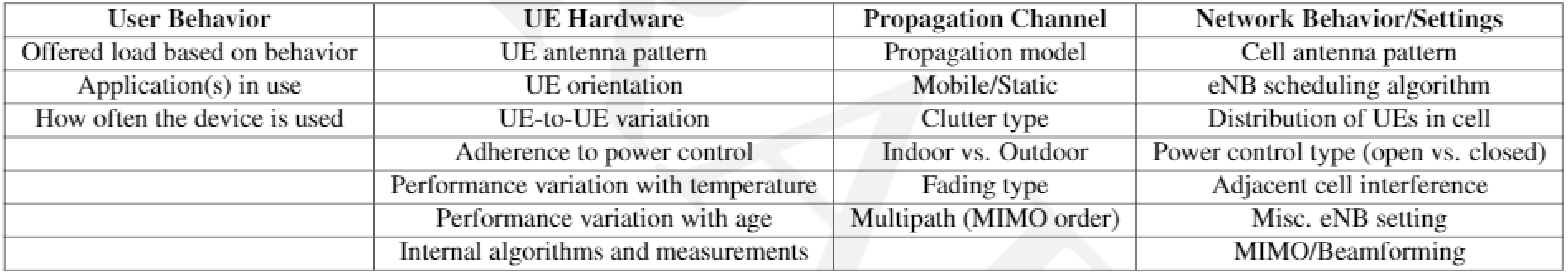
Note: preliminary data shown

Potential applications of NASCTN data

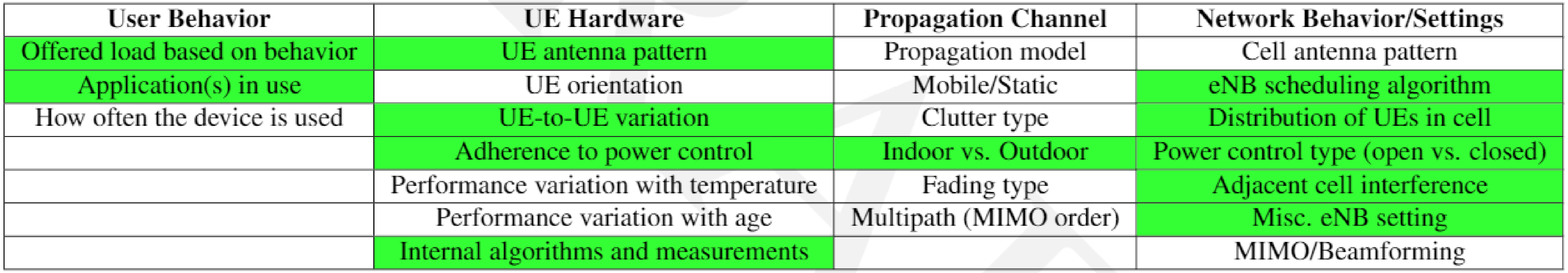
- Some applications ***may be*** addressable in the report writing of this phase
  - Others may be research projects (NIST vs. NASCTN)
  - Others may be best done by the community with input from NASCTN
- The “recipe”
  - Use of NASCTN data (or approach) to get a reference set of UE transmissions for use in AIT tools.
  - NASCTN data could be used to inform a recipe that includes other components (e.g., channel model)
- Use of NASCTN data to inform SSTD morphologies
- Use of NASCTN antenna pattern measurement data in simulations
  - Conditional probability distributions to get power in the direction of a DoD asset (given a UE transmit power)
- Informing the accuracy or AITs
  - Refinement of situations where transmit power significantly deviates from what is expected
  - CLPC data set may be most appropriate for this analysis
- How does the presence of closed loop power control effect expected transmit power.
  - What can we say about small cell applications?
    - Might the UE start at a lower power than is needed (due to being close to the base station), but is driven up by power control.
- UE variation between models and manufacturers
  - Current data set only provides another clue

Appendix: Summary of Findings

- Goal: Provide a concise summary of the NASCTN findings and insights across all three measurements efforts
  - Factor Screening
  - UE Antenna Pattern Measurements
  - Closed-Loop Power Control Characterization
- Inspired by the book of models, and the idea of developing a predictive model
- What can NASCTN about component of a model?
  - What components does NASCTN think could be included in a model?



User Behavior	UE Hardware	Propagation Channel	Network Behavior/Settings
Offered load based on behavior	UE antenna pattern	Propagation model	Cell antenna pattern
Application(s) in use	UE orientation	Mobile/Static	eNB scheduling algorithm
How often the device is used	UE-to-UE variation	Clutter type	Distribution of UEs in cell
	Adherence to power control	Indoor vs. Outdoor	Power control type (open vs. closed)
	Performance variation with temperature	Fading type	Adjacent cell interference
	Performance variation with age	Multipath (MIMO order)	Misc. eNB setting
	Internal algorithms and measurements		MIMO/Beamforming



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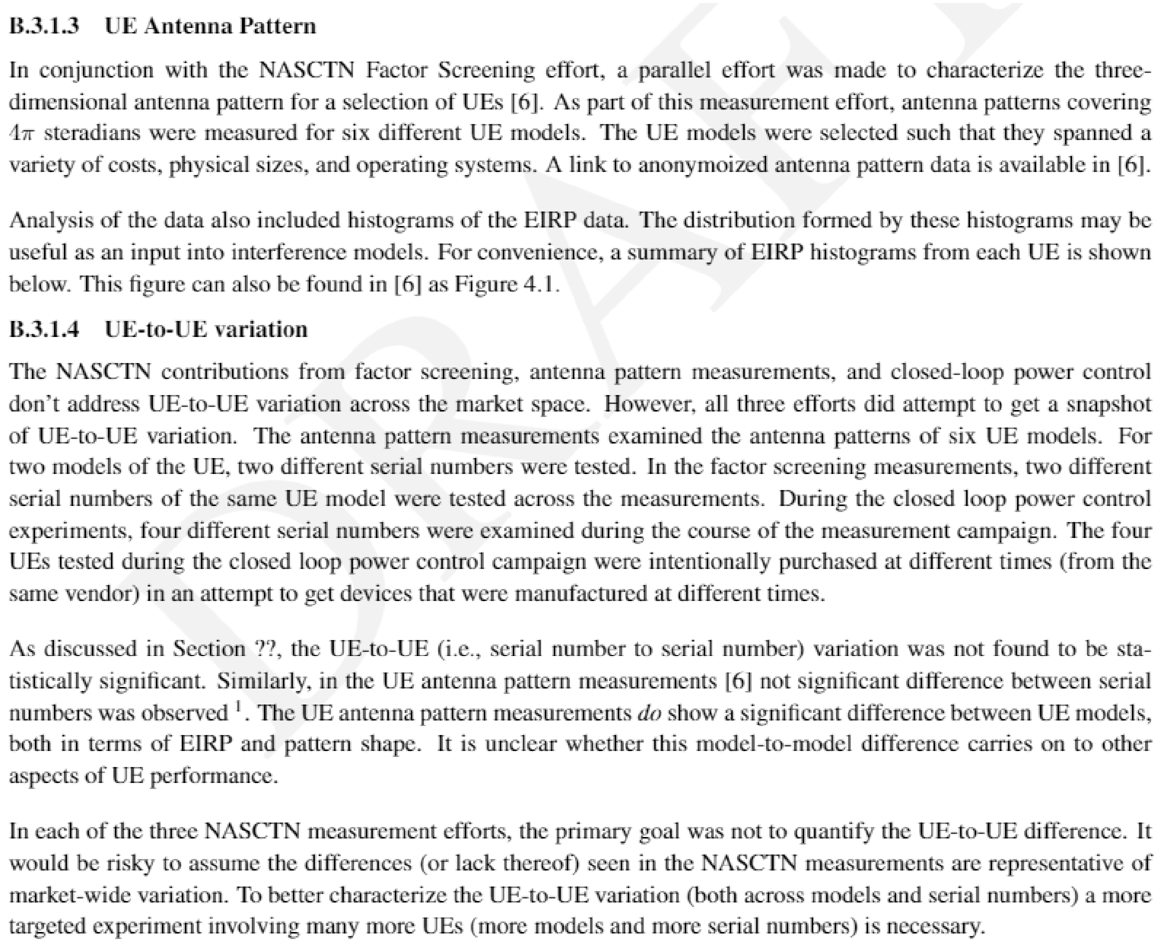
	Performance variation with temperature	Fading type	Adjacent cell interference
	Performance variation with age	Multipath (MIMO order)	Misc. eNB setting
	Internal algorithms and measurements		MIMO/Beamforming

- Green elements: NASCTN can provide insight
- Other elements: No direct NASCTN insight

- Every elements will be discussed
  - Summary of NASCTN’s contributions, and where details can be found
  - Or, why is that element particularly challenging?

Appendix Summary of Findings

- Text can be dropped into book of models, or other resources as desired
- Doesn’t comment on the weighting or combination of individual components



B.3.1.3 UE Antenna Pattern

In conjunction with the NASCTN Factor Screening effort, a parallel effort was made to characterize the three-dimensional antenna pattern for a selection of UEs [6]. As part of this measurement effort, antenna patterns covering 4π steradians were measured for six different UE models. The UE models were selected such that they spanned a variety of costs, physical sizes, and operating systems. A link to anonymoized antenna pattern data is available in [6].

Analysis of the data also included histograms of the EIRP data. The distribution formed by these histograms may be useful as an input into interference models. For convenience, a summary of EIRP histograms from each UE is shown below. This figure can also be found in [6] as Figure 4.1.

B.3.1.4 UE-to-UE variation

The NASCTN contributions from factor screening, antenna pattern measurements, and closed-loop power control don’t address UE-to-UE variation across the market space. However, all three efforts did attempt to get a snapshot of UE-to-UE variation. The antenna pattern measurements examined the antenna patterns of six UE models. For two models of the UE, two different serial numbers were tested. In the factor screening measurements, two different serial numbers of the same UE model were tested across the measurements. During the closed loop power control experiments, four different serial numbers were examined during the course of the measurement campaign. The four UEs tested during the closed loop power control campaign were intentionally purchased at different times (from the same vendor) in an attempt to get devices that were manufactured at different times.

As discussed in Section ??, the UE-to-UE (i.e., serial number to serial number) variation was not found to be statistically significant. Similarly, in the UE antenna pattern measurements [6] not significant difference between serial numbers was observed [1]. The UE antenna pattern measurements *do* show a significant difference between UE models, both in terms of EIRP and pattern shape. It is unclear whether this model-to-model difference carries on to other aspects of UE performance.

In each of the three NASCTN measurement efforts, the primary goal was not to quantify the UE-to-UE difference. It would be risky to assume the differences (or lack thereof) seen in the NASCTN measurements are representative of market-wide variation. To better characterize the UE-to-UE variation (both across models and serial numbers) a more targeted experiment involving many more UEs (more models and more serial numbers) is necessary.