Aggregate LTE:
Characterizing User Equipment Emissions
Welcome

13 September 2017

Dr. Sheryl Genco
Acting NASCTN Program Manager

What is NASCTN?

National Advanced Spectrum and Communications Test Network (NASCTN)

- Established by NIST, NTIA, and DoD in 2015
- Mission: provide robust test processes and validated measurement data necessary to
  - Develop, evaluate, and deploy spectrum sharing technologies
  - Inform spectrum policy and regulations

NIST National Institute of Standards and Technology U.S. Department of Commerce

NASCTN Core Functions

- Test plan development
- Stakeholder outreach
- Identify and facilitate access to appropriate test facilities
- Test execution
- Deliver detailed methods and results
  - Transparency, validity, and reproducibility
- Protect controlled information

Complete & Active NASCTN Projects

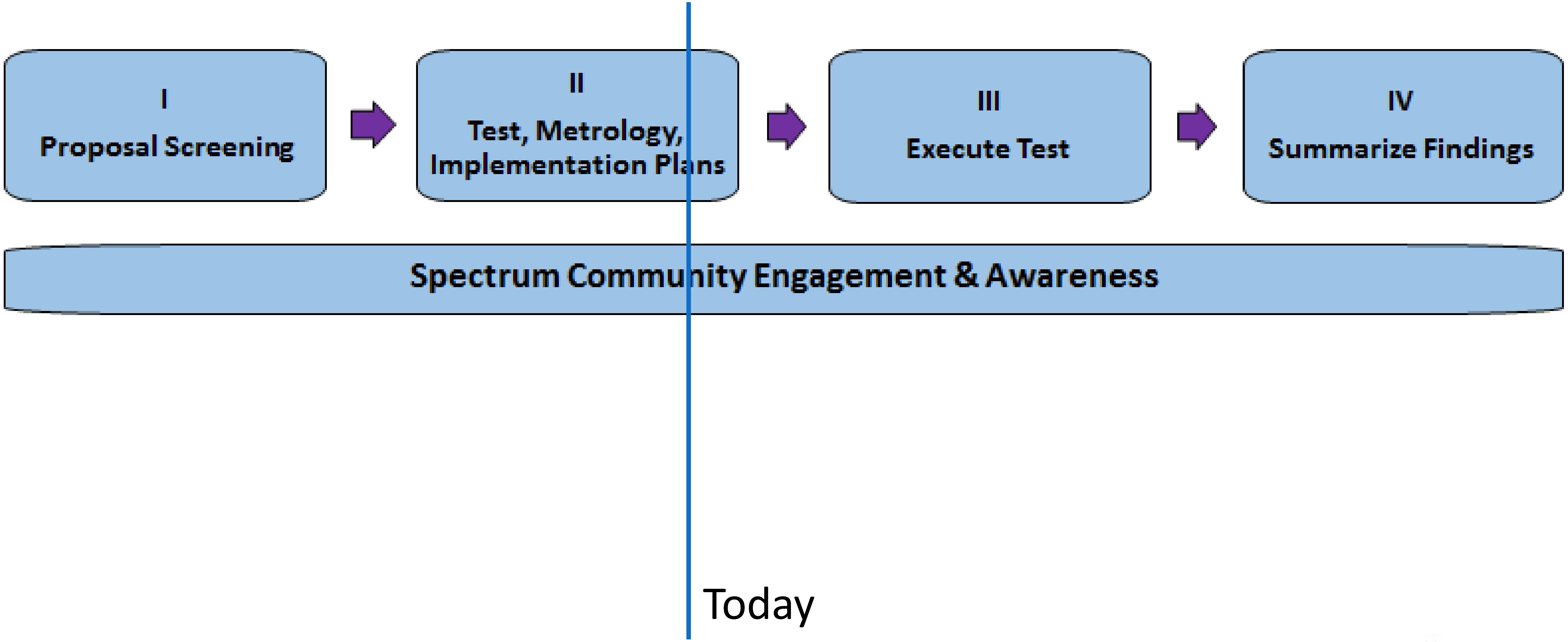
Complete (see https://www.nist.gov/ctl/nasctn/projects for more info)

- Waveform Measurements of Radars in 3.5 GHz Band
  - 2016: Test plan, Measurements at San Diego and Virginia Beach
  - 2017: Final Reports: NIST Technical Note 1954 and Public Briefing held Aug 11
- Out-of-Band Emission Measurements of LTE Devices Operating in the AWS-3 Band (proposed by Edwards Air Force Base)
  - 2016: Phase 1 test plan and measurements, phase 2 test plan
  - 2017: Phase 2 testing at Boulder and McLean, VA, Final Report: release pending
- LTE Impacts on GPS (proposed by Ligado Networks)
  - 2016: Test plan, Testing at Longmont, CO and NIST-Boulder
  - 2017: Final Reports: NIST Technical Note 1952 and Public Briefing held May 4

Current

- Aggregate AWS-3 LTE (proposed by Defense Information Systems Agency)

NASCTN Process Status



Meeting Goals and Agenda

1. Presentation of plan to measure and model emissions from smart phones
2. Panel session for clarifying questions
3. Please hold questions until the panel session
4. NASCTN seeks your comments and feedback to help make this project a success
5. Please send comments and feedback to sheryl.genco@nist.gov

- Range of eNB power control parameters (such as P_0 and α)
- Other eNB settings that might impact UL traffic (such as scheduler and number of simultaneous UEs)
- Range of geographic cell sizes (rural, suburban, urban) and corresponding user density
- Cell morphologies (user density, site topography, man-made structure, etc.)

Aggregate LTE:
Characterizing User Equipment Emissions
Phase 1 Metrology Plan: Laboratory measurements

13 September 2017

Dr. Paul Hale, Technical Lead

Jason Coder, Dr. Adam Wunderlich, Mark Lofquist, John Ladbury, Azizollah Kord, Jonathan Cook, Dr. Timothy Hall, Dr. Keith Hartley, and Dr. Sheryl Genco

Measurement Plan

- Develop a predictive model of the power and spectrum of LTE equipment emissions
- Describe a wide range of network configurations
- Controlled measurement of LTE equipment emissions in a laboratory environment
- Will include an uncertainty analysis with estimated confidence intervals

Background/Setting the Stage

- June 2010: Presidential Memorandum "Unleashing the wireless broadband revolution"
- October 2010: NTIA 'Fast Track' report identified potential bands for wireless broadband use
- January 2013: Commerce Spectrum Management Advisory Committee (CSMAC) recommended ways to facilitate the implementation of commercial wireless broadband in the 1755-1850 MHz band
  - Instructed to "..improve modeling of commercial wireless network(s) …using the Fast Track report as a baseline…"
  - Proposed a model of the power emitted by LTE devices
- March 2014: FCC Report and Order FCC 14-31
  - Established 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz as the Advanced Wireless Service – 3 (AWS-3) band
  - Included indefinite period of sharing with limited number of Federal systems
  - Federal systems are using a combination of sharing, compression into adjacent bands, and relocation to different bands

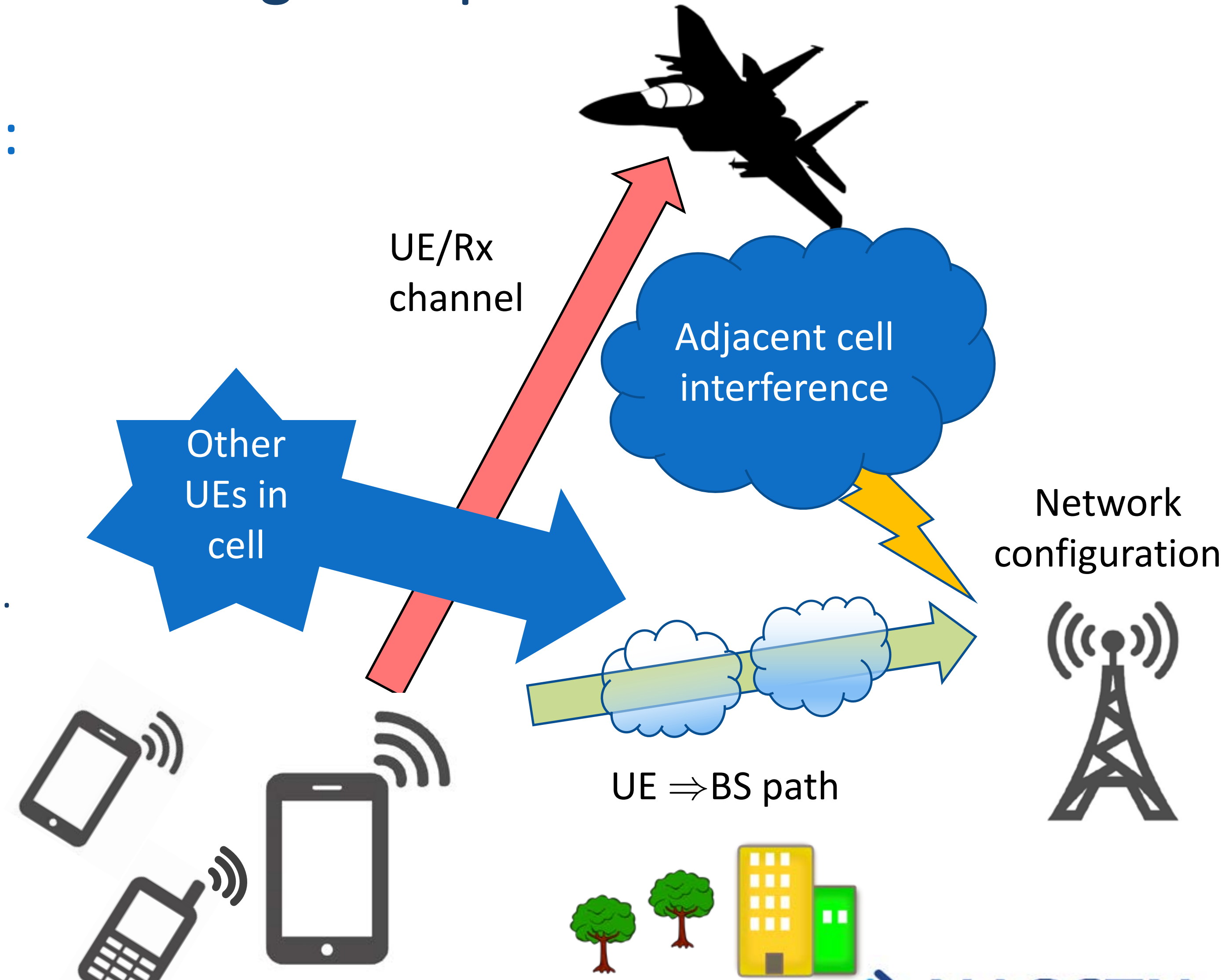
Background/Setting the Stage

- July 2014: FCC and NTIA Joint Public Notice (PN) for AWS-3
  - Refined CSMAC analysis of certain AWS-3 Coordination Zones (CZs)
    - Network loading parameters reduced to 40% for rural and 60% for urban/suburban
      - CSMAC analyses assumed 100% network loading
    - Propagation clutter is modeled for ground-to-ground and ground-to-air analyses
      - CSMAC analyses assumed no clutter loss
- January 2015: AWS-3 auctioned for commercial use
  - Raised $41B
- Ongoing DSO Coordination Efforts
  - Presently screening Coordination Requests
  - These screening evaluations make use of the CSMAC model of UE emissions
  - Seeking to refine the CSMAC analysis of LTE interference

Why UE Emissions are Important: Estimating LTE Uplink Interference in 1755 MHz to 1780 MHz Band

Aggregate interference depends on:

1. Power emitted by UE
   a) Path between UE and BS
      i. Distance, terrain, structures, foliage, weather, …
   b) Contention with other UEs in cell
   c) Interference from UEs in adjacent cells
   d) Network configuration
      i. Power control, scheduling algorithm, …
   e) Type of traffic, …
2. Number of UEs transmitting simultaneously
3. Spectral properties of UE
4. Path between UE and victim Rx
5. Properties of victim Rx
6. And more…



EIRP of Single UE

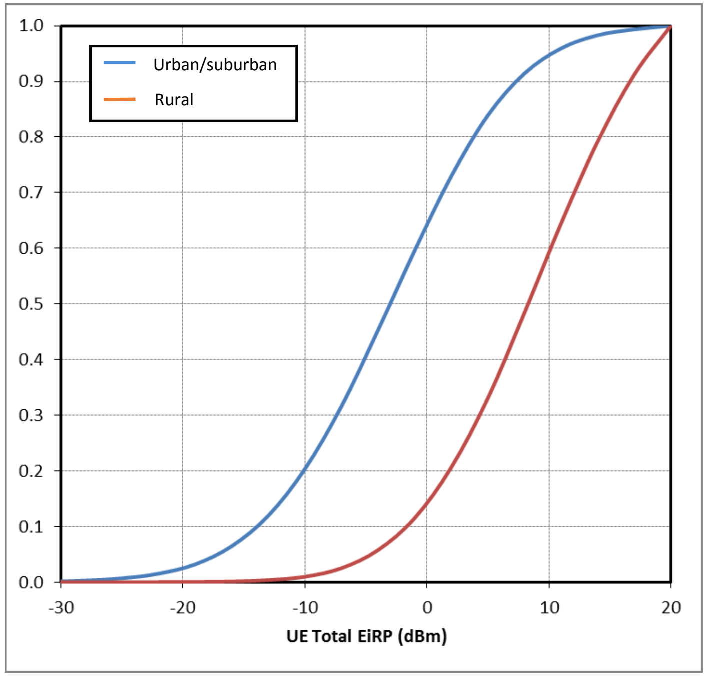
$\hat{E}^{(1)}$ = Equivalent Isotropic Radiated Power (EIRP) of one "modeled" UE

$\Rightarrow$ Behavior of one UE in an ensemble of UEs distributed throughout the cell

$\Rightarrow$ Complicated function of network parameters and morphology

$\hat{E}^{(N)}$ = EIRP of N simultaneously emitting modeled UEs in 1 ms subframe (in dBm) in 1 cell

CSMAC EIRP distribution for 1 ms

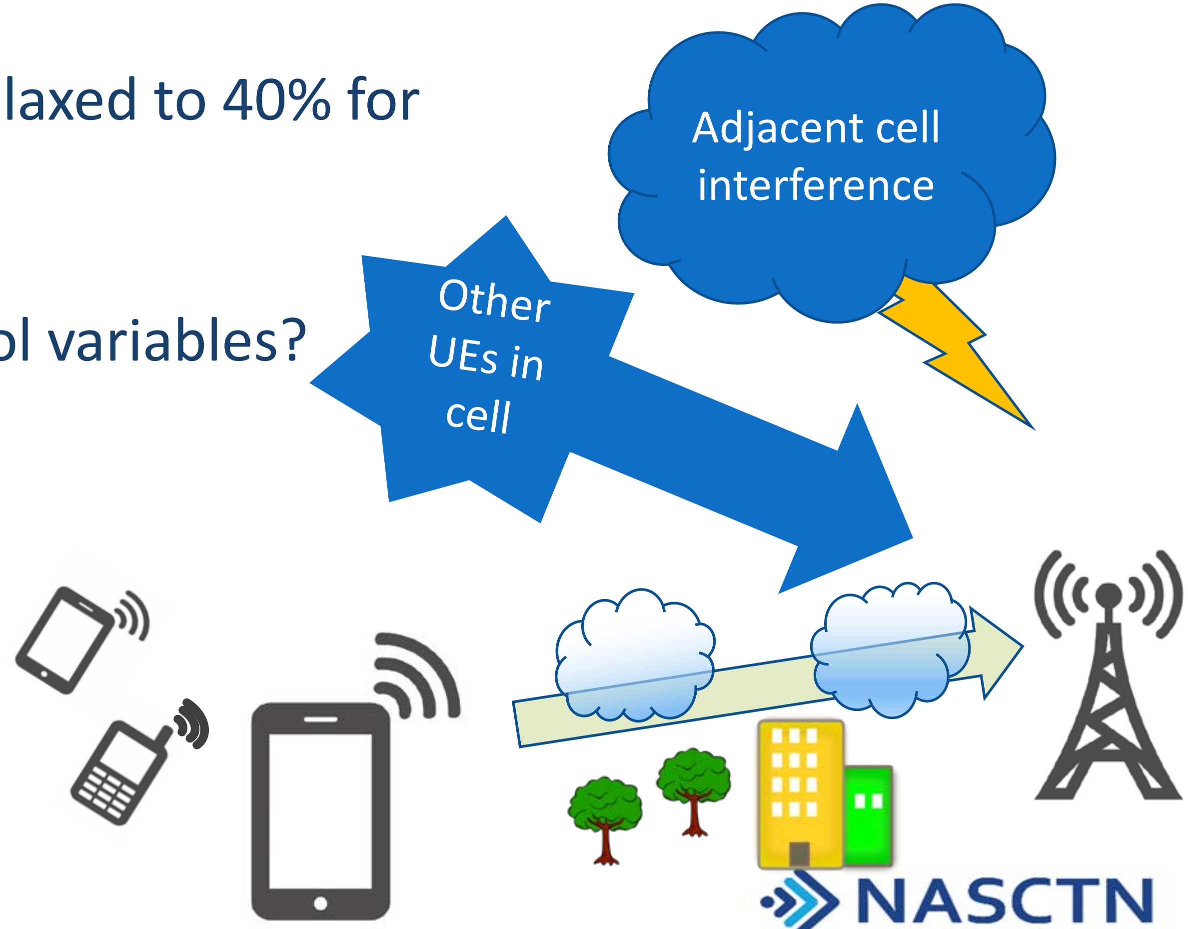


CSMAC assumptions for generation of EIRP distribution

- LTE Frequency Division Duplex (FDD) system
- 10 MHz LTE Bandwidth
- 100% system loading at LTE Base Station (eNodeB)
- All Physical Resource Blocks (PRB) are occupied at all times
- All UEs outdoors
- P0 = -90 dBm and α = 0.8 for UL Power Control (urban/suburban/rural)
- Proportional fair algorithm for LTE Scheduler
- Full-buffer traffic model (i.e. All UEs have data in their Radio Link Control (RLC) layer buffer at all times)
- Power is transmitted into a 10 MHz channel over a 1 ms subframe

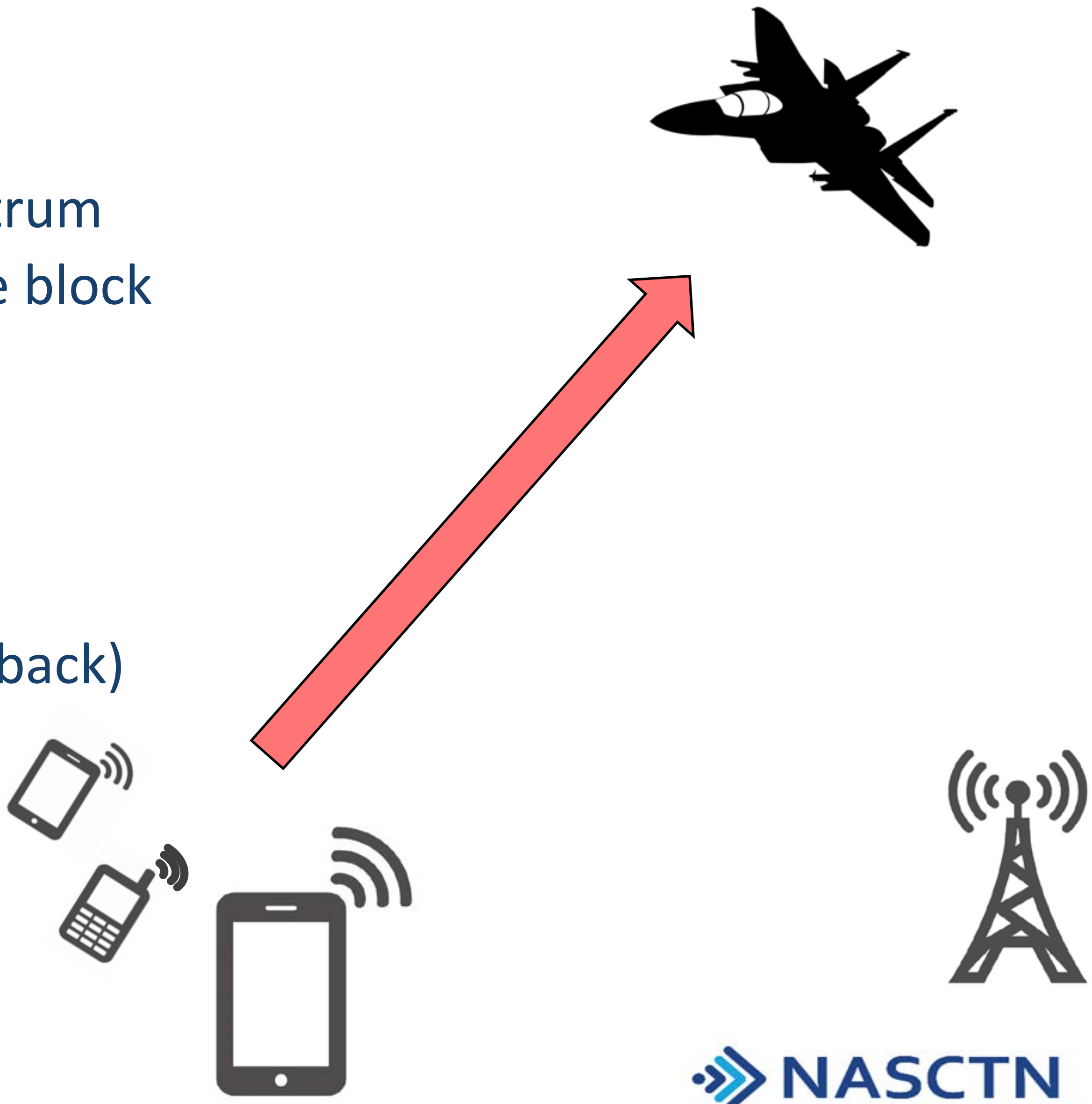
Generalizing the UE Emissions Model

- CSMAC used a conservative approach of N=6/subframe/10 MHz/cell
  - What factors affect this distribution?
- In 2014 FCC/NTIA Public Notice, Loading was relaxed to 40% for rural and 60% for urban/suburban
  - How does this affect the distribution?
- What is the effect of changing the power control variables?
- What is the effect of adjacent cell interference (not accounted for by CSMAC)?
- Realistic mobile channels have clutter that will affect $\hat{E}(1)$



UE Emitted Spectrum also Affects Interference

- Interference depends on the UE emitted spectrum
  - UE emitted spectrum depends on resource block allocation, which depends on:
    - Scheduler
    - Network loading
    - RF conditions
    - Other factors (please give us your feedback)



Deliverables

Predictive models, with uncertainties, for the following:

1. The distribution of peak and RMS $\hat{E}^{(1)}$, the EIRP emitted by one UE in a 1 ms subframe, marginalized (averaged) over the cell spatial distribution.
2. The emitted in-band spectrum of an actively transmitting UE.
3. The number N of UEs emitting into a 5 MHz or 10 MHz band per 1 ms LTE subframe per cell.

Secondary deliverables are:

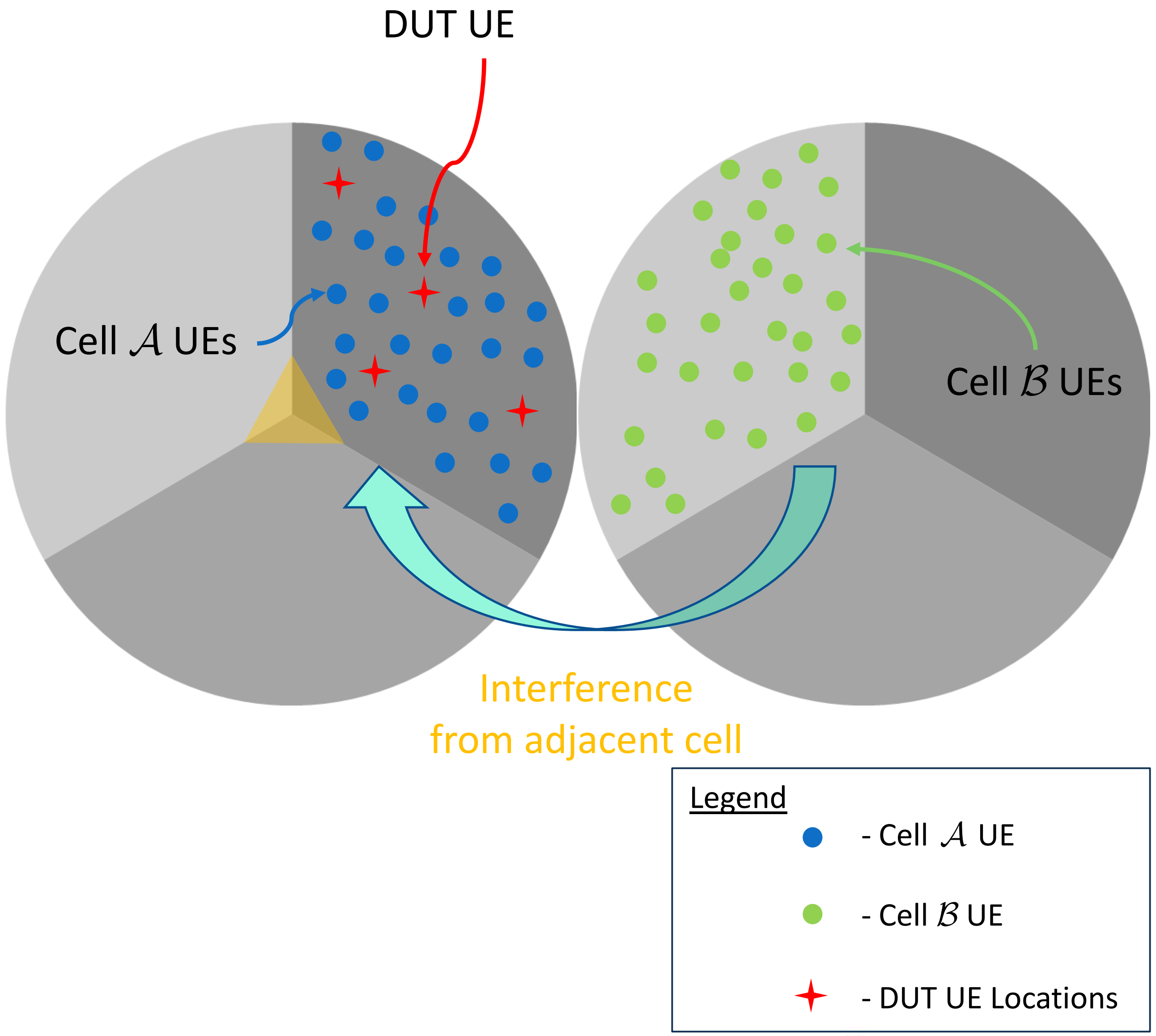
4. Characterization of the accuracy of generated power as reported by the UE and its correspondence to the EIRP.
5. Consideration of field measurements of the above variables.

Measurement Concept

1. Cell $\mathcal{A}$ and Cell $\mathcal{B}$ are loaded with UEs
2. Cell $\mathcal{A}$ UEs load eNB scheduler
3. Cell $\mathcal{B}$ UEs increase noise at eNB

At different positions of DUT UE

1. Measure DUT UE emitted power
2. Measure DUT UE emitted spectrum
3. Measure number of UEs in each 1 ms subframe
4. Pool these data over entire cell to obtain statistics for particular configuration



Laboratory vs. Field Measurements

- Laboratory measurements will allow control and manipulation of the network configuration
- Will give quantitative understanding of the UE emission and how it varies with specific network parameters
- Results will be generalizable to different network configurations and terrains
- Controlled measurements will give predictive capability

- Field measurements will only measure specific configurations
- Expensive to find and measure other cells with different configurations
- Configuration information may not be available

  $\Rightarrow$ **Low predictive ability**
- Might be used to spot check laboratory measurements

Measurement Implementation

Mr. Jason Coder

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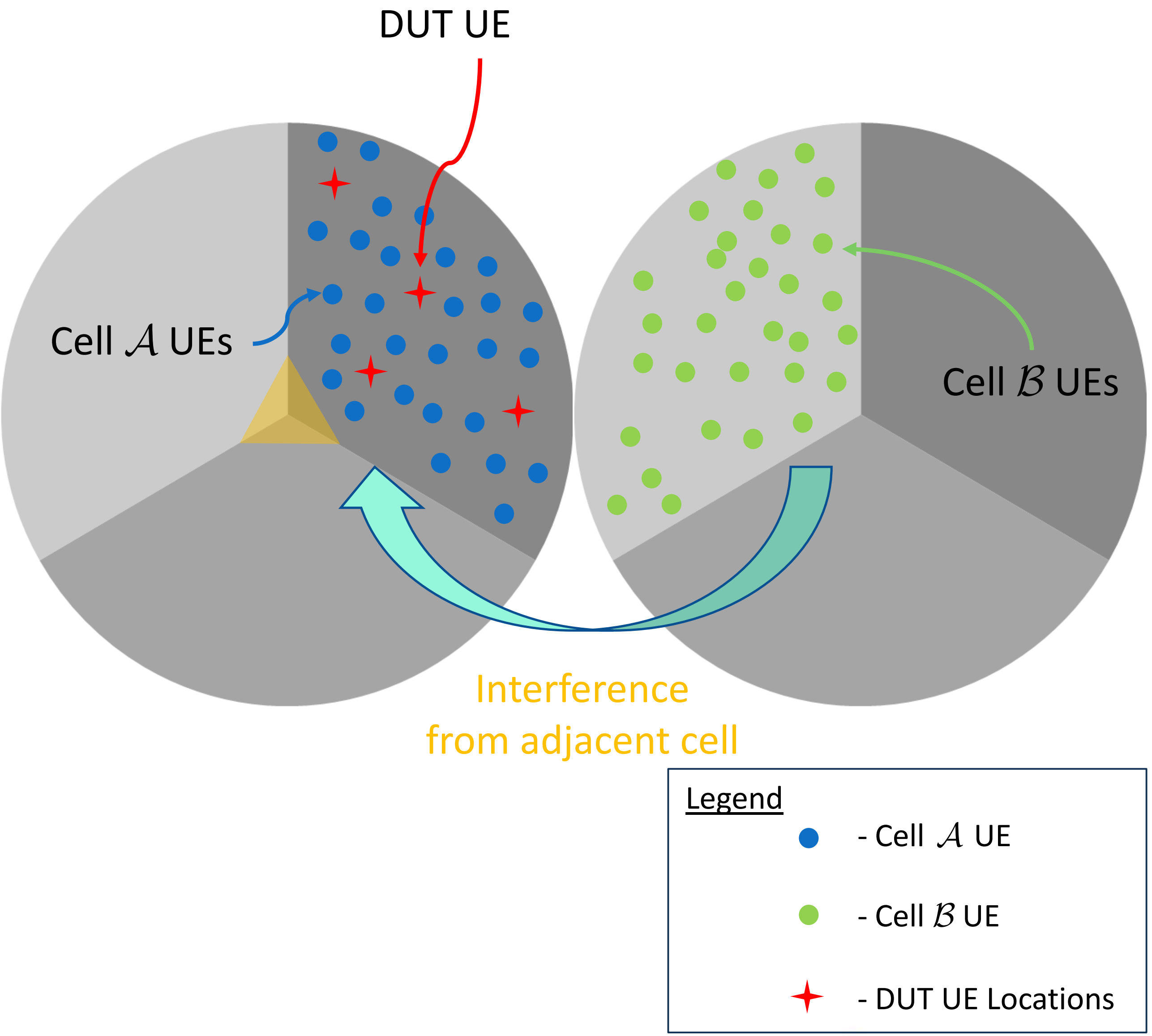
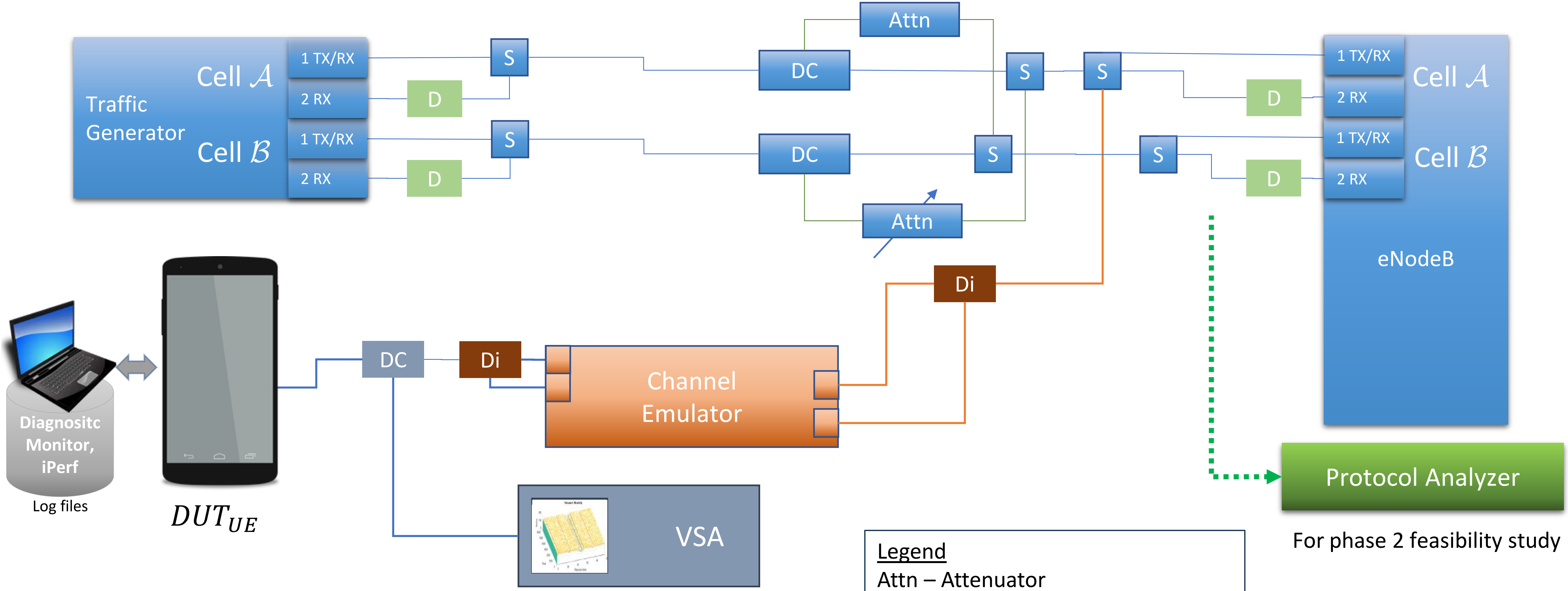


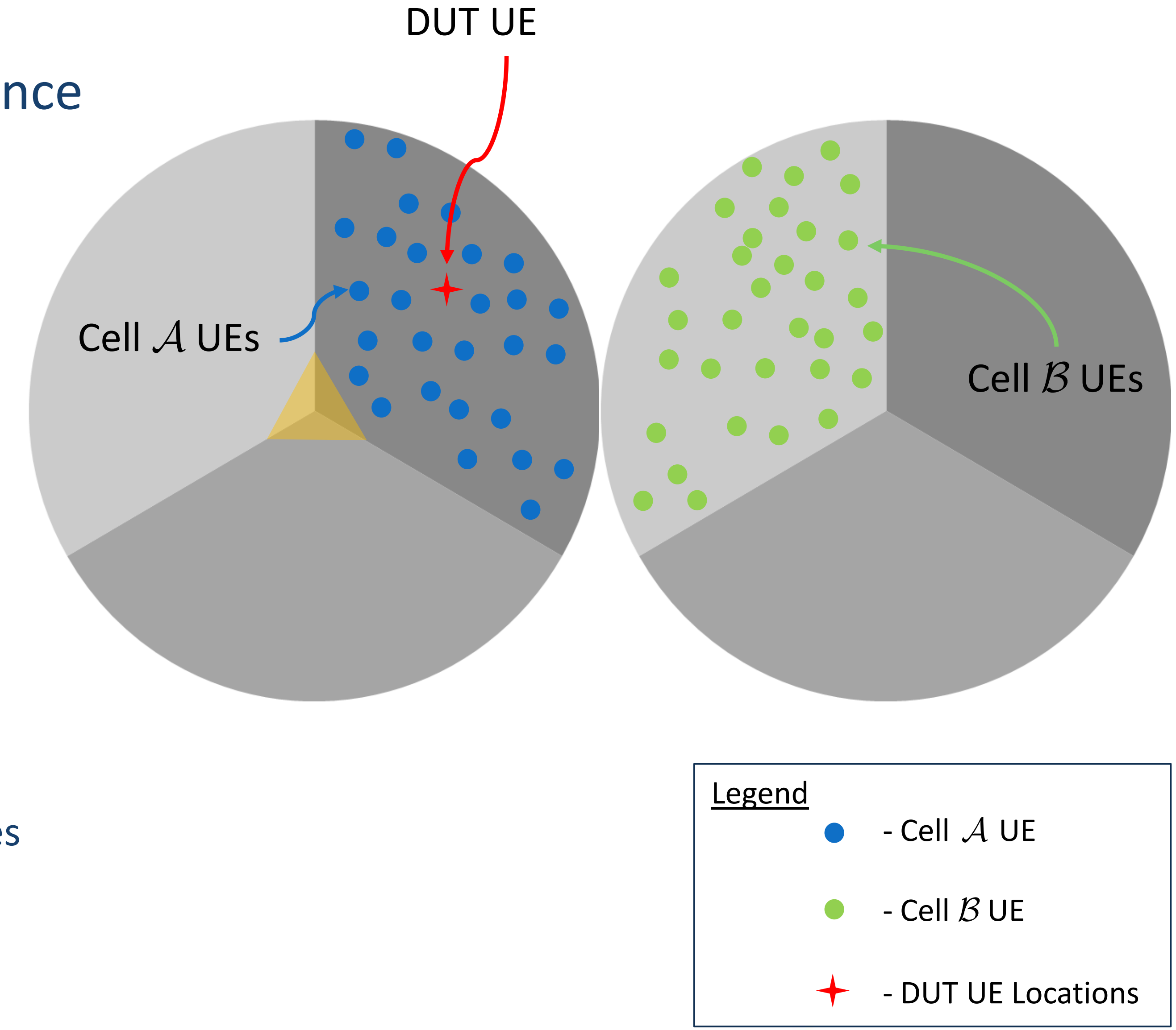
Measurement Implementation: Conducted Case



Legend
Attn – Attenuator
DC – Directional coupler
S – Splitter
D – Delay line
Di – Diplexer

Channel Emulation

- The RF channel will have a significant influence on the results
- There are three channels of interest:
  - DUT UE to Cell $\mathcal{A}$ eNB
    - Accounted for via the channel emulator
    - Highest fidelity channel emulation
    - Impacts all three deliverables
  - Loading UEs in Cell $\mathcal{A}$ to Cell $\mathcal{A}$ eNB
    - Implemented via the UTG
    - Implementation varies based on UTG
  - Cell B Loading UEs to Cell $\mathcal{A}$ eNB
    - No signaling between Cells $\mathcal{A}$ and $\mathcal{B}$
    - RF attenuators sufficient to ensure the Cell $\mathcal{A}$ eNB sees the proper amount of Cell $\mathcal{B}$ signal
    - Attenuators can be adjusted based on morphology



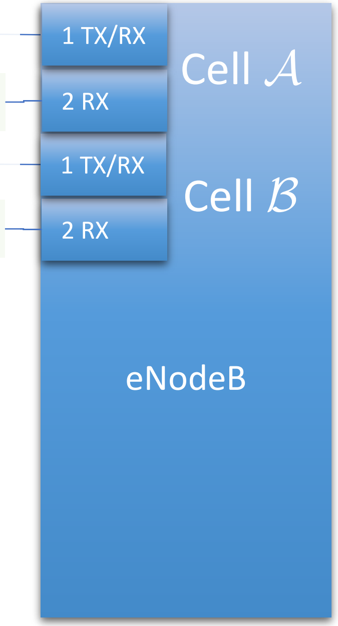
UE Traffic Generator (UTG)

- Responsible for generating the traffic, signaling, and physical layer waveforms* associated with the loading UEs
  - *Not quite. The UTG generates a real LTE waveform that carries LTE data
  - Some parameters are represented in signaling instead of physical layer
    - Example: Channel effects– implemented in the signaling layer

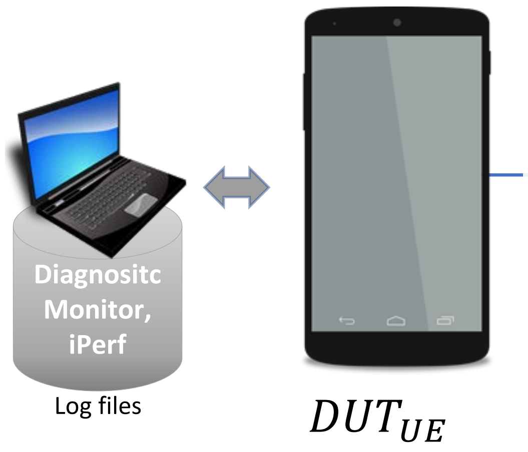
  ⇒ The RF spectrum of the UTG is not an accurate representation of a real UE
- **But**, the UTG can still recreate morphologies, simulate loading UEs in different propagation environments, and load the eNB
- Uplink traffic will be UDP type
  - Minimal handshaking on the downlink
- Loading UEs' offered load can be adjusted based on morphology
- UTG collects data including PRB allocations, throughput, etc

Macro-cell eNB

- Commercially available macro-cell(s)
- Many variables are configurable
  - identify variables that will impact uplink power or waveform allocation of PRBs
- Known variables include
  - Maximum number of users per transmission time interval (TTI) in UL
  - Method for UL power control
  - UL improved latency reaction timer
  - Scheduling method of the UL scheduler
  - Initial maximum amount of PRBs in UL
  - Extended uplink link adaptation low PRB threshold
  - UL scheduler frequency domain (FD) type
  - Use of ICIC/e-ICIC between cells (optional)



DUT UE/Monitoring Software



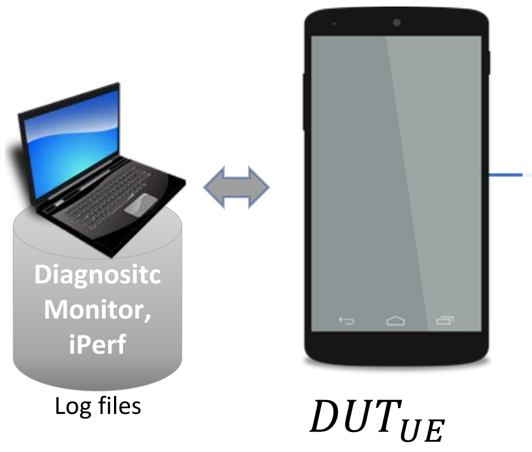
- Commercially available UEs that are representative of those deployed in the markets of interest
- Default UE configuration likely sufficient
- Data sent on the uplink will be UDP (same as loading UEs)
- Collect information on the PRB allocations, self-reported transmit power, MCS
- Monitoring software records information from the UE's chipset
  - Software must not interfere with the operation of the UE (some apps may)
- Depending on software/DUT UE, may have access to PHR and all e-UTRAN messages
- **Challenge: How do we measure the power and waveform emitted from this DUT UE?**

Determination of EIRP

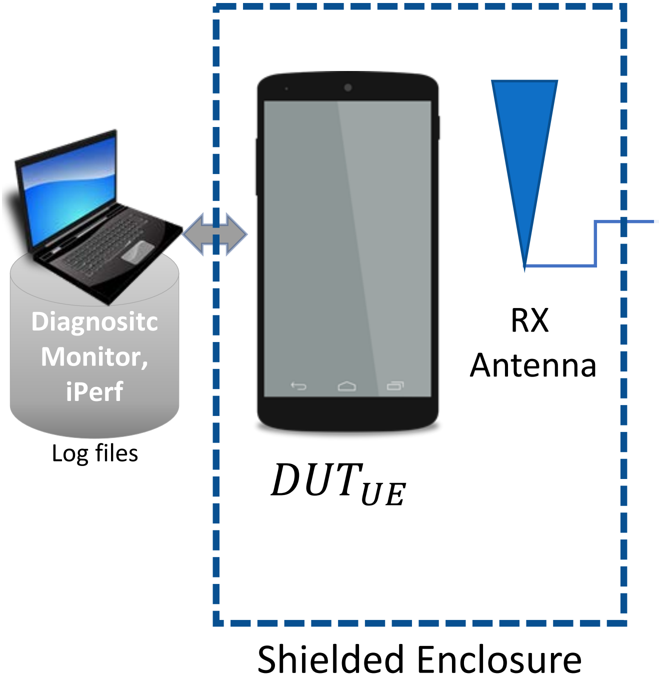
- How do we convert our measured waveforms back to the amount of power radiated by the DUT UE?
- There are many definitions of EIRP, we use:
  - *In a given direction, the directivity of a transmitting antenna multiplied by the total power radiated by the antenna (TRP) from the connected transmitter over the frequency channel of interest*
- EIRP can be determined in either an anechoic chamber or reverberation chamber
  - Either should be suitable for these purposes
- Tests done with conducted UEs will be more robust and repeatable
  - Very few UEs have accessible conducted RF ports
- **Challenge: How do we determine TRP and directivity?**

Conducted DUT UEs

- Directly connect between the DUT UE and the test setup
- Measure cable loss between DUT UE and VSA
- Estimate other parameters (loss, efficiency) to convert between conducted power and theoretical radiated power
- Generally assume that TRP is a scaled version of the measured power



Radiated DUT UEs



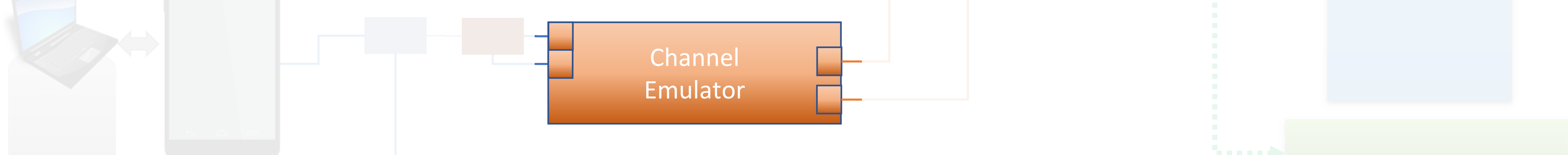
- Requires the use of an anechoic or reverberation chamber and a receive antenna
- How well do we know the propagation channel between the DUT UE and the receive antenna?
  - These channel effects have to be accounted for in the channel emulator
- How well do we know the characteristics of the receive antenna (pattern, efficiency, etc.)?
- TRP would likely still be a scaled version of the measured power, assuming a flat frequency response for the channel and receive antenna

Determination of EIRP – UE Directivity

- Once TRP is determined EIRP can be estimated based on the DUT UE's directivity.
  - Use maximum directivity value to simplify the calculation
  - TRP is then scaled by the maximum directivity
- This assumes that the DUT UE's antenna radiates the signal equally in all directions
- UE design keeps overall directivity low (i.e., omni-directional UE)
  - Directivity is unlikely to be less than that of a half-wave dipole (2.2 dB); 3 dB is a commonly used assumption
- As in CSMAC, we will assume that all UEs are outdoors
- We also assume:
  - No loading effects from humans or other structures
  - UEs are handheld, portable devices
    - If larger UEs are of interest, full antenna pattern measurements may be necessary

Channel Emulator Configuration

- Channel emulator simulates propagation channel between DUT UE and Cell $\mathcal{A}$ eNB
- “Moves” the DUT UE virtually within Cell $\mathcal{A}$ by changing channel conditions
  - Done in static steps, not dynamic (continuous) movement
- At each point, the propagation characteristics are re-calculated
- Adjusted for effects of the test setup (e.g., cable or coupling antenna loss)
- Propagation models are empirically-defined and give field-strength based on



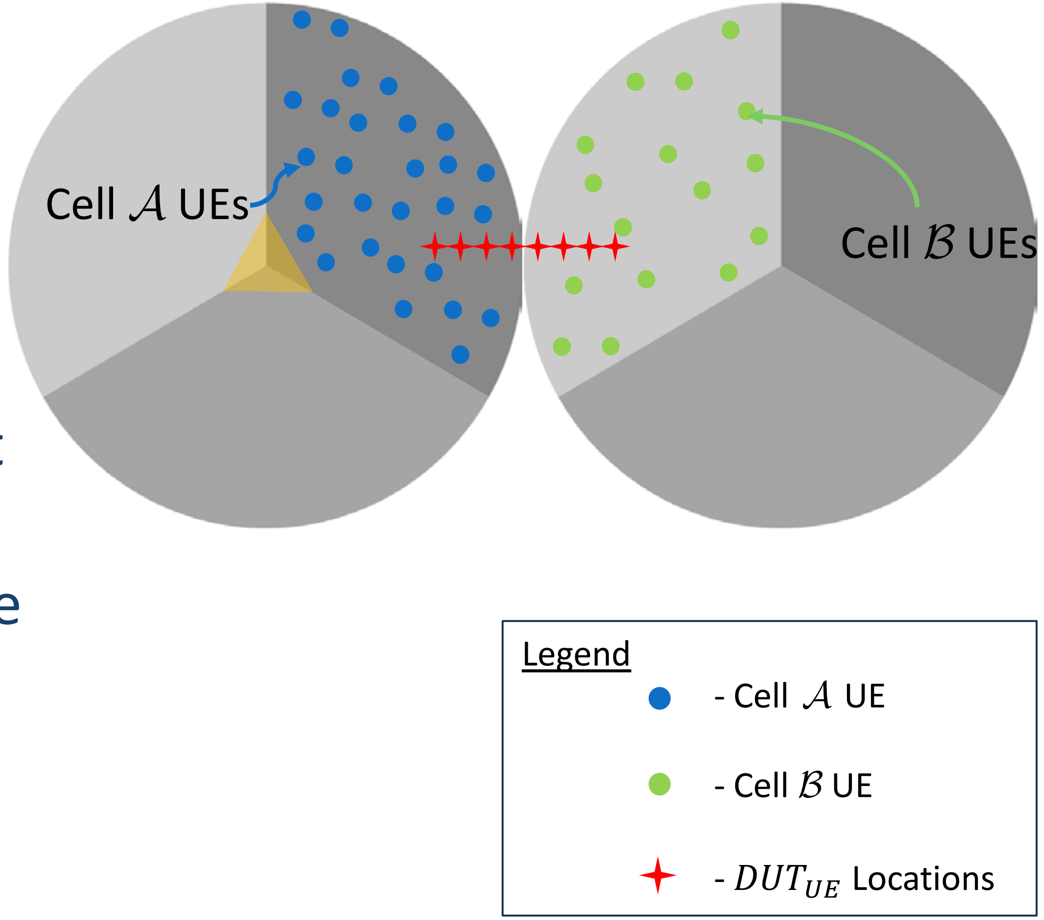
  distance, eNB antenna height, frequency, clutter near the eNB, etc.
- Uplink/Downlink channels are balanced to ensure realistic performance from eNB scheduler
- Uplink/Downlink fading is uncorrelated

Data Measured and Collected

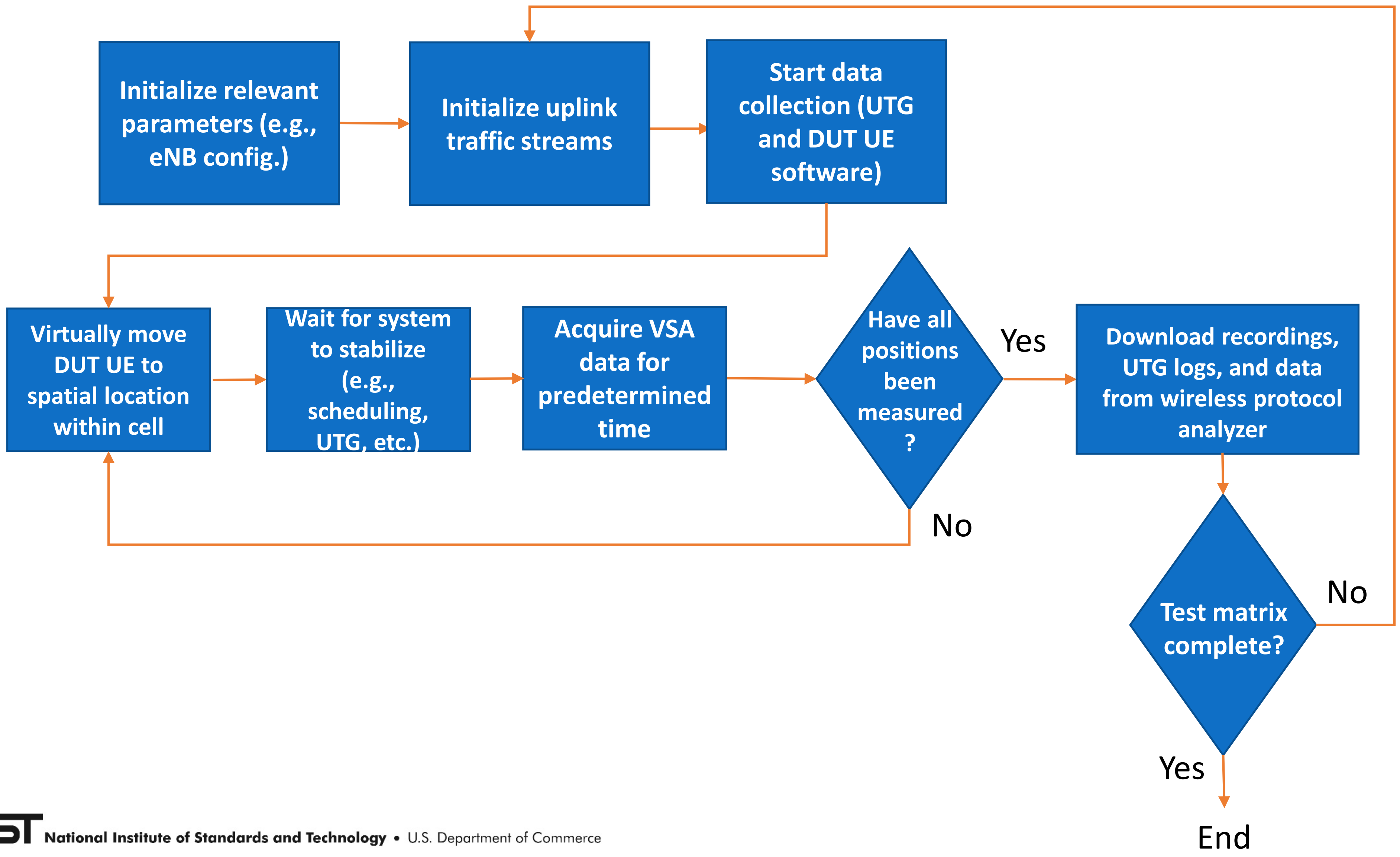
- Data are collected from:
  - UTG: **DCI** (per subframe), **C-RNTI**, reference signal power (**RSRP**), radio resource control messages (**RRC**), non-access stratum (**NAS**) messages
  - VSA: **I/Q samples** leading to the direct measurement of power of the DUT UE
  - Wireless protocol analyzer: **DCI**, **C-RNTI** (for DUT UE + Loading UEs)
  - UE diagnostic monitor: **self-reported transmit power**, **number of PRBs used**, **MCS**, **handover information**
  - No information is collected from the eNB
- Most data are not accessible in real-time, but will be time correlated in post-processing
  - Data are acquired by each device independent of the other instrumentation

Measurement of Specific Events

- **Goal:** Provide insight into how the emissions (waveform and CDF) and resource allocations change as a UE attaches to a cell and as a UE is handed over
- Handovers can occur for a variety of reasons and can be influenced by the eNB configuration
  - Examples: load balancing profiles, handover margins, neighboring cell RSRP thresholds, etc.
- What does change: DUT UE forced to detach/attach at different points in the measurement
- DUT UE should not be dynamically moved; it should be stepped up to and over the cell boundary
- Examine in a reduced number of configurations



Measurement Protocol



Design of Experiment and Statistical Considerations

Dr. Adam Wunderlich

Response Variables

For each combination of experimental factors, we will collect:

- Samples of transmitted UL waveform from DUT UE
- Traffic logs from UTG, UE diagnostic software, and LTE protocol analyzer

The following responses will be extracted from the data:

- EIRP from actively-transmitting DUT UE in a 1 ms TTI
- Power spectra of transmissions from DUT UE
- Number of actively-transmitting UEs in a cell for each 1 ms TTI

Controlled Variables (Factors)

eNodeB	
• Make and model	• Initial maximum number of PRBs in UL
• DL scheduling algorithm, e.g., proportionally fair low, proportionally fair high, round-robin)	• UL power control algorithm
• Maximum number of UEs allowed to transmit in a given 5 MHz channel over a 1 millisecond TTI	• Power control parameters: • P_0 = desired power from UE • α = scale parameter for path loss
• UL scheduling algorithm	• Extended uplink link adaptation low PRB threshold
• UL scheduler FD type	• UL improved latency reaction timer
UE Traffic Generator	
• Number of UEs in Cells	• Channel model for simulated UEs
• Spatial size of cells	• Spatial distribution of UEs
UE	
• Make and model	• Type, e.g., cell phone, dongle
Channel Emulator	
• Location of UE under test relative to eNB	• Channel type, e.g., urban, rural
Special Conditions	
• Handover between cells	• Detach/reattach

Uncontrolled Variables and Sources of Uncertainty

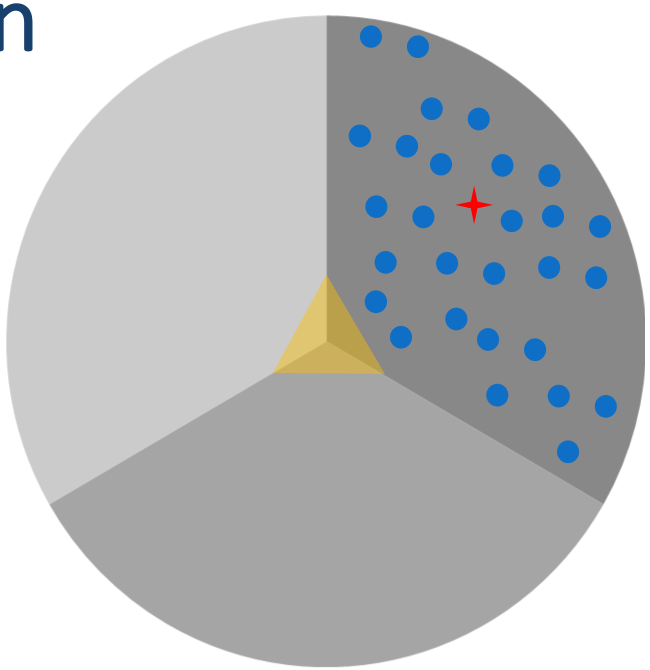
Uncontrolled Variables

- Stray signals from external sources
- Environmental temperature and humidity
- Changes in equipment performance due to heating from power dissipation

Sources of Uncertainty

- eNB scheduling implementation
- eNB power control of UEs
- UE traffic emulation
- Emulated uplink channel from UE to eNB
- Laboratory environmental conditions
- Antenna characteristics and positioning
- Measurement equipment (*e.g.*, the VSA’s ability to acquire and digitize an RF signal)

Experimental Design: Sample-Size Determination



Determine:

- Duration of data collection for each DUT UE location
- Number of spatial locations for DUT UE
- Data storage requirements

For a nominal test configuration:

1) Collect measurements for range of durations, e.g., 1-4 min at representative fixed spatial locations, e.g., near eNB, intermediate distance from eNB, near cell edge
2) Choose measurement duration to yield stable response with acceptable uncertainties
3) Collect measurements for various amounts of random DUT UE spatial locations, e.g., 3, 5, 10, 20, 50, 100
4) Estimate spatially-averaged responses
5) Establish minimum number of spatial locations required for stable spatially-averaged responses with acceptable uncertainties

Experimental Design: Test Matrix

- Approximately 20 experimental factors → full factorial design not practical

  e.g., 2 levels (settings) per factor for 20 factors would require 2^{20} measurements

- Small number of factors typically drive most of the effects

Factor Selection Process

1) Prioritize factors based on engineering expertise and stakeholder feedback
   - See Appendix B of the metrology plan for an example
2) Factor screening experiment with "small" number of measurements
   - Two-level fractional factorial design of resolution V
     - Single factor effects and two-factor interactions not confounded by other main effects or two-factor interactions
     - 2-level, 20-factor design requires 512 runs
   - Infer sensitivity of response variables to each factor

Final Design

- Construct final experimental design with fewer factors and more levels per factor

Data Analysis

- Use VSA recordings to estimate
  - Distributions of peak and RMS EIRP for 5 MHz block over 1 ms TTI for actively-transmitting DUT UE, marginalized over UE location
  - Peak and RMS power spectra over 1 ms TTI for actively-transmitting DUT UE, marginalized over UE location
- Use traffic generator logs to estimate
  - Distribution of number of actively-transmitting UEs in a cell per 1 ms TTI
- Note that the distributions and power spectra are multivariate since factor space is multi-dimensional
- Estimate predictive models for
  - EIRP
  - Power spectrum
  - Number of active UEs per TTI

Potential Biases

- Experimental parameters may not cover the full range of real-world systems and environments
- Final experimental design may not include all relevant factors or may confound important factor interactions
- Frequency-dependence of losses in the RF testbed
- Selection bias due to extraction of active UE emissions
- Time-correlations in the measurements could bias uncertainty estimates for empirical distributions

Measurement Plan Summary

- Characterize emissions of handheld UEs in the AWS-3 band
- Controlled experimental environment will enable prediction
- Deliverable: Predictive models for UE emissions for a variety of network settings
- We need your feedback for this project to be a success!

Comments and Feedback

Range of eNB power control parameters (such as P_0 and α)
Other eNB settings that might impact UL traffic (such as scheduler and number of simultaneous UEs)
Range of geographic cell sizes (rural, suburban, urban) and corresponding user density
Cell morphologies (user density, site topography, man-made structure, etc.)

- Please send comments or feedback to sheryl.genco@nist.gov
- Comment period ends September 25, 2017
- Comments template is available at

https://www.nist.gov/communications-technology-laboratory-ctl/nasctn/projects/aggregate-lte-emissions