Qualcomm Technologies, Inc.

LTE-U Technology and Coexistence

May 28th, 2015

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Outline

- Overview of LTE-U coexistence algorithms design
  - Channel selection, CSAT and OSDL
  - How to coexist with Wi-Fi BSSs within and outside CCA-ED
- Lab & OTA results for coexistence above and below CCA-ED
  - Different traffic applications
  - Wi-Fi/Wi-Fi, Wi-Fi/LTE-U fairness study
- Demos
  - Stress room demo with three different Wi-Fi AP vendors
  - OTA on-campus demo with two different Wi-Fi AP vendors

Introduction

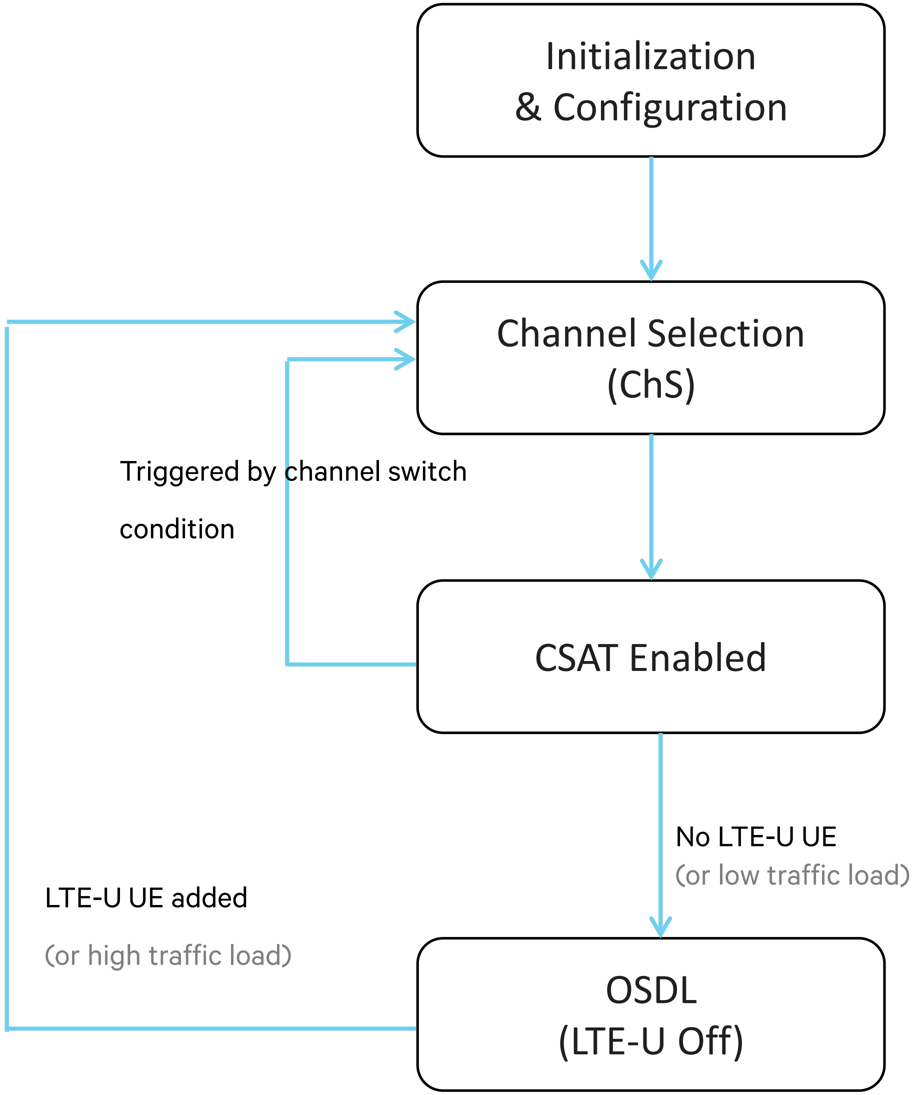
- Throughout the LTE-U design and testing, coexistence has been a main principle that has been studied thoroughly with different applications, devices, and deployment models

- We couldn't rely just on 802.11 spec due to divergence by many implementations
  - Wi-Fi benchmark based on testing of Wi-Fi AP and chip vendors with the highest market shares

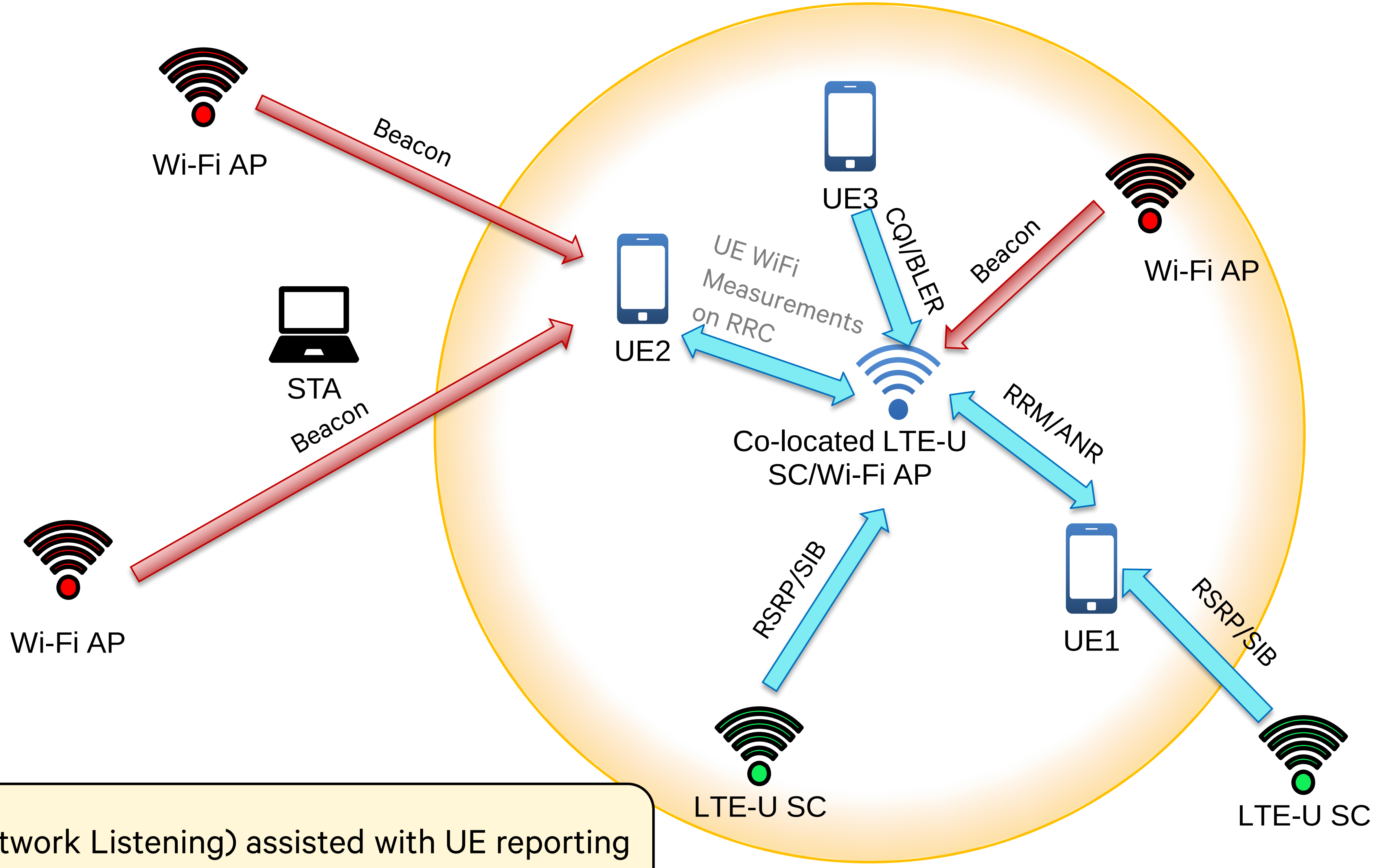
- What is presented here is Qualcomm's design in accordance with LTE-U Forum spec
  - The spec provides guidelines and testing scenarios to be passed but doesn't dictate specific implementations
  - This is obviously not the only way for implementation

- The design covers a larger set of scenarios than those mandated by spec

LTE-U Coexistence Solutions State Diagram

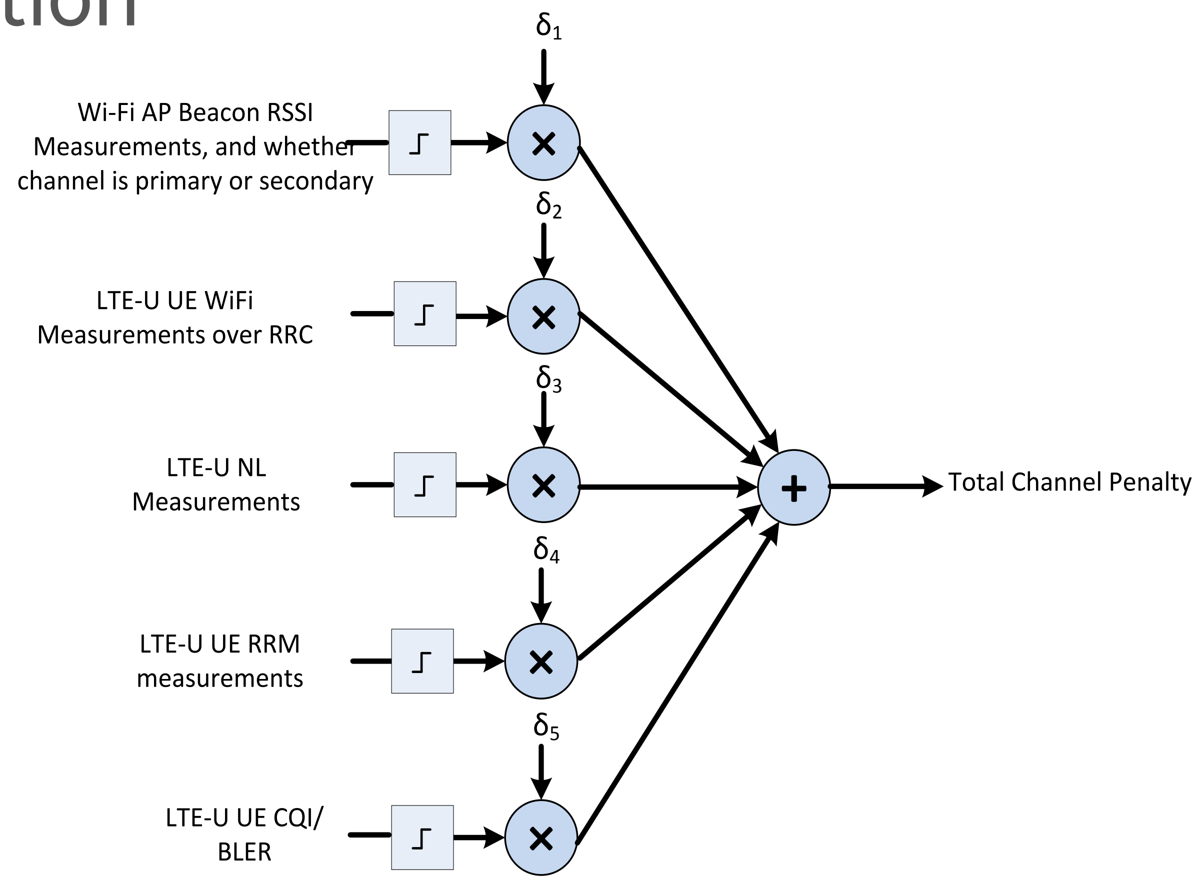


Channel Selection



LTE-U and WiFi NL(Network Listening) assisted with UE reporting LTE & Wi-Fi measurements and CQI/BLER to detect hidden nodes

Channel Penalty Function



- Different penalty weighting for different interference sources, e.g. WiFi primary channel has higher penalty compared to secondary channel
- <u>Quantized penalty for robustness to measurement errors and to reduce bias due to outliers</u>
  - <u>Measures % of coverage area with some desense due to other AP interference</u>
- <u>Built in mechanisms to detect and mitigate frequent channel switching</u>

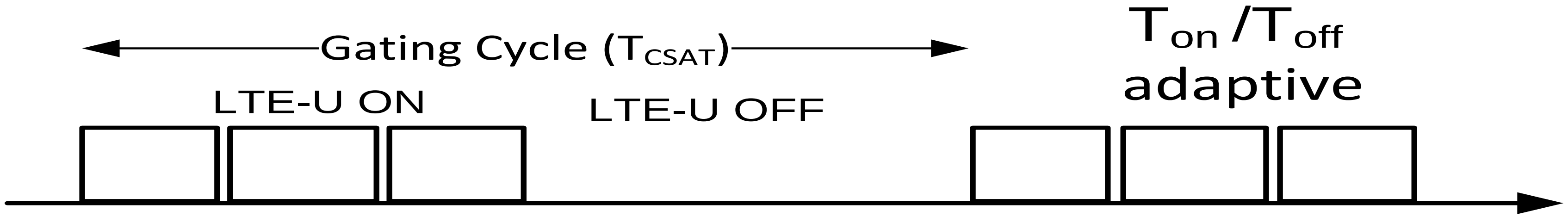
Channel Selection- Summary

1. Has to be both during initial boot up as well as dynamically during operation
2. Choose the cleanest channel in general
3. If possible avoid primary channels of WiFi
4. If possible avoid channels occupied by other LTE-U operators and choose channel occupied by the same LTE-U operator (Forum coexistence spec 6.1.2)

- Channel selection is aided by Small Cell NL(Network Listening) and/or UE measurements
- Can be done through passive or active scan- our design uses active
- Scanning typically happens every few seconds
- Channel selection can happen at any time, but typically within 10s seconds
- Channel selection is conservative in that it considers any found beacon to be active
  - Taking channel loading in consideration is for further optimization

Carrier Sense Adaptive Transmission (CSAT)

- A TDM transmission pattern on the LTE-U SCell with T_{CSAT} cycle
  - This pattern leverages existing LTE carrier aggregation MAC signaling (MAC control element for activating and deactivating an SCell)
  - This pattern is triggered based on transmissions measured from Wi-Fi APs
- Wi-Fi medium utilization measurement is performed during LTE-U SCell OFF time, to adjust ON/OFF duty cycle
  - Adaptive trade-off between LTE-U and other systems (e.g. Wi-Fi) performance.



Wi-Fi Medium Utilization (MU) Estimation

Input to CSAT loop

- Wi-Fi MU monitoring is done where all LTE-U small cells are required to turn 5GHz RF transmission OFF in this period
  - guarantees overlapping OFF time across neighbor LTE-U small cells for sensing Wi-Fi

- Sensing time is selected sufficiently large to allow the co-located Wi-Fi NL module for reliable MU monitoring of the operating channel. MU is also averaged across multiple observations

- Wi-Fi NL decodes the preamble of any WiFi packet detected during this time and records its corresponding received signal strength indicator (RSSI), duration in µs (or NAV), modulation, coding scheme (MCS) and source/destination address

Wi-Fi MU Estimation

Averaged weighted observed activity over a monitoring window

- The algorithm divides packets into different categories based on their attributes and each category is assigned a weight
- If the packet is found to be an ACK, or CTS, and the preceding data packet is not detected, the packet is classified as generated from a hidden node and count the packet as full duration (nominal value of around 4msec)
- Let $\mathrm{W_i}$ and $\mathrm{D_i}$ denote the weight and duration of i-th detected packet during MU monitoring time, assume that K packets were detected during the monitoring time. The instantaneous MU is computed as

$$MU(n) = \frac{1}{MonitoringTime} \sum_{i=1}^{K} W_i \times D_i$$

- WiFi medium utilization is filtered as follows:

$$\overline{MU}(n) = \alpha_{MU}\, MU(n) + (1 - \alpha_{MU})\, \overline{MU}(n-1)$$

where filter coefficient α_{MU} could be set small for smaller monitoring time to allow more averaging

CSAT Adaptation

Outer loop to decide on Ton in a given CSAT cycle

- CSAT algorithm will increase/decrease T_{ON} if MU is below/above a certain threshold
- CSAT adaptation is done as follows:

$$T_{ON}(n+1) = \min\left(T_{ON}(n) + \Delta T_{UP}, T_{ON,max}\right) \quad if\ \overline{MU}(n) < MU\_Thr_1$$
$$T_{ON}(n+1) = T_{ON}(n) \quad if\ MU\_Thr_1 \leq \overline{MU}(n) \leq MU\_Thr_2$$
$$T_{ON}(n+1) = \max\left(T_{ON}(n) - \Delta T_{DOWN}, T_{ON,min}\right) \quad if\ \overline{MU}(n) > MU\_Thr_2$$

where

- $T_{ON,min}$ *bounds LTE-U ON interval to ensure LTE-U receives a fair share of the medium*
- $T_{ON,max}$ *bounds LTE-U OFF interval to allow time to sense Wi-Fi activity*
- ΔT_{UP} *and* ΔT_{DOWN} *determine the convergence speed of CSAT adaptation*

Adjust $T_{ON,min}$ for Fairness

Selecting $T_{ON,min}$ independent of the number of neighbor Wi-Fi APs and LTE-U SCs might result in unfair resource sharing. To mitigate this issue, $T_{ON,min}$ is selected as below after every AP scan:

$$T_{ON,min} = min\left\{TONminInMilliSec, \frac{(N+1) \times T_{CSAT}}{N+1+M+NumWiFiNodes}\right\}$$

where

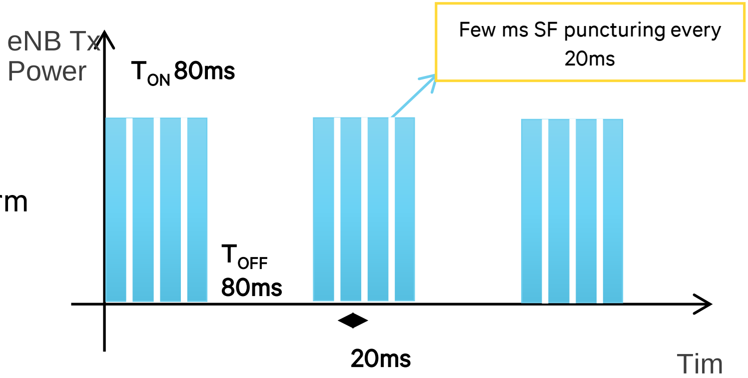
- $TONminInMilliSec$ is a configurable parameter controlling minimum duty cycle below ED
- N is the number of LTE-U SCs with the same PLMN ID measured by the specific LTE-U SC
- M is the number of LTE-U SCs with different PLMN ID
- Number of Wi-Fi Devices (*how to weigh in STA activity (visible to the algorithm) is still being optimized*)
  - Always go 1/num_of_Tx vs 1/num_APs vs a mix

Protecting Latency Sensitive WiFi Applications - Subframe Puncturing

Gaps inside Ton

- Subframe puncturing introduces frequent gaps **in the LTE-U ON duration** to help Wi-Fi flush delay-sensitive data and management packets that may be queued at the AP because of LTE-U transmissions
- In the specified punctured pattern, the subframes which are punctured are not used for scheduling any data
- Typically few msec every few 10s of msec (2/20msec is typical)

Example: Punctured CSAT Waveform



- Another way to accommodate latency sensitive applications is to run short CSAT cycles
  - Recent design allows LTE-U to go to as low as 20msec of Ton

CSAT Cycles

- Typical CSAT cycles
  - 80msec total ON/OFF duration (i.e. like 40/40) & 160msec (i.e. like 80/80msec)
- CSAT cycles on primary WiFi channel are typically shorter to enable beacon transmissions and connection setup activities
- In general CSAT cycles are constant but can change in scenarios where LTE-U share is too small
  - i.e. 10% LTE-U share may be 40msec/360msec as opposed to 10msec out of 100msec

Benefit of WiFi NL

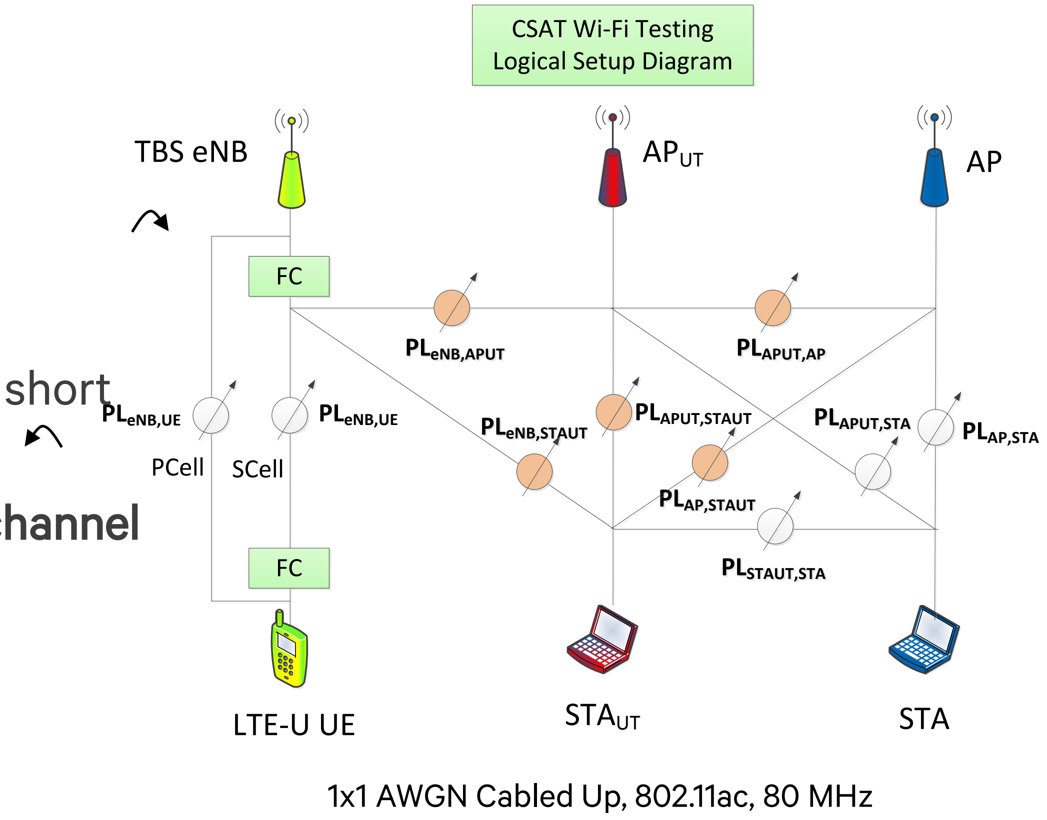
Not fundamental

- Most coexistence functionalities can be achieved without NL albeit more complexity and less optimal trade-offs
- Examples:
  - NL can help though reacting to some less common scenarios like hidden nodes
  - NL may allow better tradeoff of coexistence since it allows distinction between one node vs multiple nodes when both scenarios show same medium activity
  - NL allows distinction between LTE-U and WiFi nodes allowing the ability to run reuse 1 if need be on the former

Lab and OTA Testing

LTE-U / Wi-Fi Coexistence Setup

- Extensive lab test on LTE-U coex
  - Wi-Fi: Multiple AP and STA brands
  - LTE-U: Test eNB and UE MTP
- Current focus: Non-LBT/CSAT design
  - LBT-based test depend on 3GPP progress
  - Key Non-LBT coex feature is CSAT
  - CSAT has dynamic duty cycle, max 100-ms ON time, and long + short OFF gaps
  - **Note LTE-U coexistence in reality would be better with proper channel selection**
- Cabled-up test in controlled environment
  - 80 MHz max bandwidth assumed for Wi-Fi
  - LTE-U on one of secondary channels of Wi-Fi



Full Buffer TCP Throughput Results (Below ED)

Below ED

AP ID	CINR	TCP Throughput
1	0 dB	0.9x
1	5 dB	1.1x
1	15 dB	1.8x
2	0 dB	0.9x
2	5 dB	0.95x
2	15 dB	1.85x

- Baseline throughput = x (50% of isolated Wi-Fi throughput – *optimistic assumption*)
- CINR = Wi-Fi signal energy / LTE signal energy at Wi-Fi STA

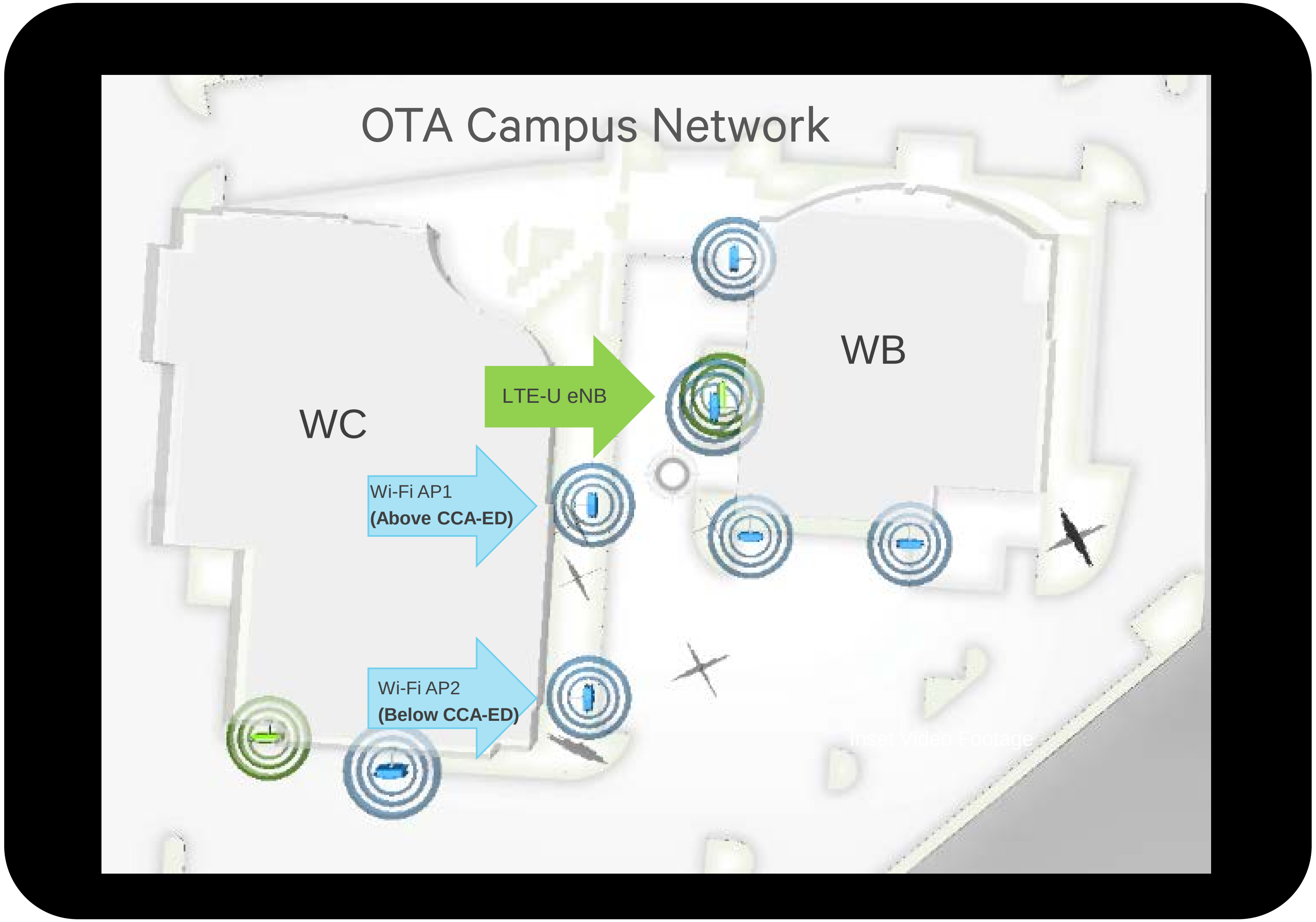
Wi-Fi YouTube Streaming Results – Wi-Fi/Wi-Fi vs. Wi-Fi/LTE-U

Below ED

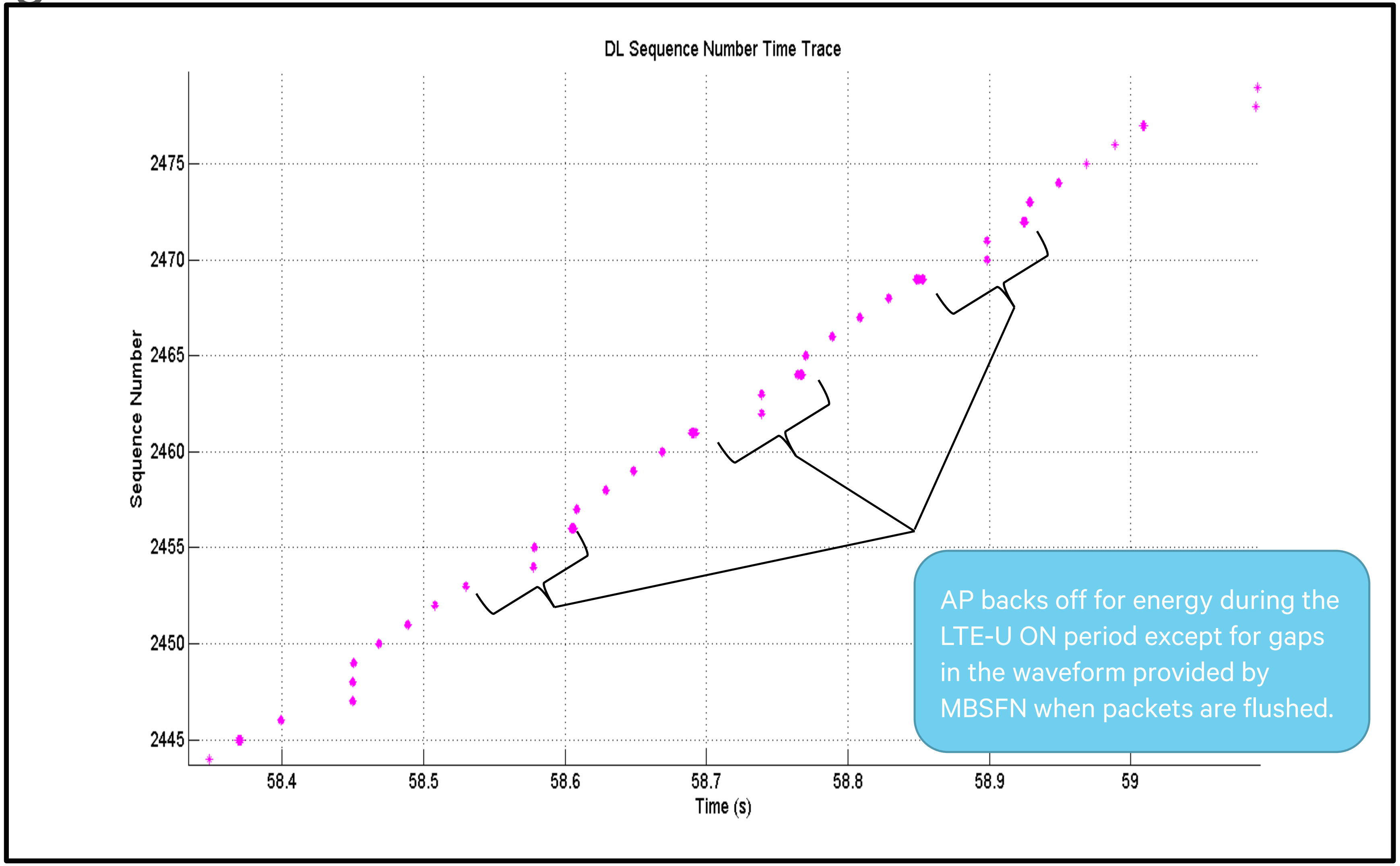
Metrics	AP 1		AP 2	
	Baseline (w/ Wi-Fi)	w/ LTE-U	Baseline (w/ Wi-Fi)	w/ LTE-U
No. of video stalls	**6.00**	**1.67**	**12.33**	**2.67**
Playback interrupt time (s)	7.94	7.40	4.77	2.00
Initial Buffer Time (s)	0.67	1.33	0.33	0.33
Avg. Thpt (Mbps)	3.49	4.49	3.17	5.89
Avg. PHY Rate (Mbps)	19.81	39.88	65.65	83.55

LTE-U hit is an erasure
LTE-U with CSAT is a better neighbor than Wi-Fi

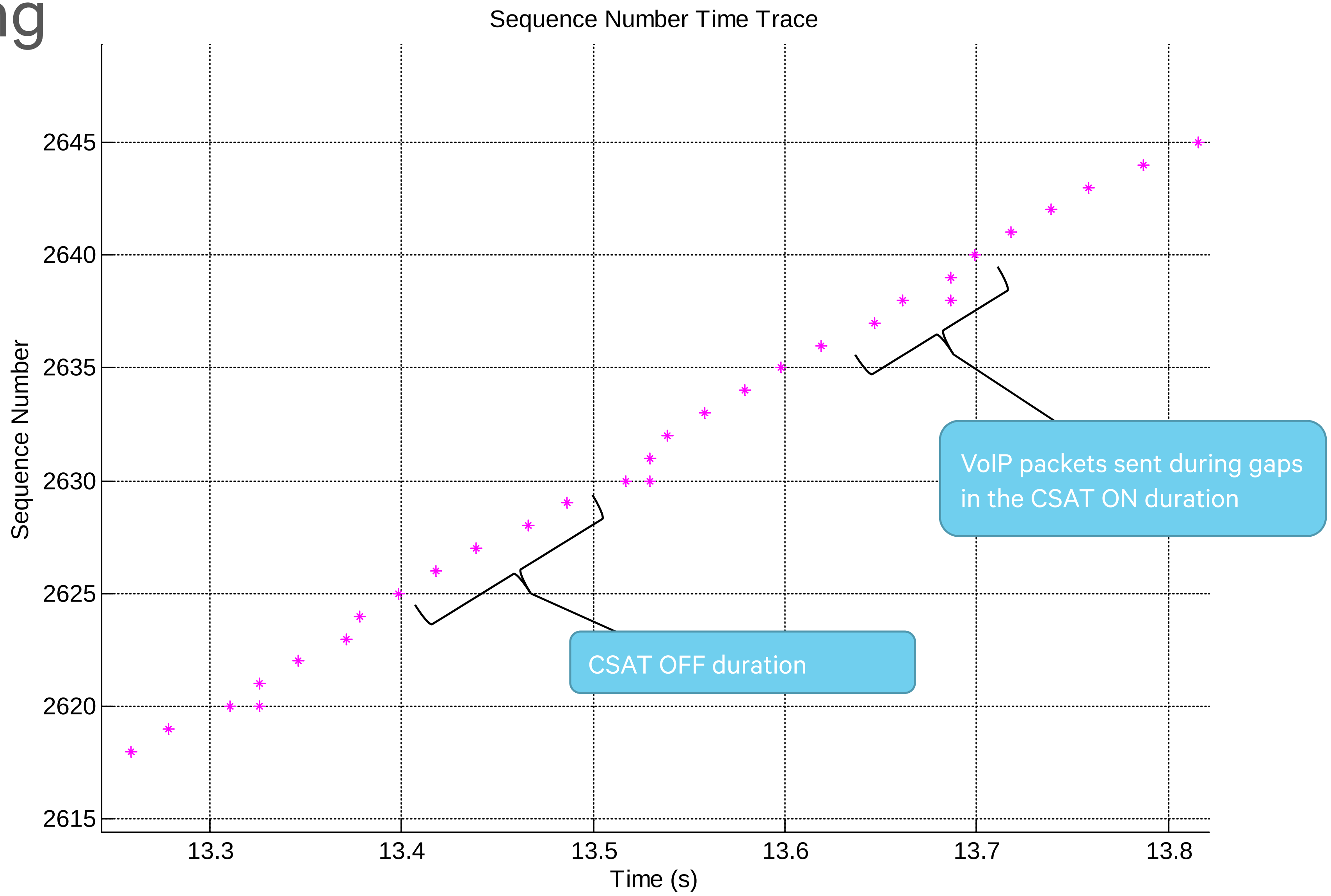
Overview of OTA Campus Network



Carrier Wi-Fi VoIP: Primary CH, Above ED, 160msec CSAT, 2/20 Puncturing



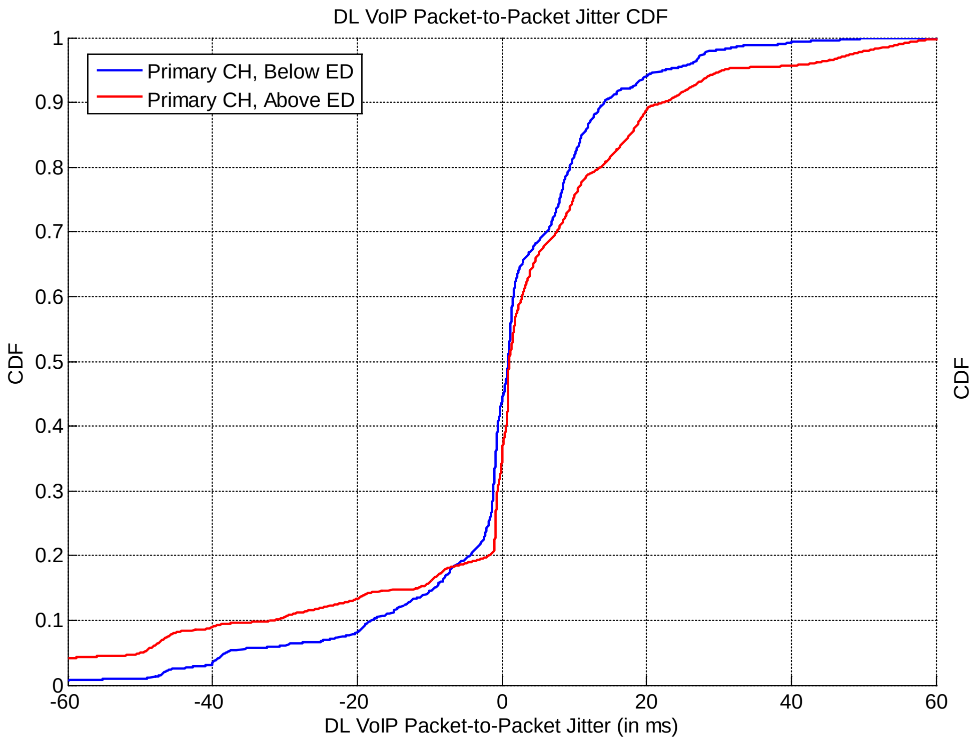
Carrier Wi-Fi VoIP: Primary CH, Below ED, 160ms CSAT, 2/20 Puncturing

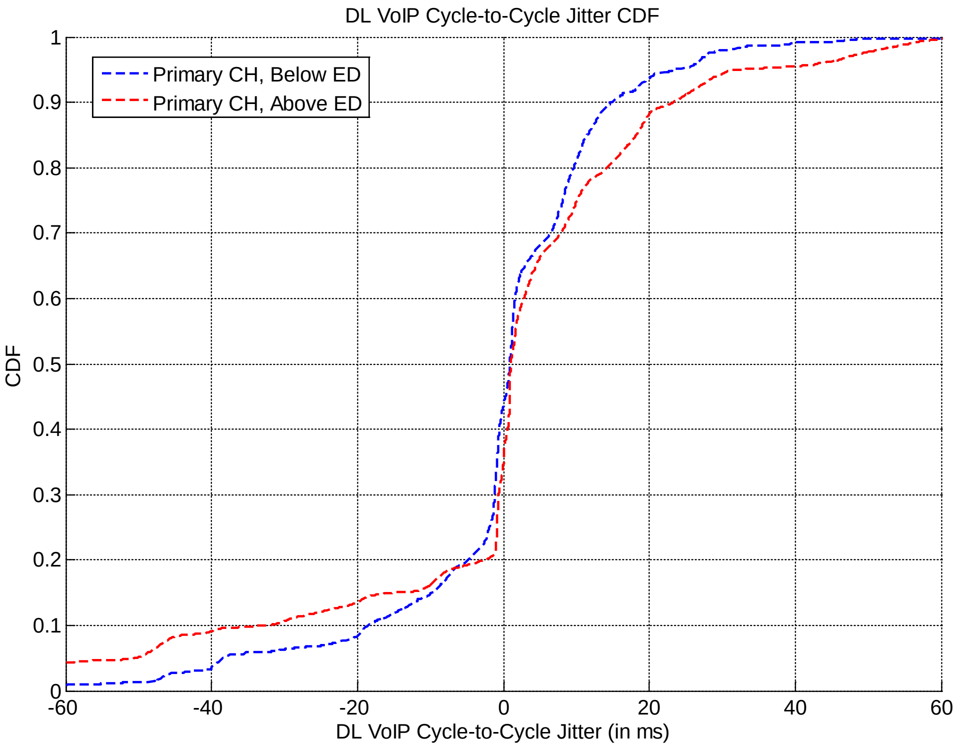


Carrier Wi-Fi VoIP: Primary CH, 160ms CSAT, 2/20 MBSFN

- Wi-Fi VoIP Calling Statistics†

Scenario	|Jitter| > 50ms	Packet Loss	> 3 Consec. Packet Loss
Above ED	6.6%	1.1%	0.1%
Below ED	1.0%	0.7%	0.0%

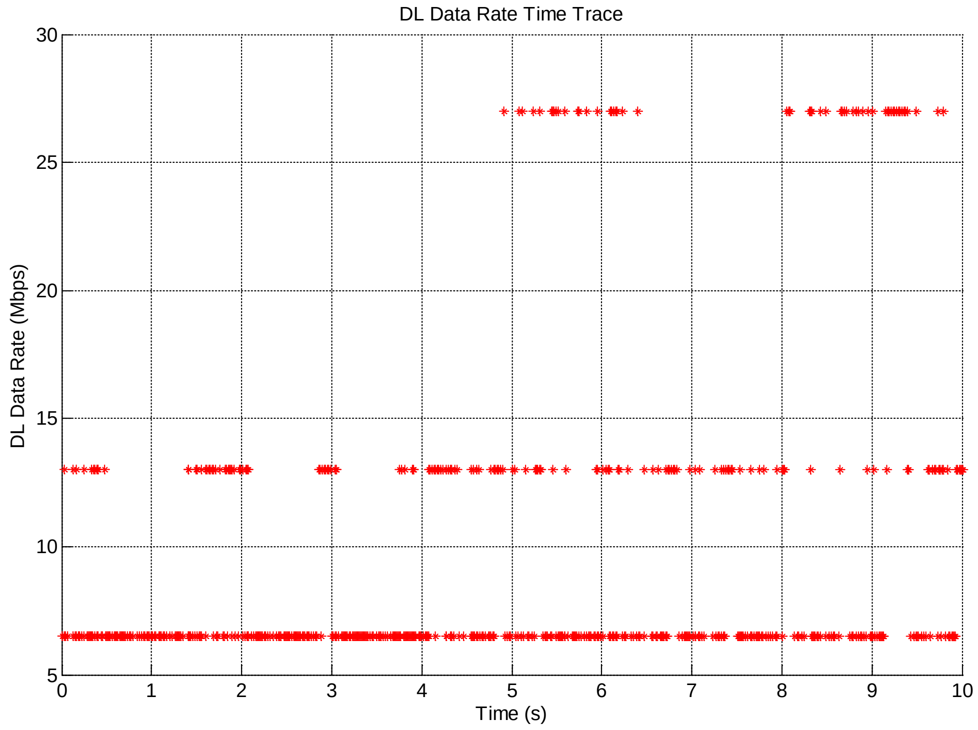


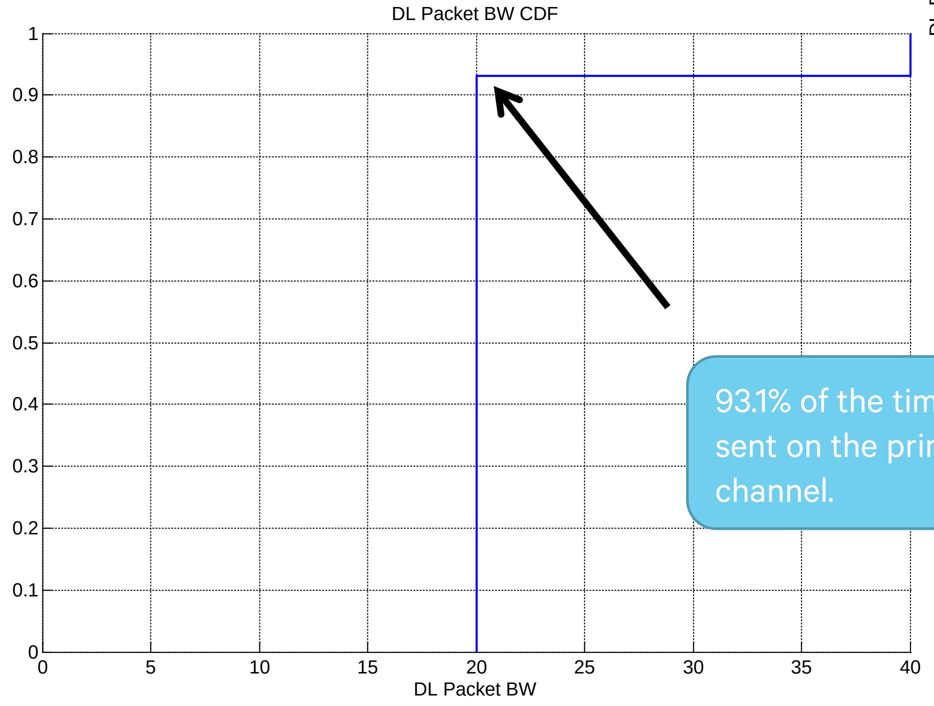


†Calculated per WFA-VE guidelines; Packet arrival one approx. every 20ms

Carrier WiFi VOIP: Secondary CH, Below ED, 640ms CSAT, 2/20 MBSFN

Smart BW mgmt. forces VoIP to go on the clean primary channel for PER. No degradation in voice quality.

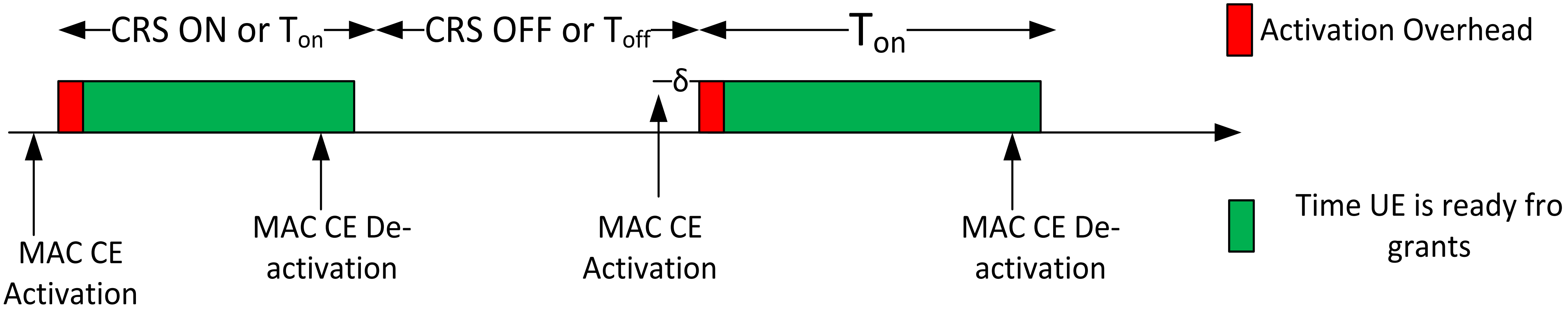




93.1% of the time packets are sent on the primary 20MHz channel.

Fast CSAT: Low latency MAC Activation/Deactivation

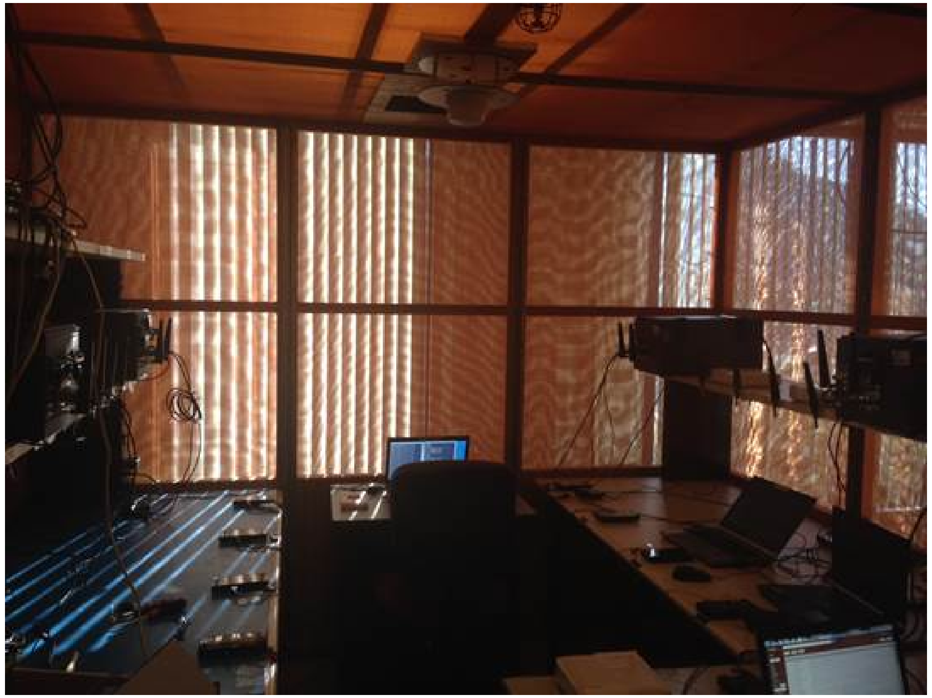
- MAC CE for activation is sent xms before start of on time
- If deactivation time (Toff) is < Thr, UE is expected to be ready to decode PDCCH in 1-2ms (*short cDRX behavior*)-no minimum 8ms for activation as in spec
- MAC CE for deactivation is sent before end of Ton
- Error events of losing or misinterpreting activation/deactivation have to happen ith low probability by design (to the level the can be handled and absorbed by UE tracking loops)



- To be accompanied with sending CTS2S with MAC activation after contention
  - To protect against BI
  - To protect WiFi rate control

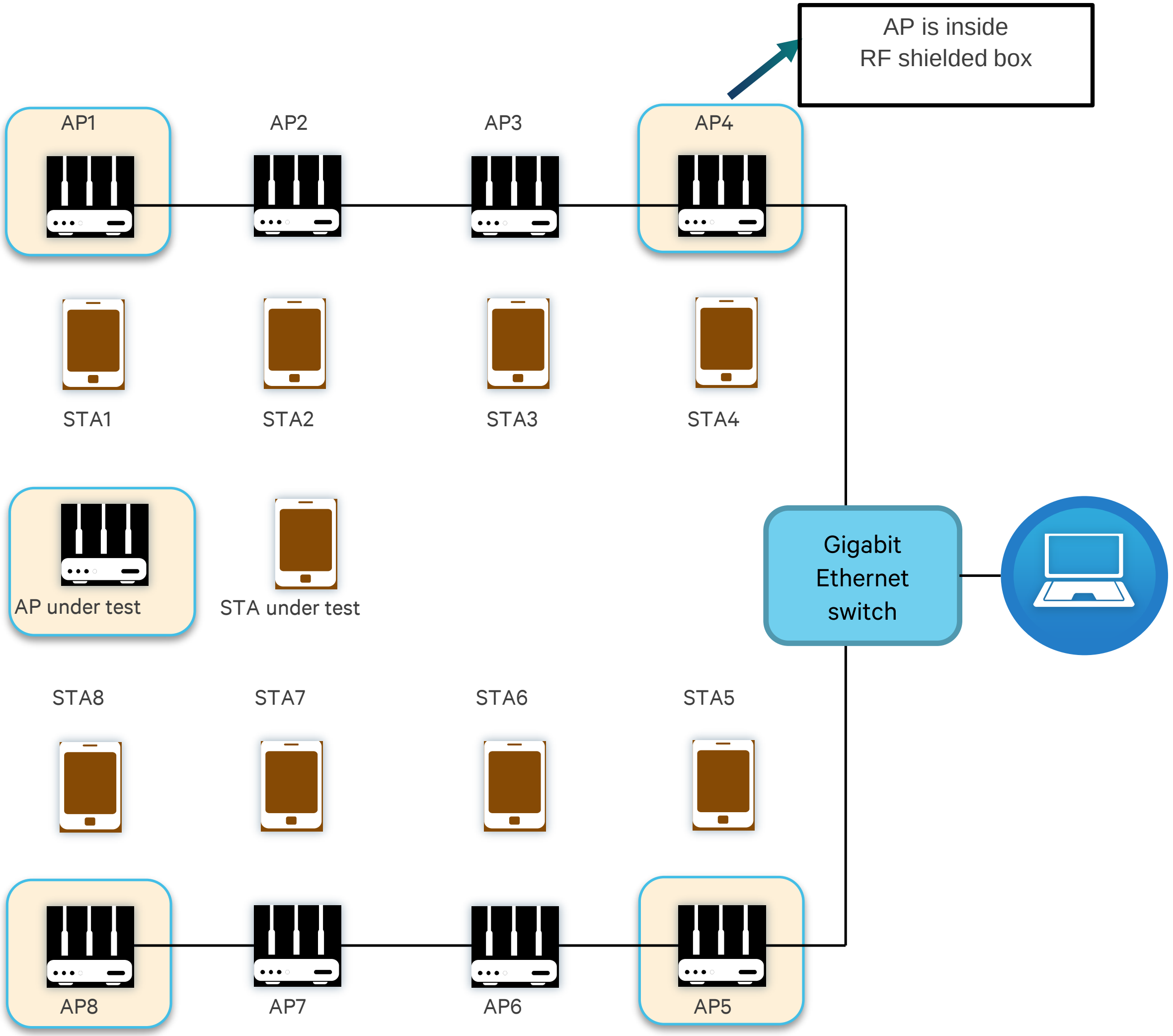
Stress Room Testing

Stress Test Chamber

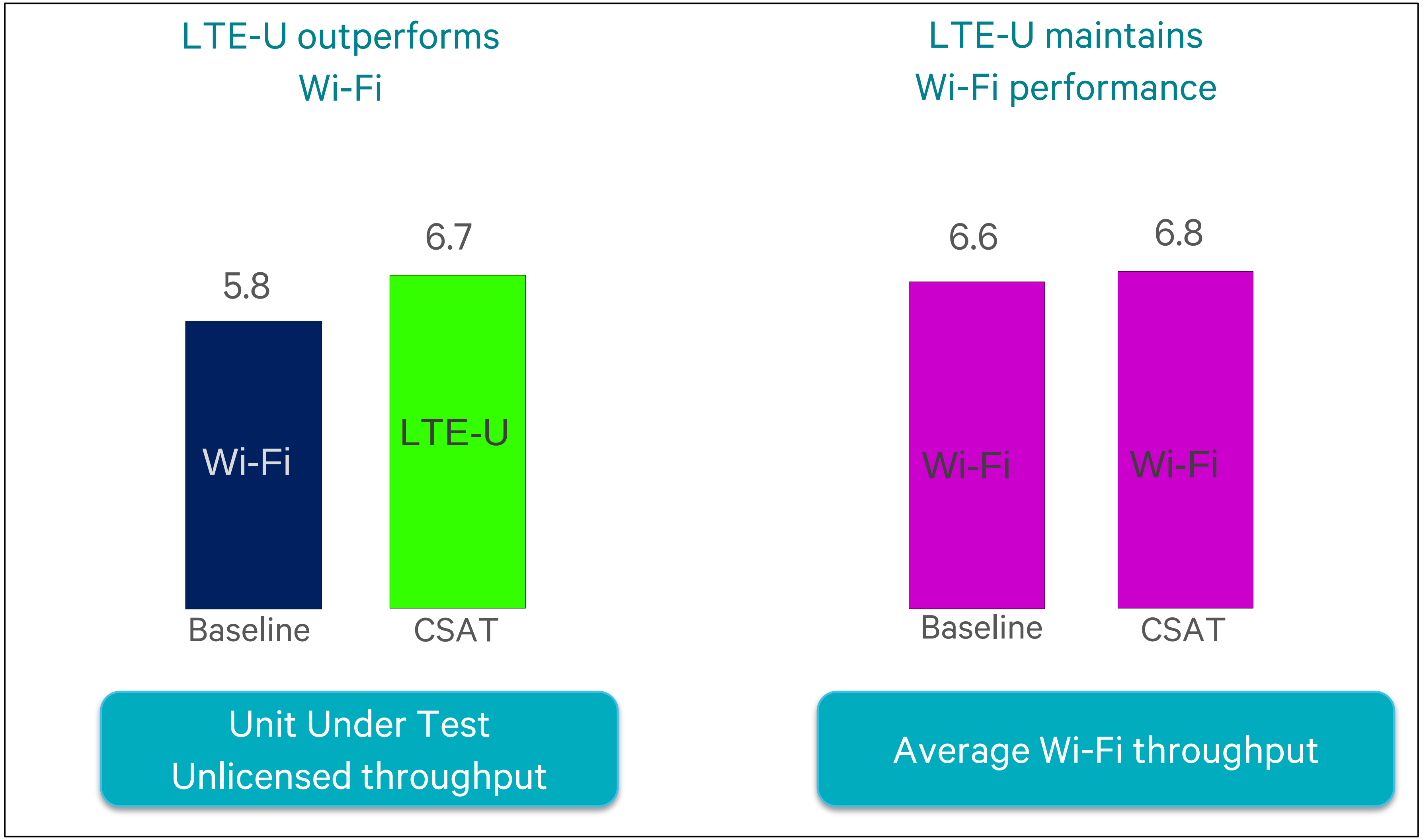


Stress Test Chamber Setup

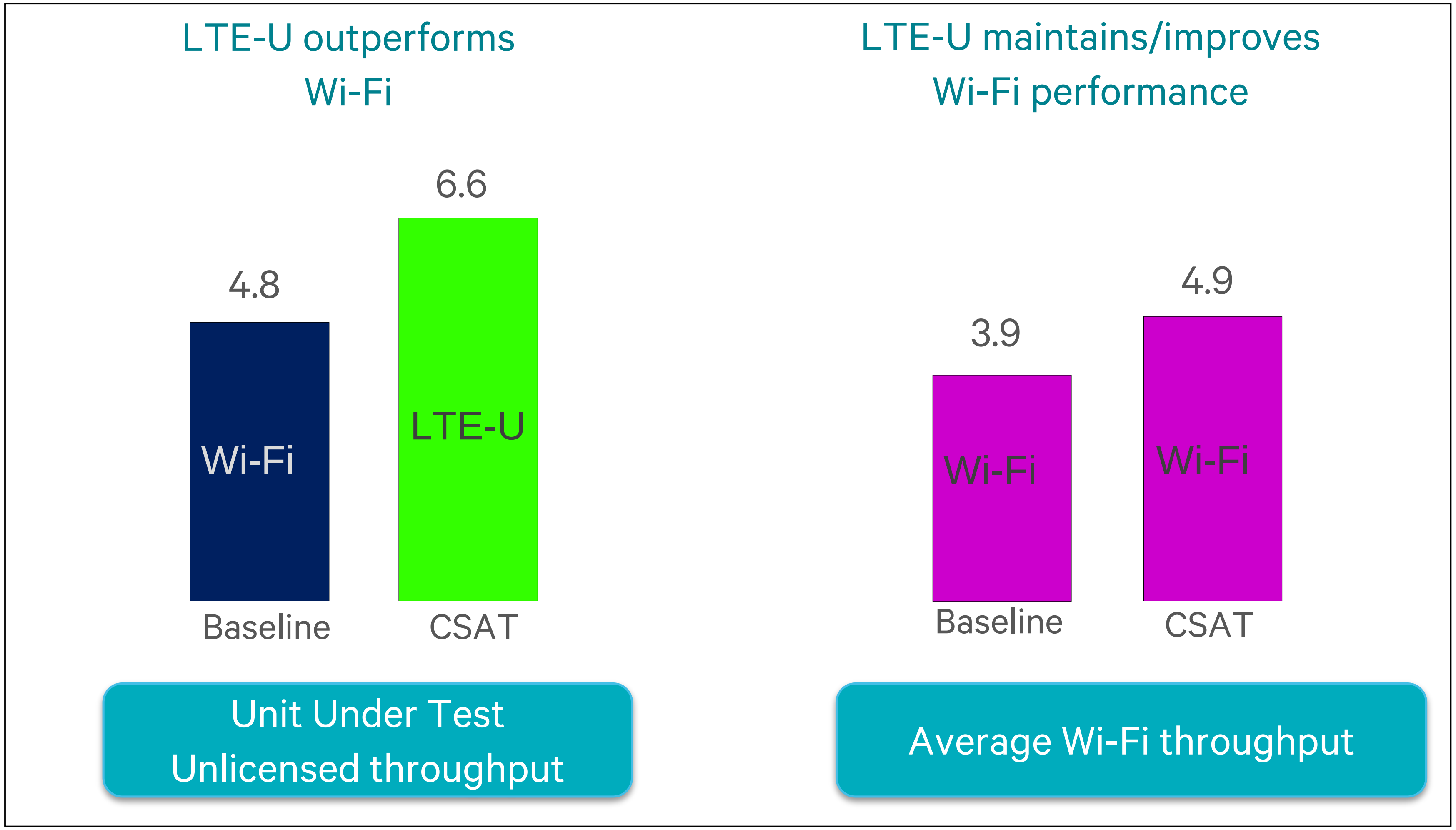
- 1 WiFi AP and 1 LTE-U node under test
  - The WiFi AP-UT is inside an RF shielded box
- 8 Reference WiFi nodes
  - 4 APs inside RF box to allow below ED scenarios
- 3 Enterprise grade WiFi APs + Controller
  - Referred to as Vendor A, B, and C
- Results presented in these slides
  - All links above CCA-ED
  - 8WiFi+WiFi vs. 8WiFi+LTE-U
  - LTE-U duty cycle = 1/9



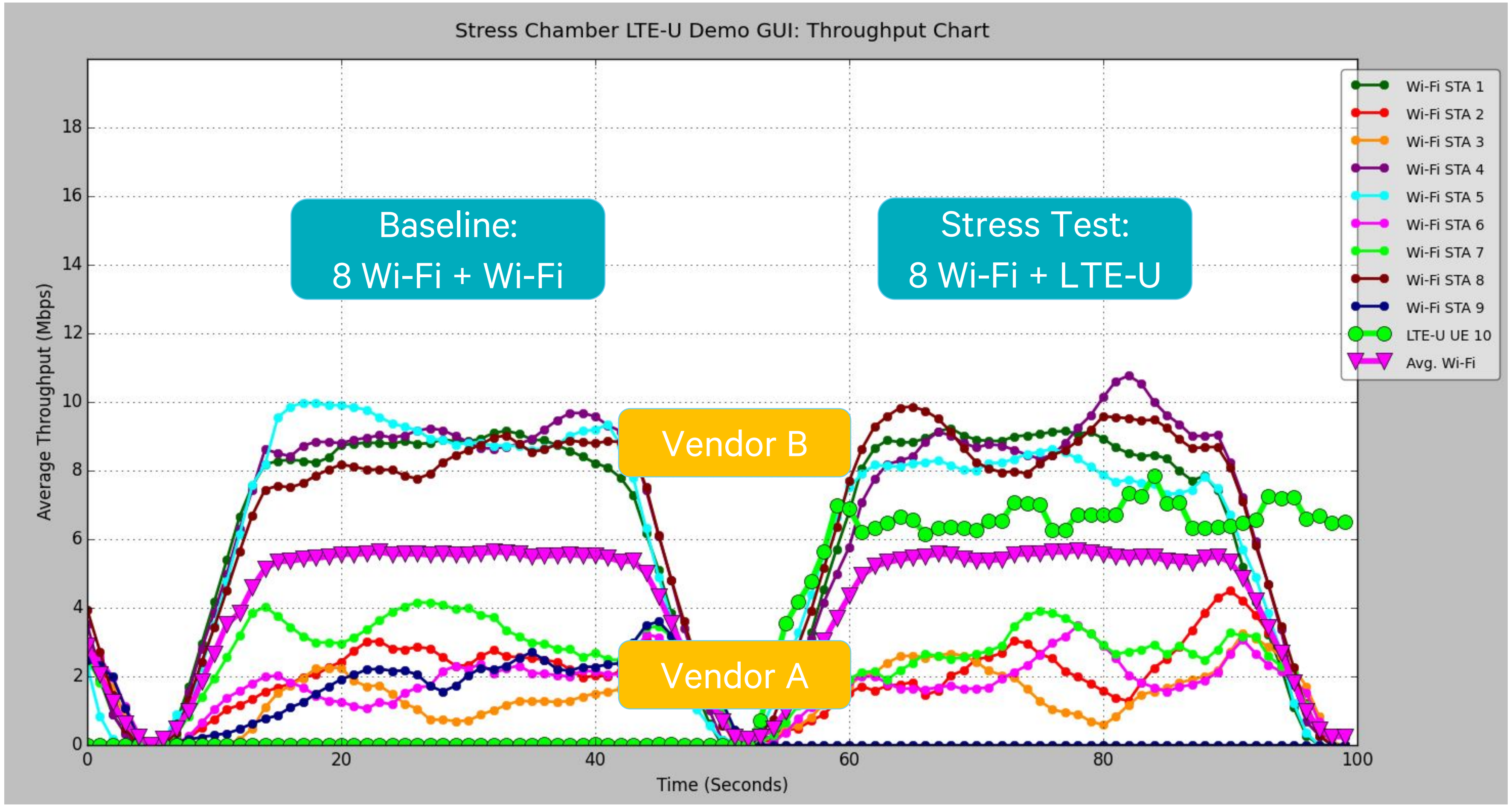
Demo GUI Summary (Vendor A)



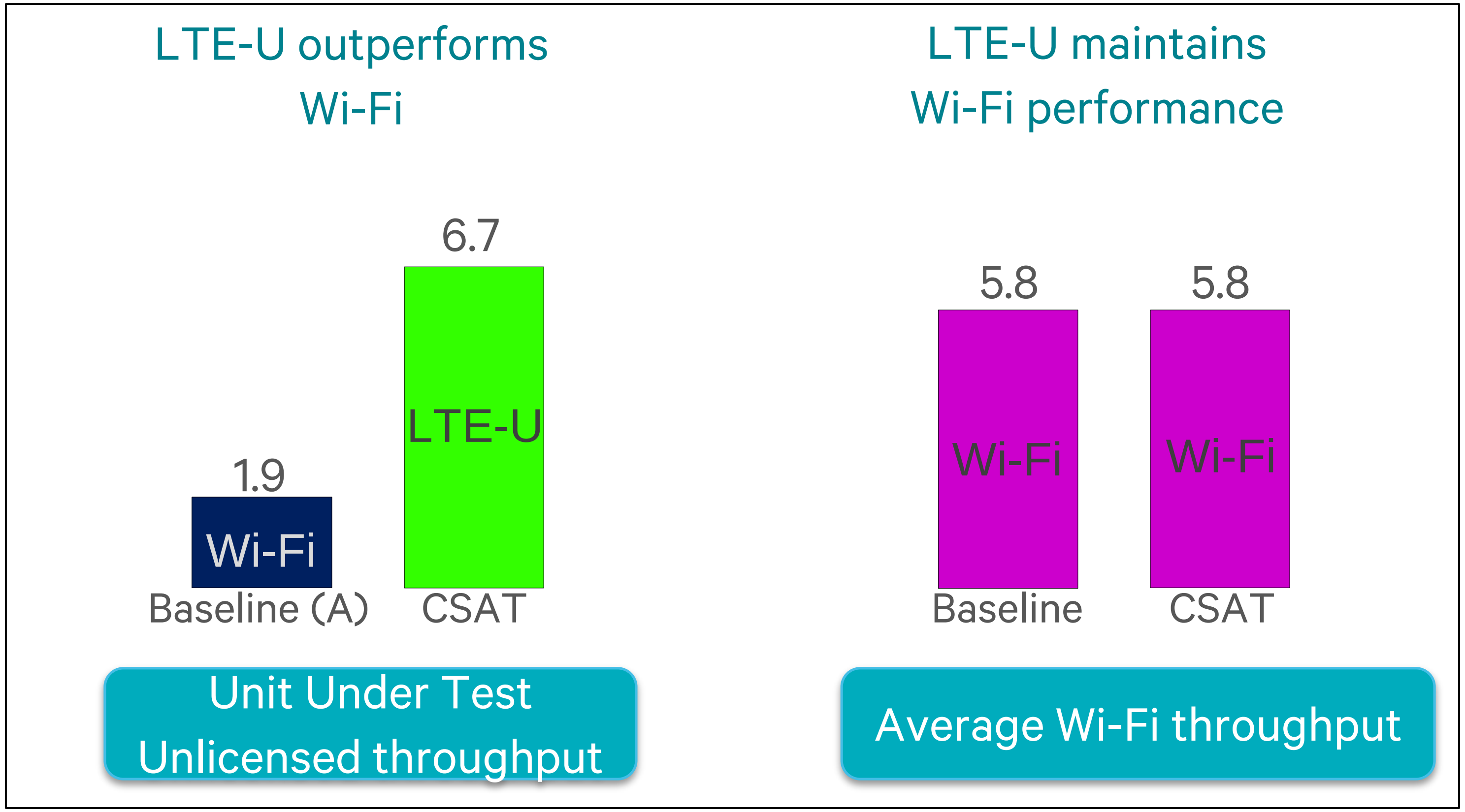
Demo GUI Summary (Vendor B- *more aggressive in winning medium*)



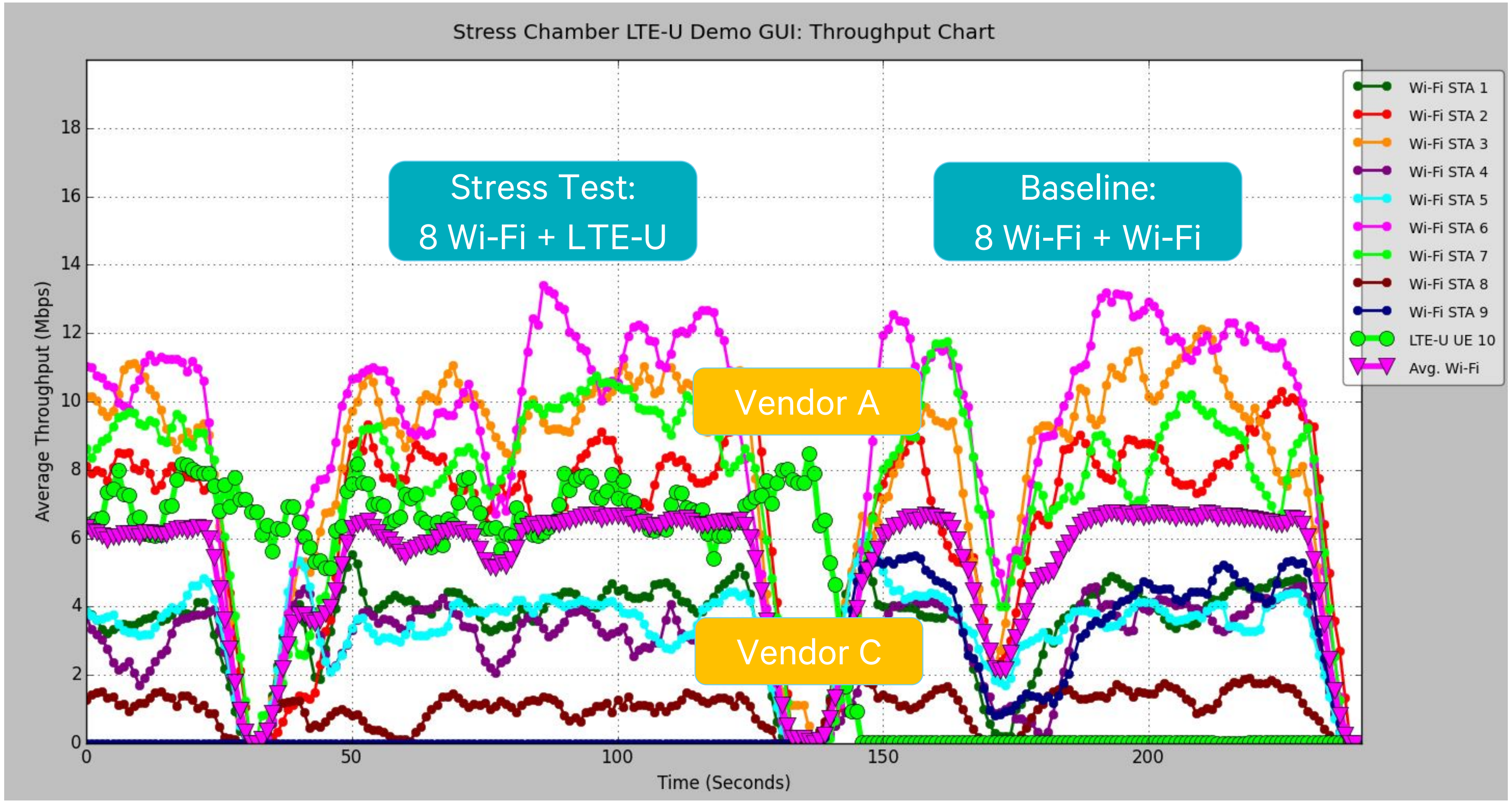
Demo GUI Screenshot (Mixture of Vendor A and B)



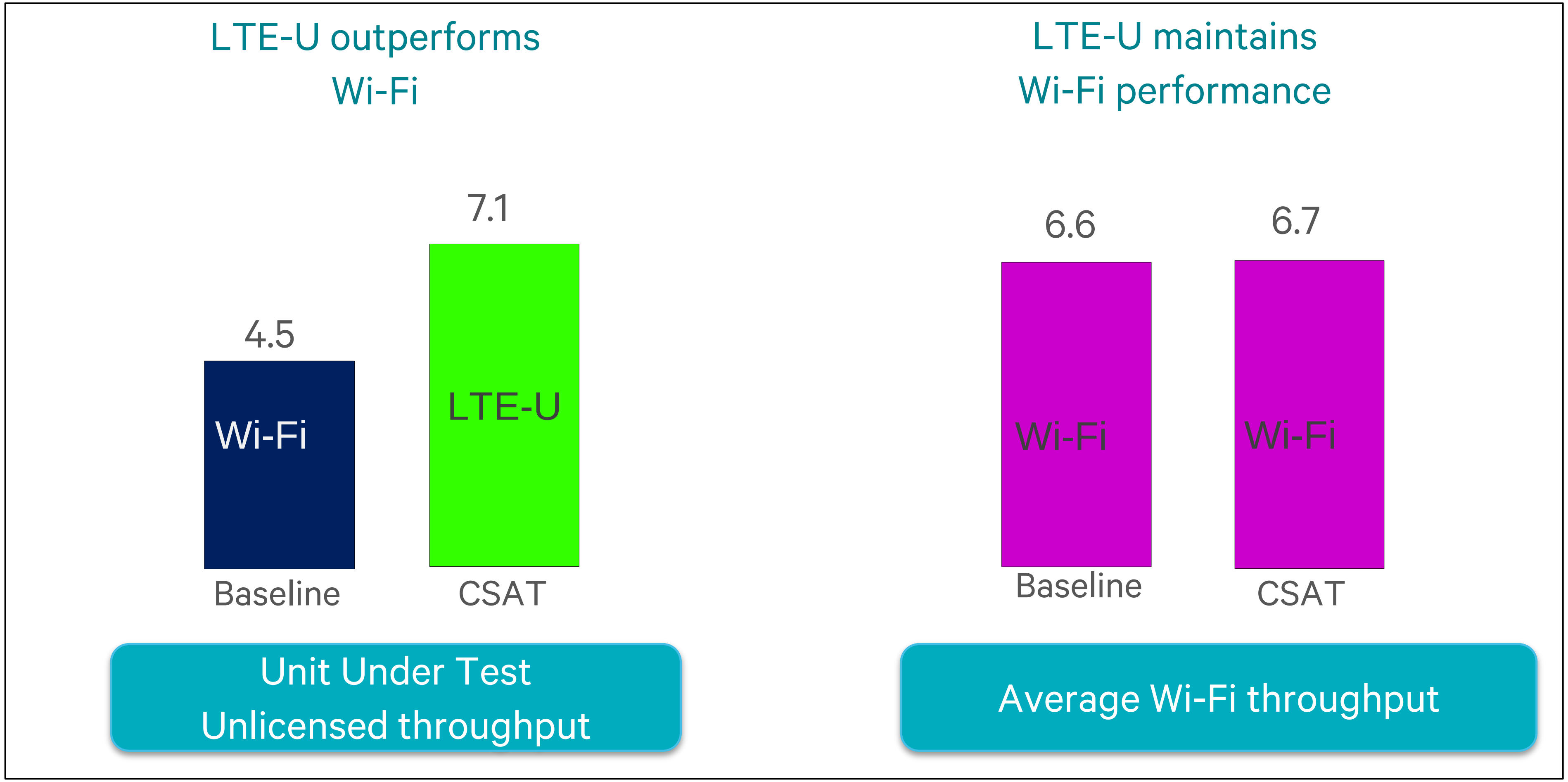
Demo GUI Summary (Mixture of Vendor A and B)



Demo GUI Screenshot (Mixture of Vendor A and C)



Demo GUI Summary (Mixture of Vendor A and C)



Summary of Stress Room Testing

Main Observations

- In general LTE-U preserves or enhances Wi-Fi user experience

- If Wi-Fi nodes are fair in medium sharing, LTE-U gains are lower, as its link level gains are not exposed by this dense setup

- If Wi-Fi nodes are aggressive in medium occupancy, frequent collisions occur and LTE-U provides better user experience for WiFi nodes by deterministically clearing the medium after its fair share decreasing relative number of collisions
  - LTE-U gains over Wi-Fi are more pronounced in this case and mostly due to MAC

Fairness Testing

Introduction to fairness study

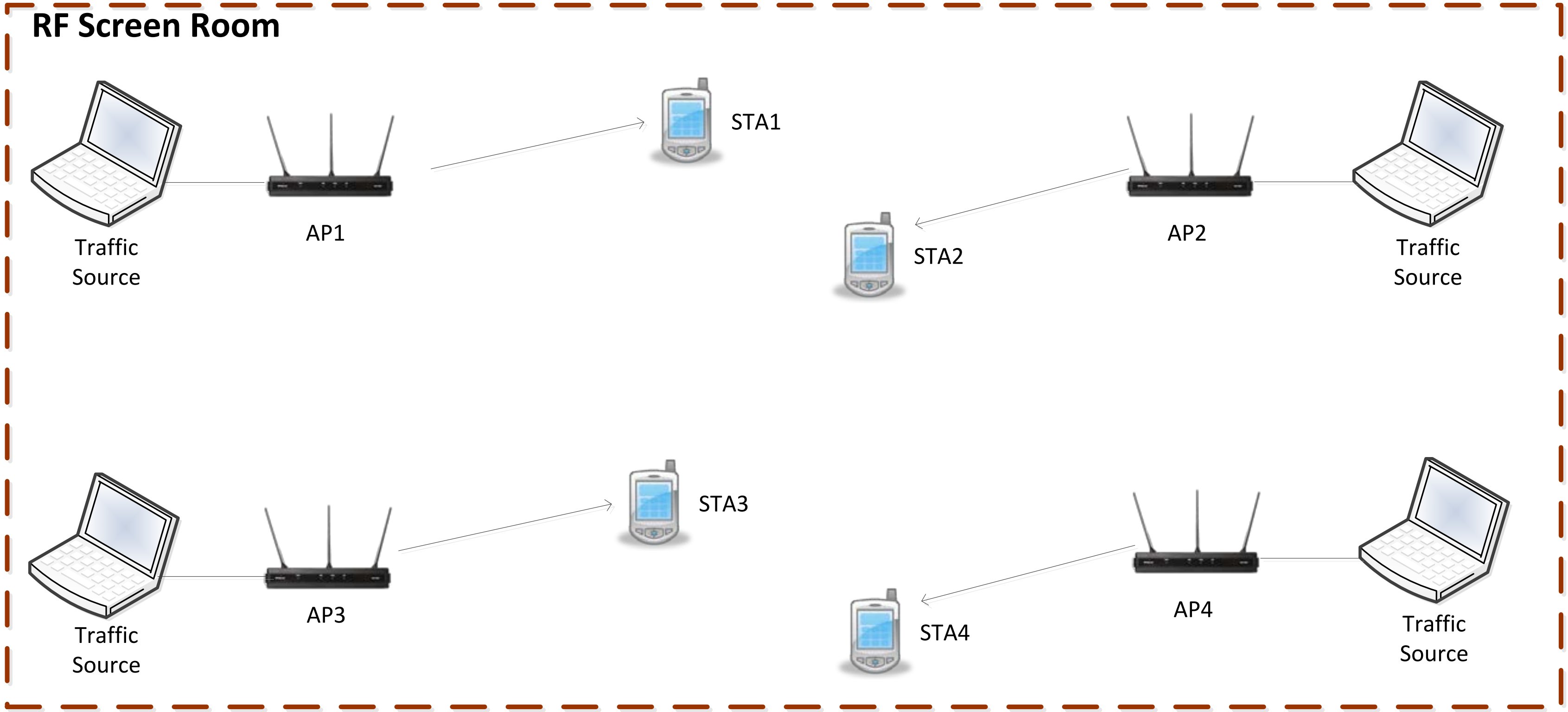
- We studied how different Wi-Fi APs coexist with each other
  - Later compared to coexistence with LTE-U as well

- Conducted measurements using commercially available Wi-Fi Certified WLAN devices
  - 5 top-selling retail APs (11ac) based on 'best-seller lists' determined from top industry magazines and online-retailers
    - Product diversity of 5 OEMs and 3 chipset-vendors
    - Labelled – A thru E
  - STA (11ac, 1x1) – a top-selling mobile-device
    - Same brand of STA device used with all APs to limit combinations

Test Setup

- Four Networks with 1 AP having 1 STAs each
  - All APs set to VHT20 in Ch#153
  - All combinations of APs from set of 5 considered

- Both APs are doing full-buffer downlink traffic (iperf) to the STAs
- Average throughput determined over a 90sec period



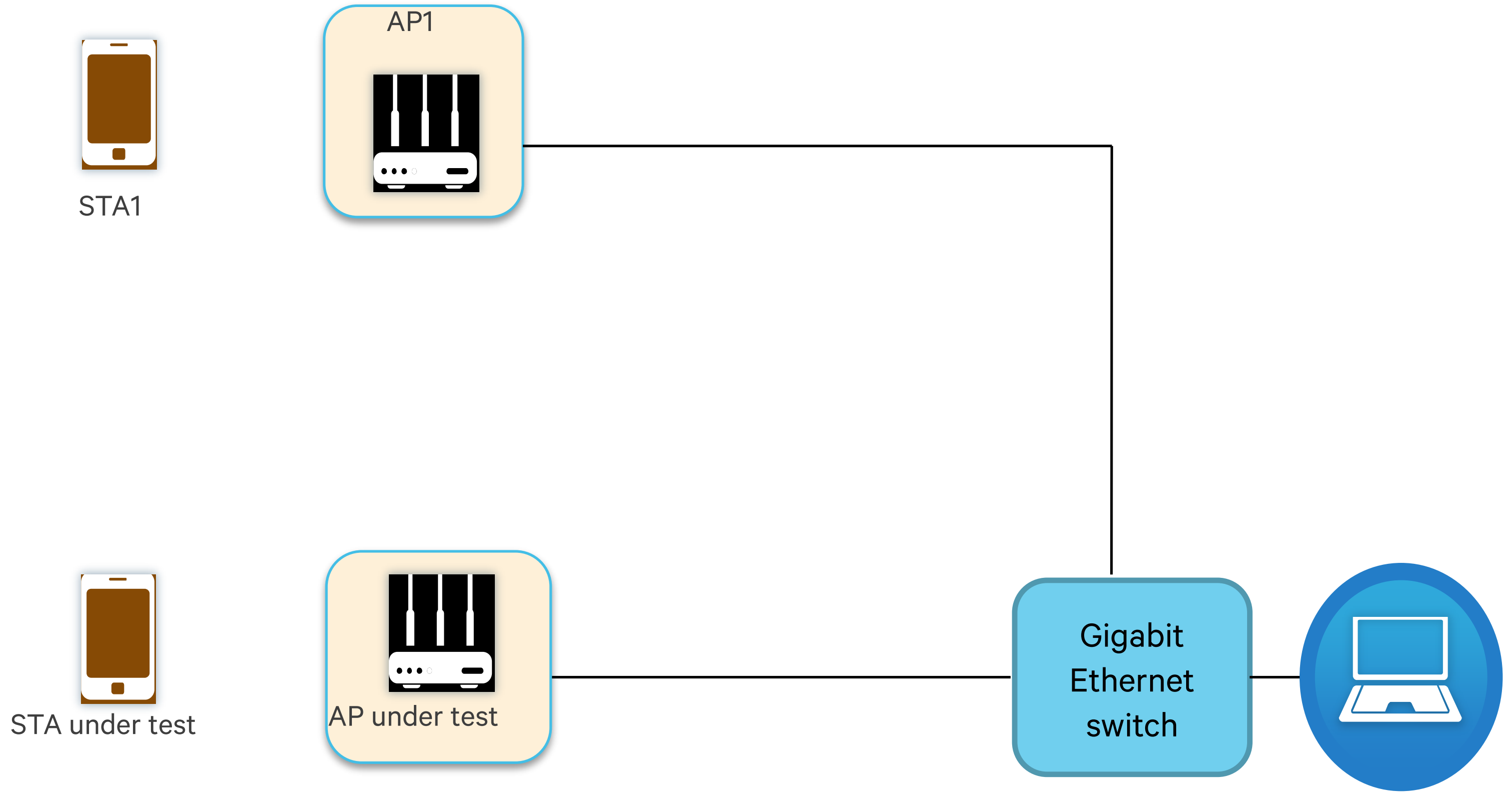
Test Results

APs				Throughput (Mbps)				Aggregate (Mbps)
AP 1	AP 2	AP 3	AP 4	AP 1	AP 2	AP 3	AP 4	
A	B	C	D	40.9	3.9	5.6	3.4	53.7
B	C	D	E	19.4	8.2	7.4	12.9	47.9
C	D	E	A	3.7	2.2	3.6	49.8	59.3
D	E	A	B	4.8	4.6	40.8	4.7	54.9
E	A	B	C	3.9	49.0	2.4	4.3	59.6

- Different APs achieve different levels of throughput share
- Wide variation in channel aggregate throughput of different devices despite similar link conditions (high SNR regime)

Fairness between Wi-Fi/Wi-Fi and Wi-Fi/LTE-U

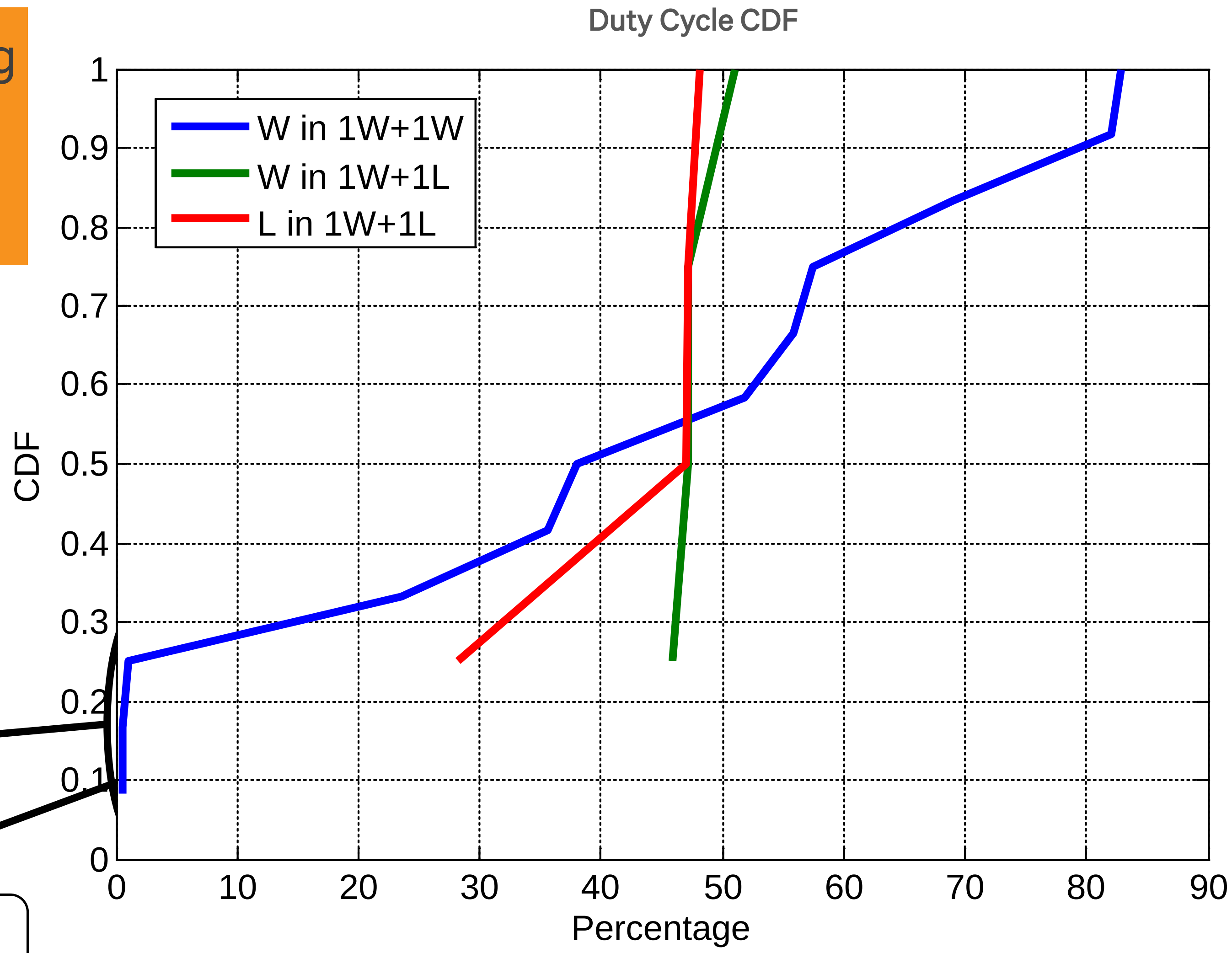
Test Setup



Tests are performed using two Wi-Fi connection pairs across different AP models, and one LTE-U link with one Wi-Fi AP link across different AP models

Consumer grade Fairness with and without LTE-U (*Air time*)

Testing pair-wise airtime sharing across 4 Wi-Fi AP models and between Wi-Fi/LTE-U



- Points corresponding to coexistence with AP model A
- AP model A does not obey CCA-ED rule and does not backoff to LTE-U

Points corresponding to all 4 Wi-Fi AP models

Thank you

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