Spectrum Sharing: Overview

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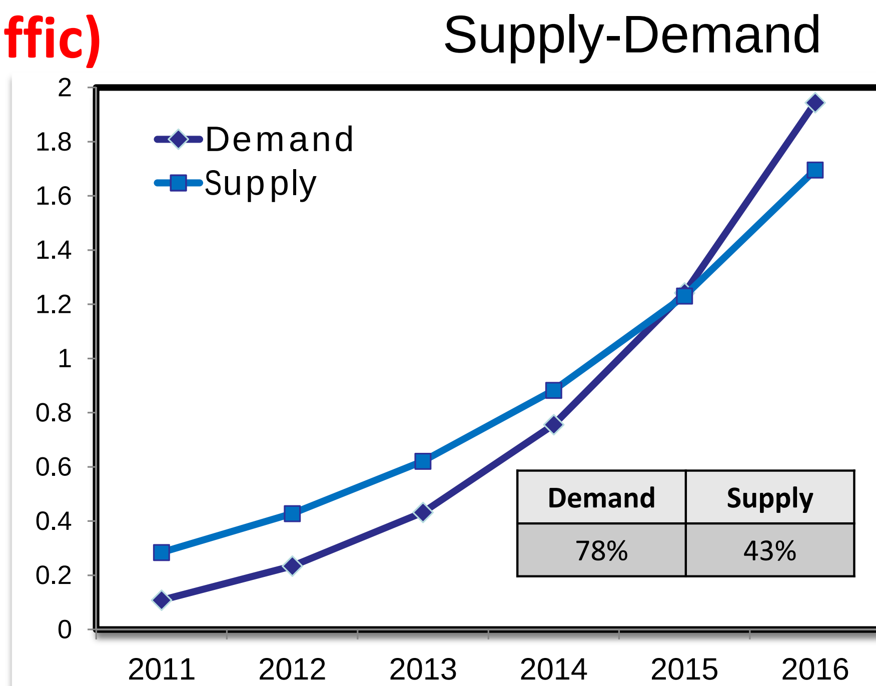
IEEE DL

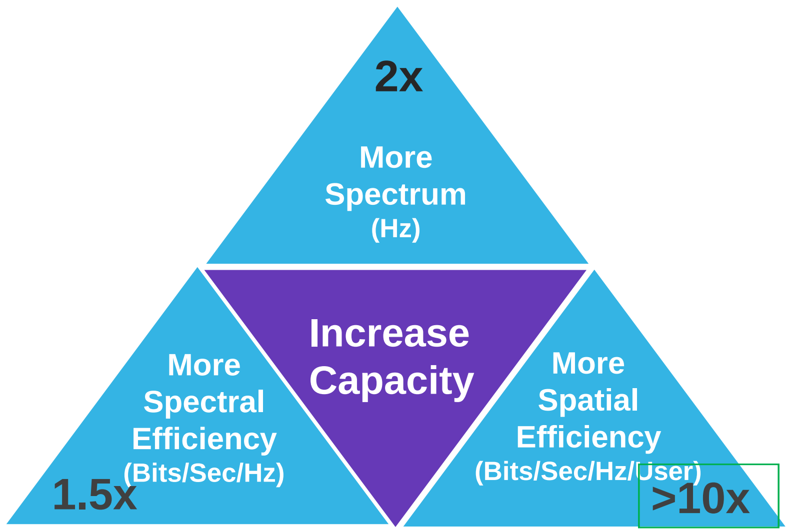
Acknowledgements: Current & Past Students;
Support from NSF, AFRL, Nokia Research, WiFi Alliance

Spectrum Crunch

- **Gap between network demand (aggregate traffic) & supply (capacity increase) is projected to worsen !**
- **Desired availability of *new spectrum* towards alleviation of this gap is unlikely**

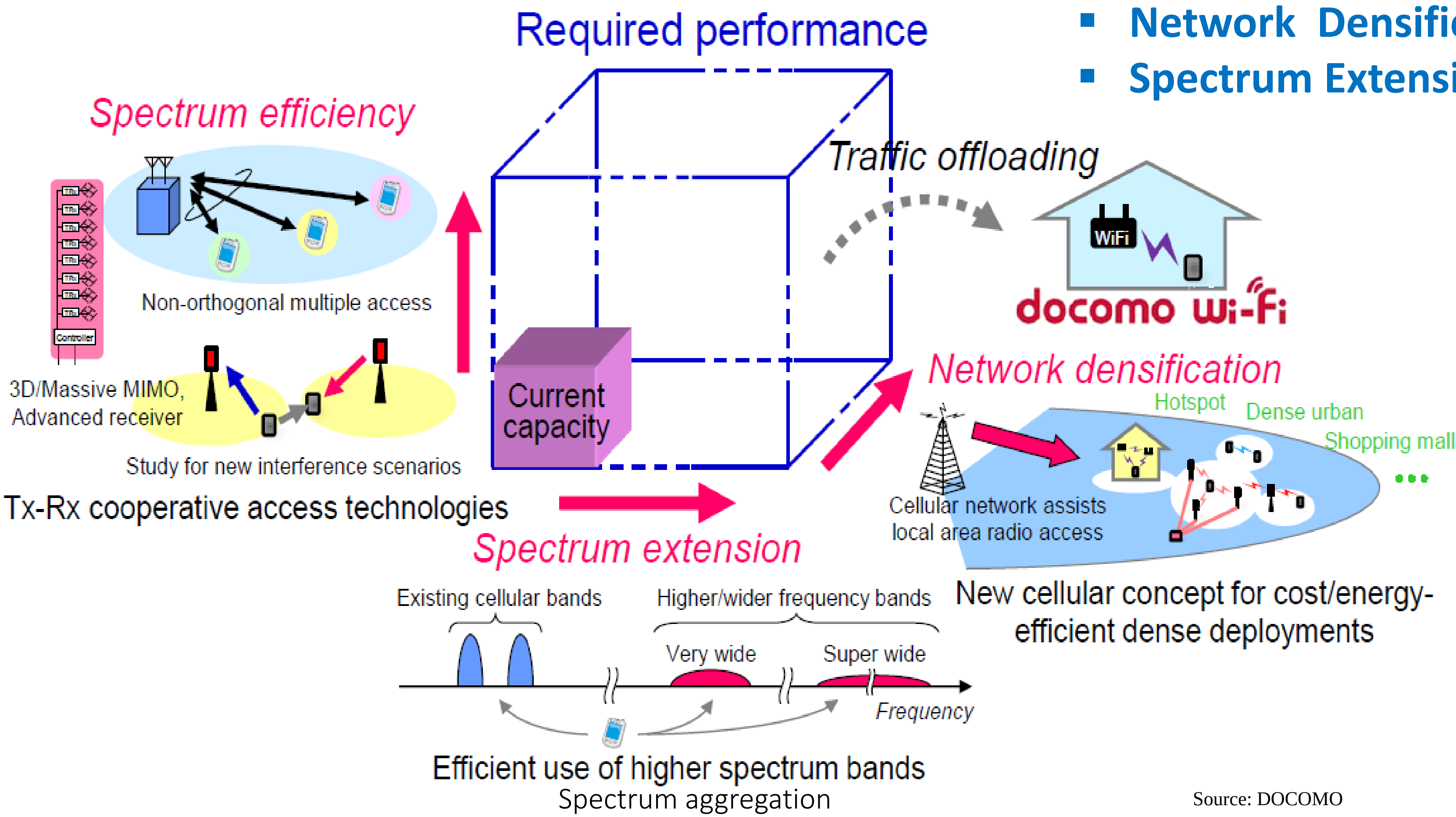


WAYS TO ADD NETWORK CAPACITY



5G Cube for Capacity Enhancement

- **Spectrum Efficiency** **(Co-existence**
- **Network Densification**
- **Spectrum Extension**



Source: DOCOMO

Outline

I: Co-existence Problem I (3.5 GHz) : Radar/Wi-Fi

- Past Lessons - 5 GHz DFS for WLANs
- New Art: Exploit inherent opportunities in CSMA/CA WLANs for detect & avoid

II: Co-existence Problem II (5 GHz): LTE Small Cells/WiFi

- Unresolved issue: Fair sharing between LTE & WiFi

III: Metro-scale Spectrum Monitoring

- I-Q Data Repository (public cloud storage)

RADAR/COMM COEXISTENCE

Presidential Jun 2010 Memorandum (calling on FCC and NTIA) to make 500 MHz of Federal & Non-Federal Spectrum available for commercial wireless by 2020.

NTIA Fast Track Rpt. 2010 identifying DoD Spectrum to be re-purposed

→ AWS-3 SPECTRUM AUCTION (1695-2010, 1755-1780, 2155-2180 MHz)

ADDITIONALLY: 3.5 GHz CBRS (3550-3700 MHz)

DoD Spectrum Relocation

- **DoD will transition systems to allow for commercial operations in the 1695-1710 & 1755-1780 MHz bands**
- 38+ systems/capabilities affected by the AWS-3 transition that must **relocate to another DoD band**, **compress into**, or **share spectrum**

Example: DoD Plans for 1755-1780 MHz

- **DoD will modify selected systems to operate at both 1780- 1850 MHz and 2025-2110 MHz:**
  - Small Unmanned Aerial Systems
  - Tactical Targeting Network Technology
  - Tactical Radio Relay
  - High Resolution Video systems
- **DoD systems will remain in the 1755-1780 MHz band and share spectrum with commercial users as follows:**
  - Satellite Operations at 25 locations
  - Electronic Warfare
  - Air Combat Training System (within two designated polygons in the West)
  - Joint Tactical Radio System at six key sites
- **DoD will compress the remaining 1755-1780 MHz operations into 1780 - 1850 MHz:**
  - Air Combat Training System
  - Joint Tactical Radio System at all other sites
  - Precision Guided Munitions
  - Aeronautical Mobile Telemetry

TWO OPERATIONAL APPROACHES TO CO-EXISTENCE

> **Non-collaborative** **(no information exchanged in operational time between radar & comm. system)**

- **Good utility with minimum effort**
- **Preferentially: changes on the comm side (i.e. retrofitting of Wi-Fi/LTE)**

> **Collaborative** **(side channel for info exchange in operational time)**

- **Potential for Improved re-use and protection but**
- **Significant increase in complexity (network coordination etc.)**

Radar/WiFi Coexistence: Non-Collaborative

> **Two fundamental aspects**

1. **How to protect the radar @ operation time?**
   → sensing by WiFi nodes + Dynamic Frequency Selection (DFS)

   - **Prior Art: DFS regulations on 802.11a WLANs (5 GHz)**

(Additional) Sensing by Wi-Fi for radar Detect-n-Avoid will lead to some WiFi t'put degradation !

DESIGN IS ABOUT ACHIEVING ACCEPTABLE TRADE_OFFS –
satisfy radar protection requirements *while* minimizing t'put loss !

Example Regulatory Requirements (5 GHz)

- **Transmit Power Control (TPC)**
  - **Adjusts a transmitter's output power based on the signal level at the receiver[1].**

- **Dynamic Frequency Selection (DFS)**
  - **Detects the presence of radar signals and dynamically guides a transmitter to switch to another channel whenever a particular condition (indicating a conflict with an active radar operation) is met. Prior to the start of any transmission, a U-NII device equipped with DFS capability must continually monitor the radio[1].**

- **Out-of-Service Monitoring of Radar: achieve Pd=99.99% for any radar signal above -62 dBm within 60 sec.**
- **In-Service Monitoring of Radar: achieve Pd=60% for any radar signal above -62 dBm within 60 sec.**

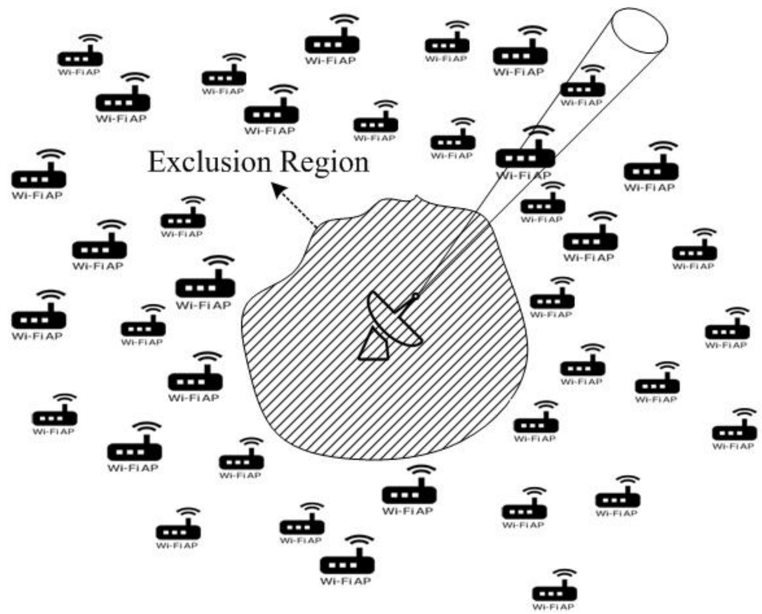
1 FCC Revision of Part 15 for Operation of Devices in 5GHz, NPRM, April 2014

RADAR PROTECTION (from WiFi)

EXCLUSION REGIONS

> Defn (Exclusion): An area around the radar with no co-channel reuse by WiFi.

> Design Objective: minimize exclusion region subject to protection of primary.



Exclusion Region depends on multiple factors: sensitivity of victim receiver, interference margin
Txmit power of secondary
path loss/propagation models

Incumbent Licensee: 'primary' (to be protected from interference)
New Unlicensed User: `secondary' (no interference protection)

EXCLUSION REGIONS (3.5 GHz): ShipBorne Radar

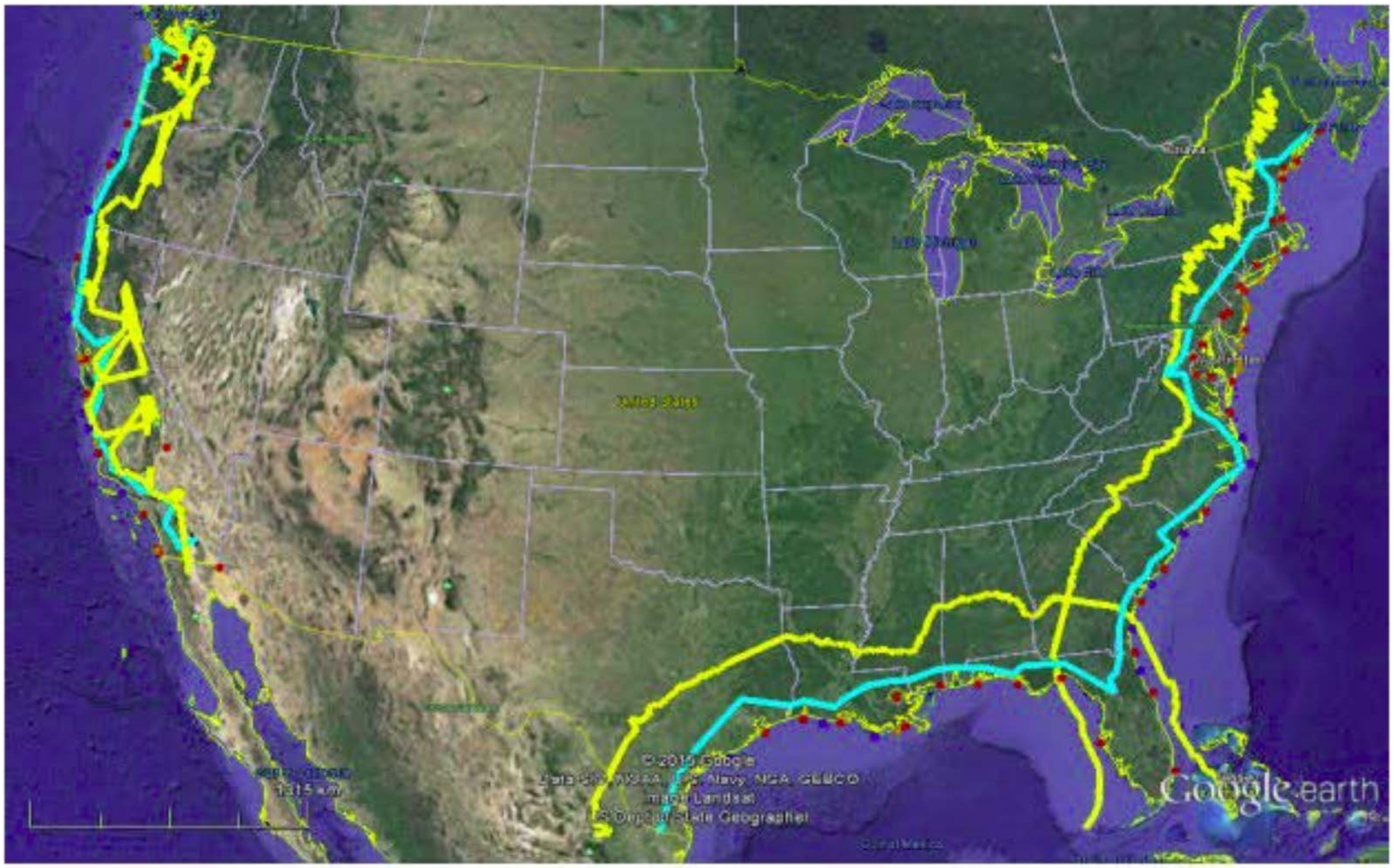


Figure B-1. Shipborne Radar 1–exclusion zone lower 48 states (yellow line–fast track exclusion zone and blue line–revised exclusion zone)

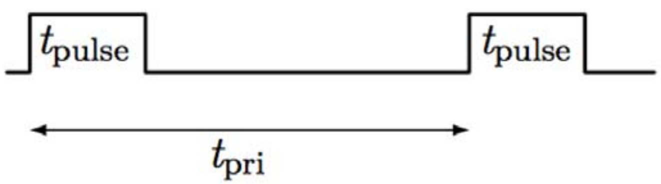
NTIA Rpt. 15-517
Jun 2015
(Exclusion Zone Analyses & Methodology

Highlights impact of Conservative model Assumptions !

DETECTION - SEARCH RADAR

Spatio-temporally varying use of Spectrum Resources

- > **Radar rotates in azimuth with angular rotation speed (e.g. once in few sec)**
- **At any location: emits a burst of pulses → a) pulse duration (1 micro-sec)**
  b) pulse repetition interval (10 micro-se

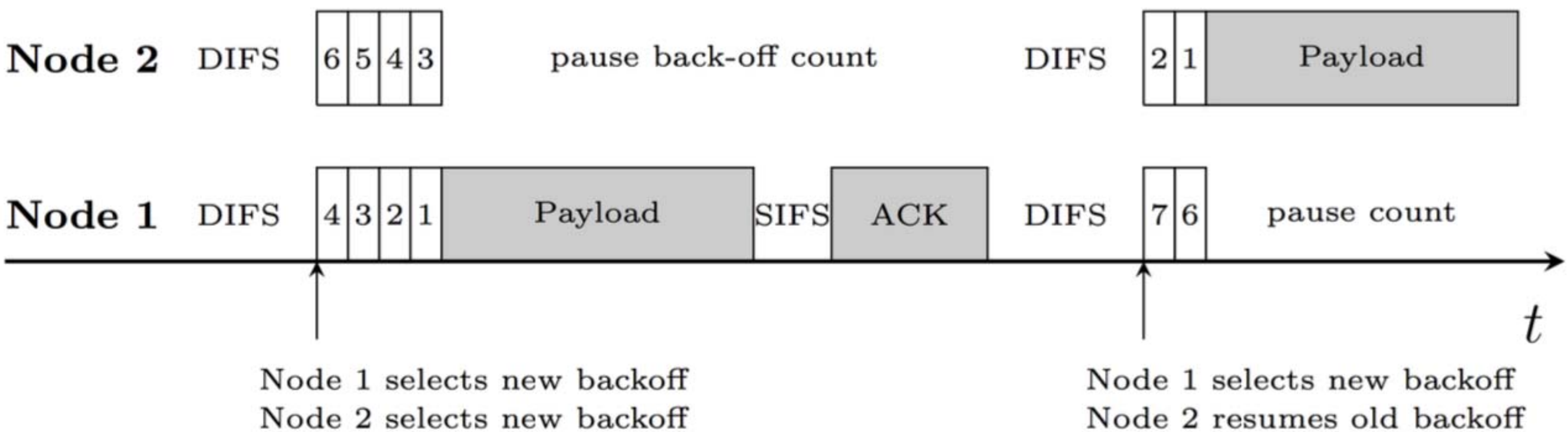


A burst of 9 pulses

- **Assume: pulses can be detected perfectly when the Wi-Fi network is idle**
  → **Schedule (new) idle periods in WiFi for sensing (DFS) at the cost of some t'put loss**

Wi-Fi MAC Overview: CSMA/CA

Nodes use Carrier Sensing Followed by Random Back-Off



t_{slot}	t_{bo}	t_{difs}	t_{sifs}	t_{ack}	$t_{payload}$
$1\mu s$	$9 \times t_{slot}$	$34 \times t_{slot}$	$16 \times t_{slot}$	$48 \times t_{slot}$	up to $\approx 3000 \times t_{slot}$

CSMA/CA: QUIET PERIODS OCCUR NATURALLY

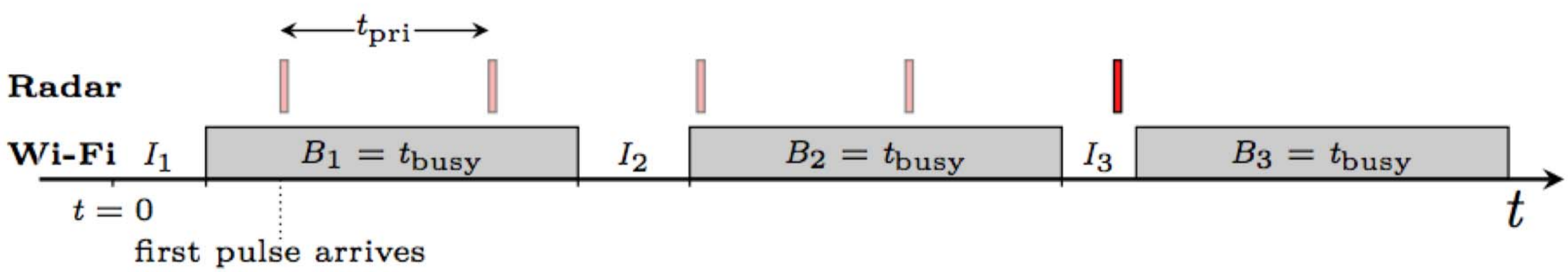
> A Wi-Fi network **INHERENTLY** provides ***randomly placed silent periods of random lengths !***

> **Hence given a pulse burst, what is the probability that one of pulses lands in a quiet period of WiFi?**

> **What is the statistics of the detection delay - count (index) of the first pulse to land in a quiet period?**

<u>What WiFi Network Parameters Impact the Above?</u>

✓ **# active WiFi nodes in the network (more the # of nodes, lower the probability)**

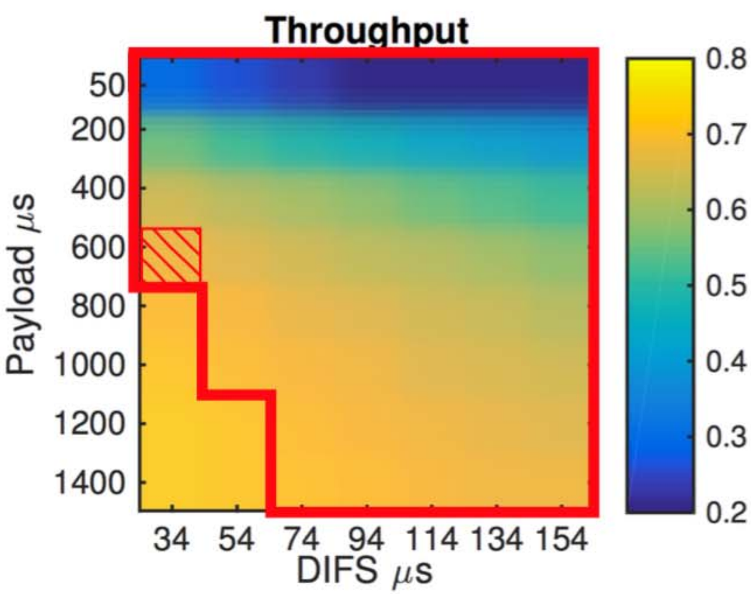


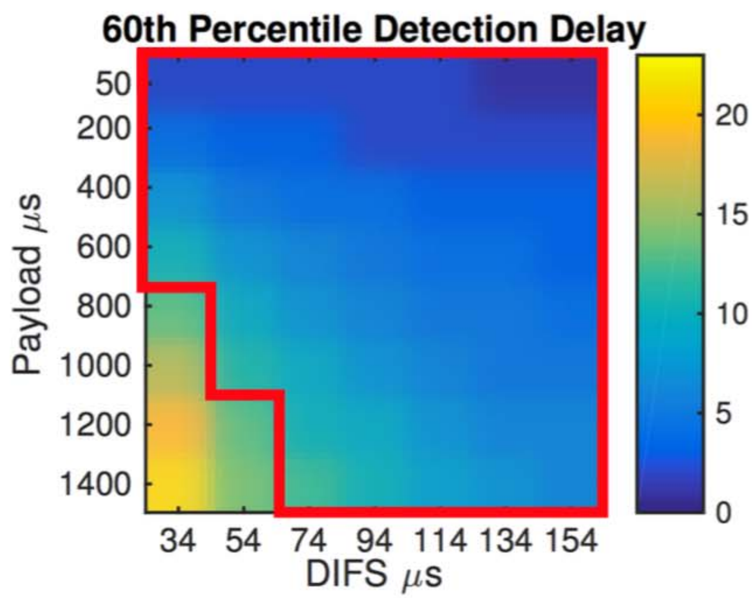
D The detection delay or the *index* for the first pulse that arrives in an idle period. In this case, $D = 5$.

THROUGHPUT VS. DETECTION TRADE-OFF

WiFi Knobs: Payload Size & DIFS duration

- ❖ Increased DIFS → more quiet periods ⇒ better detection, lower throughput
- ❖ Increased Payload → higher throughput





PRI	$250\mu s$	$1429\mu s$
Pulse Duration	$1\mu s$	$1\mu s$
d_{burst}	25	18
Target Burst P_d		0.6
Clients		10
Max Throughput	0.7363	0.715
Payload Duration	$1.5ms$	$930\mu s$

II. LTE-LAA/Wi-Fi Coexistence (5 GHz)

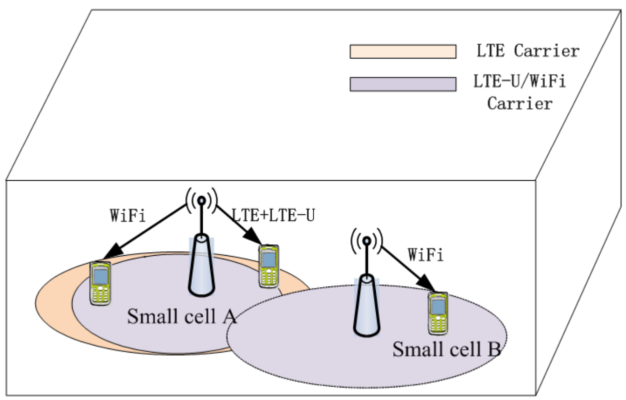
- Primary Carrier on Licensed Spectrum (control, data) [**Carrier**
  Secondary Carrier on Unlicensed (DL best effort data) **Aggregation**]

➢ Requirement: Fair co-existence with another operator

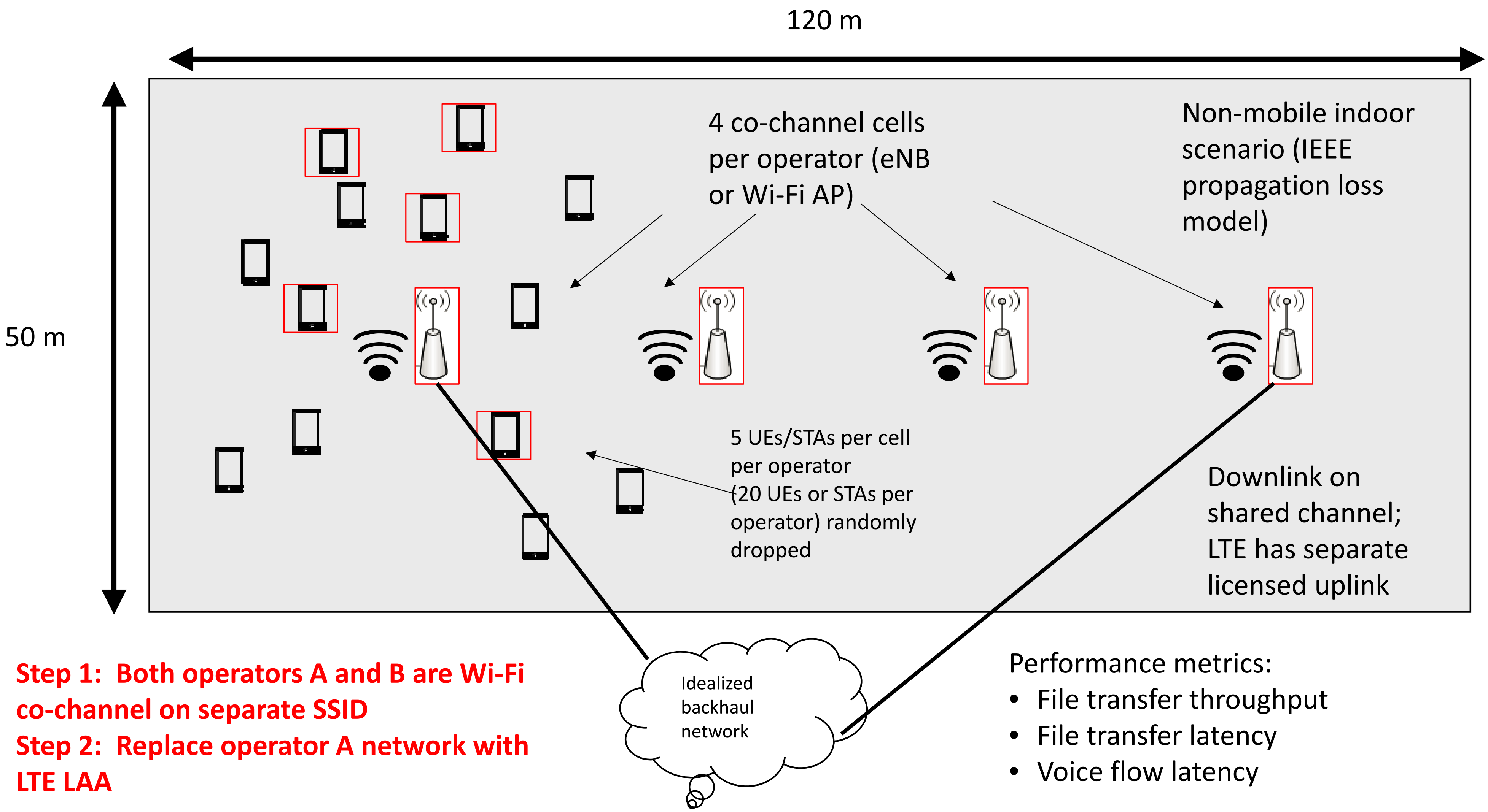
"A LAA network should not impact a co-channel WiFi network any differently than another WiFi network"

<u>Instruments (Secondary Carrier)</u>

➢ Listen-before-talk (Clear channel assessment) by LTE to detect co-channel WiFi and back-off



3GPP Defined Co-existence Scenarios



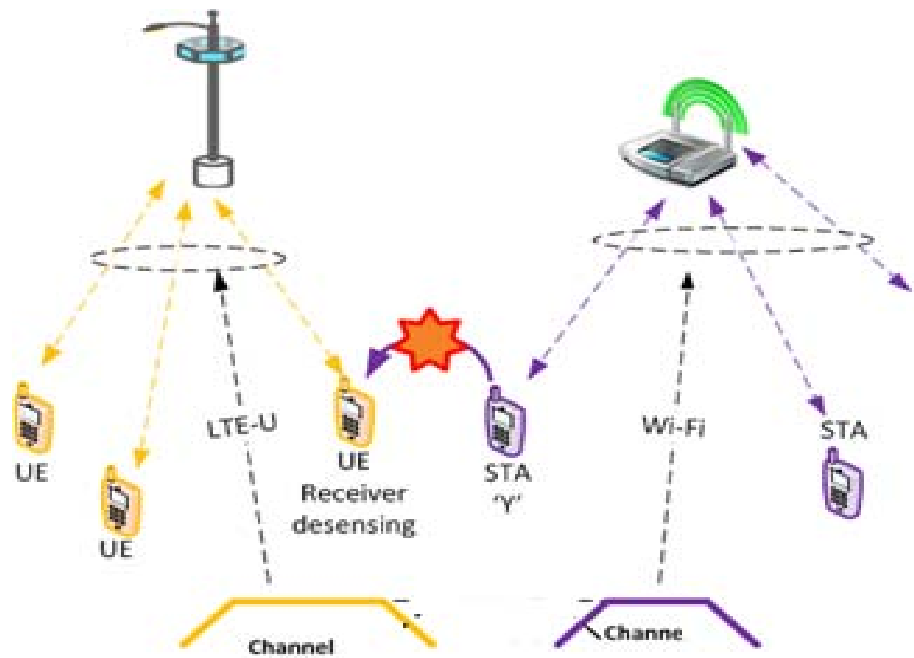
Step 1: Both operators A and B are Wi-Fi co-channel on separate SSID
Step 2: Replace operator A network with LTE LAA

Performance metrics:

- File transfer throughput
- File transfer latency
- Voice flow latency

LTE/WiFi Fair Coexistence : Issues

- Impact of LTE into WiFi and WiFi into LTE are ***very*** asymmetric: their resp. phy and (lower) MAC are ***very*** different !
  - LTE is a scheduled synchronous system, control info sent on primary carrier
- Carrier Sensing by WiFi impacts differently than LTE/LAA:
  - CSMA/CA (Clear Channel Assessment) by WIFi uses -82 dBm as threshold for sensing other WiFi transmissions and -62 dBm for LTE
- Fraction-of-time fairness (50-50) does NOT translate to throughput fairness.

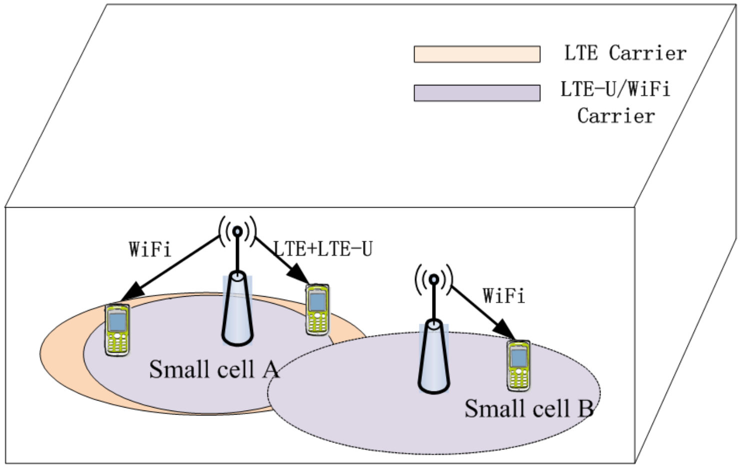


LTE receiver de-sensing due to 802.11 STA transmission

LTE-LAA/Wi-Fi Coexistence Study using ns-3

- Added ns-3 features essential to build scenarios mapping to TR36.889 LAA Release 13 scenarios
- Develop initial indoor and outdoor scenarios corr. to TR36.889 + initial test plan

3GPP TSG RAN WG1 Meeting #83 R1-156621
Anaheim, CA, November 16 2015
Source: Wi-Fi Alliance
Title: Coexistence simulation results for DL only LAA (UW and CTTC, Barcelona)



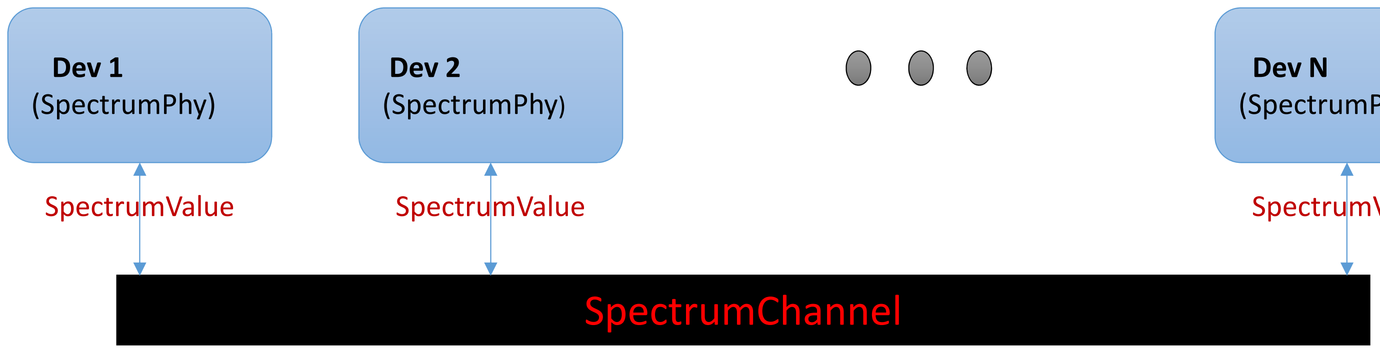
❖ **Network simulation via ns-3**
[NSF funded most popular open source network simulator]

ns-3 Feature: SPECTRUM AWARE PHYSICAL LAYER ABSTRACTION

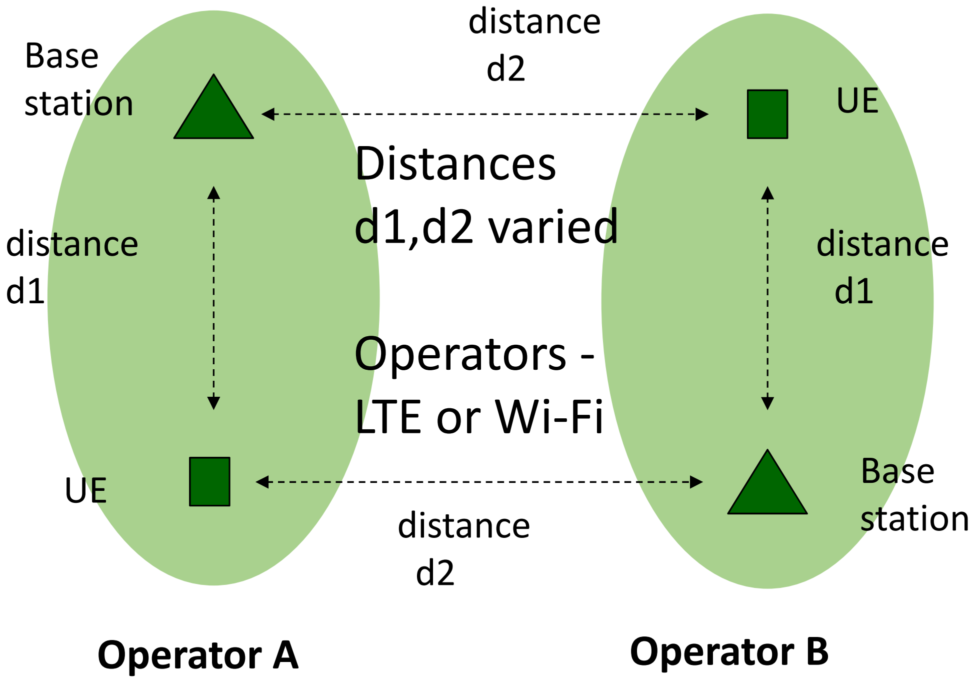
> SpectrumPhy - first introduced for LTE in ns-3

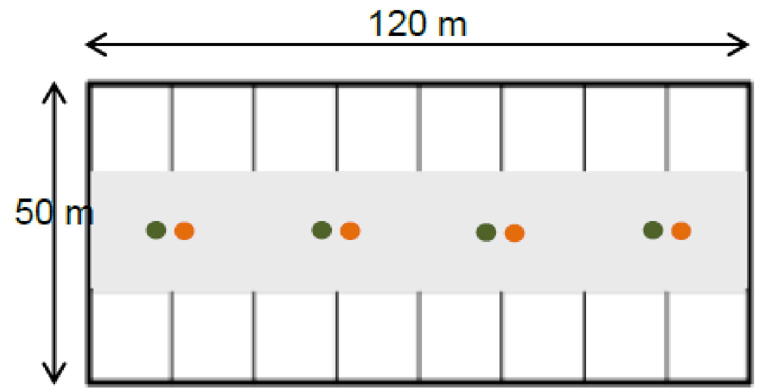
> Uses a power spectral density representation of signals

- Adjustable granularity at the time a transmitter/receiver is implemented
- Converts between signal formats (i.e. various granularities used by different wireless systems e.g. LTE and Wi-Fi)
- Can implement frequency selective channels



LAA-Wifi: Basic Scenario (2 cell)

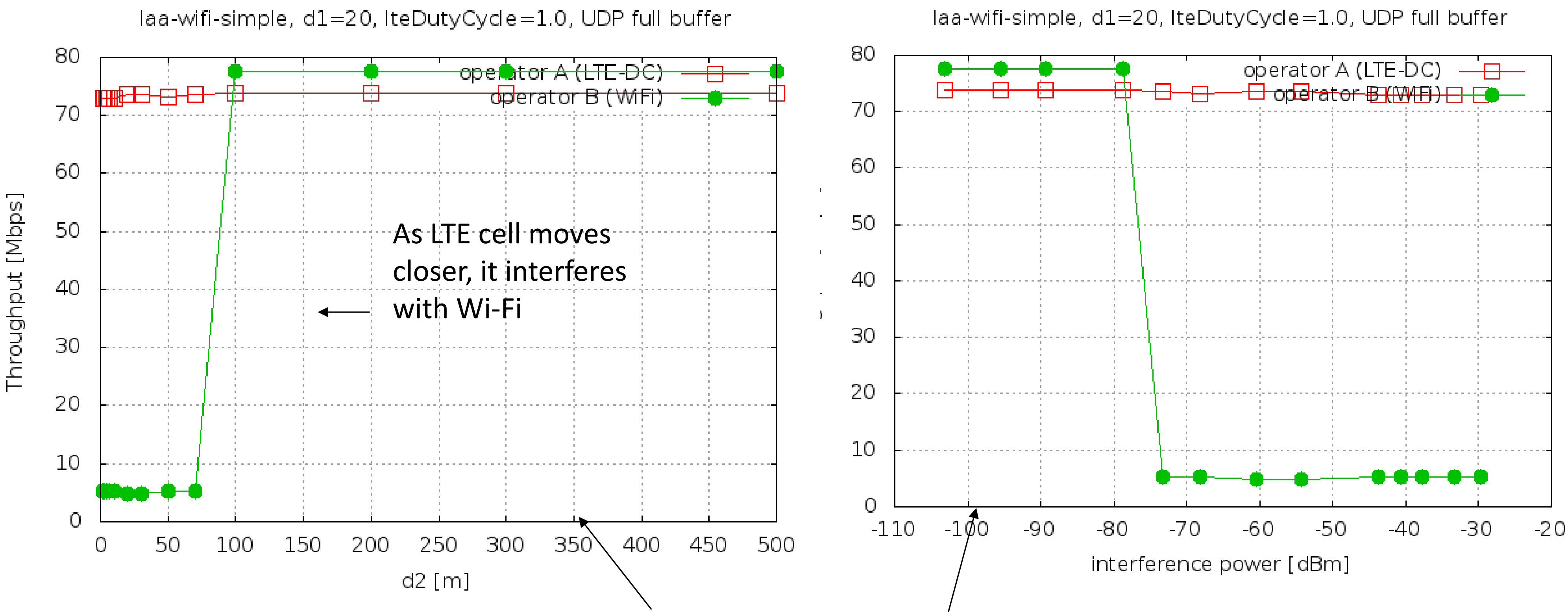




- **UDP** data transfer, **FTP** application
  - Indoor channel model
  - LTE DT Mode

Varying cell separation (d2): 2-cell case

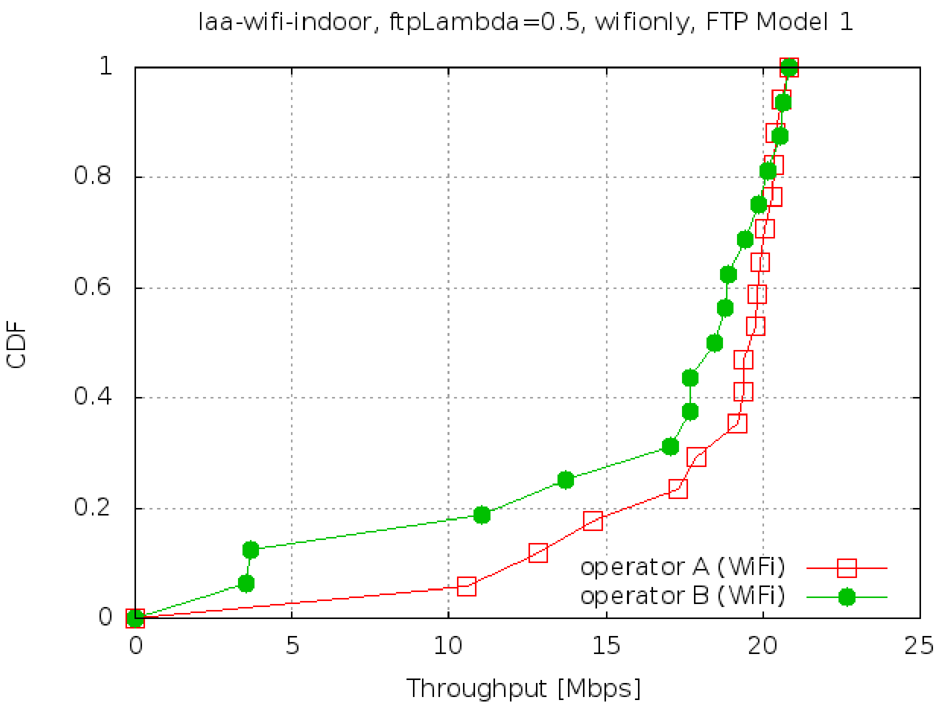
UDP full buffer (saturation) traffic, **no LTE duty cycle**, BS/UE separation 20m
802.11n SISO model at 5.18 GHz, 20 MHz (ideal rate control)



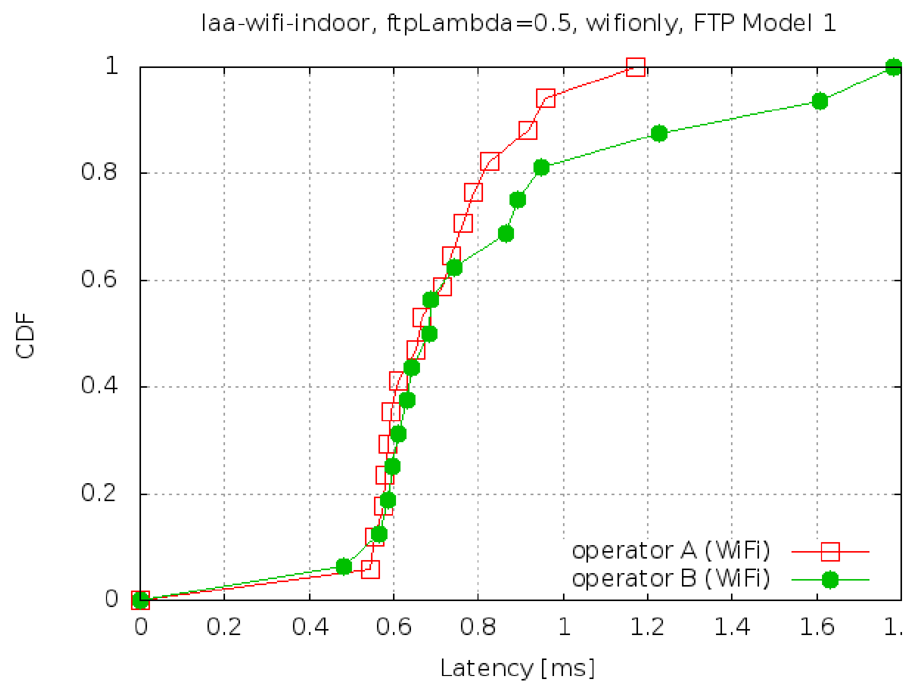
Same data plotted using two different x axes (distance and interference power)

3GPP TR36.889 indoor scenario (4 cells)

4 cells per operator, 10 UEs per cell (80 UEs total). **Both networks Wi-Fi**.
FTP Model 1 traffic load, **LTE duty cycle of 0.5**
802.11n SISO model at 5.18 GHz, 20 MHz (ideal rate control)



Throughput CDF from one run; in general networks are identical so over many runs performance (sharing) will be equal



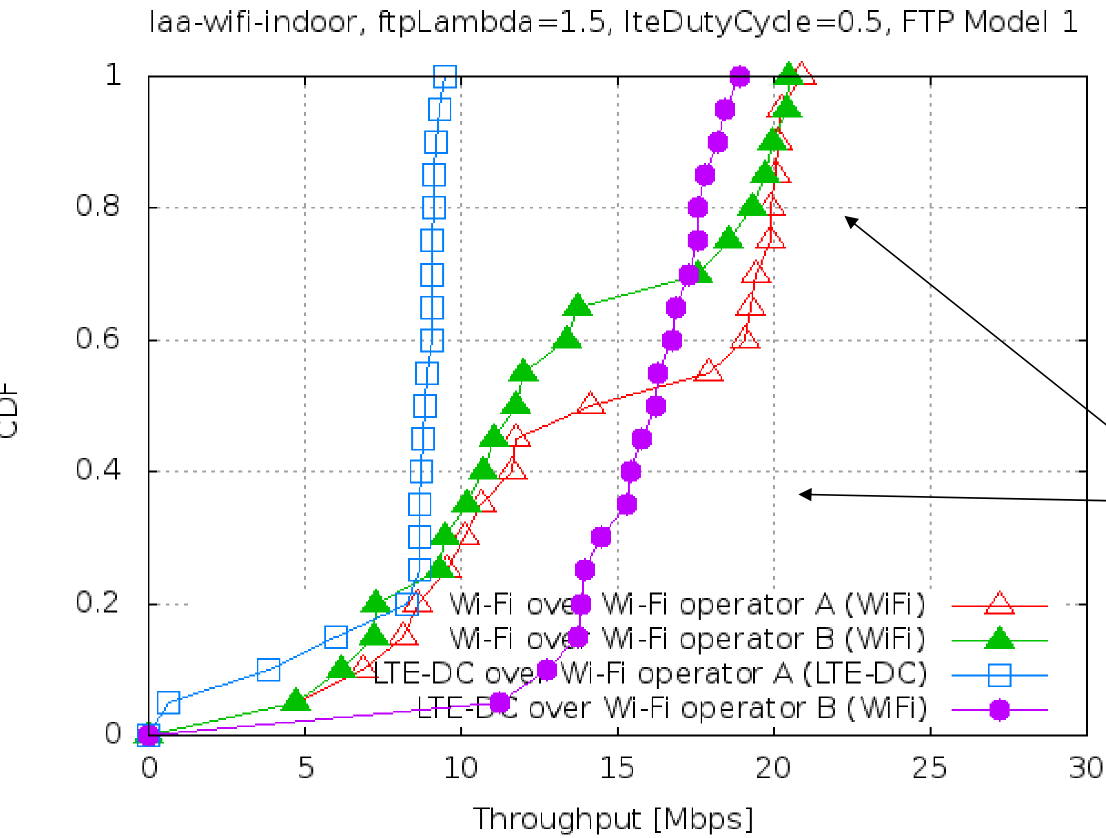
Latency statistics measured end-to-end at the IP layer

3GPP TR36.889 indoor scenario (4 cells)

10 UEs per cell (80 UEs total); **One Wi-Fi Operator replaced with LTE**

FTP Model 1 traffic load, **LTE duty cycle of 0.5**

802.11n SISO model at 5.18 GHz, 20 MHz (ideal rate control)



Two CDF plots are overlaid:

1) Wi-Fi on Wi-Fi run (red/green)
2) LTE on Wi-Fi run (blue/purple)

Replacing one Wi-Fi operator with an LTE operator changes the Wi-Fi throughput distribution;

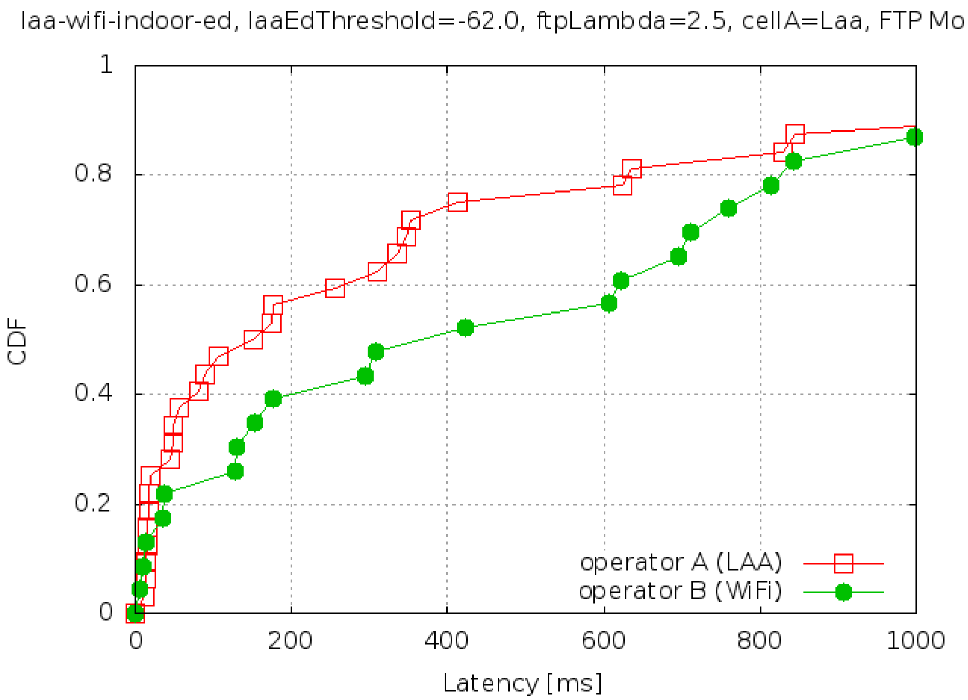
- peak FTP throughputs decrease but slowest FTP throughputs are boosted

Each FTP transfer - flow of fixed file size, the FTP takes a variable amount of time to complete, leading to a per-flow throughput CDF

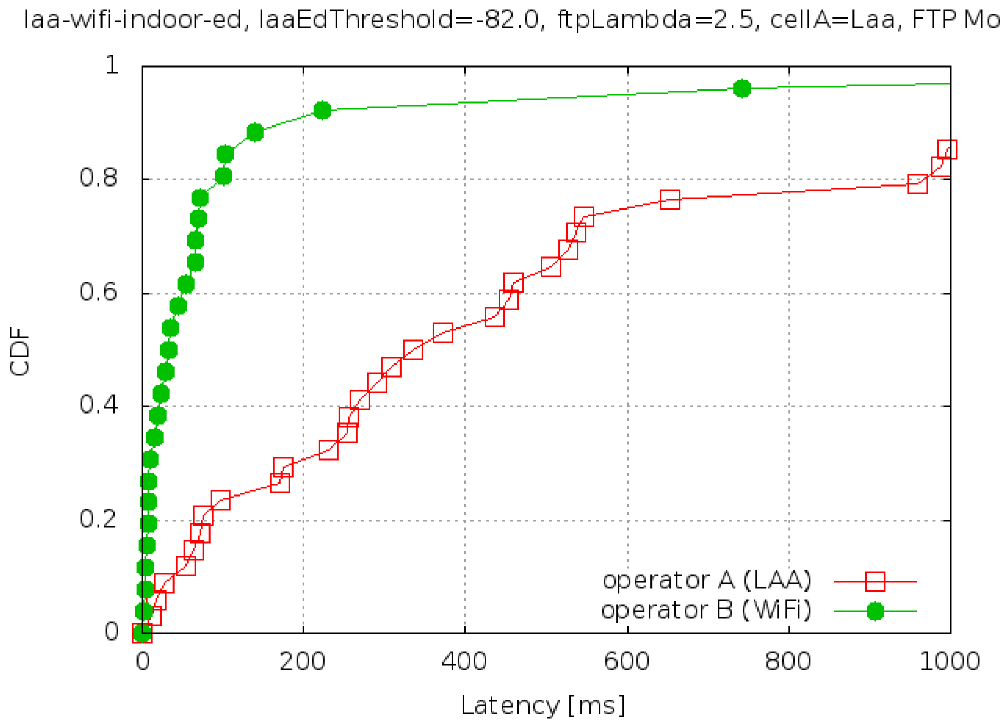
Lowering Energy Detect Threshold for LAA

Latency (per-packet, FTP flows)

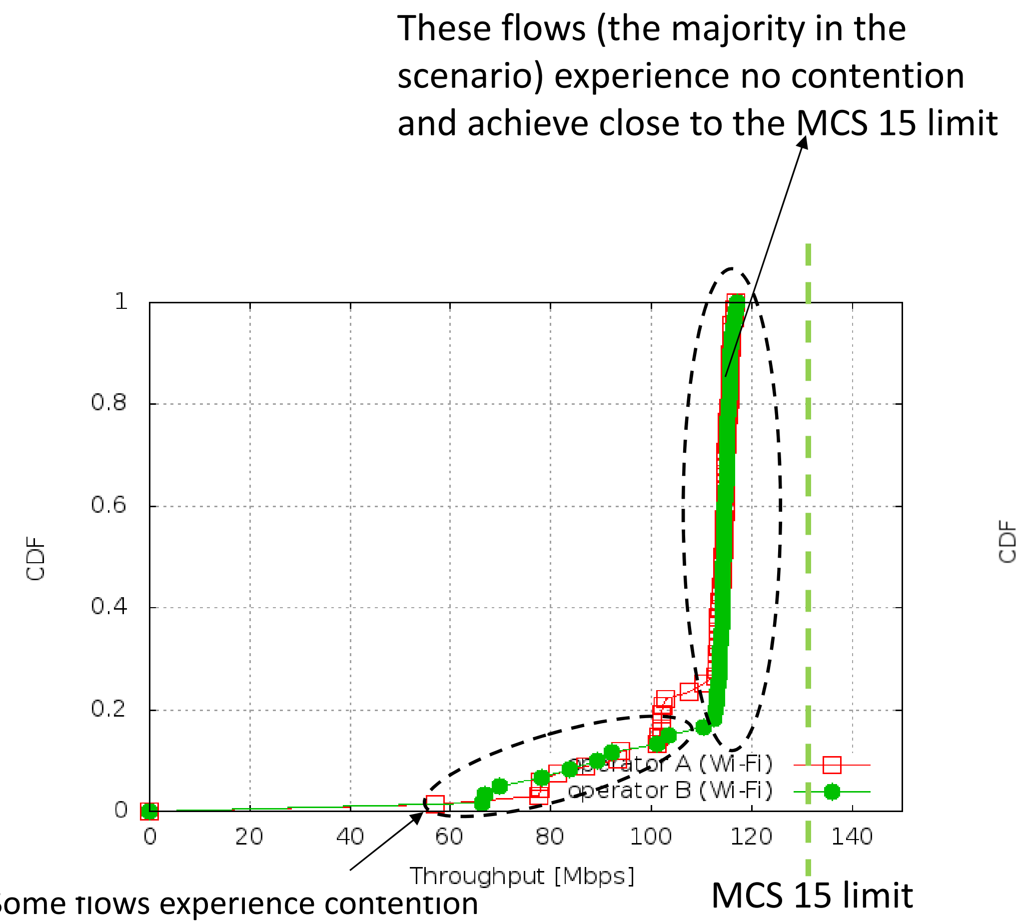
- **Note the green curve pulls leftward**



-62 dBm LAA ED threshold

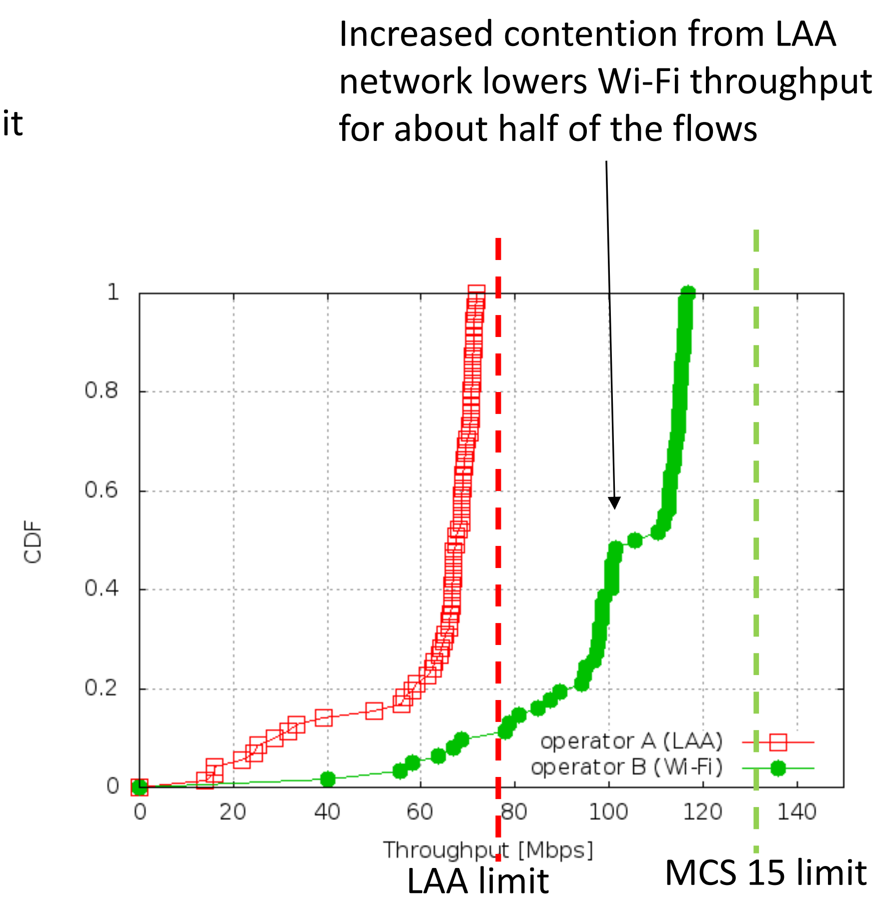


-82 dBm LAA ED threshold



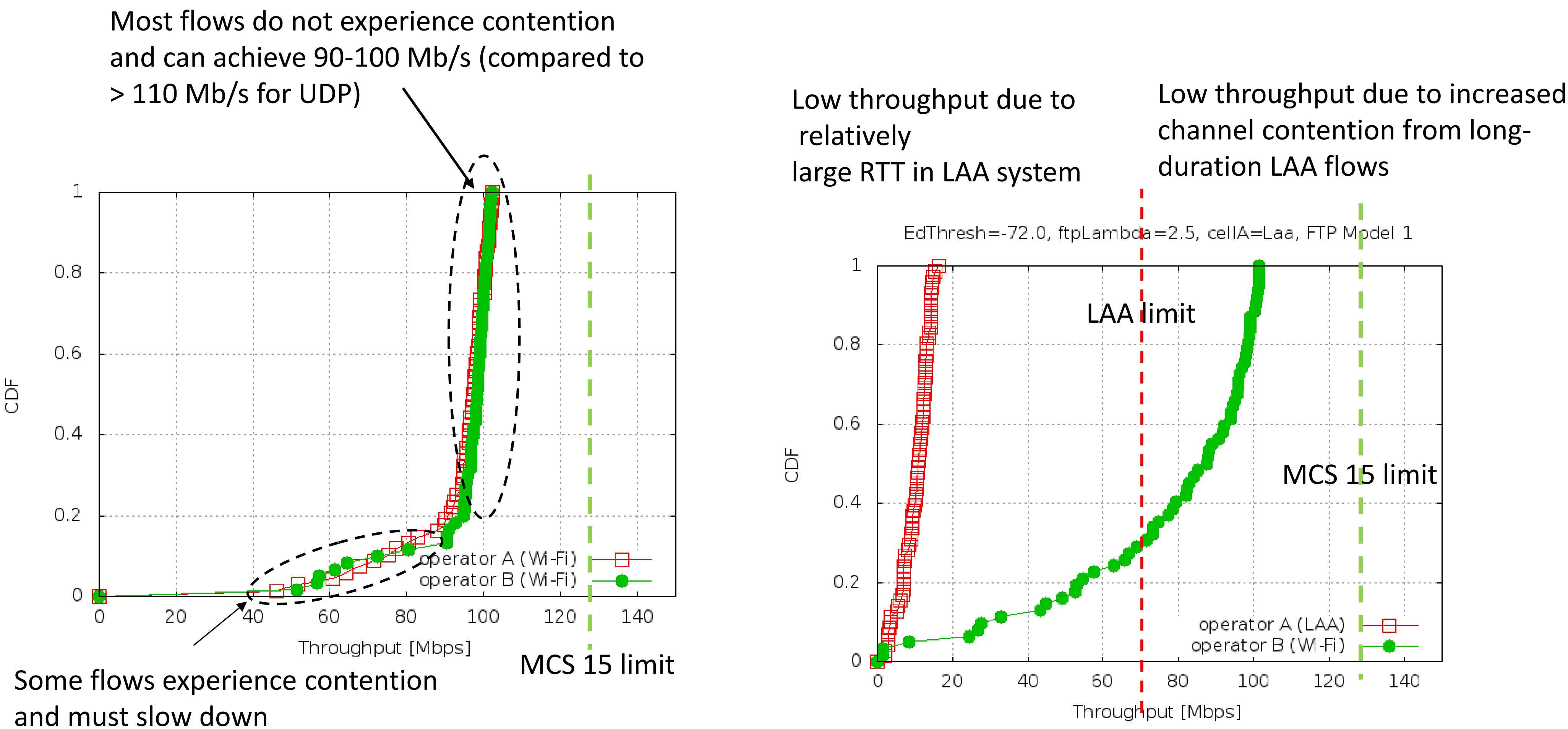
Some flows experience contention and must slow down

a) Step 1 (Wi-Fi)



b) Step 2 (LAA)

FTP UDP



a) Step 1 (Wi-Fi)

b) Step 2 (LAA)

TCP Performance

Key Observations

Observation 1: Coexistence performance is highly sensitive to all factors that affect the *channel occupancy*: resp. PHY-MAC layers including LAA access parameters, but also upper layer protocols, such as TCP/UDP and RLC.

Observation 2: Very bursty-like traffic pattern, like the FTP1 model run over a UDP-like transport, may be a best case scenario for coexistence in LBT/LAA. Other less bursty traffic models, or other transport protocols, e.g. TCP, may cause LTE LAA to occupy much more of the channel.

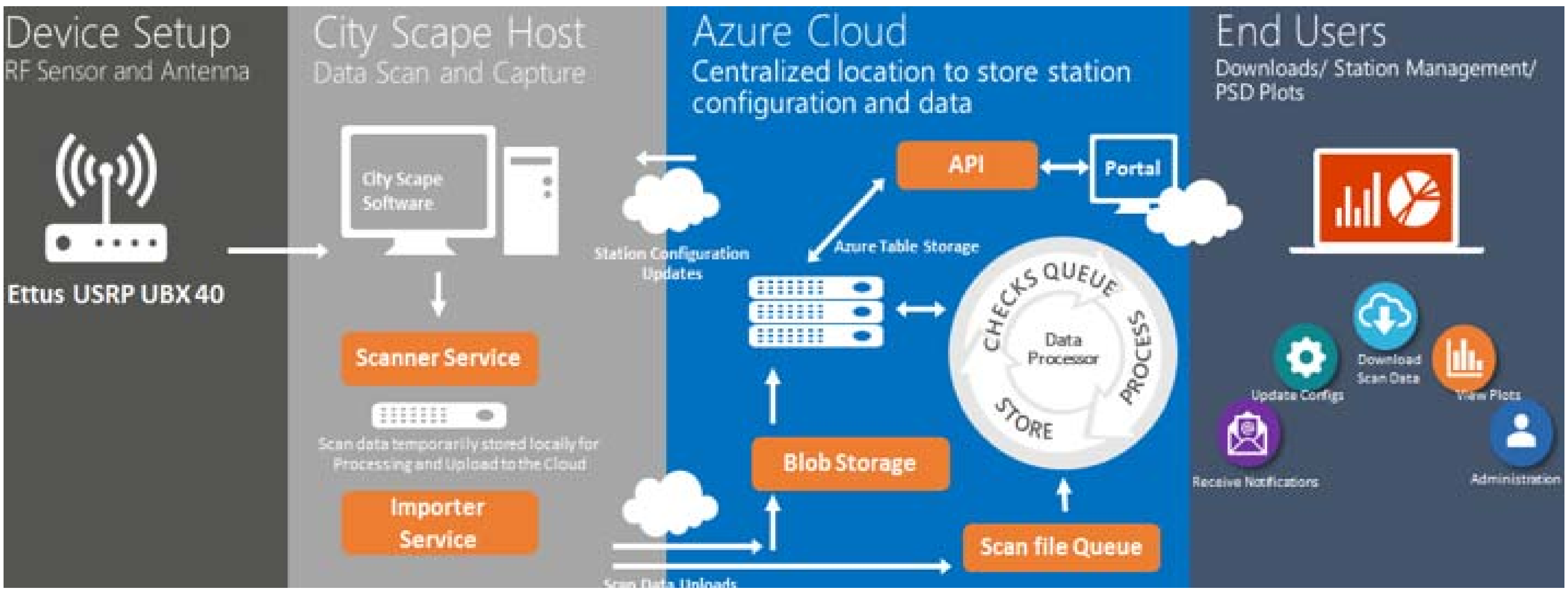
Observation 3: Implementation details (mostly vendor dependent) regarding how asynchronous channel access by WiFi is reconciled with the synchronous way the LTE protocol stack works, may significantly affect the channel occupancy and coexistence.

- ❖ Specific vendor implementation resulting in delays between MAC-scheduler events and when the channel is actually occupied, also severely affect the channel occupancy.

III. Spectrum Monitoring: CityScape

cityscape.cloudapp.net

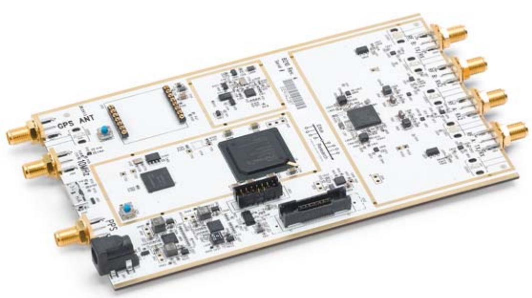
- Enable researchers with access to archived **I-Q** and **time-averaged p.s.d** data from multiple ROOFTOP sensor locations in a metro area.
- A web-based control & operations management framework:
  - allows station owners to set data acquisition parameters
  - allows 3rd party users to download archived data for own use
- Significant effort w.r.t DATA QUALITY aspects



Enabler: Commodity SDR Hardware as Spectrum Sensor

USRP

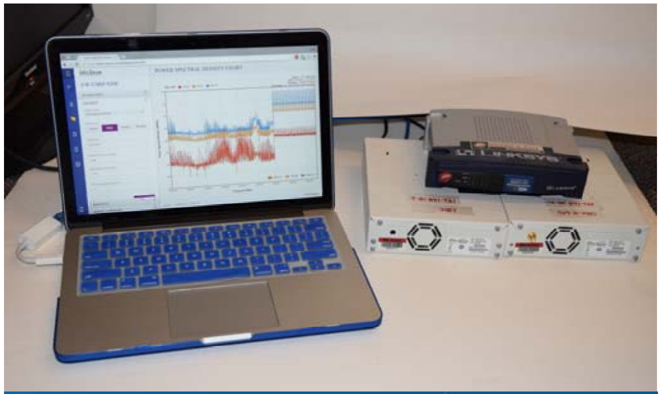
USRP **N210** (used by MSFT SpecObs)



USRP **B210**

Antenna

MultiPolarized Super-M Ultra Base Station antenna
(25MHz to 6GHz Rx; 88MHz - 6GHz Tx)



Installation on the rooftop of Sieg Hall, UW

Observatory Architecture

ScanFile: File format for all spectrum data storage (client and server)

Scanner Service (Client PC): Responsible for communicating with RF sensor and writing data in ScanFile format

Upload Service (Client PC): Responsible for reliably uploading ScanFiles to the Azure cloud.

Upload Web Service (Azure): Responsible for queueing complete ScanFile uploads for processing by the data processor worker.

Data Processor Worker (Azure): Responsible for processing the uploaded ScanFiles and aggregating the information to Azure tables.

Azure Table Storage: All aggregated data for time periods (Hourly, Daily …) + metadata.

Azure Blob Storage: All raw ScanFiles stored in blob storage.

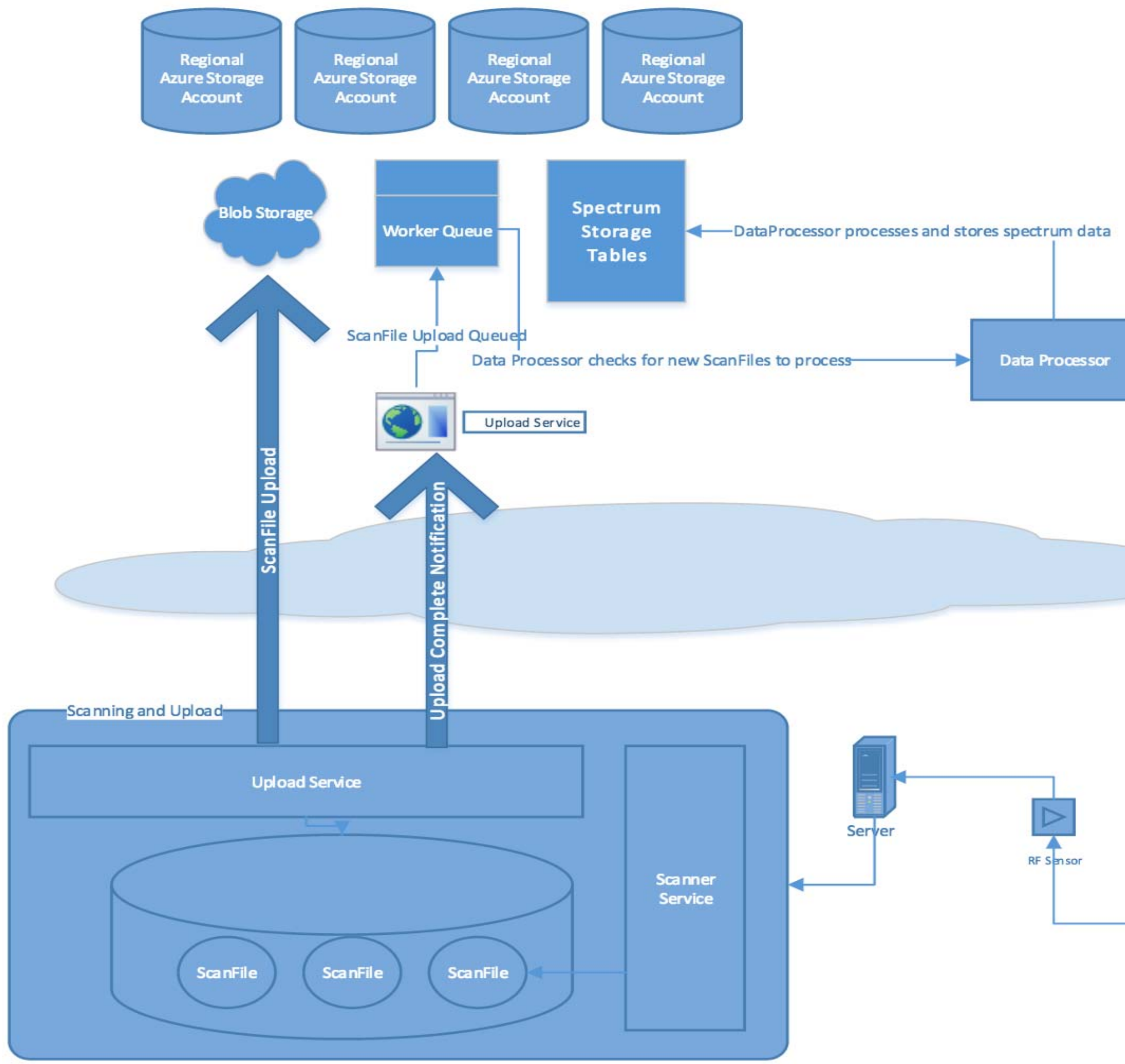
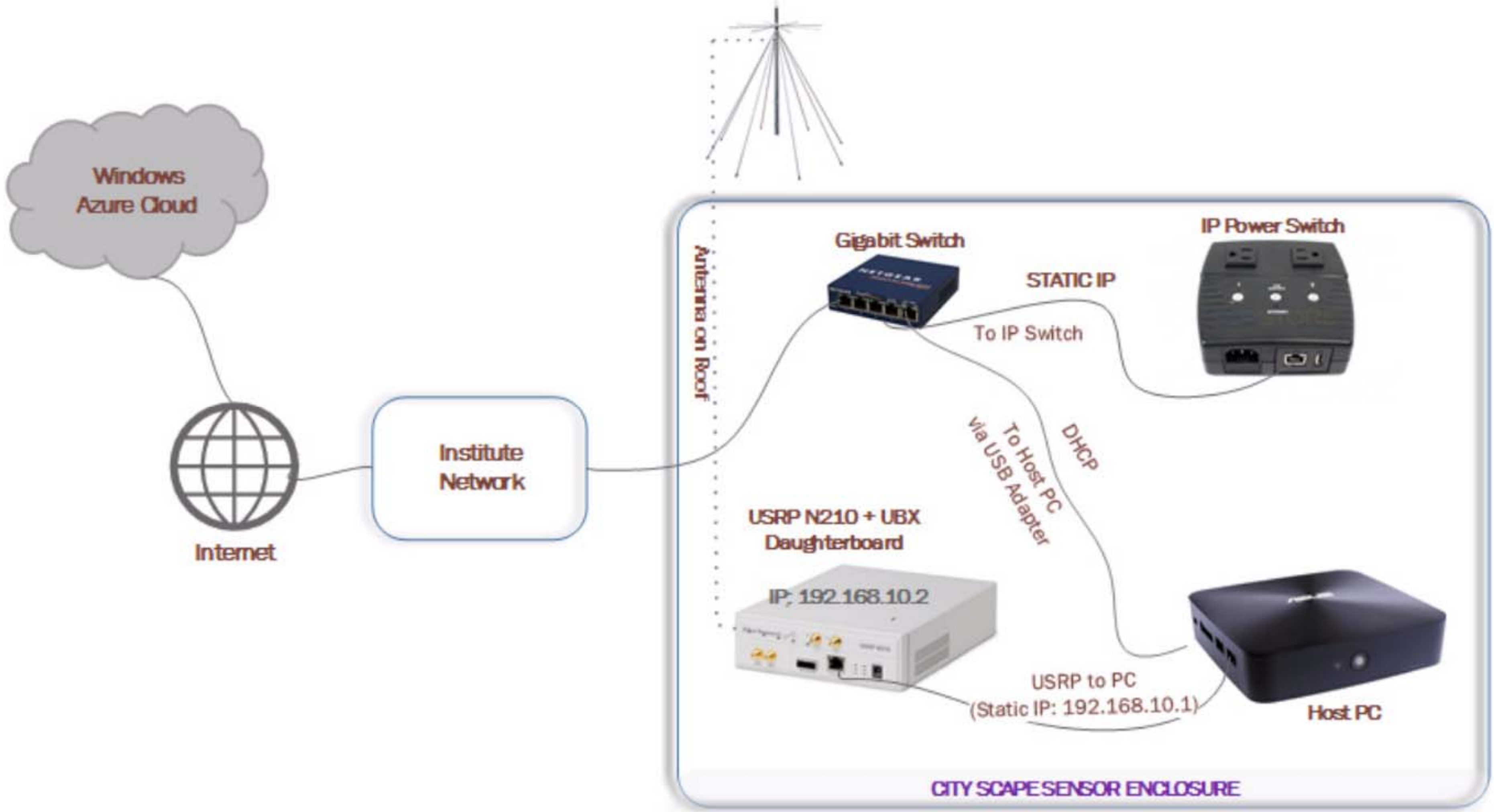
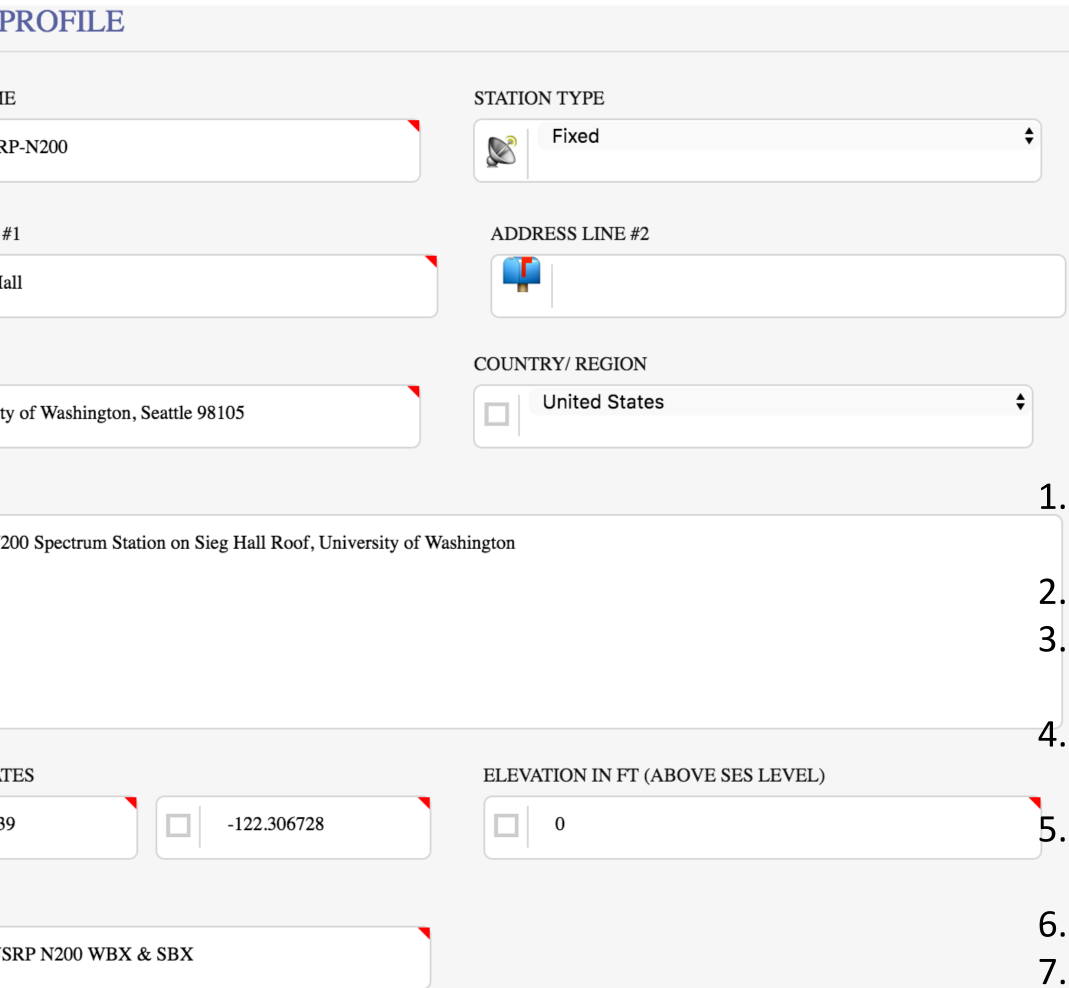


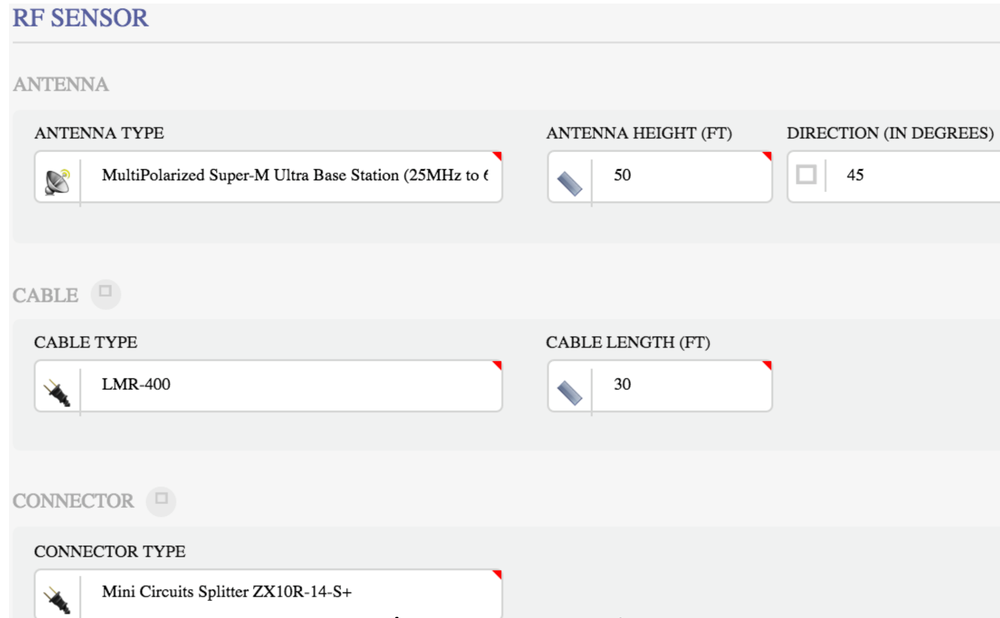
Figure 1 Microsoft Spectrum Observatory Overview

SYSTEM OVERVIEW



Web Interface Screenshot





1. Name – Station HW ID/device name (for logging purposes only.
2. Device type – Types of USRP supported.
3. Start frequency in Hz – Frequency at which device starts collecting data.
4. Stop frequency in Hz – Frequency at which device stops collecting data.
5. Device address – IP Address of the device on network (String; 192.168.10.2)
6. Gain – Adjusts gain (dB) in the USRP Rx
7. Antenna port – Antenna receiver port on the USRP. (String; RX1 or RX2)

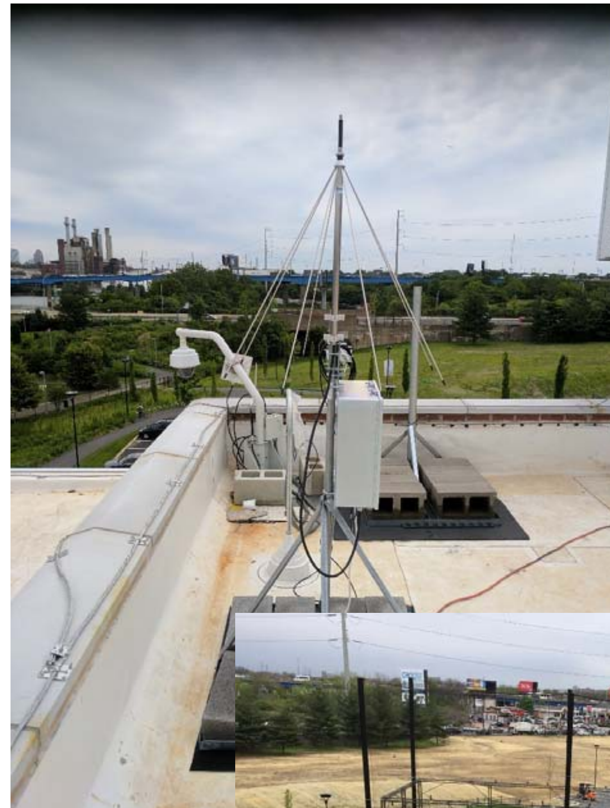
Knobs

Knob	Description
Start/Stop Frequency in MHz	Frequency(inclusive) at which device starts/stops collecting data.
RX Gain	Adjusts the receive gain (dB) of the USRP.
Scan Pattern	The scan pattern (StandardScan or DCSpikeAdaptiveScan).
Effective Sampling Rate (MS/s)	Determines the effective sampling rate (rate after decimation) of the scanner. Instantaneous Bandwidth of the sensor is equal to this value (low-pass filter width = effective sampling rate). For USRP N2x0, this value must be (25/N) MS/s, where N is an integer from 1 to 128.
PLL Flag Poll Delay	Period of time between each PLL Lock flag polling (which occurs after each frequency retune).
Additional Tune Delay	Duration to wait after each frequency retune before resuming the data collection (in addition to the PLL flag poll delay).
Samples Per Snapshot	Indicates number of samples to capture per each snapshot.

UPENN 01 (Main Campus)

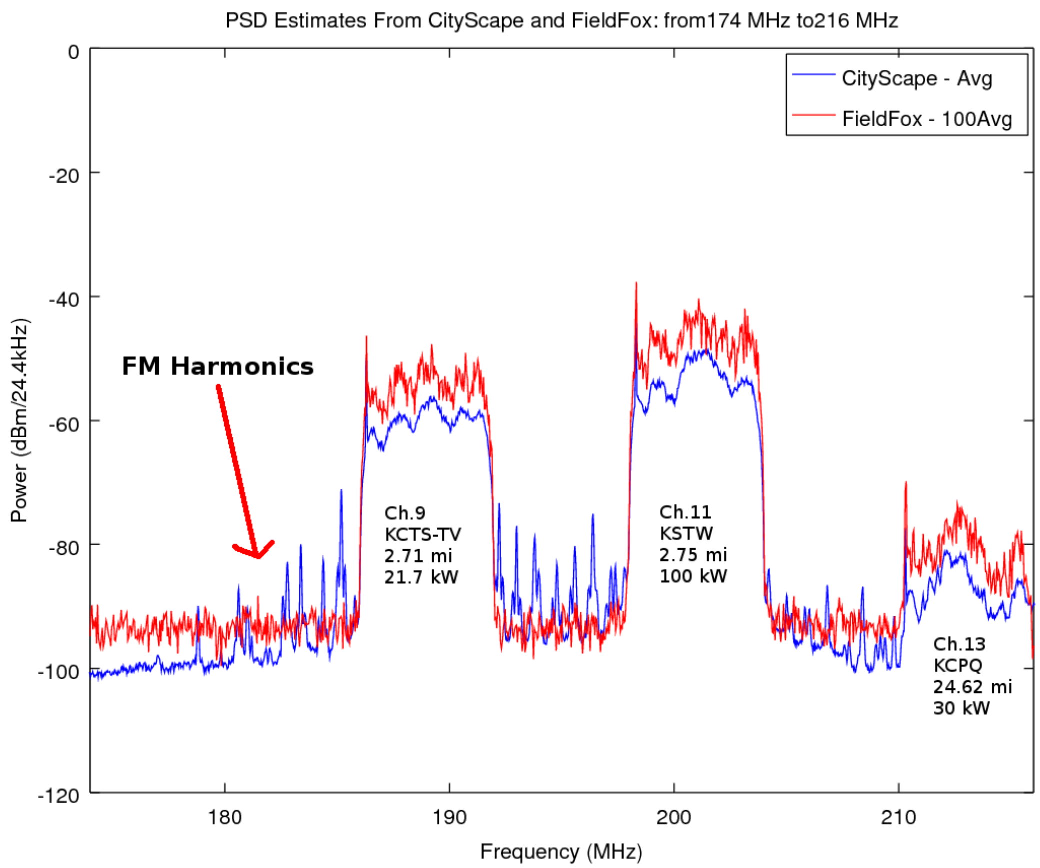
Elevation: 66 ft AGL
115 ft ASL

UPENN 02 (Grey's Ferry)



Elevation: 48 ft AGL
68 ft ASL

PSD Estimate Plot – Data Quality



CONCLUSIONS

- **Spectrum Co-existence is fundamental and (largely) unsolved !**
  → Plenty of new (system centric) problems
  - Solutions will need creative PHY/MAC enhancements !
  - Fairness among DIS-SIMILAR networks a vexing problem !!
- **Spectrum Monitoring Infrastructure**
  - a necessary complement to enabling Dynamic Spectrum Access (yet sorely lacking) !