The Future is Unlicensed
On Coexistence in the Unlicensed Spectrum

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Motivation

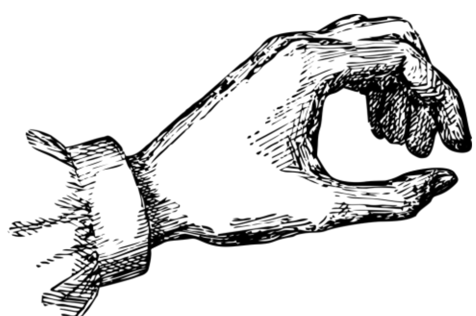
- **Rapid growth** in the use of smart phones / tablets and appearance of **new applications** like multimedia streaming & cloud storage.
- **WiFi** is the **dominant access technology** in residential/ enterprise environments and there is strong trend towards further **densification**,
  - Concerts,
  - Stadiums,
  - Airports,
  - Malls

- **5 GHz band** is spectrum of choice for next-gen WiFi as 2.4 GHz is already very crowded.

Trend in Mobile Networks

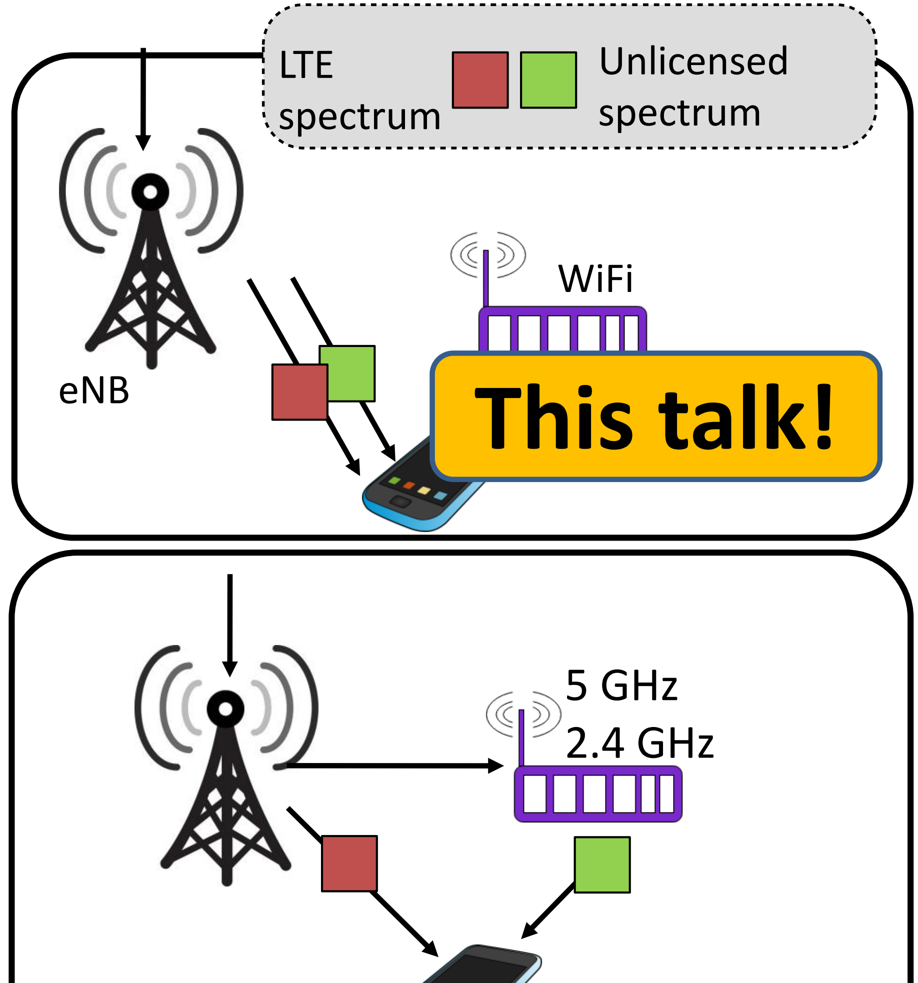
- **Mobile Internet connectivity** has gained a wide spread popularity with LTE,

- To support rapid traffic growth cost-effective solutions for capacity expansion are needed,
  - Massive network densification using (small) cells with higher capacity per cell,
  - **Direct usage of unlicensed (free) spectrum**



Options to Use Unlicensed Spectrum

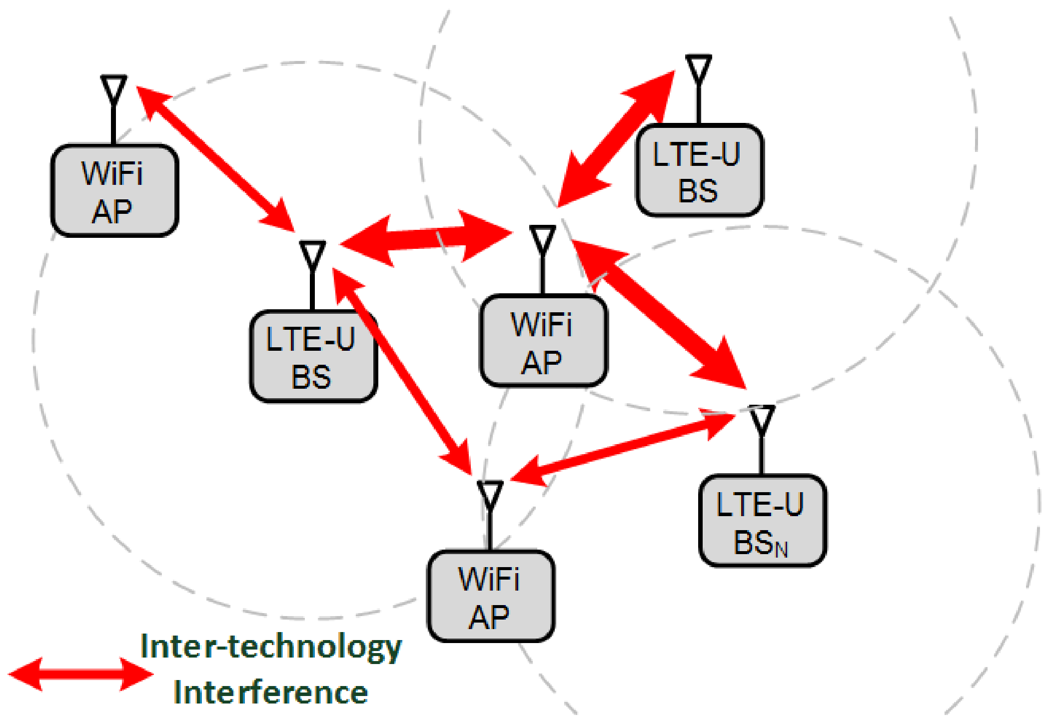
1. Direct usage of unlicensed spectrum
   - LTE-Unlicensed,
   - Licensed-Assisted Access LAA,
   - MulteFire
2. Usage of WiFi infrastructure
   - LTE/WiFi aggregation (LWA)
   - WiFi offloading



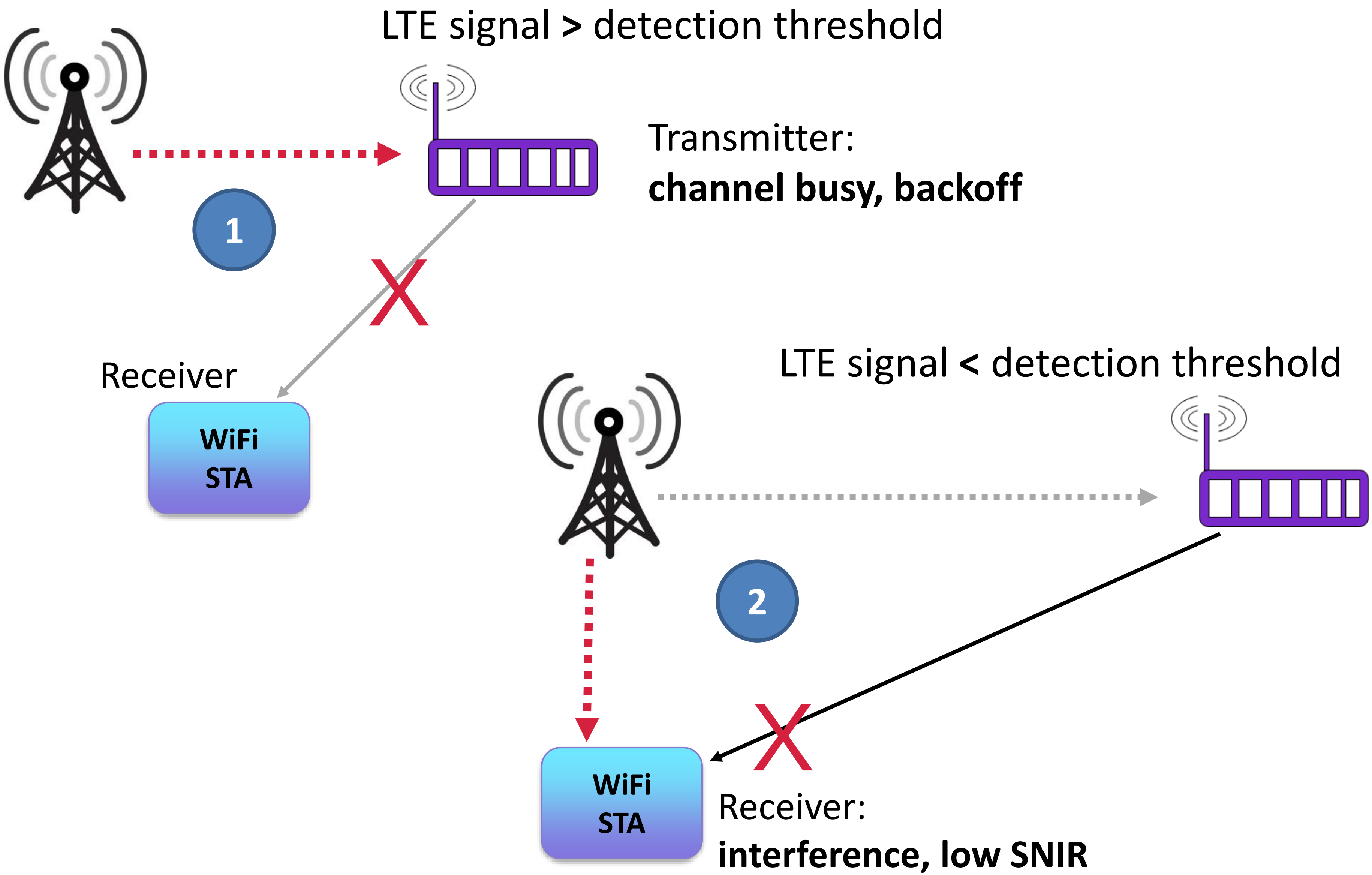
Enabling Flexibility of Traffic Split Function in LTE-WiFi Aggregation Networks through SDN, WSA 2018, S.Bayhan and A.Zubow

Uncoordinated Coexistence

- LTE and WiFi compete for **shared radio resources**
  - Leading to performance degradation in both NWs due to:
    i) increased **contention**,
    ii) mutual **interference**

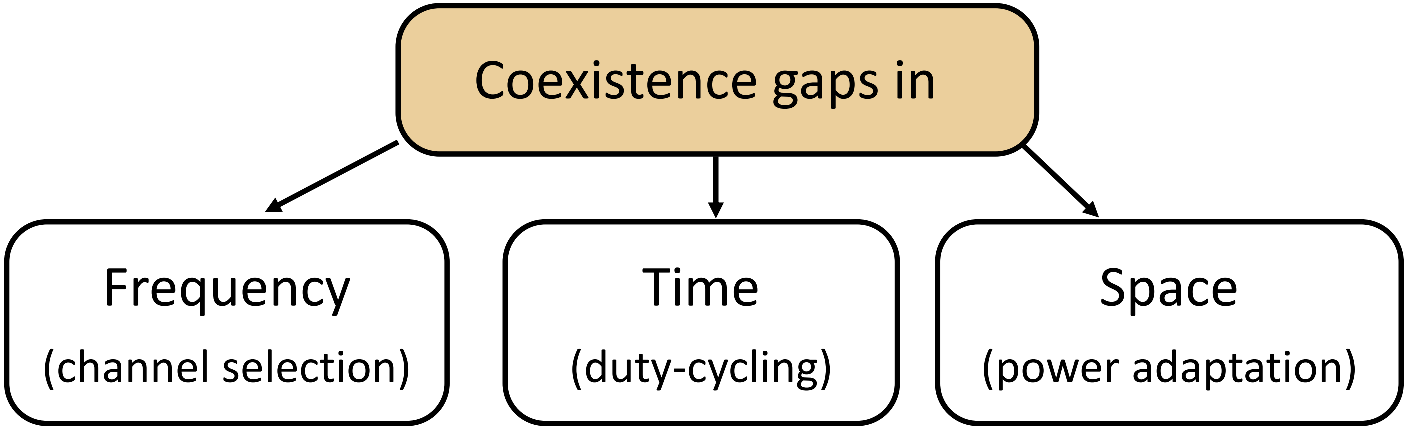


How does LTE interference affect WiFi?



Uncoordinated Coexistence

- Current solutions focus on simple but inefficient **uncoordinated coexistence**
  - LTE creates **coexistence gaps** in frequency/time/space domain,
  - E.g. LTE-U: channel access w/ adaptive duty cycling



Towards Coordinated Coexistence

- Our goal is to introduce **explicit cooperation** between LTE-U & WiFi NWs,

- Leads to more efficient operation as advanced coordination schemes can be applied:
  - Cross-technology interference & radio resource management,
  - "Better" usage of radio resources by considering QoS, fair sharing
- But such coordination requires a control channel between co-located nodes of heterogenious technologies (LTE-U & WiFi),

Cross-technology communication (CTC)

- Challenging as LTE/WiFi have incompatible PHY layer

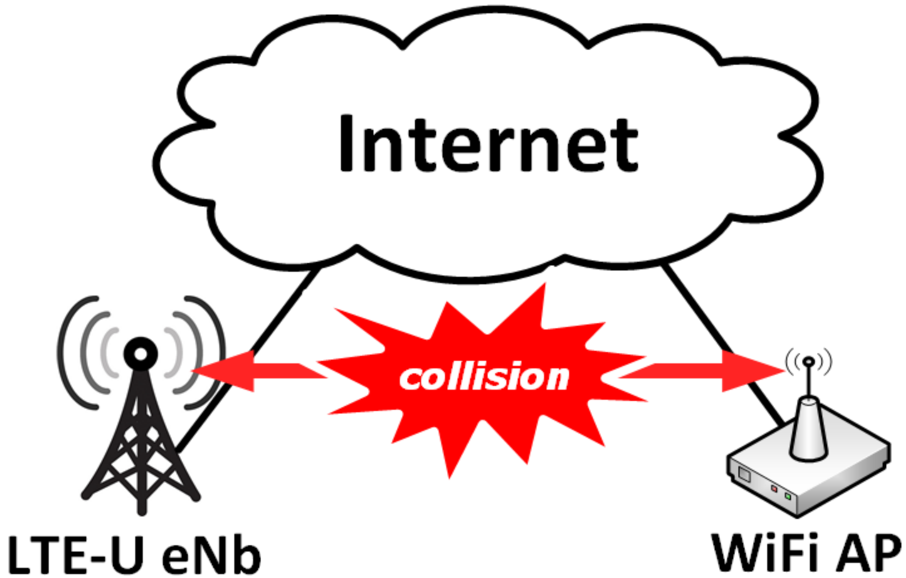
LtFi

– Enabling Cross-technology communication between LTE-U and WiFi –

P. Gawłowicz, A. Zubow, and A. Wolisz, "Enabling Cross-technology Communication between LTE Unlicensed and WiFi," in INFOCOM 2018, to appear.

How to start collaboration?

- Common control channel is required
- WiFi AP and LTE-U BS can connect over Internet



- .... but have no clue:
  - who is interfering with them?
  - how to reach co-located neighbors?

Over-the-air Neighbor Discovery

- A node advertises itself to others
- Homogenous technologies:
  - Automatic Neighbor Relation (ANR) in LTE
  - ResFi[1] in WiFi (by TUB)
- How to perform neighbor discovery between nodes of heterogenous technologies?

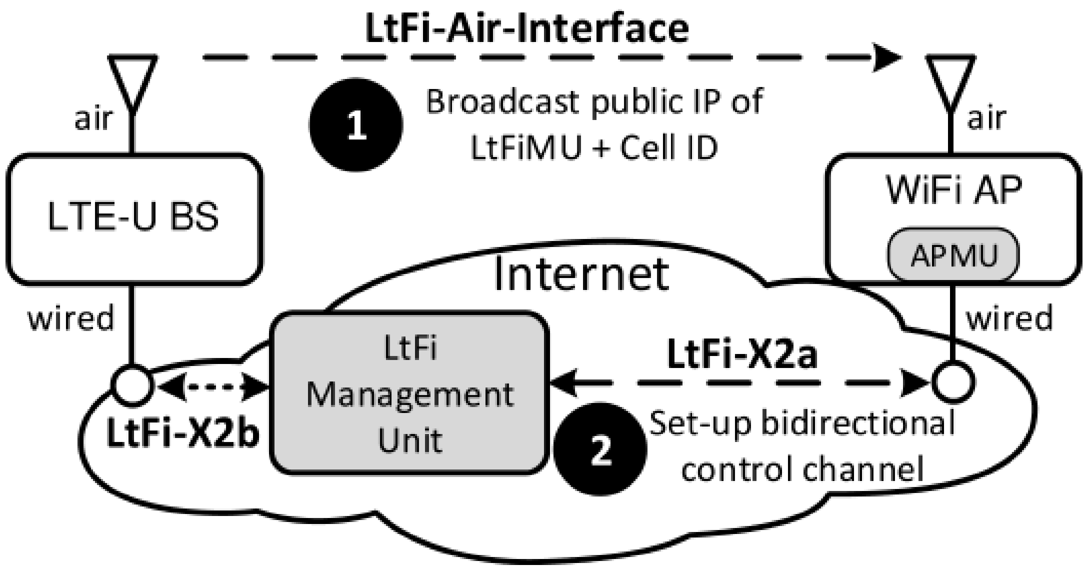
[1] S.Zehl *et al.*, „Resfi: A secure framework for self organized radio resource management in residential WiFi networks", WoWMoM 2016

Cross-technology Communication

- CTC enables heterogeneous devices to talk directly
  - Simple side-channel on top of normal transmission (e.g. duration of gaps)
  - Low data rates (up 100s bps) – enough for control data

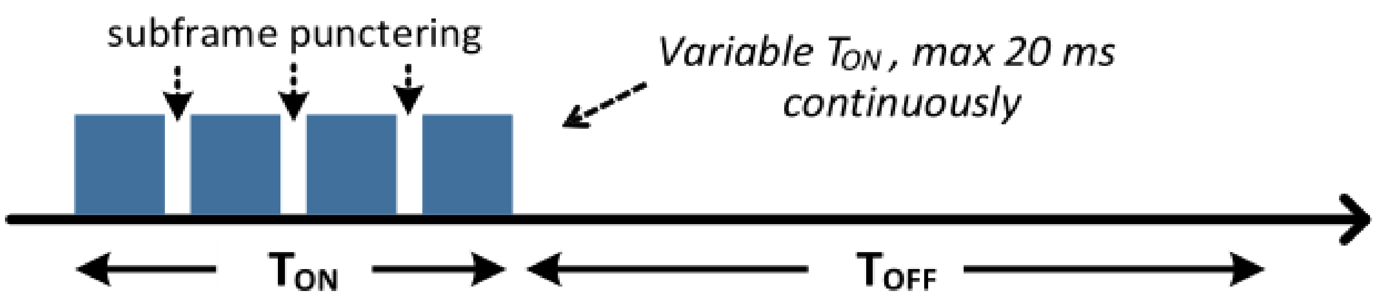
LtFi – Architecture Overview

- **LtFi: Lt**e->Wi**Fi**
- LtFi consists of two interfaces:
  - Air-Interface – over-the-air **CTC broadcast** channel
  - X2-Interface – over-the-wire **bidirectional** channel
- LtFi Management Unit (MU) manages a LTE network
- Access Point Management Unit (APMU) manages a WiFi AP



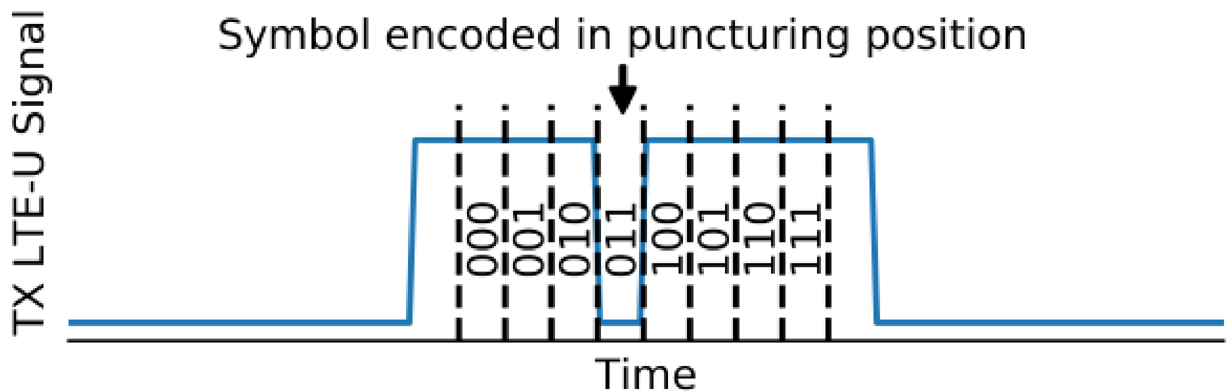
LTE-U Primer

- The first cellular solution for use of 5GHz band
  - only downlink (DL)
  - secondary carrier in addition to the licensed anchor
  - channel bandwidth is 20MHz
- Two versions of LTE-Unlicensed: LTE-LAA(LBT) and **LTE-U**(CSAT)
- Carrier Sense Adaptive Transmission (CSAT):
  - period 40, 80, 160ms
  - duty cycle adaptation based on number of WiFi and LTE nodes, max 50%
  - puncturing for low-latency WiFi traffic



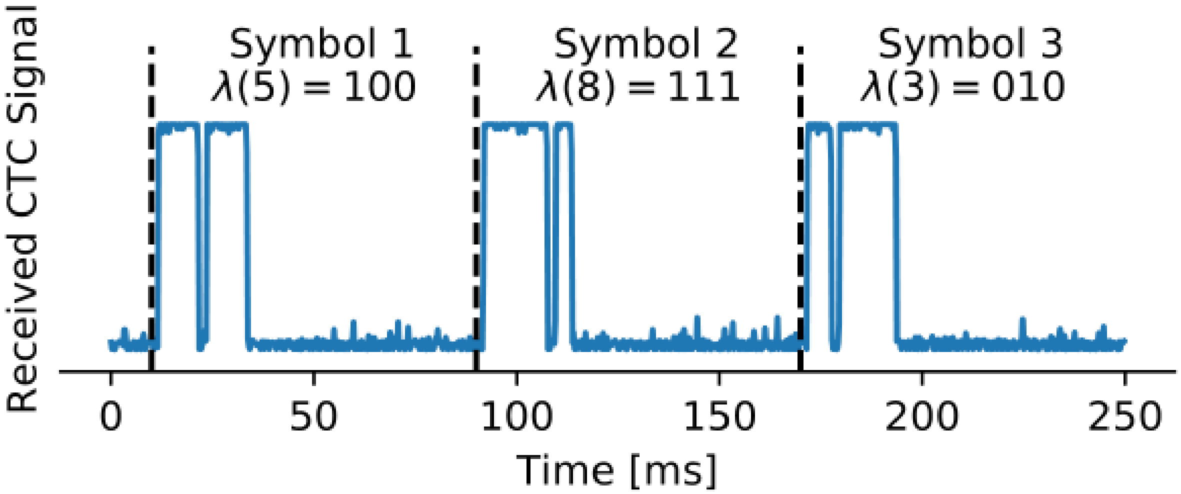
LtFi-Air-Interface: PHY Layer

- LtFi exploits the freedom to put puncture within LTE-U's on-time
- The position of the puncture encodes the data bits
  - standard compliant
  - introduced delay is negligible (1-2ms)
- A 20ms LTE-U transmission chunk is used to encode single LtFi symbol



LtFi Frame Structure

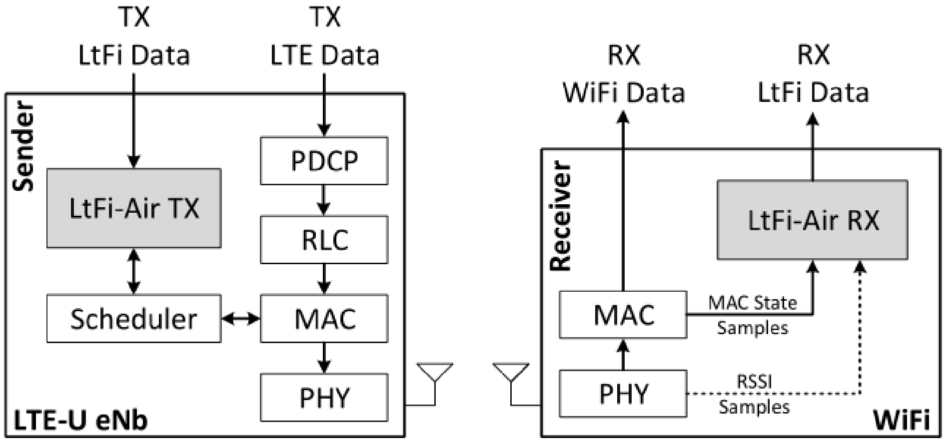
- LtFi frame consists of multiple LtFi symbols



- Frame Structure:
  - Preamble – 4 LtFi symbols - the start of the frame
  - Data Payload – IP address (4B) and Cell ID (2B)
  - CRC Field – error detection using CRC16

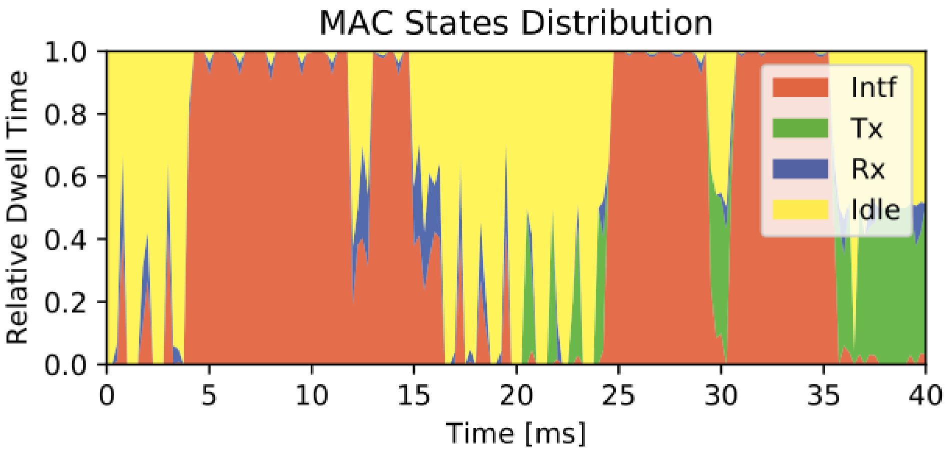
LtFi-Air-Interface: Integration

- LtFi is only a software add-on
  - No hardware changes!



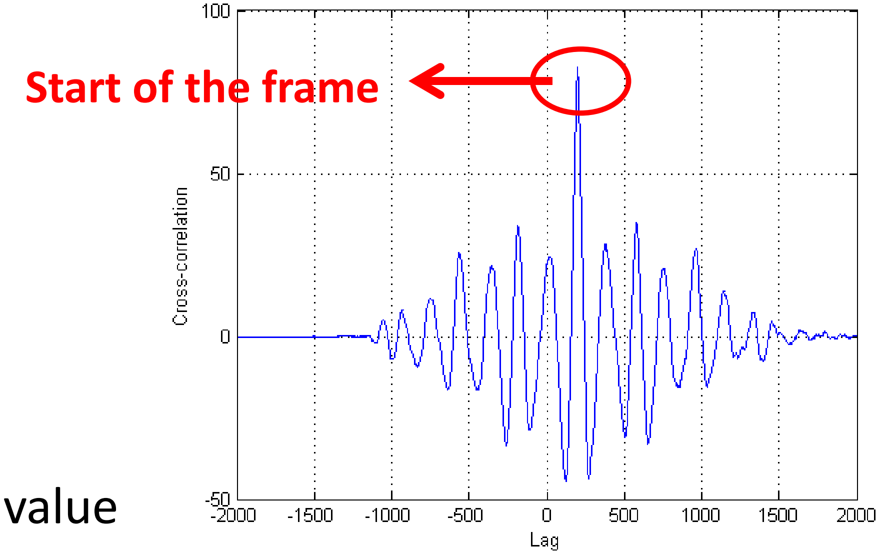
- At LTE-U side, LtFi TX interacts with LTE scheduler

- At WiFi side, LtFi RX samples MAC state distribution:
  - the time spent in the energy detection (ED) state without triggering packet reception (RX) i.e. interference (Intf)



LtFi-Air-Interface: Demodulation

- Frame detection and synchronization
  - cross-correlation based preamble detector



- Symbol demodulation:
  - take samples of one symbol
  - compute CC to each valid symbol
  - take the one with the highest CC value
  - decode bits

- Repetition coding : LtFi frames are transmitted in loop

Theoretical Throughtput Analysis

- The number of available symbols **M**:

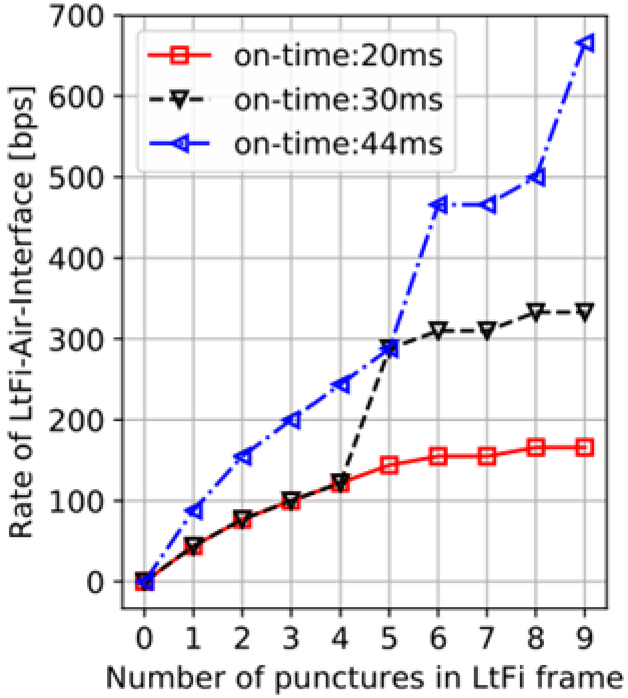
$$M = \binom{n}{k} = \frac{n!}{k!(n-k)},\quad 0 \le k \le n$$

where ***n*** - number of possible puncture positions, ***k*** - number of used punctures

- Transmission rate:

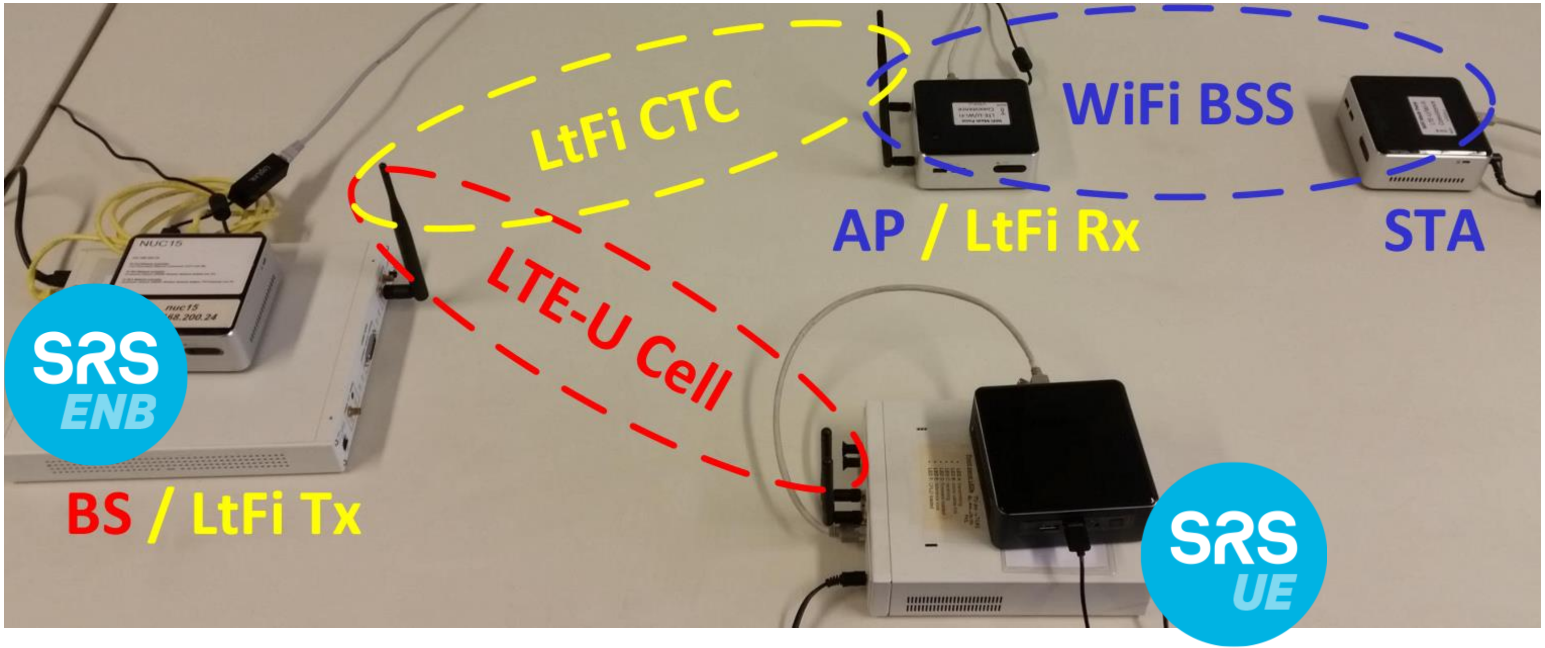
$$R[bps] = \frac{\lfloor log_2(M) \rfloor \cdot z}{T_{cycle}}$$

where ***Tcycle*** is LTE-U cycle and ***z*** is number of LtFi symbols of 20ms in one cycle

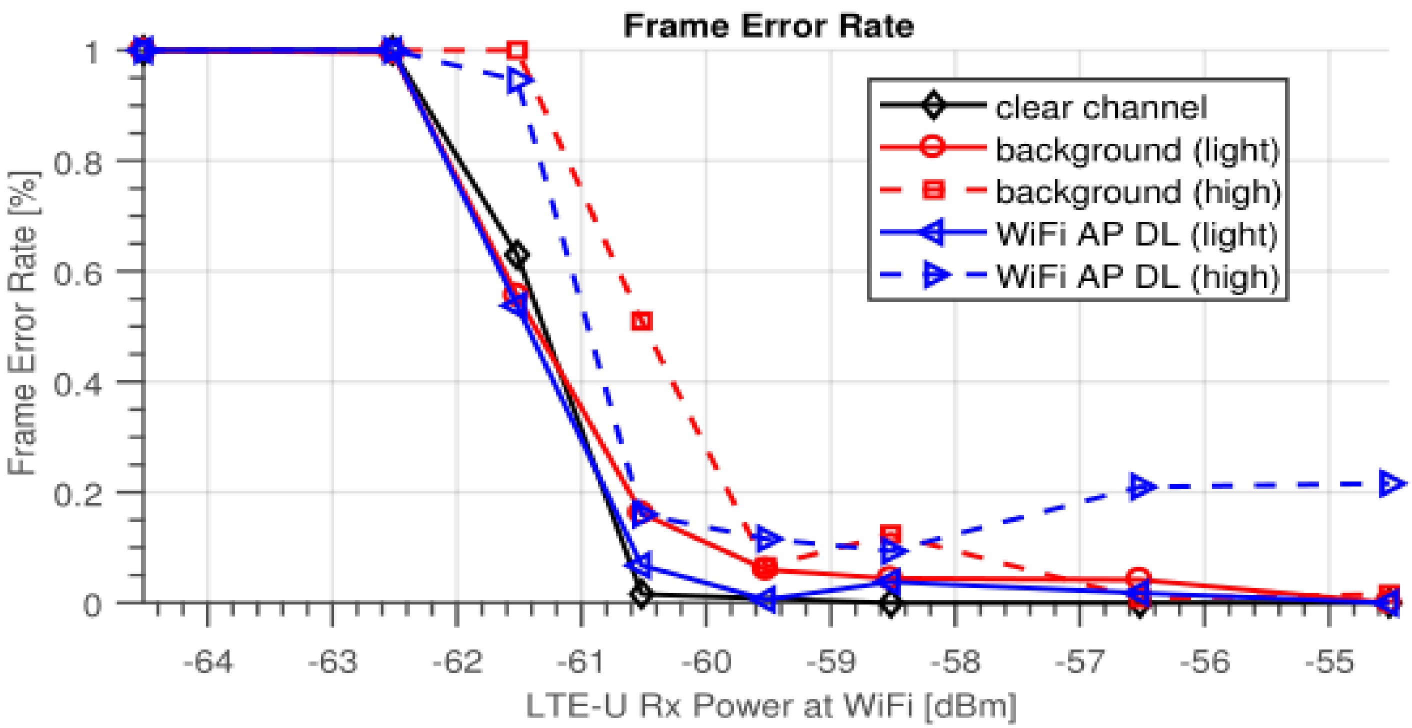


Prototype Implementation

- **Hardware:**
  - **TX:** Ettus USRP X310
  - **RX**: COTS WiFi NIC (Atheros AR928x)
- **Software**:
  - **TX**: srsLTE modified to support duty-cycled operation
  - **RX:** ath9k driver with RegMon tool, LtFi RX implemented in Python

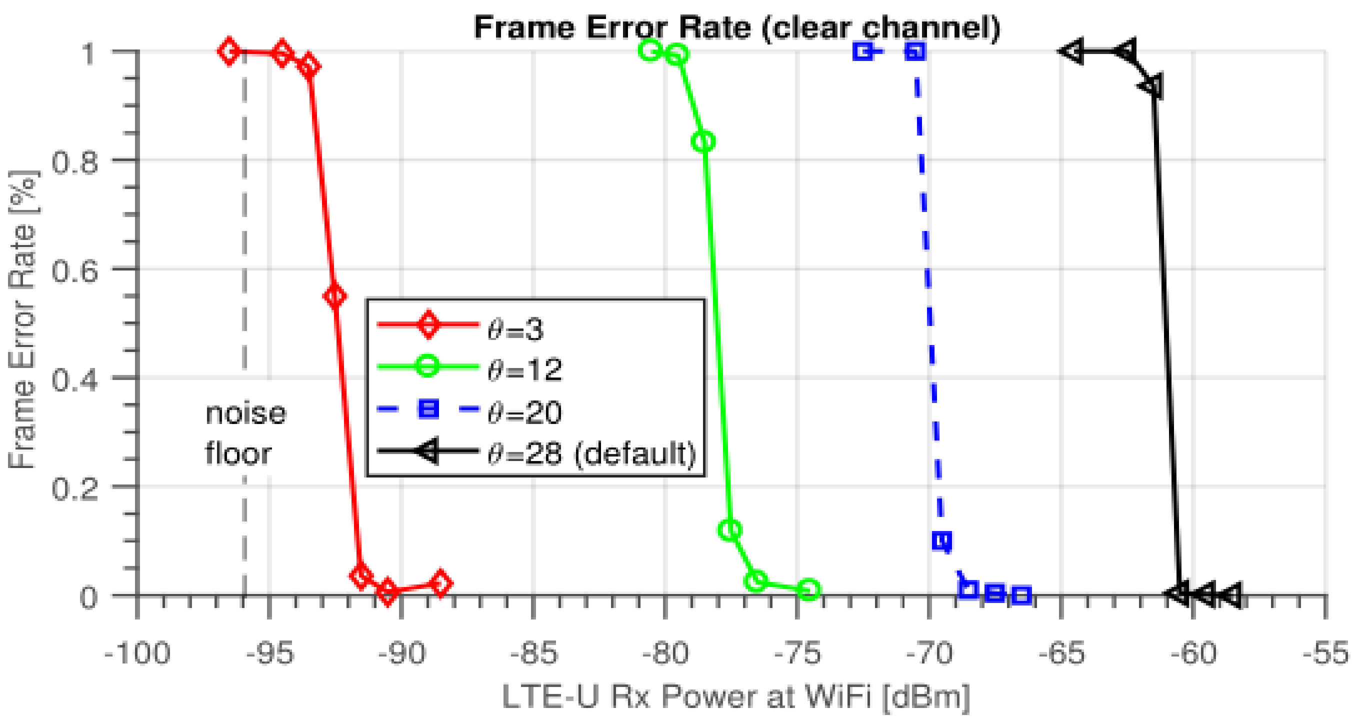


Frame Error Rate



- Works even with ongoing WiFi traffic
- Half-duplex constraint in case of high DL traffic (node is deaf)
- Performs good until 2-3dB over ED Threshold (-62dBm), but...

ED Threshold adaptation



- ED threshold can be adapted down to -92dBm

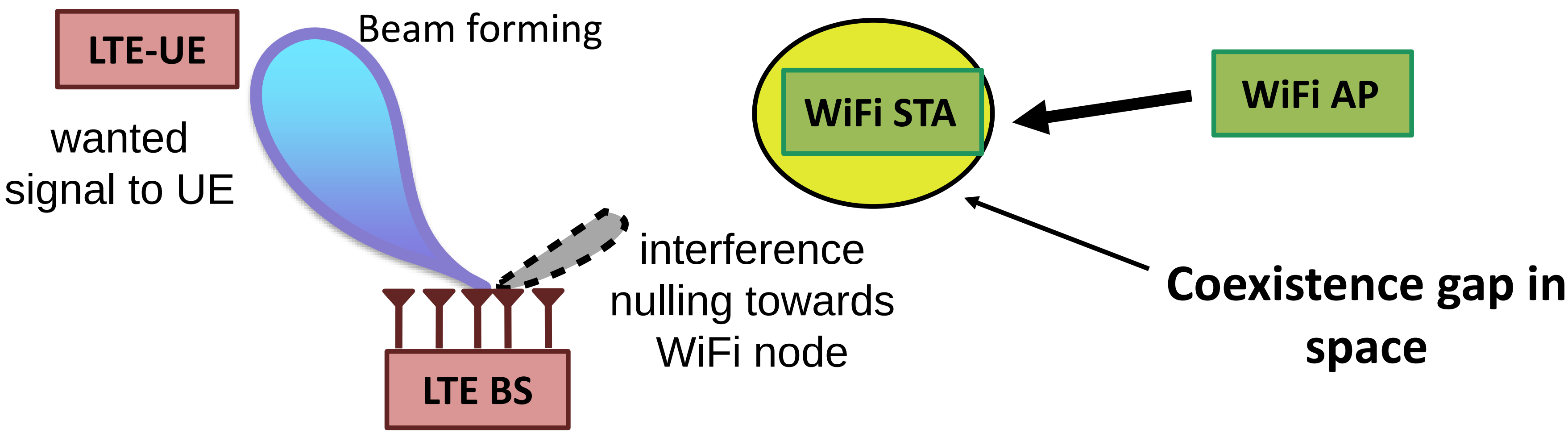
Advanced Cross-technology Coordination Schemes
- *Interference Nulling* -

[1] S. Bayhan, A. Zubow, and A. Wolisz, "Coexistence Gaps in Space via Interference Nulling for LTE-U/WiFi Coexistence" in IEEE WoWMoM 2018, to appear.

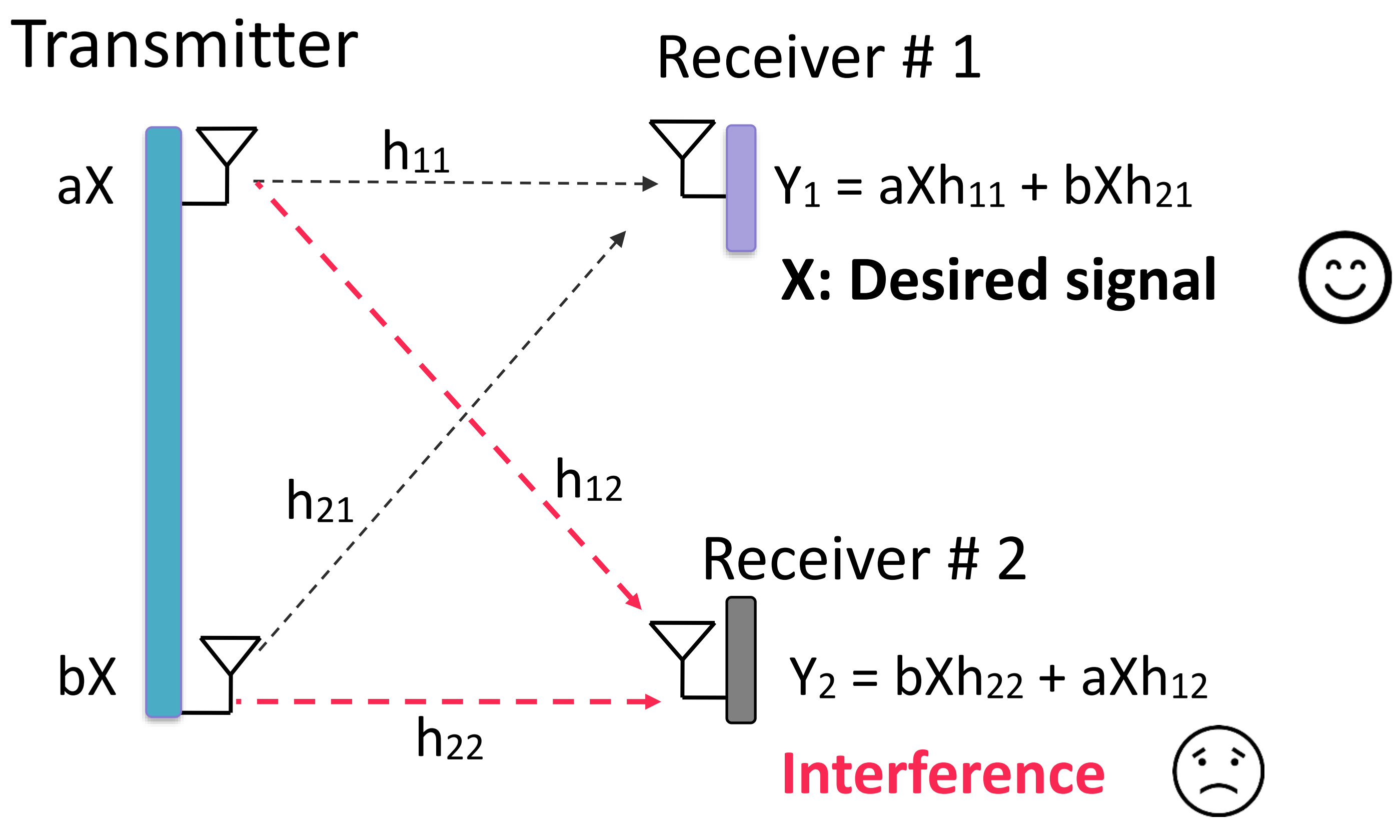
[2] A. Zubow, P. Gawłowicz and S. Bayhan, "On Practical Coexistence Gaps in Space for LTE-U/WiFi Coexistence" in European Wireless 2018, to appear.

Interference-nulling for Coexistence

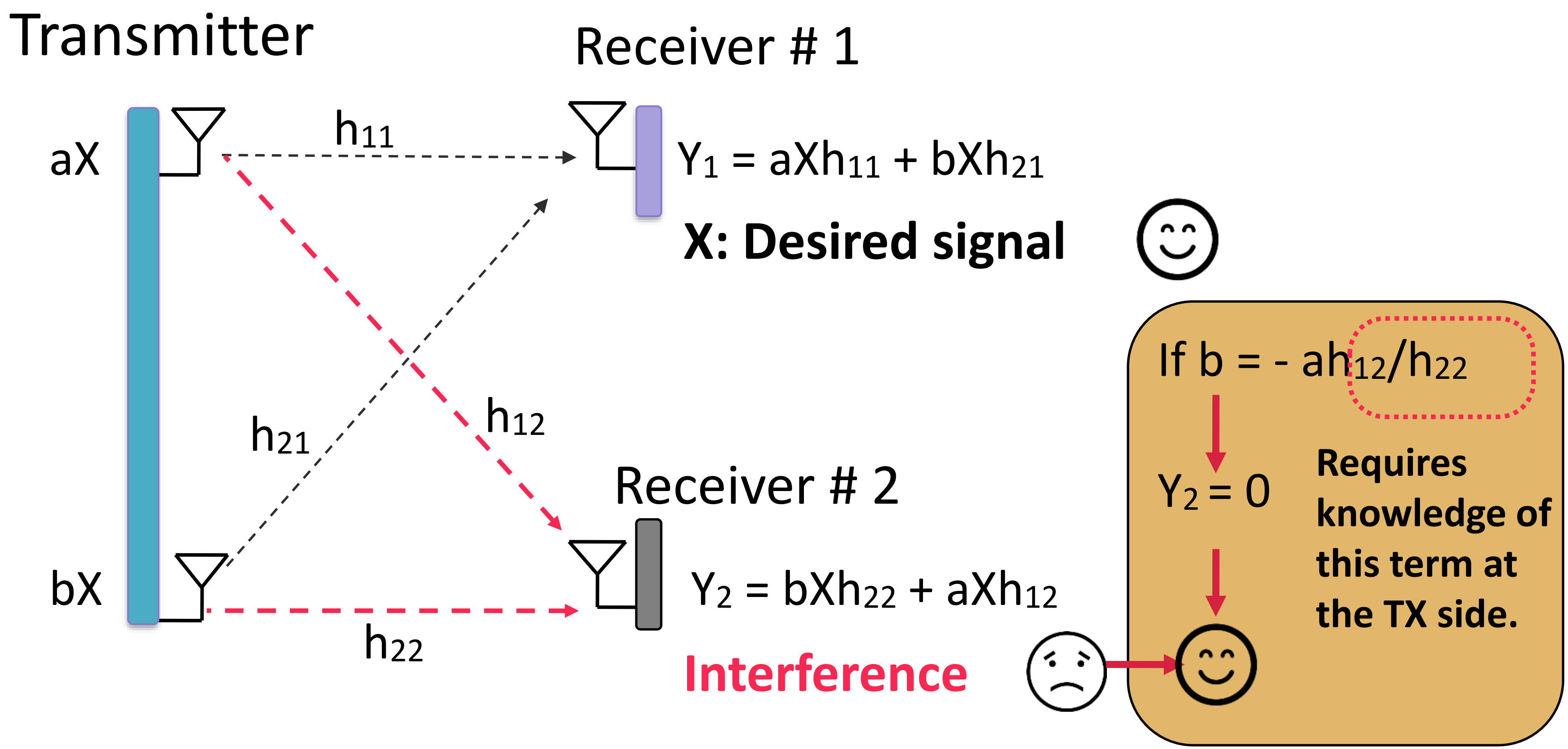
Our idea: exploit the MIMO capabilities of LTE-U BS for **cross-technology interference nulling (CTIN)** towards WiFi nodes



Primer on Interference Nulling

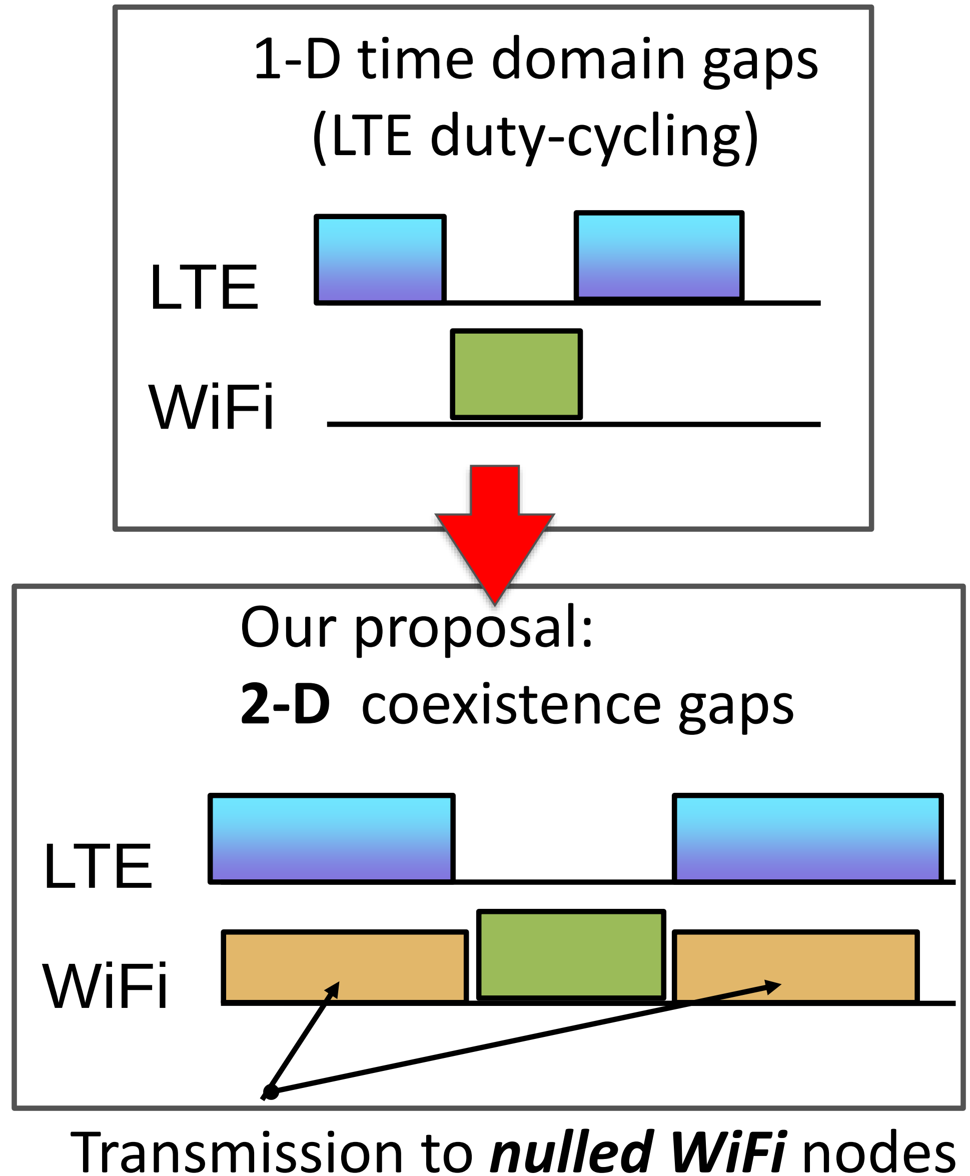


Primer on Interference Nulling



Coexistence Gaps in Space

- Favorable as competition for shared time/freq resources is reduced,
- Promises a **win-win** solution for both LTE & WiFi
  - Increased throughput,
  - Lower medium access delay
- Trend towards massive MIMO even for small cells



Why is Nulling beneficial for LTE-U?

- LTE-U must leave the medium for WiFi proportional to the number of WiFi nodes observed in its neighborhood.
- With nulling LTE-U can increase its airtime usage:

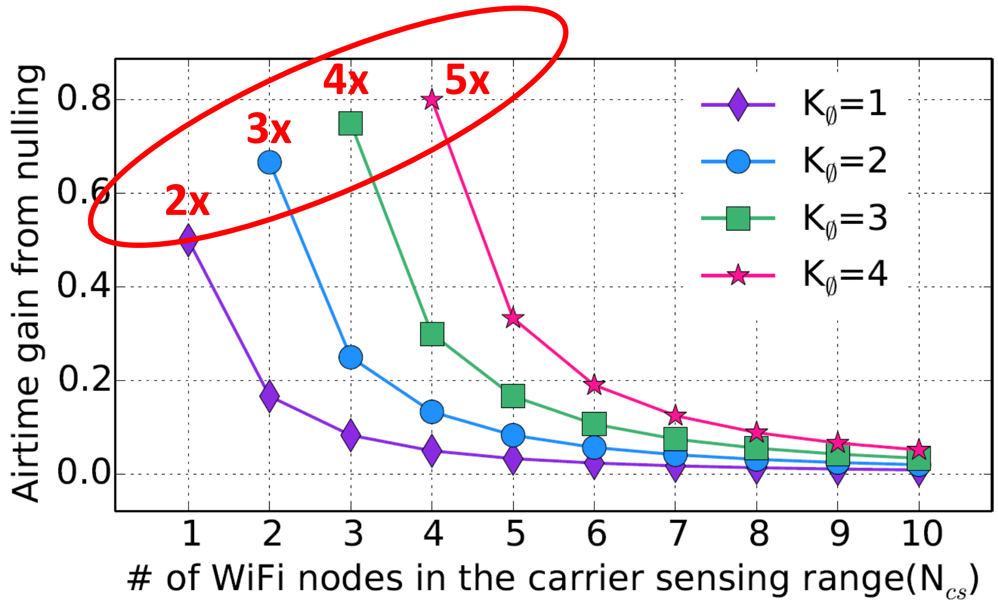
1/ No nulling:

$\alpha_{no} = 1 / (N_{cs}+1)$

2/ Nulling $K_{\emptyset}$ Wifi nodes:

$\alpha(K_{\emptyset}) = 1 / (N_{cs} - K_{\emptyset} + 1)$

where N_{cs} is number of detected WiFi nodes

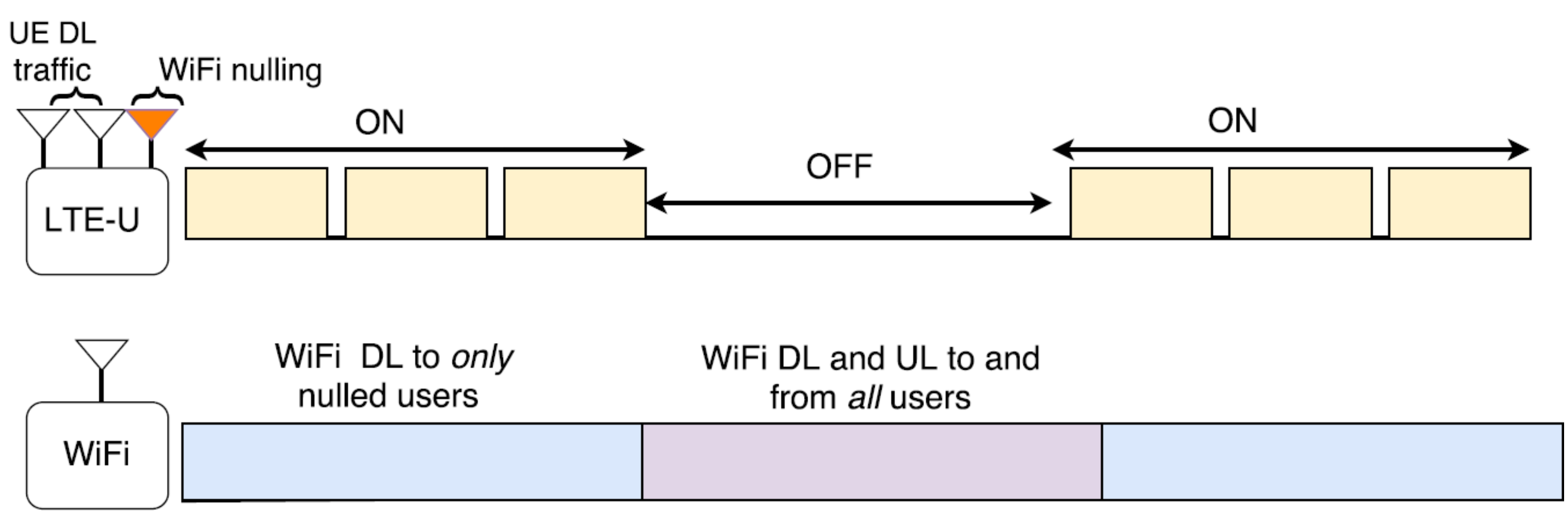


- … with some reduction in SNR on BS-UE link -> tradeoff,
- Interesting case when $K < N_{cs}$, where only a subset of WiFi nodes can be selected for nulling -> optimization problem [1]

[1] Bayhan, Zubow, Wolisz, "Coexistence Gaps in Space via Interference Nulling for LTE-U/WiFi Coexistence", WoWMoM 2018.

WiFi Channel Access under Nulling

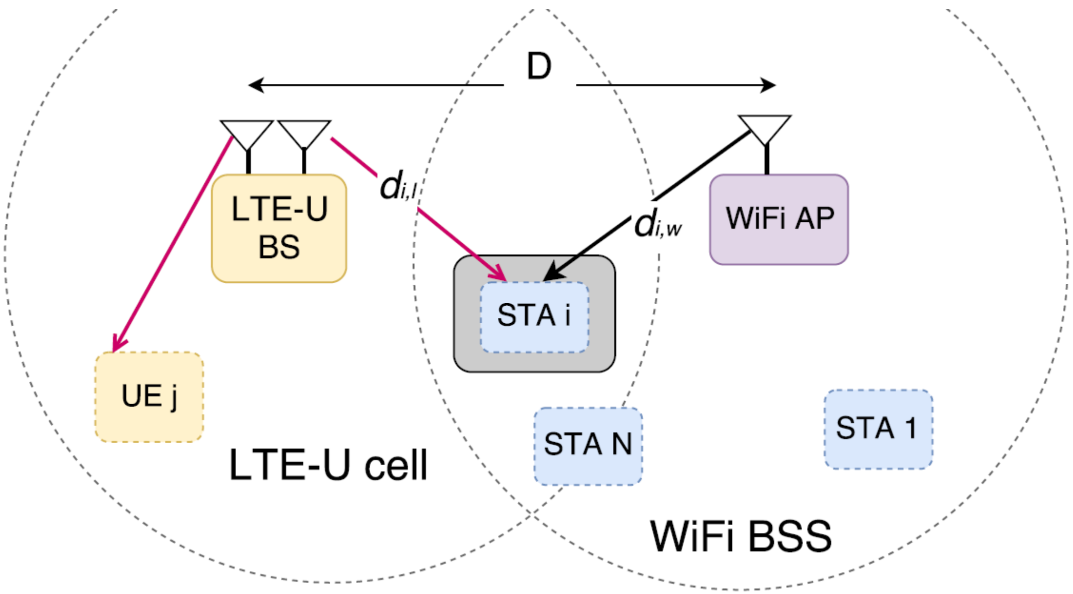
- During the LTE-U ON-period transmissions from “nulled” WiFi nodes are possible in both UL + DL,
- But impossible for LTE-U BS to predict which WiFi node will transmit → random channel access of WiFi,
- Hence BS’s nulling configuration should only depend on the location of WiFi nodes and NOT on their unpredictable traffic,
- **Our approach** is to focus on just WiFi DL traffic

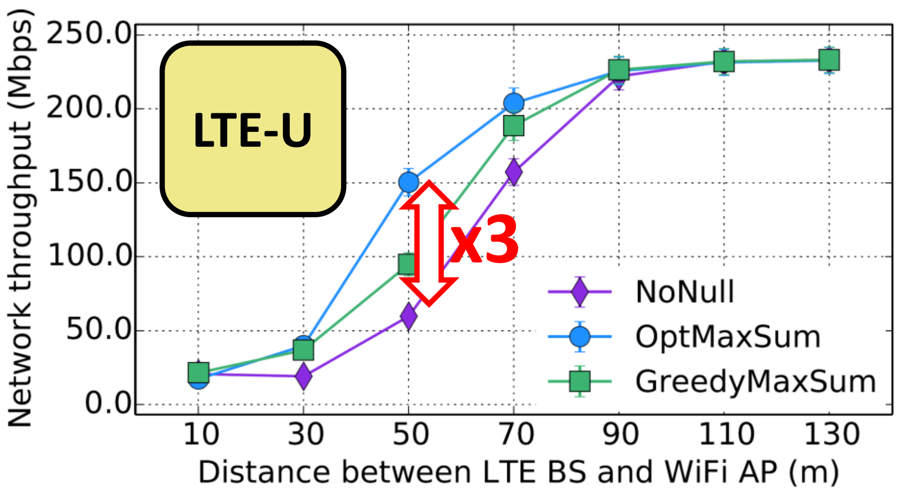


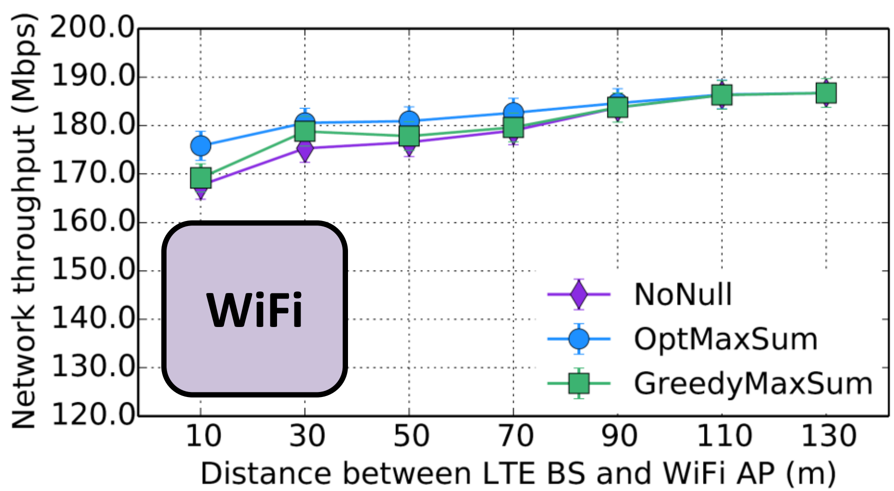
Selected Results from Simulations

- From system-level simulations,
- ULA w/ K=6 antennas, N=8 no. of WiFi STAs,
- Distance between BS and AP was varied,
- Network throughput

Coexistence setting:





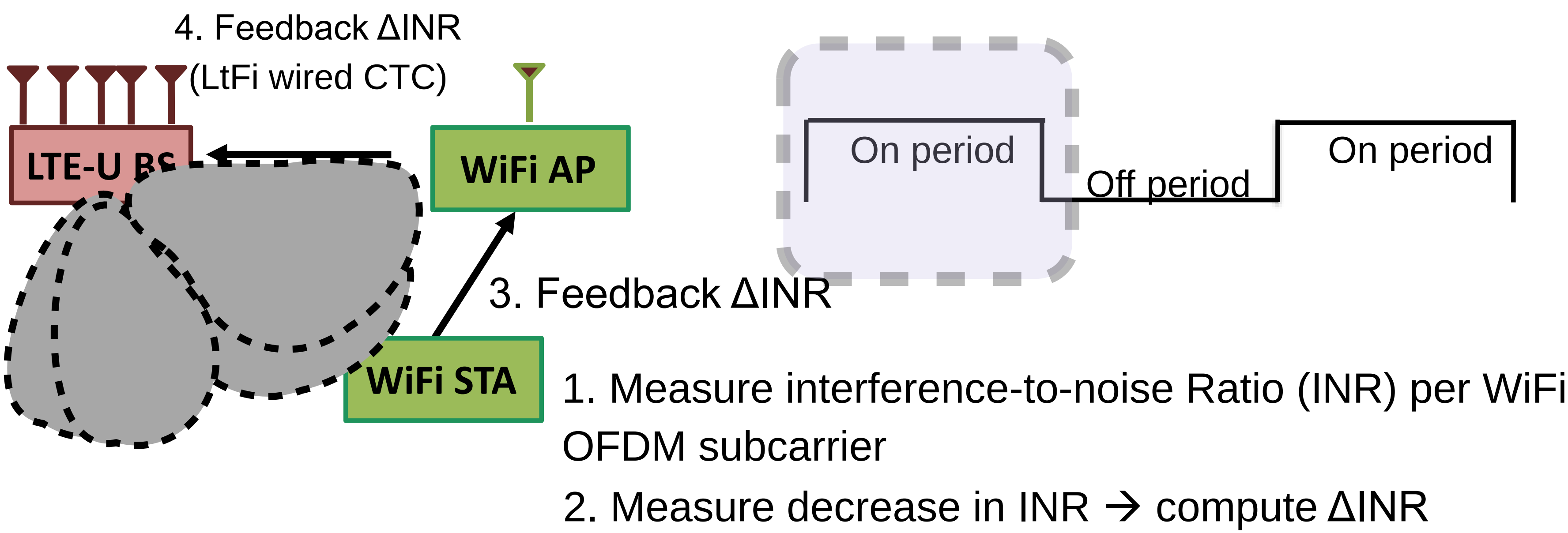


Is Cross-technology Interference-Nulling practically feasible?

- Such coordinated co-existence scheme requires:
  - **1.** CTC channel for the exchange of control messages
    - LtFi-CTC
  - **2.** Interference nulling requires channel state information (CSI) at transmitter side, i.e. LTE-U BS
    - Cannot be obtained over LtFi-CTC

XZero: Our Approach to Practical CTIN

Our idea: Do not estimate channel state information (CSI) but perform null search steered by the feedback from the WiFi nodes to be nulled

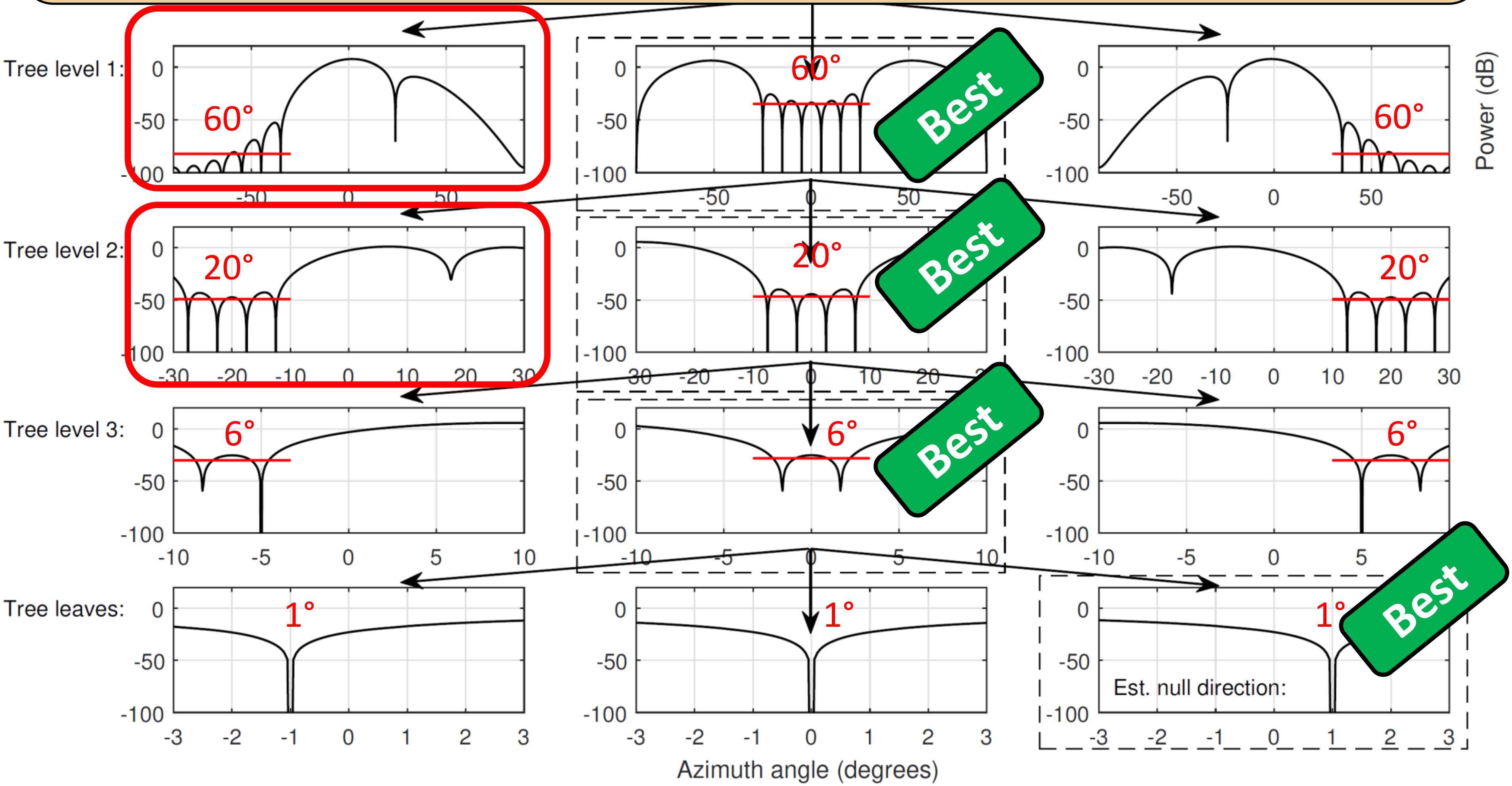


5. Continue with testing next nulling configuration

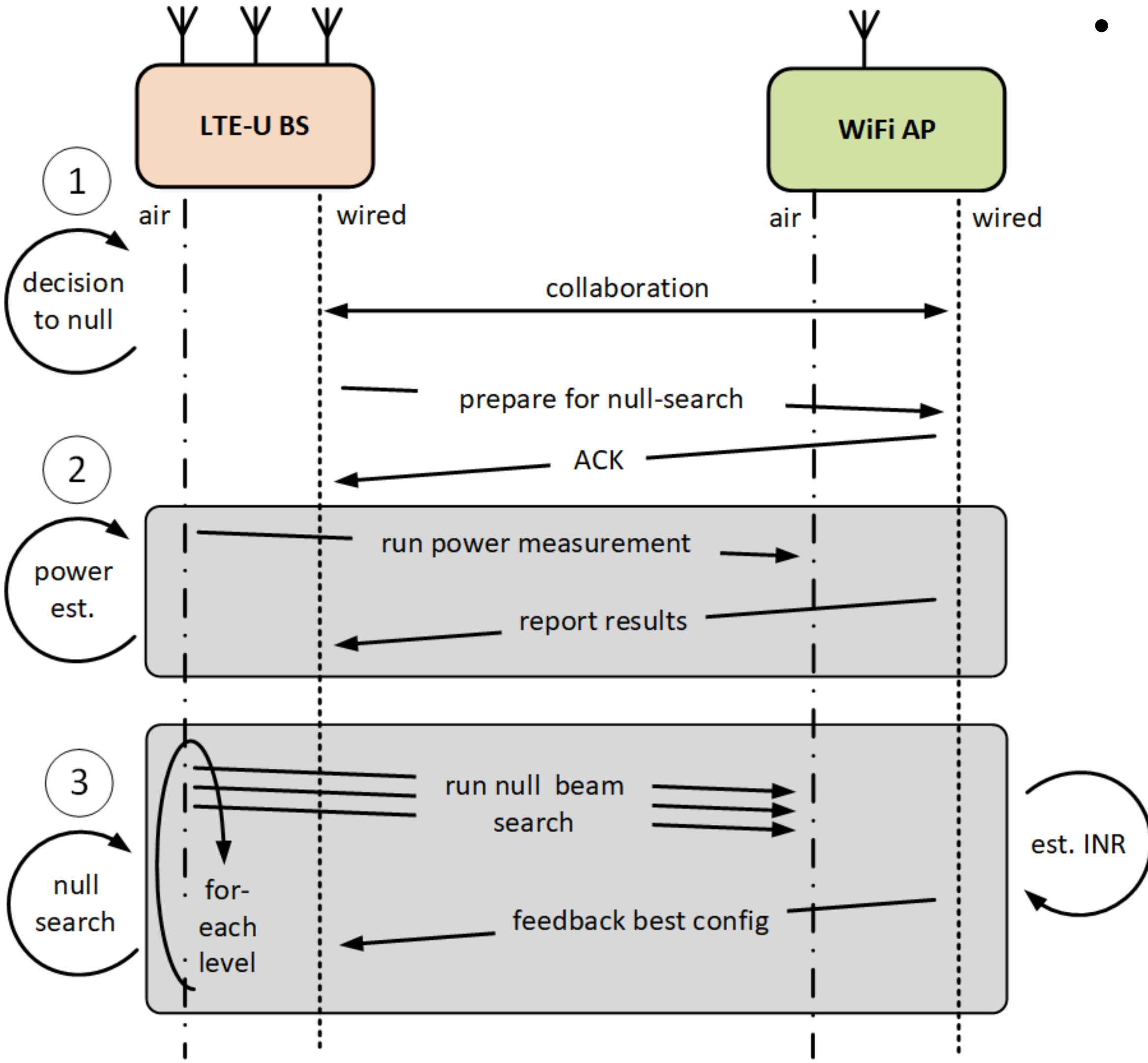
Tree-based Null Search

Problem: Linear (exhaustive) search is very slow

Our idea: Tree-based search testing null regions



Main Steps in XZero



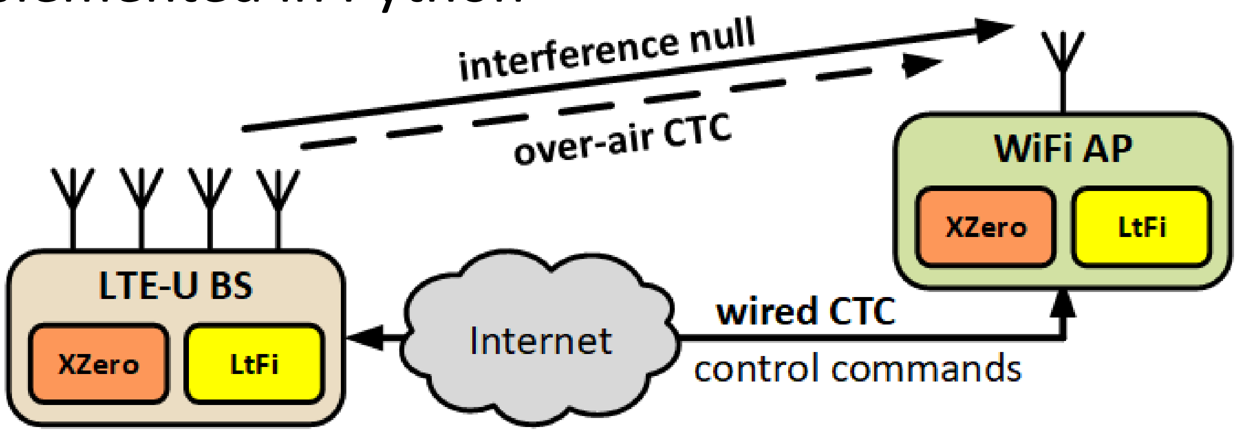
- **Challenges:**
  - Power correction for precoding vector needed to tackle multi path propagation,
  - Backhaul latency for feedback from WiFi to LTE,
  - Precoding weight: for each LTE OFDMA RRB,
  - WiFi-side measurement: OFDM subcarrier,
  - A mapping needed between WiFi side and LTE side

XZero Prototype

- Is custom hardware needed?
  - No, prototype based on SDR-USRP (LTE) and COTS (WiFi)
- Is special software needed?
  - No, usage of open-source software-based LTE stack (srsLTE) & WiFi driver (ATH9k),
  - Most functionality of LtFi & XZero implemented in Python

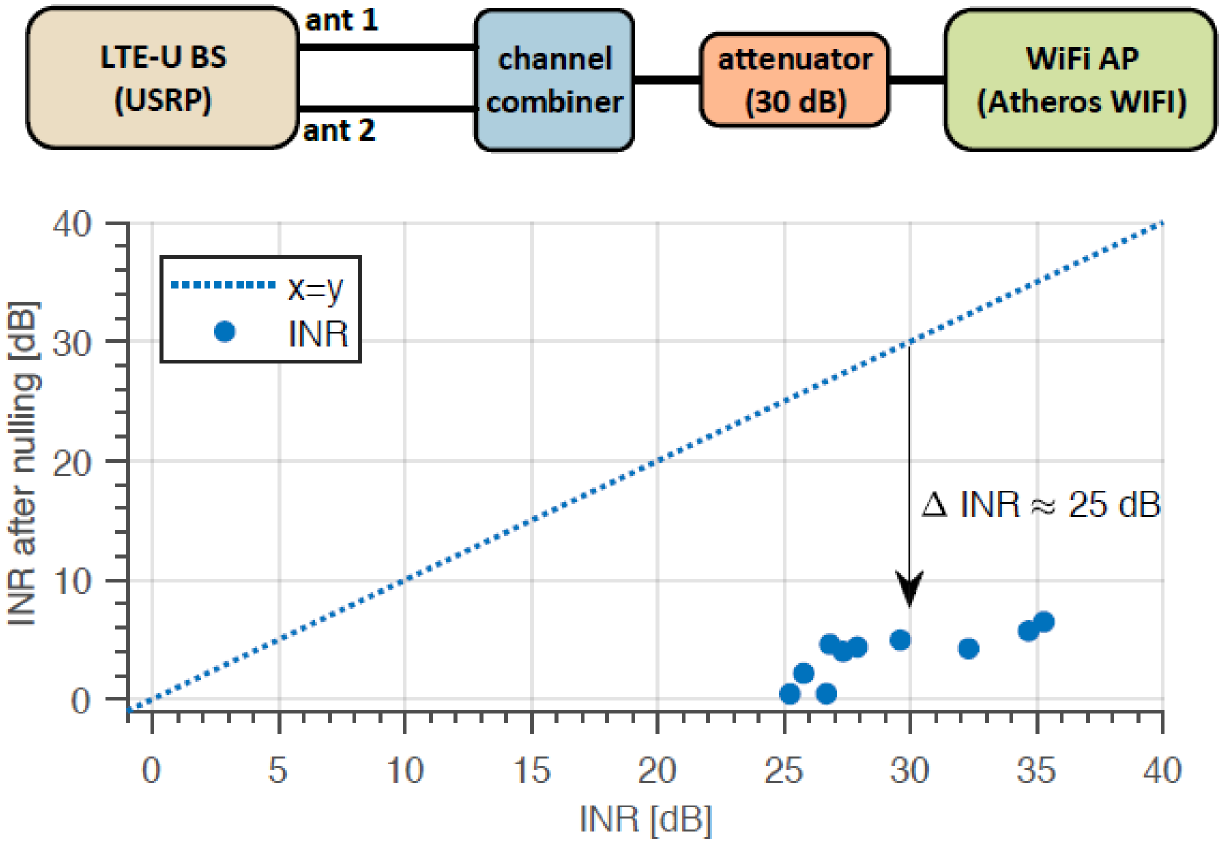
LTE-U BS+UE

WiFi nodes (Atheros AR95xx)



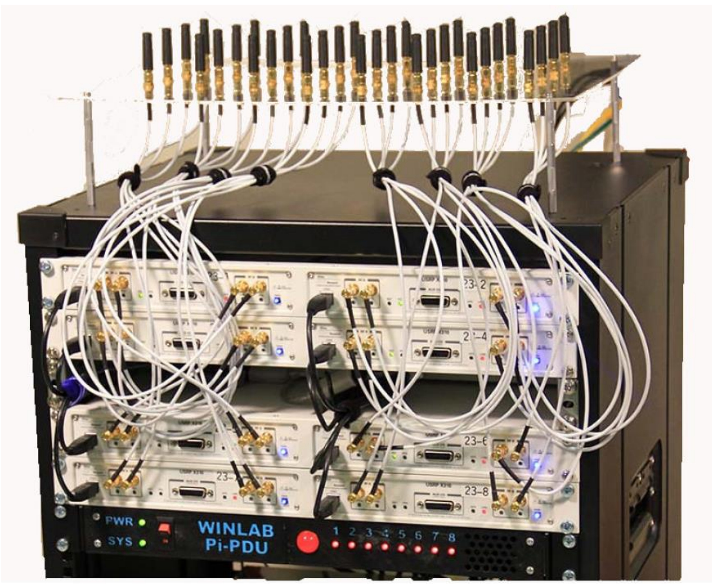
Small-scale Evaluation at TKN

- Interference-to-noise ratio (INR) reduction under optimal conditions - frequency-flat wired channel



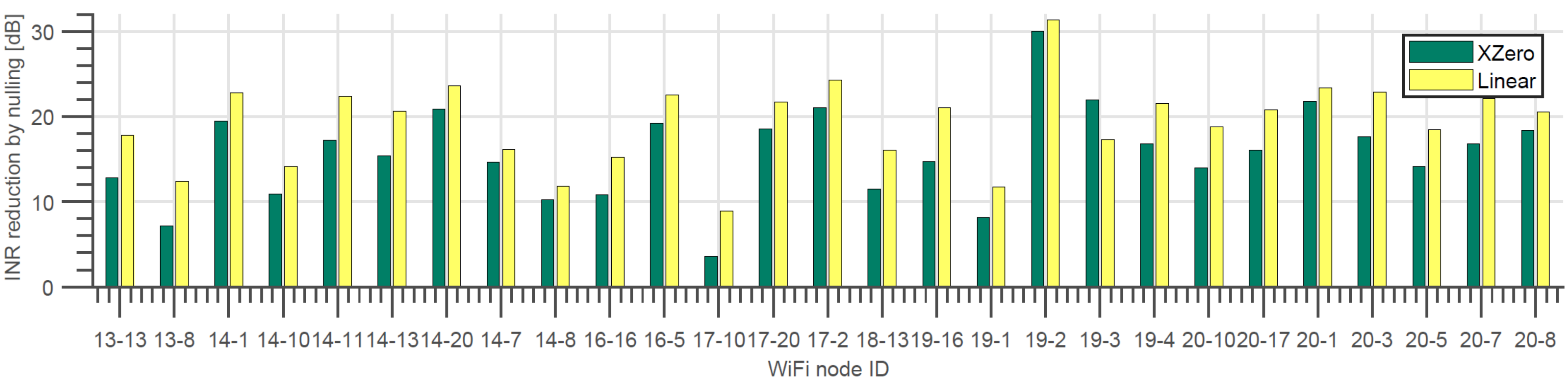
Large-scale Evaluation in ORBIT Grid

- Real wireless (frequency-selective) channel, 2.4 GHz



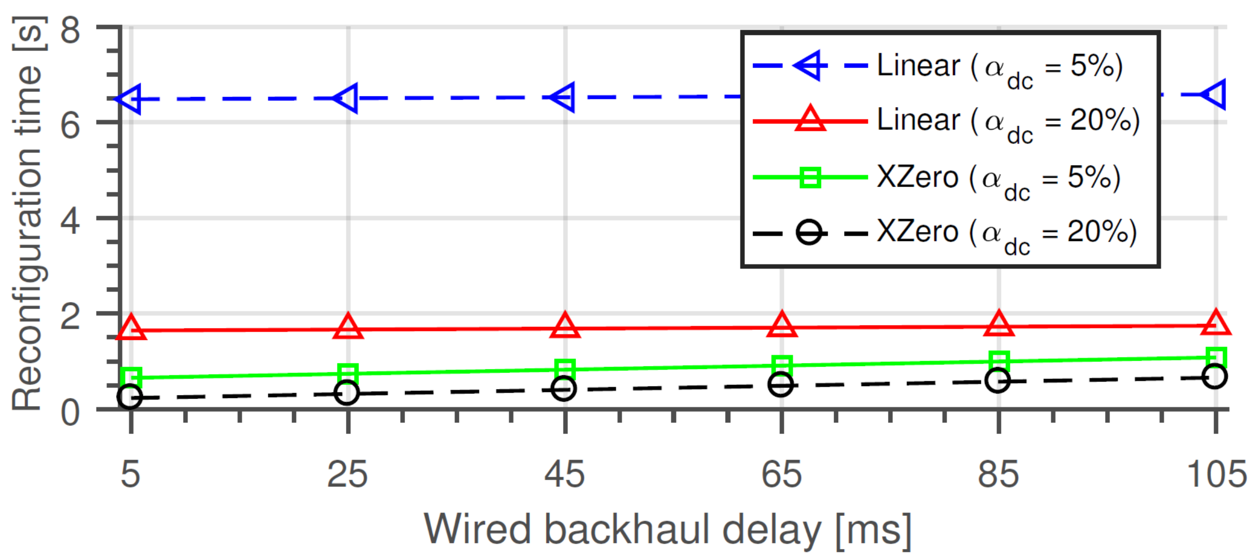
ULA w/ K=4 antennas selected

- 27 randomly selected WiFi nodes
- Main results:
  - 15.7 dB decrease in INR at nulled WiFi nodes
  - Linear-search slightly better: higher INR
  - Tree-search: 10× faster than linear search



Reconfiguration Delay

- Null search has to be performed upon change in network topology,
- Parameters affecting configuration delay:
  - Selected angular resolution, length of LTE-U on-period, WiFi sampling frequency, LTE-WiFi backhaul latency, tree-search fan-out
- For single WiFi node: < 1 sec & speed-up of 10x compared to linear search



Take-aways

- Need for **efficient coexistence** schemes for operation in unlicensed 5 GHz spectrum,
- We propose **explicit cooperation** between co-located LTE-U and WiFi networks,
- We suggest to create coexistence gaps in space by means of **cross-technology interference nulling (CTIN)**,
- XZero is practical CTIN on SDR/COTS hardware
- LtFi enables **cross-technology communication (CTC)** which is needed for coordinated coexistence