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King Abdullah University of
Science and Technology

Indoor and Outdoor Broadband Internet Connectivity on KAUST Campus using 3.5GHz & 6GHz Bands

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KAUST Vision for 6GHz Coverage

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- Establish a comprehensive next-generation wireless network that extends across the entire 36 km² campus using 6 GHz Connectivity.

- Leverage 6 GHz spectrum for seamless, secure, and high-performance connectivity—indoors, outdoors, and in remote areas—providing the foundation for advanced research, innovation, and community life.
    - Indoor coverage via Cisco next-generation Wi-Fi 6E APs
    - Outdoor and remote coverage via Cisco rugged Wi-Fi 6E APs
    - Tarana Wireless backhaul over the 6 GHz band

Indoor Coverage

- The 6GHz band is highly effective for indoor environments, particularly for high-demand applications using Wi-Fi 6E/7.

- **Cisco Catalyst Access Points**:
  - 9136I – Tri-band (2.4/5/6 GHz) Wi-Fi 6E indoor AP
  - 9166D – High-density Wi-Fi 6E AP, ideal for lecture halls, labs, & auditoriums

- **Key Specs**:
  - 8x8 MU-MIMO on 5/6 GHz, 4x4 on 2.4 GHz
  - Up to 10 Gbps uplink (multi-gigabit Ethernet)
  - WPA3 security, OFDMA, BSS Coloring
  - Built-in IoT radios (BLE, Zigbee, Thread)

Why 6GHz Wi-Fi 6E?

- 1,200 MHz of new spectrum (vs. 500 MHz at 5GHz)
- Cleaner airspace with fewer legacy devices → minimal interference
- High-capacity channels: 59 × 20 MHz channels (or 7 × 160 MHz for ultra-high throughput)
- Low latency: <5ms, ideal for research & real-time applications
- Future proof: Enables AR/VR, AI, big data & cloud-driven workloads

More users and bandwidth

Less wired infrastructure

Less Interference

Performance Comparison

Feature	Wi-Fi 5 (802.11ac)	Wi-Fi 6 (802.11ax)
Spectrum	5GHz only	2.4/5/6 GHz
Max Channel Width	80 MHz	160 MHz
Max Throughput (Theoretically)	~3.5 Gbps	~9.6 Gbps
Users Supported	~100/AP	~400/AP (OFDMA)
Latency	30–50 ms	<10 ms

5GHz vs 6GHz (Wi-Fi 6E)

Metric	5GHz Wi-Fi	6GHz Wi-Fi 6E
Channels (20 MHz)	~25	~59
Max Bandwidth	500 MHz	1200 MHz
Interference	High	Very low
Throughput Potential (Theoretically)	4–6 Gbps	9.6+ Gbps
Latency	<15 ms	<5 ms

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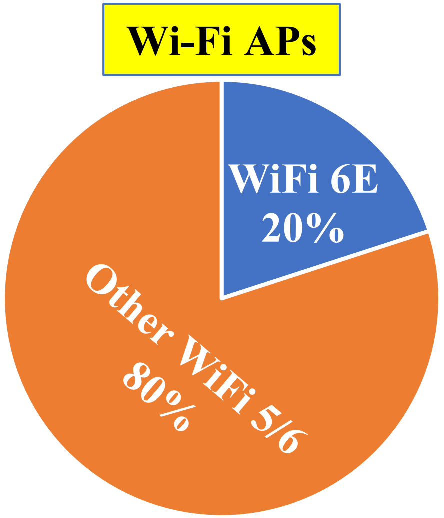
❑ Various 6GHz Wi-Fi access points (APs) are currently deployed indoors in various buildings on the KAUST campus.

Indoor Wi-Fi 6E (6GHz) in KAUST



Wi-Fi 6E

6 Buildings
1,235 APs
1,605 Clients

Capable Wi-Fi 6E (6GHz) Clients:

- 55% over academic buildings.
- 11% over the overall campus.

Outdoor Coverage

- The feasibility of 6GHz outdoors has been enabled by recent regulatory developments that require an Automated Frequency Coordination (AFC) system to prevent interference with existing licensed users, such as satellite and microwave links.

- It is ideal for outdoor spaces with high user concentration, such as stadiums, venues, urban parks, and university campuses.

- 3.5GHz band is a foundational component of modern mobile networks (4G/5G) and is highly feasible for wide-area outdoor connectivity. In Saudi Arabia, it is completely licensed for 4G/5G mobile services by the major mobile operators.

Cisco Catalyst 9163E – Ruggedized Wi-Fi 6E outdoor AP

- IP67 weather-resistant design
- Flexible antenna options for broad outdoor reach
- Reliable connectivity in exposed, harsh environments

Tarana Wireless Backhaul:

- High Capacity: Supports multi-gigabit backhaul per link
- Resilient to Interference: Advanced interference cancellation maintains stability even in congested areas
- Long Range: Can deliver up to 20 km links while sustaining high throughput
- Rapid Deployment: Wireless backhaul avoids trenching fiber - deployable in days.
- Cost Efficient: Significantly lower cost per km compared to fiber rollout.
- Adaptive Performance: Works in non-line-of-sight (NLoS) conditions, solving connectivity challenges in KAUST’s outdoor research zones, remote housing, and marine facilities

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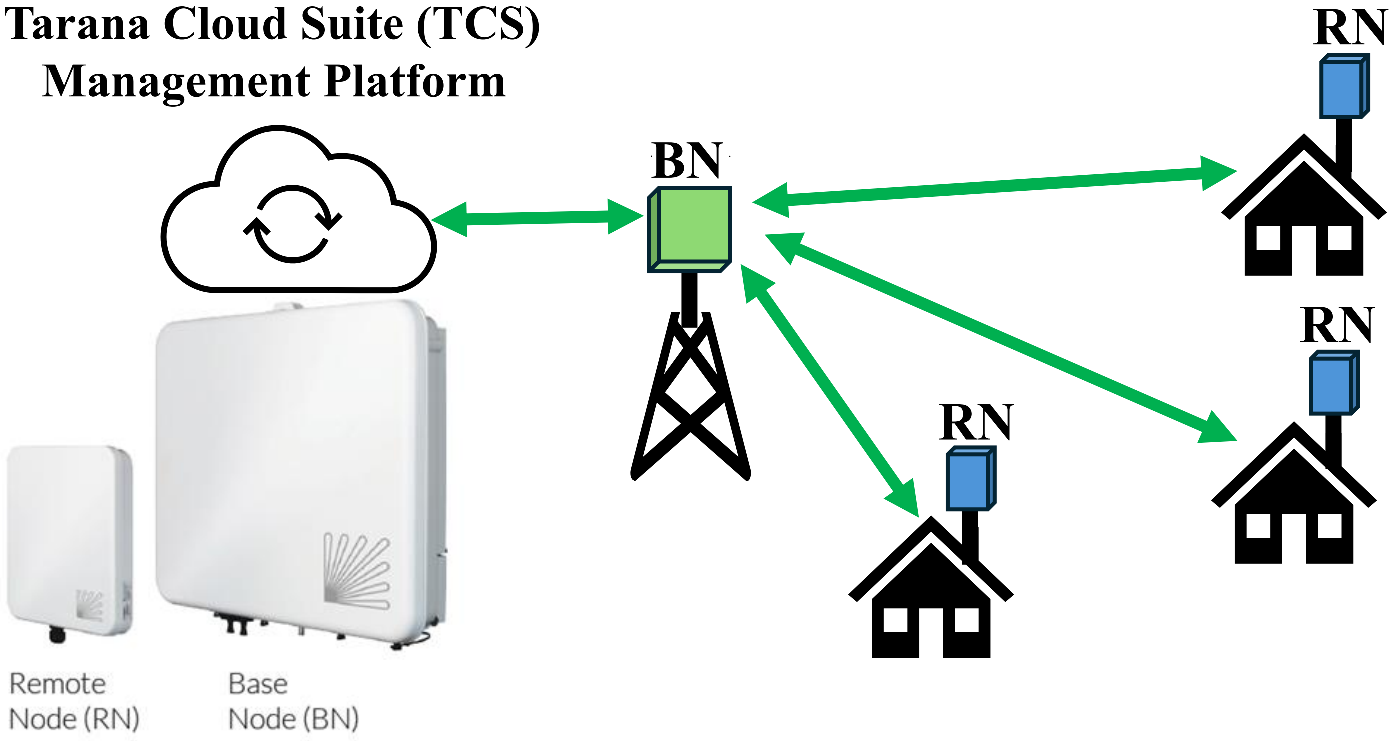
- ✓ TARANA supports both licensed CBRS (3.5 GHz) and unlicensed (5 GHz, 6 GHz) bands.
  - ❑ CBRS: 3550 - 3700 MHz in the US.
  - ❑ 5 GHz: 5.150-5.895 GHz
  - ❑ 6 GHz: 5.925-6.865 GHz
- ✓ **Features (Advertised by TARANA):**
  - ❑ Works in NLoS and nLoS.
  - ❑ Interference cancellation.
  - ❑ Distributed Massive MIMO.
  - ❑ Range: NLOS ~ 3km, LOS ~ 30km
  - ❑ Latency (one-way average) < 5ms
  - ❑ ~ 250 RNs per BN (i.e., one sector)

Tarana Cloud Suite (TCS) Management Platform



BN: Base Node
RN: Remote Node

LOS: line of sight
NLOS: non-line of sight
nLOS: near line of sight

Outdoor Measurements

BN Type	BN 6 GHz	BN 3.5 GHz
Max Data Rate (Advertised by TARANA)	1.6 Gbps per link 3.2 Gbps per sector (BN) 12.8 Gbps per cell (4 BNs)	0.8 Gbps per link 2.4 Gbps per sector (BN) 9.6 Gbps per cell (4 BNs)
Channel Aggregation	4 x 40 MHz =160 MHz [we use 2 x 40MHz = 80MHz]	2 x 40 MHz = 80 MHz

EIRP: 36dBm (Gain~16dBi + TX Power~20dBm)

- ✓ **BN:**
  - ❑ Height above ground level: ~50m.
  - ❑ Location: 22.3103403, 39.1034717
- ✓ **RN:**
  - ❑ Height above ground level: ~2.5m.
  - ❑ Location: 7 Locations as shown in the Table.

RN Locations

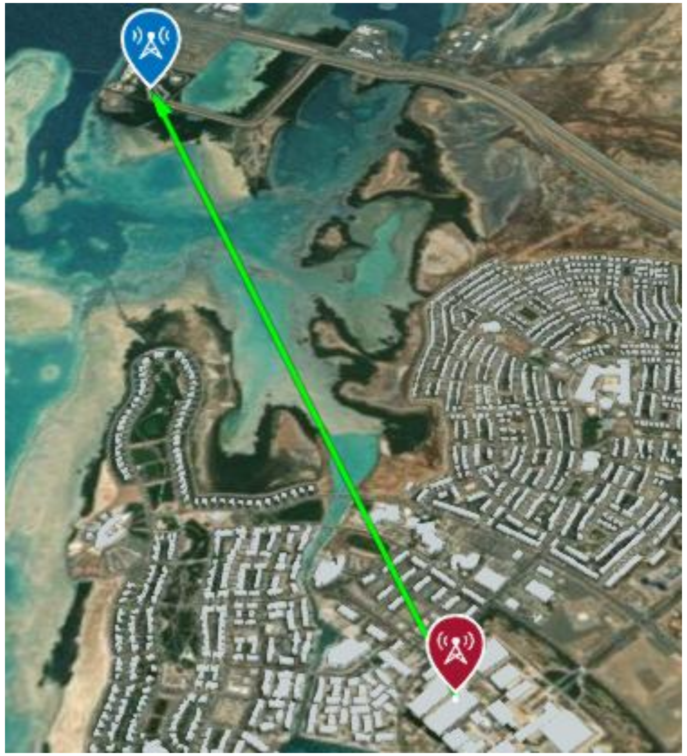
Name	Coordinates	Distance (Km)
Tamimi Parking	22.316022 39.104342	0.64
Amphitheater 2	22.305514 39.095662	0.94
Amphitheater 1	22.303306 39.095271	1
Garden	22.3217407 39.1040323	1.3
South Beach	22.292775 39.090902	2.4
King Abdullah Monument 2	22.341485 39.089996	3.7
King Abdullah Monument 1	22.341819 39.090017	3.75

LOS/nLOS Links

Amphitheater 1

King Abdullah Monument 1

King Abdullah Monument 2



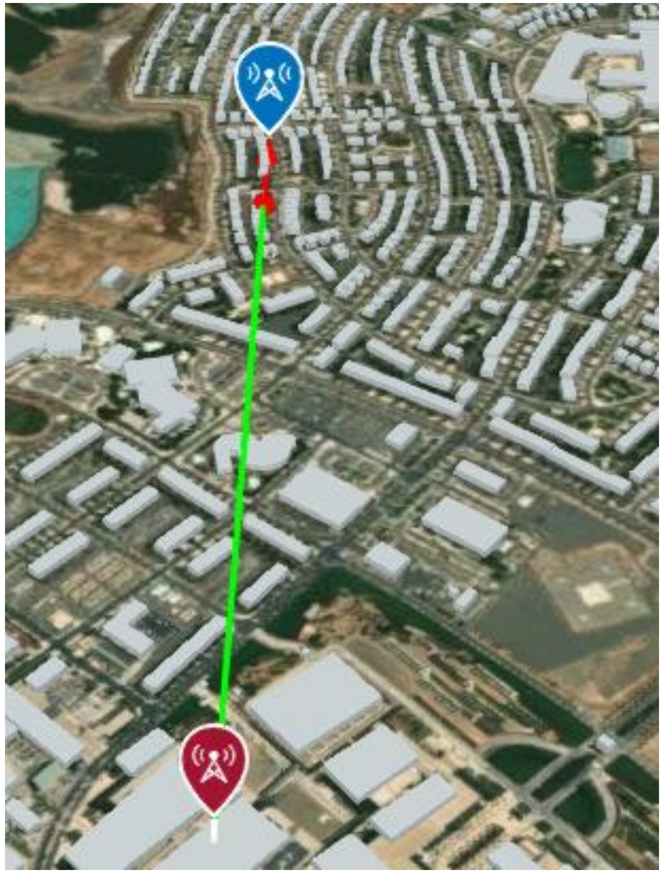
South Beach

NLOS Links

Tamimi Parking

Amphitheater 2

Garden



Results (3.5 GHz)

Results for 3.5GHz using 2 carriers (40MHz x 2) = 80MHz

Name	Distance (Km)	LOS	Path	RSS (dBm)	PL (dB)	SNR (dB)	Internet Speed (DL/UL) Mbps	Round-Trip Latency (ms)
Tamimi Parking	0.64	NLOS	Few houses	-87	132	23	517/104	41
Amphitheater 2	0.94	NLOS	Large building	-90	152	8	159/30	30
Amphitheater 1	1	LOS	No obstacles	-87	130	23	570/87	36
Garden	1.3	NLOS	Many houses	-89	147	10	193/30	166
South Beach	2.4	nLOS	One tree	-67	130	25	413/90	6
King Abdullah Monument 2	3.7	NLOS	Trees	-89	154	6	30/8	NA
King Abdullah Monument 1	3.75	LOS	No obstacles	-86	132	24	555/119	33

- NC : no connection
- LOS : line-of-sight
- NLOS : non-LOS
- nLOS : near-LOS
- PL : pathloss
- RSS : received signal strength
- SNR : signal-to-noise ratio
- DL : downlink
- UL : uplink

Results (6 GHz)

Results for 6GHz using 2 carriers (40MHz x 2) = 80MHz

Name	Distance (Km)	LOS	Path	RSS (dBm)	PL (dB)	SNR (dB)	Internet Speed (DL/UL) Mbps	Round-Trip Latency (ms)
Tamimi Parking	0.64	NLOS	Few houses	-92	145	9	38/13	10
Amphitheater 2	0.94	NLOS	Large building	NC	NC	NC	NC	NC
Amphitheater 1	1	LOS	No obstacles	-89	133	16	225/92	6
Garden	1.3	NLOS	Many houses	NC	NC	NC	NC	NC
South Beach	2.4	nLOS	One tree	-92	137	14	281/72	6
King Abdullah Monument 2	3.7	NLOS	Trees	NC	NC	NC	NC	NC
King Abdullah Monument 1	3.75	LOS	No obstacles	-90	136	15	272/71	6

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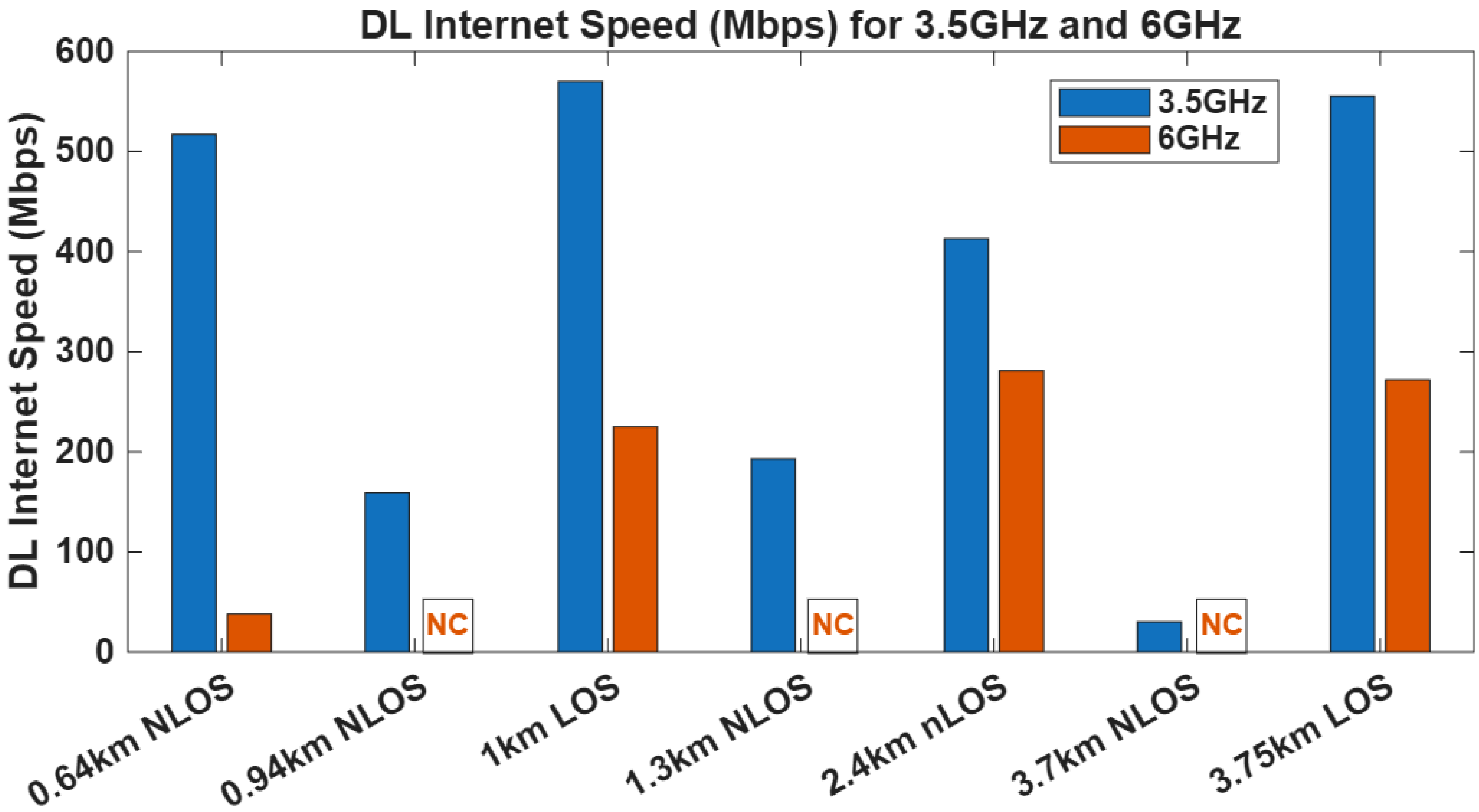
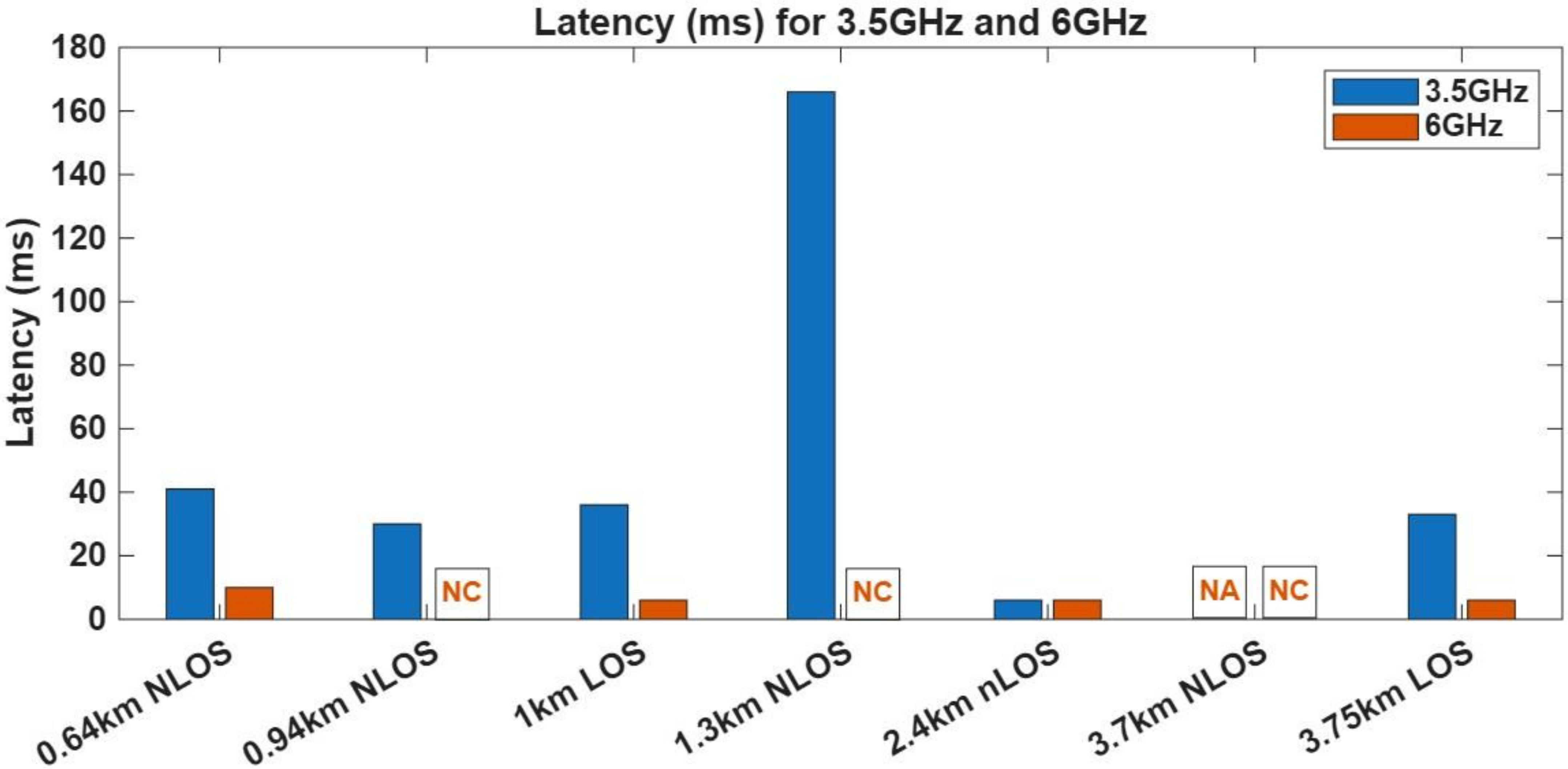
Results (3.5GHz & 6GHz)



Results (3.5GHz & 6GHz)



Conclusion

- Using the same number of carriers (2x40MHz), the 3.5GHz TARANA system provides higher DL/UL internet speeds compared to the 6GHz system.
- In the NLOS scenario, the 6GHz TARANA system mostly loses the connection.
- This may happen because the 6GHz signal has worse penetration and shorter range compared to the 3.5GHz signal in the NLOS scenario. This makes it more susceptible to physical obstacles like buildings and walls.
- In the LOS scenario, the 6GHz TARANA system provides less speed than the 3.5GHz system. This could be because of higher path loss, and more precise alignment is needed for the 6GHz RN with BN.
- The 6GHz TARANA system provides less latency compared to the 3.5GHz system.
- Both 3.5GHz and 6GHz systems perform poorly through trees. This is because trees absorb and scatter higher-frequency signals, leading to decreased throughput and may cause a complete loss of connection.

Conclusion

- Further Inspection for 6GHz Tarana System: examine the alignment between BN and RN, including the azimuth and tilt angles. Scanning the channel for any interference in the 6GHz band.

- KAUST Impact:
  - Full 36 km^2 campus coverage indoors & outdoors
  - High-density classrooms & labs supported with ultra-fast Wi-Fi
  - Remote & marine areas connected with Tarana wireless backhaul
  - Affordable, scalable & future-ready research infrastructure

Acknowledgment

We gratefully acknowledge the cooperation with KSA CST and the permission of Salam Mobile and GO Telecom for allowing the use of the 3.4 GHz frequency spectrum for testing the Tarana wireless solution in the KAUST campus.

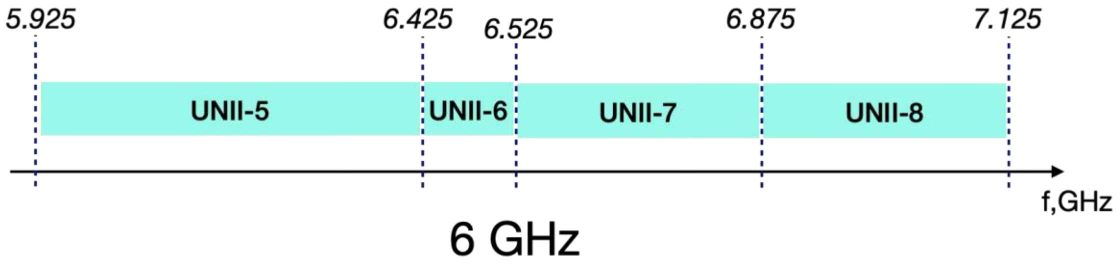
salam mobile

GO Telecom

WiFi NR-U Coexistence

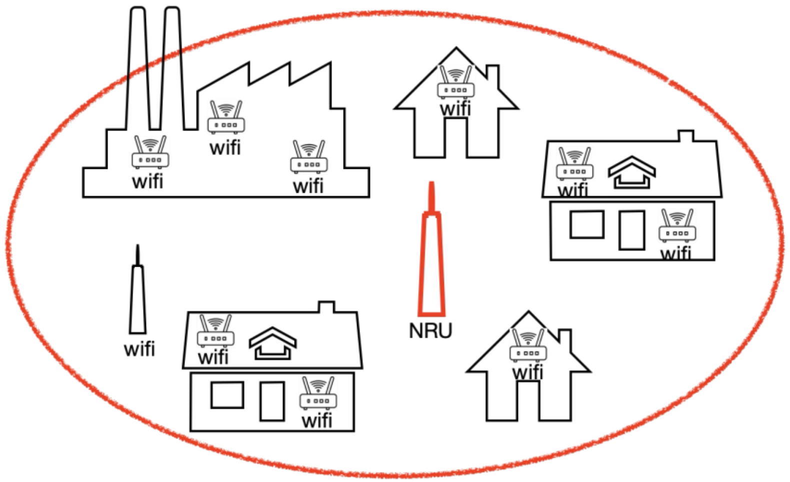
◆ Motivation

- 6 GHz band (5.925 – 7.125 GHz)
  - Recently unlicensed in many countries including Saudi Arabia
  - Up to 1.2 GHz bandwidth
  - Indoor and outdoor use
  - High-throughput use-cases
  - WiFi 6e and WiFi 7 can exclusively use this band



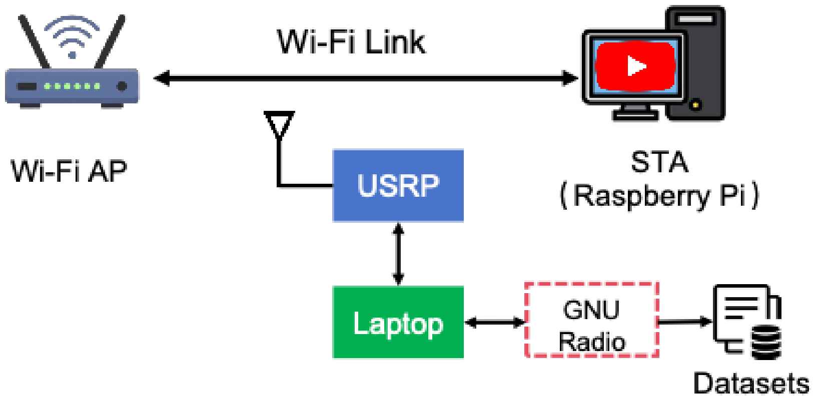
◆ Objectives

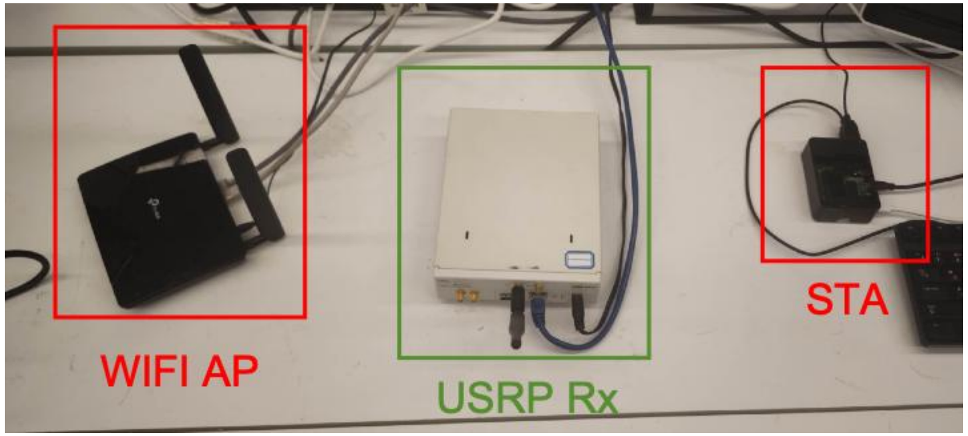
- NR-U system features
  - Private 5G Networks
  - Deploy in campus, companies, clinic and factories
  - Utilize 6 GHz unlicensed band
  - Co-exist smoothly and smartly with co-located, neighboring WiFi networks
  - Autonomous operation, no co-ordination with WiFi networks



Data collection and analysis

- Testbed consists of
  - COTS WiFi AP and STA
  - SDR which collects WiFi IQ data
- WiFi transmits:
  - 5 GHz unlicensed band
  - Fixed on ch44 (fc = 5220 MHz, BW = 20 MHz)
  - Ensured ch44 is clear from interference
  - 10 min 4K video streaming traffic (Youtube)
- SDR (USRP):
  - Sensing the same channel
  - Sample data at 20 Msps (Wifi sampling rate)
  - Store IQ data
  - Collected data processed to extract feature and inference

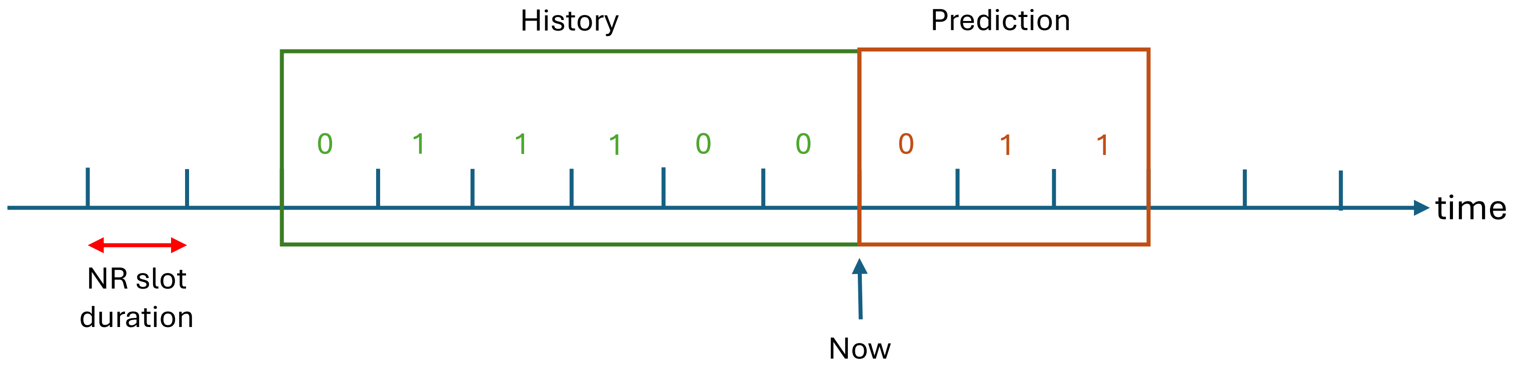




◆ Prediction-based channel access scheme

- NR-U and WiFi
  - use same frequency and spatial resources
  - share time resources
- Key idea: Predict channel availability from WiFi activity history to trigger NR-U transmission immediately when the channel becomes free

Proposed sliding window prediction scheme



0: not occupied by WiFi

1: occupied by WiFi

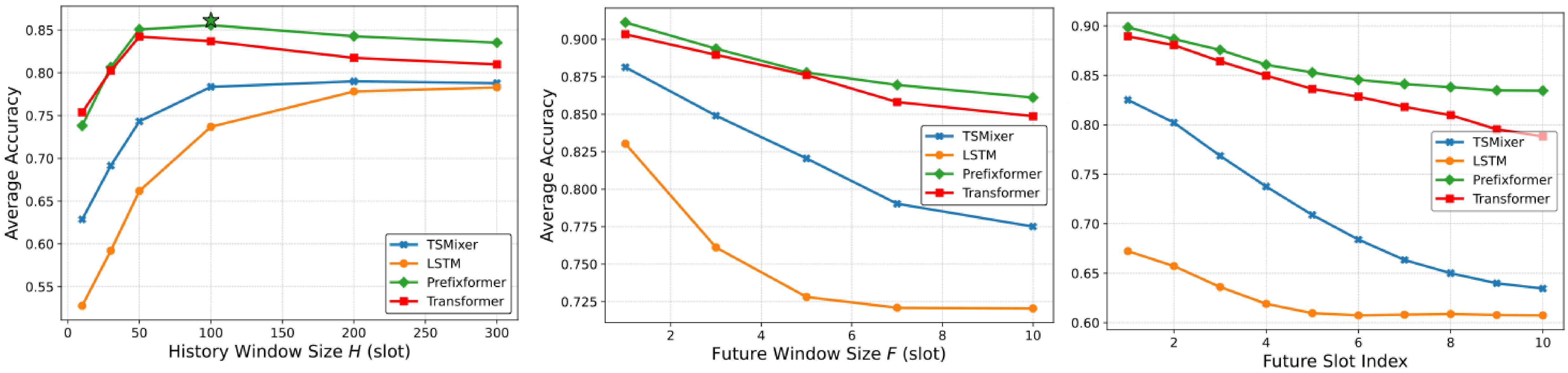
◆ Model Performance Assessment

- Baseline:
  - TSMixer: linear based architecture model (fast, low computation cost)
  - LSTM: recurrent neural network model (widely applied in communications)
  - Transformer: conventional transformer model
- Proposal: Prefixformer model

Model performance versus history window size (fixed F = 10)

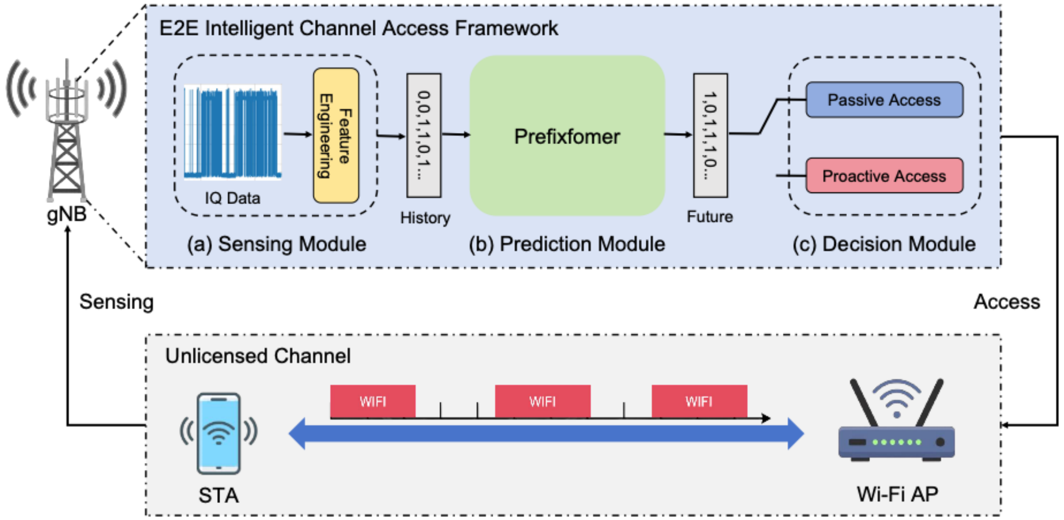
Model performance versus future window size (fixed H = 100)

Model performance across each future slot (H = 100, F = 10)



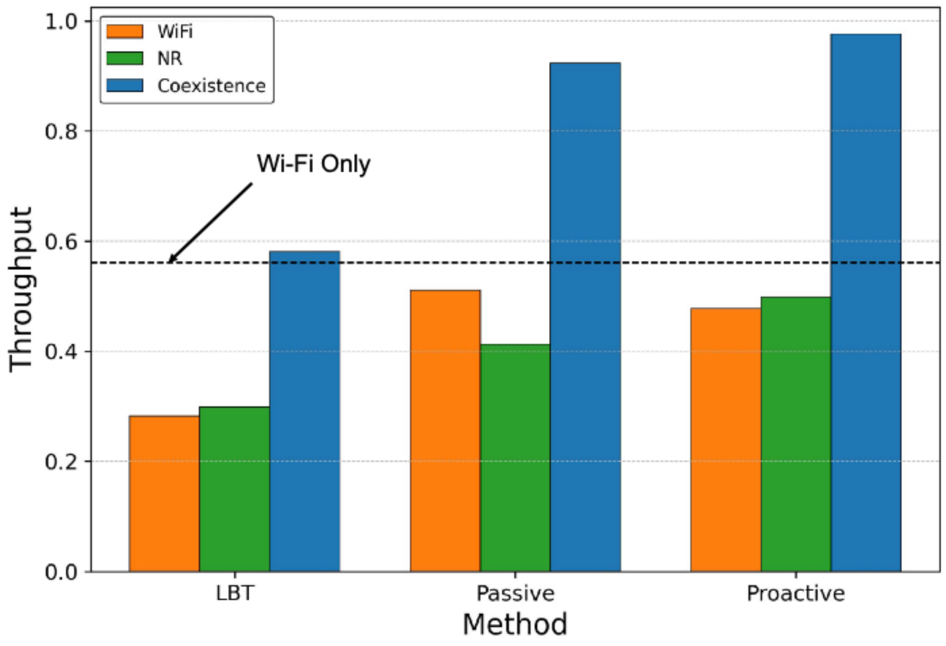
Method

- WiFi traffic prediction
  - gNB senses WiFi traffic
  - Predict the channel availability using ML
  - Use channel gaps proactively and efficiently (minimum delay)
- Conventional scheme: listen before talk (**LBT**)
  - Waste resources on sensing and backoff time
- Our ML scheme:
  - Predict WiFi and can transmit as soon as channel is clear
- Smart coexistence algorithm
  - Flexible channel access:
  - [**Passive**] Fill the channel gaps without impacting WiFi
  - [**Proactive**] manipulate WiFi transmission
    - Predict and interrupt a WiFi transmission to take its place.
    - Intentionally leave the channel empty for WiFi to use.

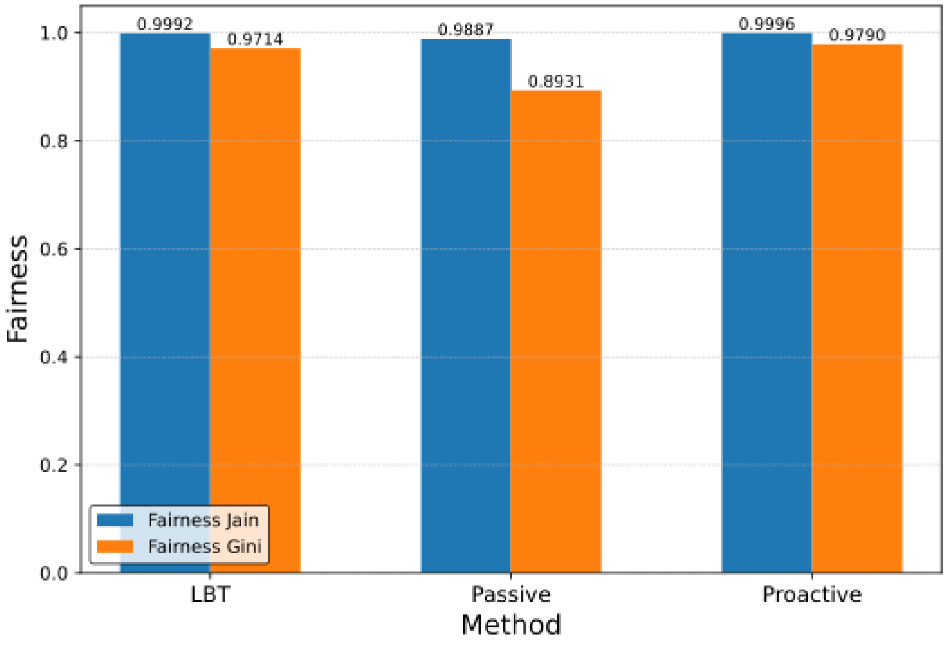


◆ Simulation Results

Relative Throughput (1: channel is fully occupied)

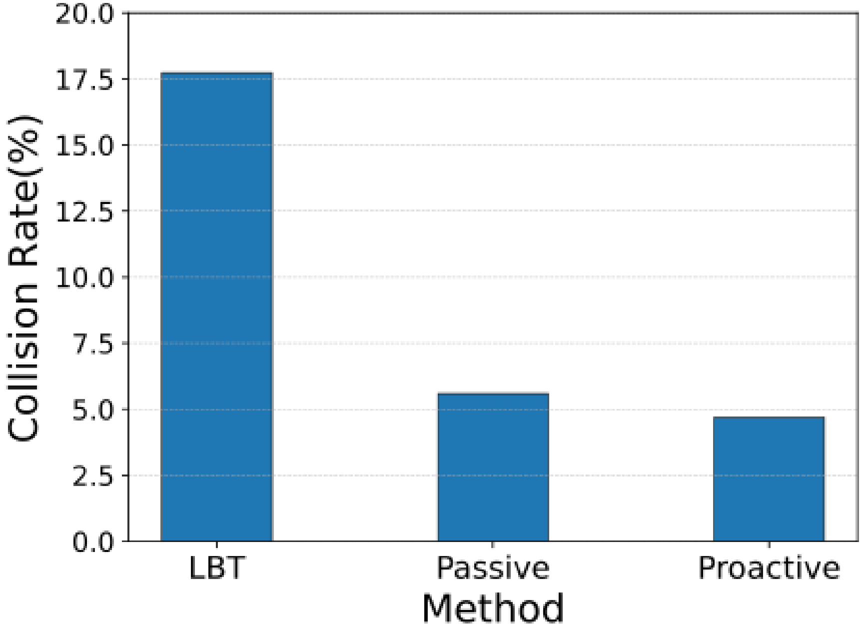


Fairness on channel use between WiFi and NR-U

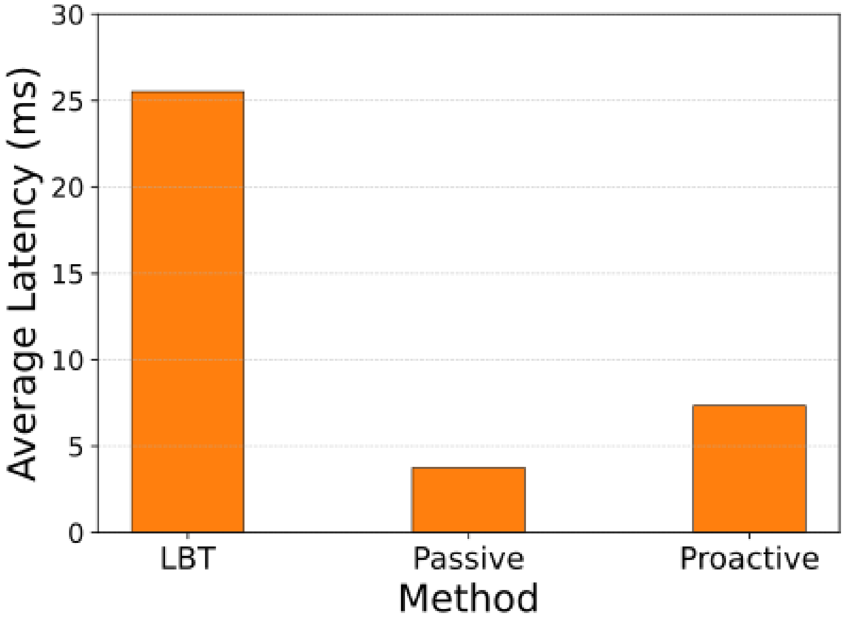


◆ Simulation Results

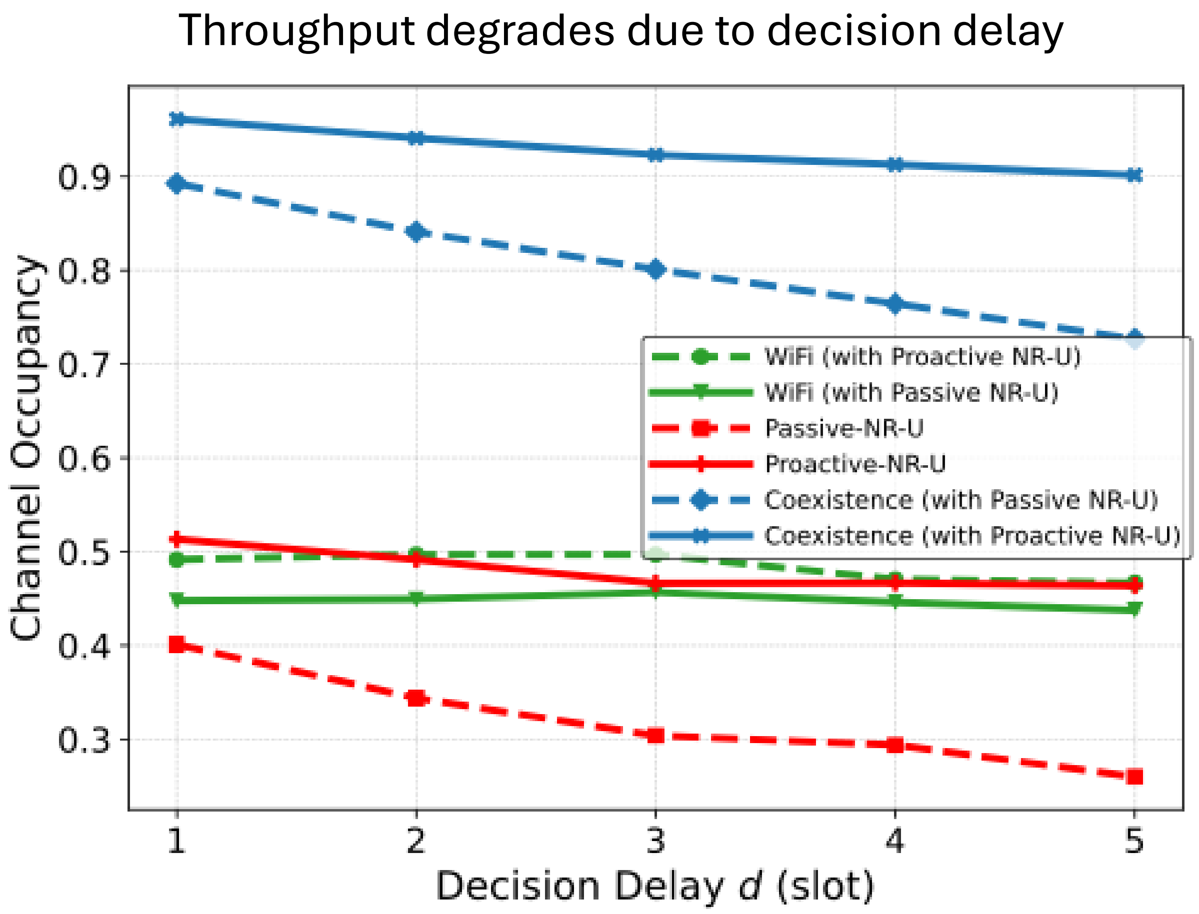
NR-U collision rate over all transmissions



Latency on WiFi due to coexistence



◆ Simulation Results



H. Huang, H. Al-Shatri, M-S. Alouini, “Intelligent Channel Access in Unlicensed Spectrum: A Transformer-Based Prediction Approach”, submitted