Analysis of Multi-band Heterogeneous Wireless Network for Nuclear Applications

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Project Overview

Research scope

- Different wireless technologies need to ***co-exist*** without impacting the wireless network performance for efficient nuclear plant operation.
- Complete experimental and simulations of multi-band heterogeneous network in representative environments.
- Utilize the data and knowledge gained from the **experiments and simulations**, and utilize that to optimize the network performance.
- Develop a learning-based approach to optimize network performance i.e., complete coverage and enhanced connectivity.

Strategy:

- Evaluate and optimize the wireless multiband heterogeneous network performance metrics such as packet error rate, throughput, latency, power consumption, and relative signal strength, and others.

Project Details

Principal Investigator: Vivek Agarwal, Idaho National Laboratory

Collaborators: University of Utah

Period of performance: FY 2024

Funding: $200,000

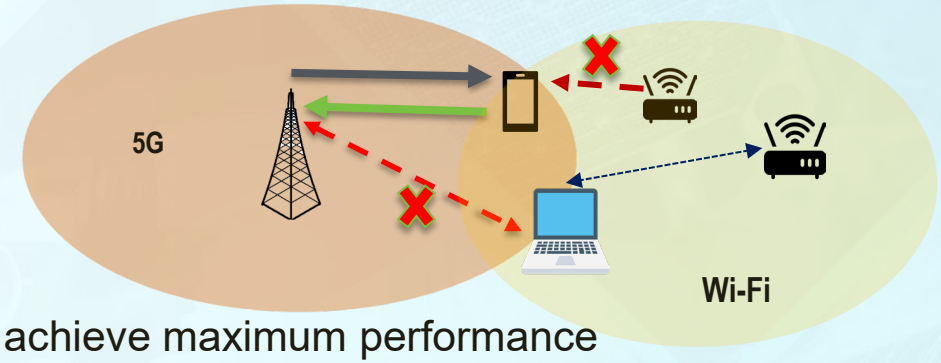
TPOC (Technical Point of Contact): Craig Primer

Milestones/deliverables: Complete experimental testing of multi-band heterogeneous network in representative environments and development a learning-based approach to optimize network performance.

Technology Impact

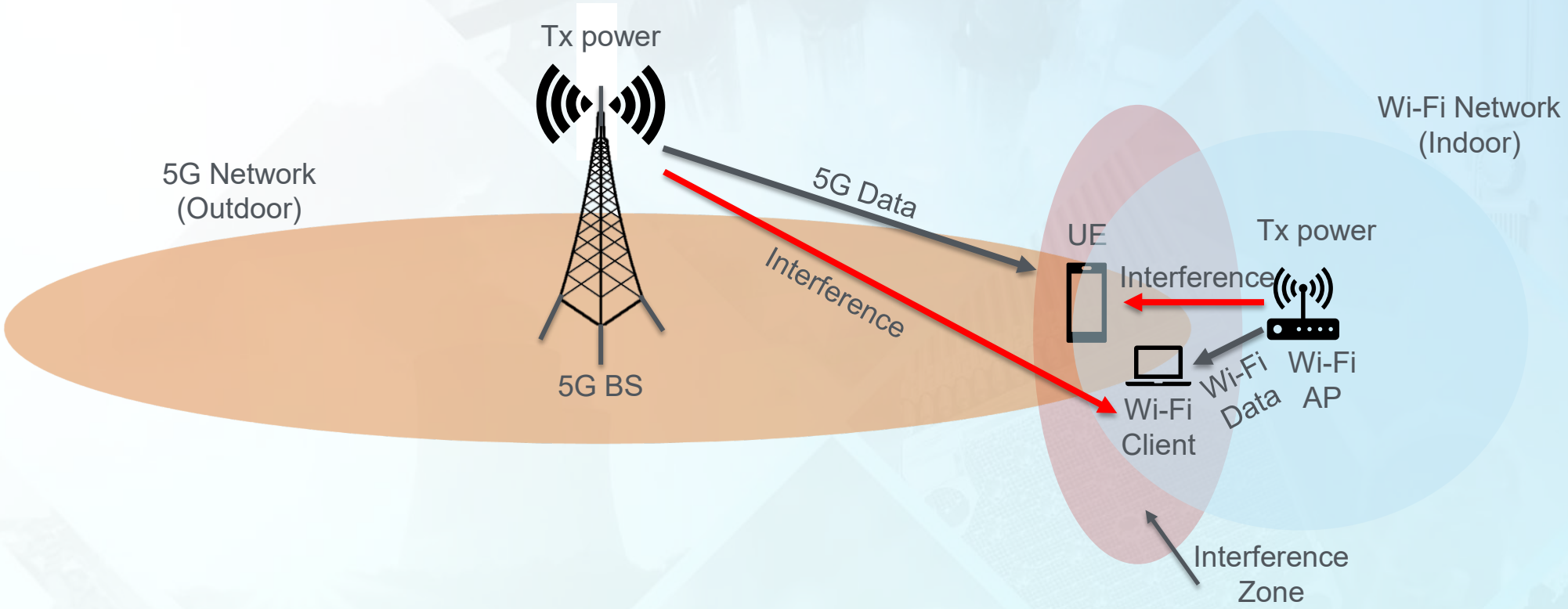
- Wireless application in nuclear environment has gathered high interest
- Advanced wireless capabilities are critical for **modernization** of existing nuclear fleet
- Wireless technologies can support **automation and remote monitoring** of advanced nuclear reactors

- Current nuclear stakeholders are very interested to deploy advanced wireless capabilities for efficient operation
- Can help **reduce operating costs** and **labor-intensive activities** for remote monitoring



- Different wireless technologies can be adopted simultaneously to achieve maximum performance
- Coexistence of heterogeneous networks is challenging due to interference, impact of signal power, transmitter-receiver node distance, channel access mechanism etc.

Coexistence of Wi-Fi & 5G-NR-U



Coexistence of Wi-Fi and 5G-NR-U can cause interreference to each other due to:

- Difference in transmit power level
- Distance between transceivers
- Difference in channel access mechanism

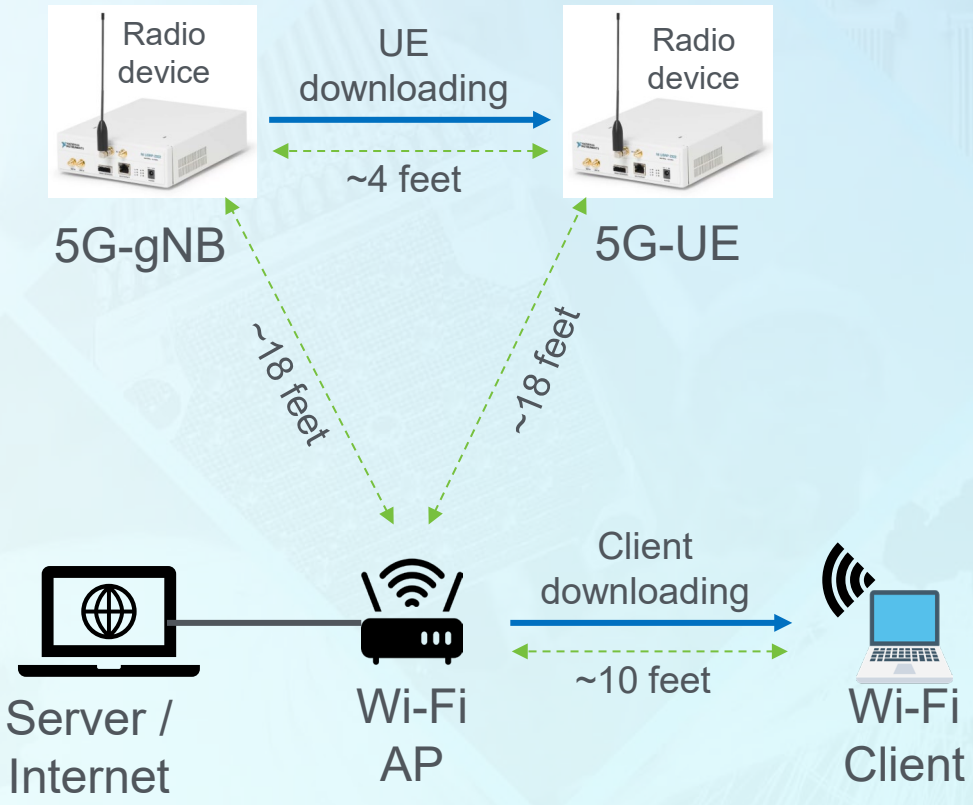
Experiment: Wi-Fi & 5G-NR-U Coexistence

Experiment was carried out in POWDER test-bed (indoor) at University of Utah

- Received power at 5G-UE (~-110 dBm).

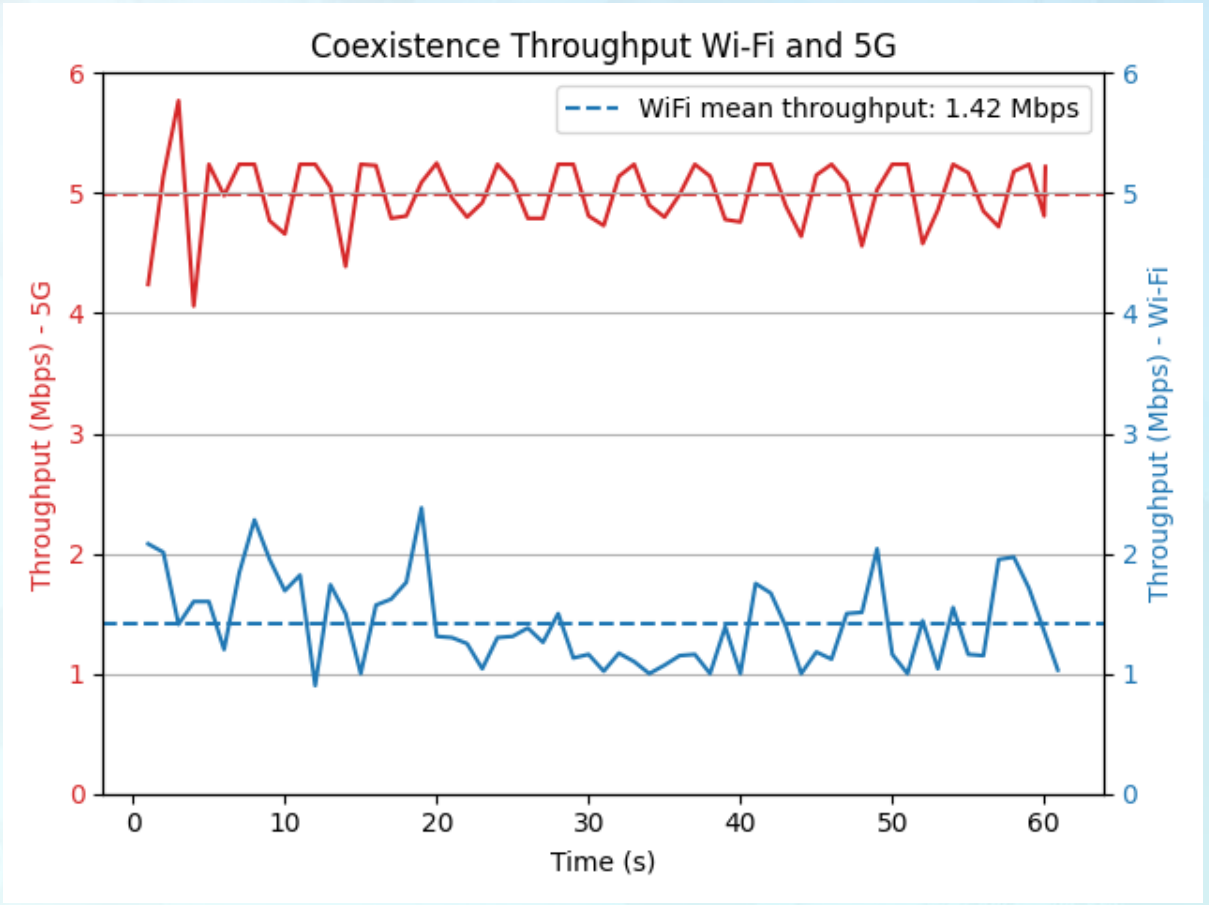
Range	3GPP range UE Rx (-157.0 to 30.0) dBm		
	mmWave	Sub 6 GHz	Sub 1 GHz
Excellent	≥ −90	≥ −85	≥ −80
Good	-105 to -90	-100 to -85	-95 to -80
Fair	-115 to -105	**-115 to -100**	-115 to -95
Poor	< -115	<-115	<-115

- This replicates a typical scenario for a 5G network where UE is within the coverage area of gNB.

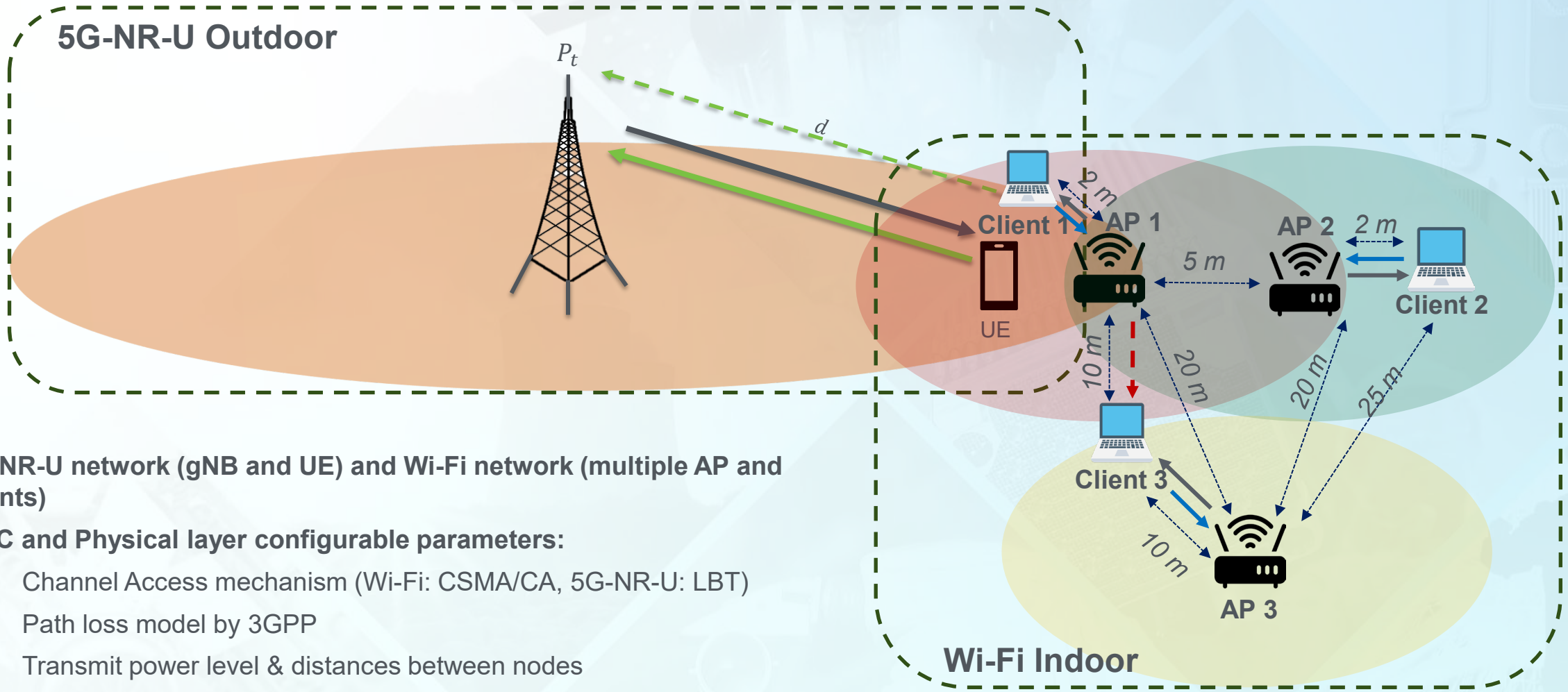


Experiment: Wi-Fi & 5G-NR-U Coexistence

- 5G-UE downloading at ~5 Mbps.
- Wi-Fi data rate range kept within a limit (1-3)Mbps. Higher Wi-Fi data rate impacts 5G periodic signaling (default 20 ms) which disconnects UE. A manual restart of 5G system is required at this moment (software bug).
- Increased 5G signaling periodicity to max value of 160 ms, such that probability of collision between Wi-Fi packet and 5G signaling is low.
- Implemented dynamic control of Wi-Fi packet rate: If 5G BLER > 15% for consecutive 2 sec, Wi-Fi packet rate (from network layer with token bucket filter) is decreased at a step of 250 Kbps, else increased.
- With this approach the **networks can coexist**. But does not guarantee that collision will not happen.
- The 5G software (OpenAirInterface) does not include any channel sensing and access mechanism (e.g., LBT), therefore fair channel sharing is not guaranteed.

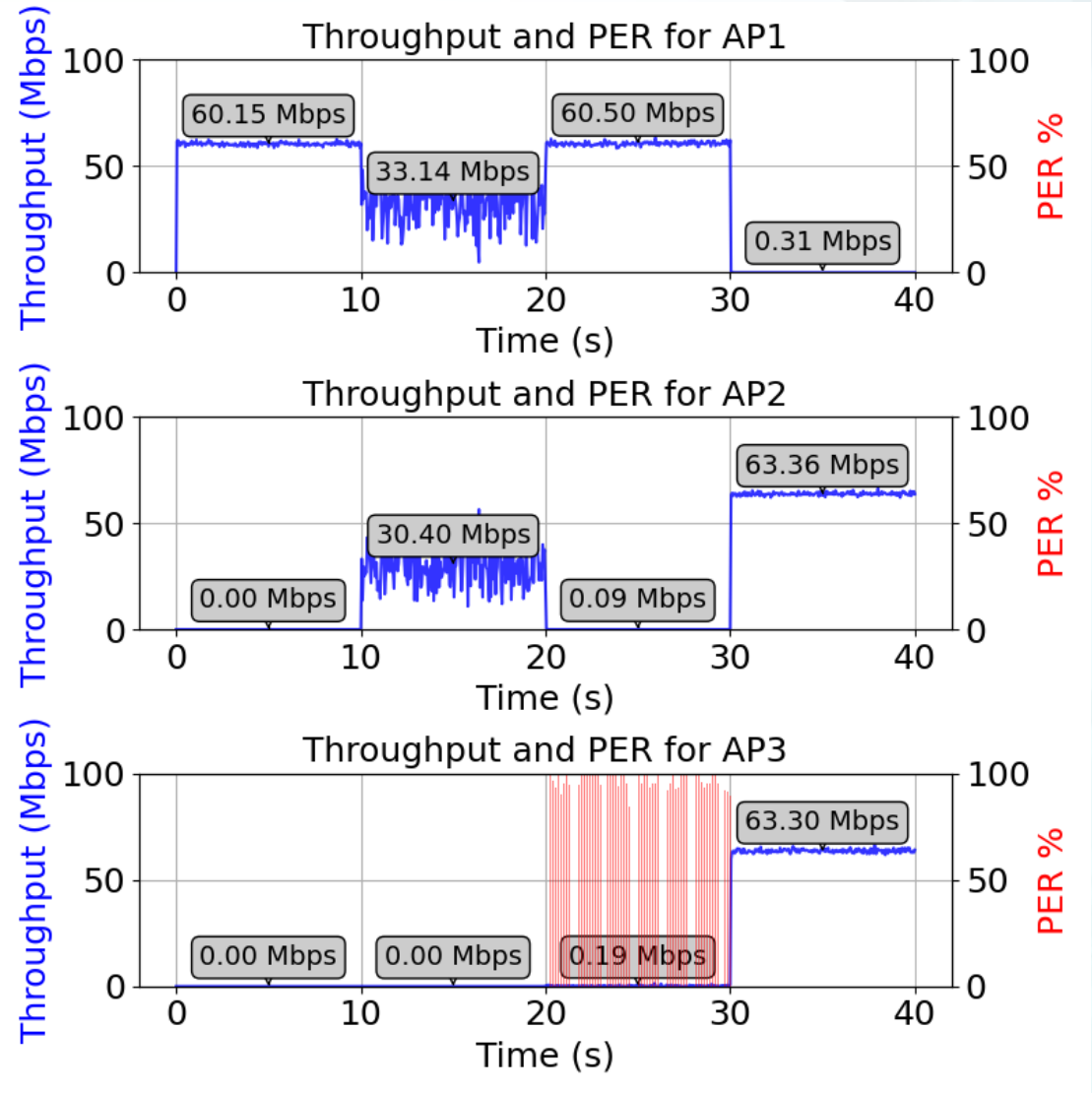


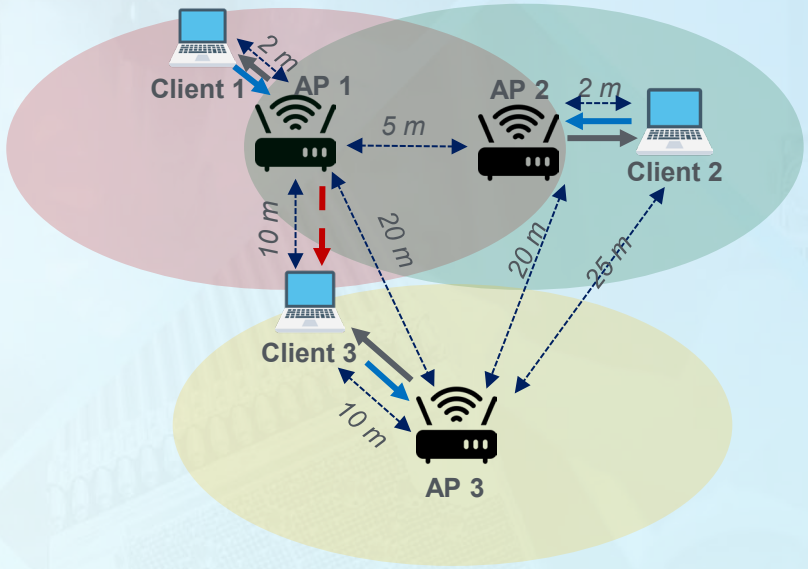
Python Simulator : Wi-Fi & 5G-NR-U



- **5G-NR-U network (gNB and UE) and Wi-Fi network (multiple AP and clients)**
- **MAC and Physical layer configurable parameters:**
  - Channel Access mechanism (Wi-Fi: CSMA/CA, 5G-NR-U: LBT)
  - Path loss model by 3GPP
  - Transmit power level & distances between nodes
- **Performance measurement:**
  - Throughput
  - Packet error rate

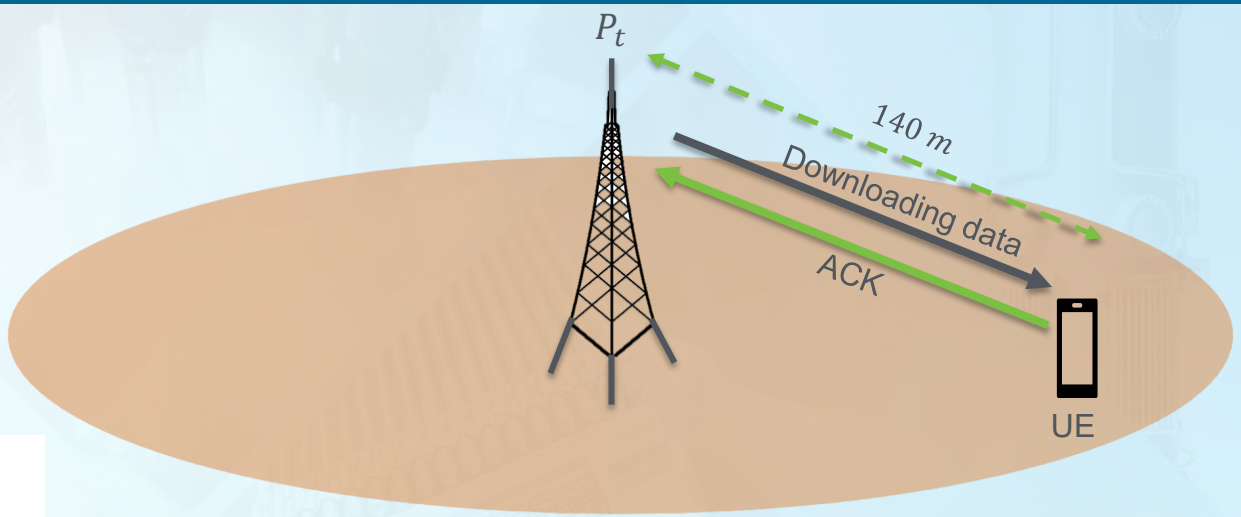
Python Simulator : Wi-Fi Network Performance

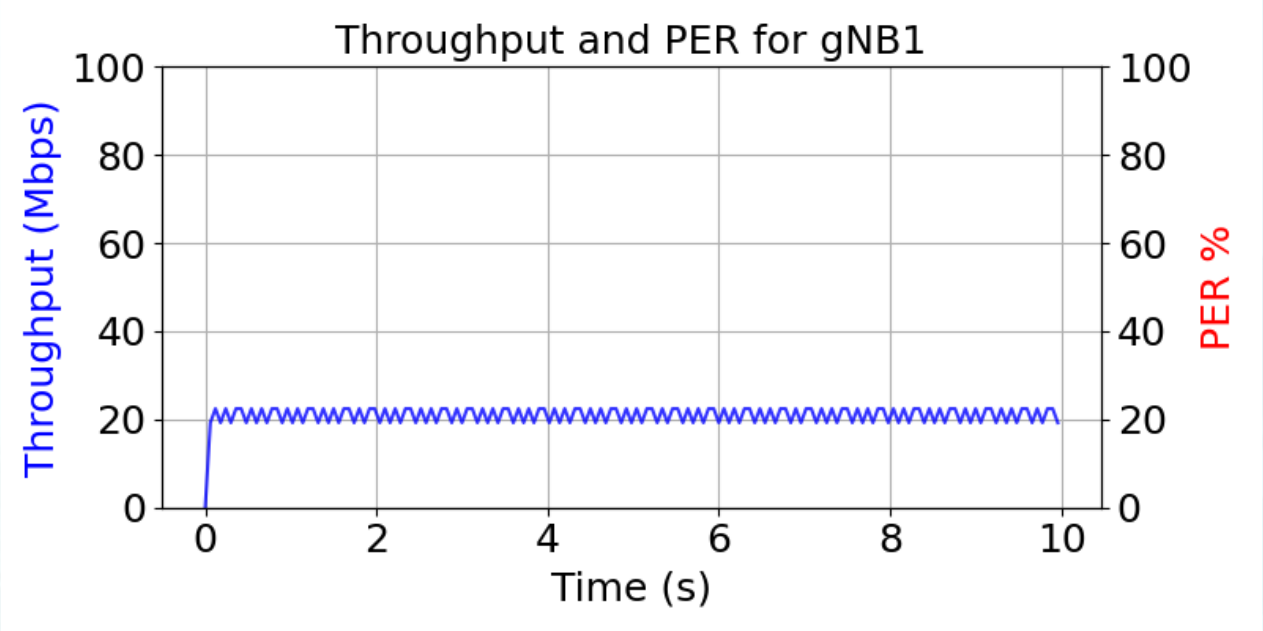




- Each AP is associated with its own client (e.g., AP1-Client1)
- Default max throughput ~60 Mbps (w/o any interference)
- 10th to 20th sec: AP1 and AP2 able to sense each other's transmission and backs off when another node is transmitting (sharing the channel).
- 20th to 30th sec: AP1 and AP3 are far apart and cannot sense each other's transmission. Client 3 falls within the coverage area of both AP1 and AP3. Client 3 receives interference from AP1. Packet error occurs, degrades throughput due to re-transmission.
- 30th to 40th sec: (AP2 – Client 2) and (AP3 – Client 3) each within their own coverage area. No interference / no packet error.

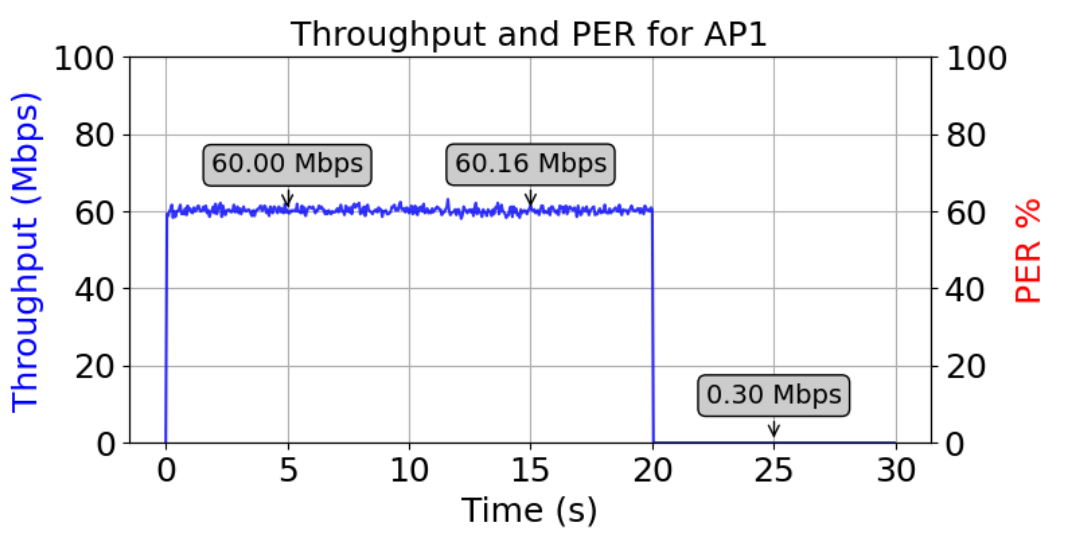
Python simulation : 5G-NR-U network performance

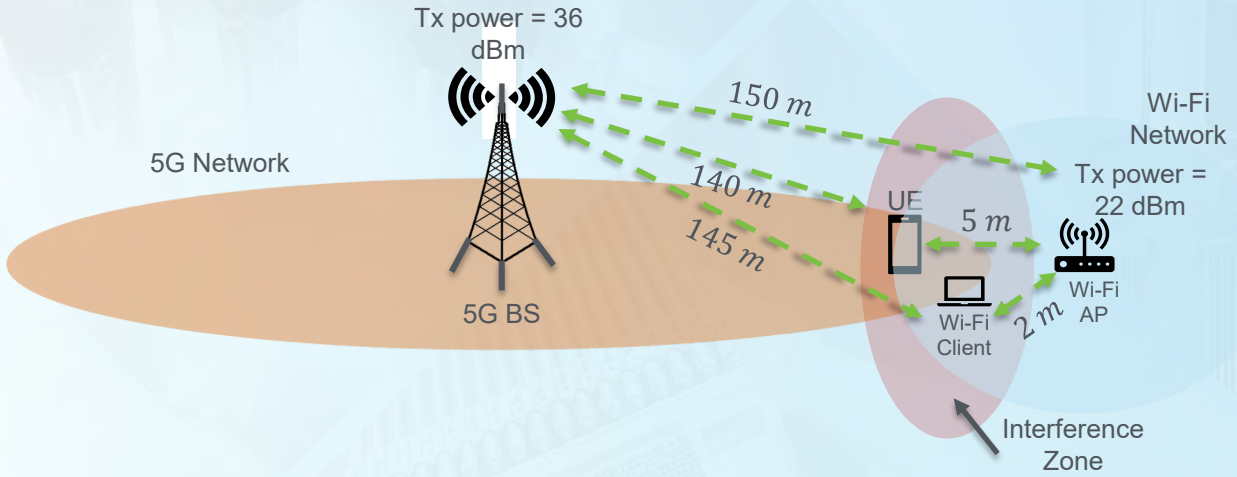




- Default distance *d* between gNB-UE is 140m (variable).
- With Max Tx-power (36 dBm), Rx-power = ~ -98 dBm (within coverage area: fair signal power (3GPP)).
- Without any interference from Wi-Fi network average throughput is ~23Mbps

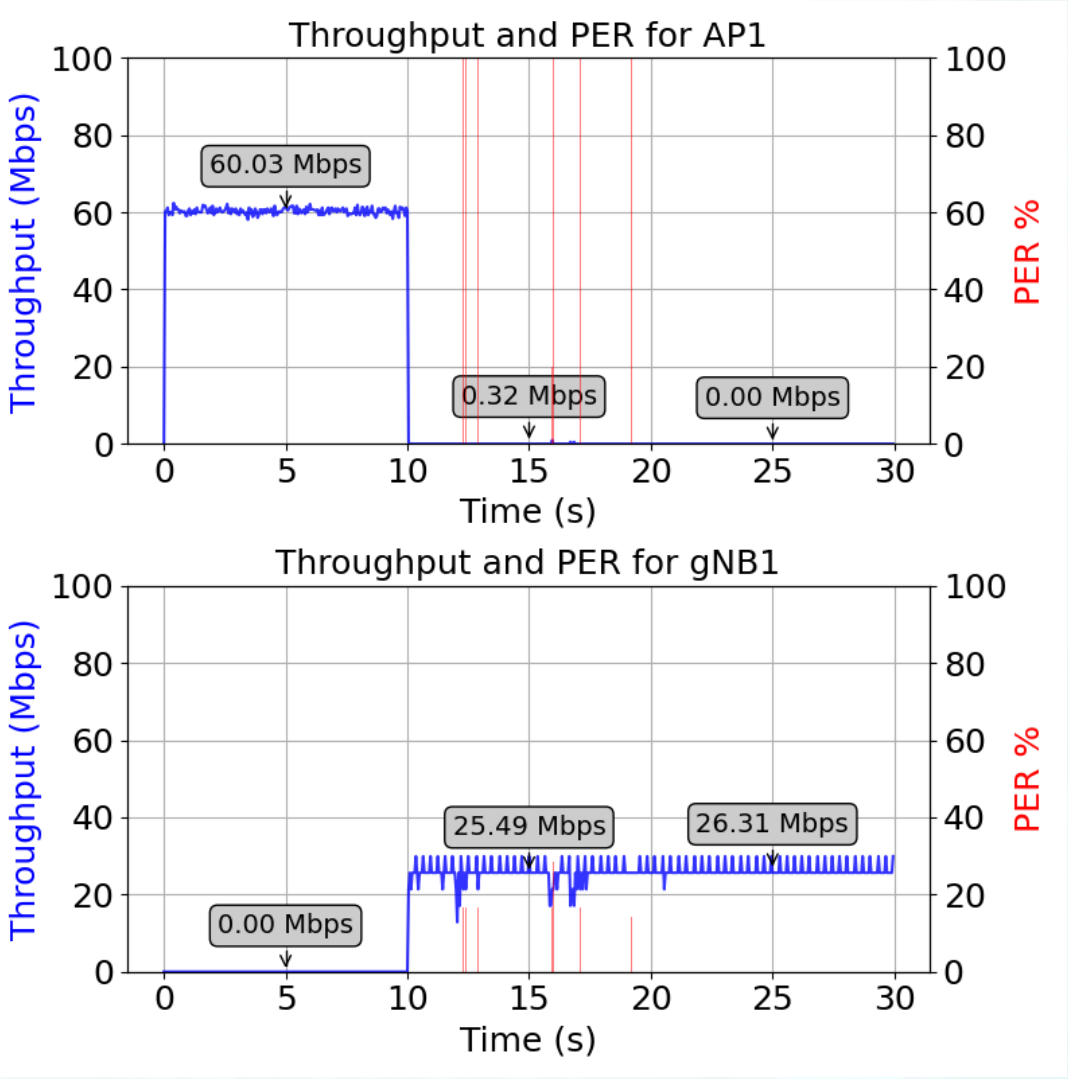
Python simulation : Wi-Fi & 5G-NR-U coexistence performance

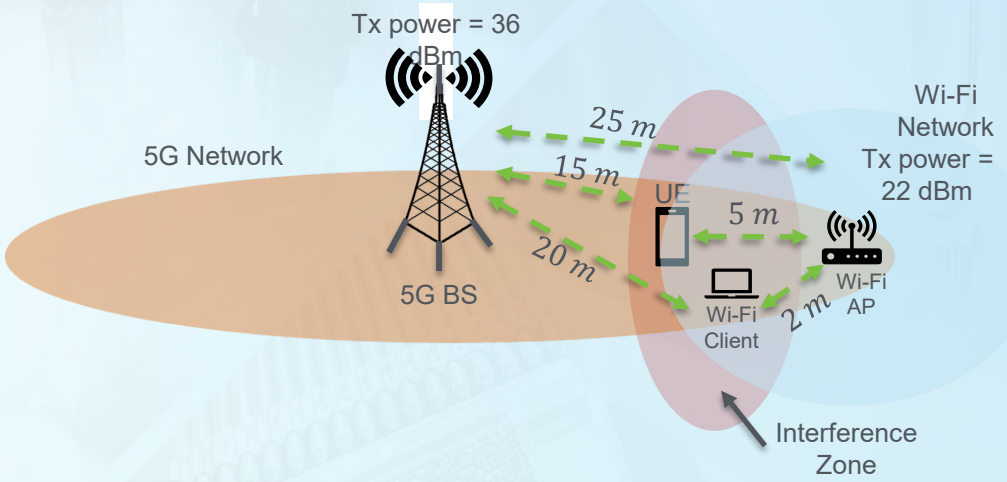




- Wi-Fi network (AP1 – Client 1) active from 1 – 20th sec. While 5G network (gNB– UE) active from 10th to 30th sec.
- Coexistence : 10th – 20th sec
- gNB and Wi-Fi AP are far apart (150m), not able to sense each other.
- UE is much closer to Wi-Fi transmitting AP (see distance value in fig.), the interference power (from AP) is higher than signal power (from gNB). Causes received packets at UE to be corrupted. Continuous retransmission occurs until max value reached.
- 5G throughput gets severely affected as all packet gets dropped.

Python simulation : Wi-Fi & 5G-NR-U coexistence performance





- Coexistence : 10th – 20th sec
- Distance updated (see fig.) : gNB is now closer to both UE and Wi-Fi AP.
- Due to higher transmit power of gNB (compared to Wi-Fi), Wi-Fi AP able to sense gNB transmission and refrains from transmitting. gNB senses Wi-Fi AP transmit power too but finds it below the threshold limit (-82 dBm). Therefore transmits.
- Wi-Fi throughput degrades as packets are not transmitted.
- **Advantage of such simulations** to understand the scenario with varying distance and transmit power.

5G-NR Slot boundary

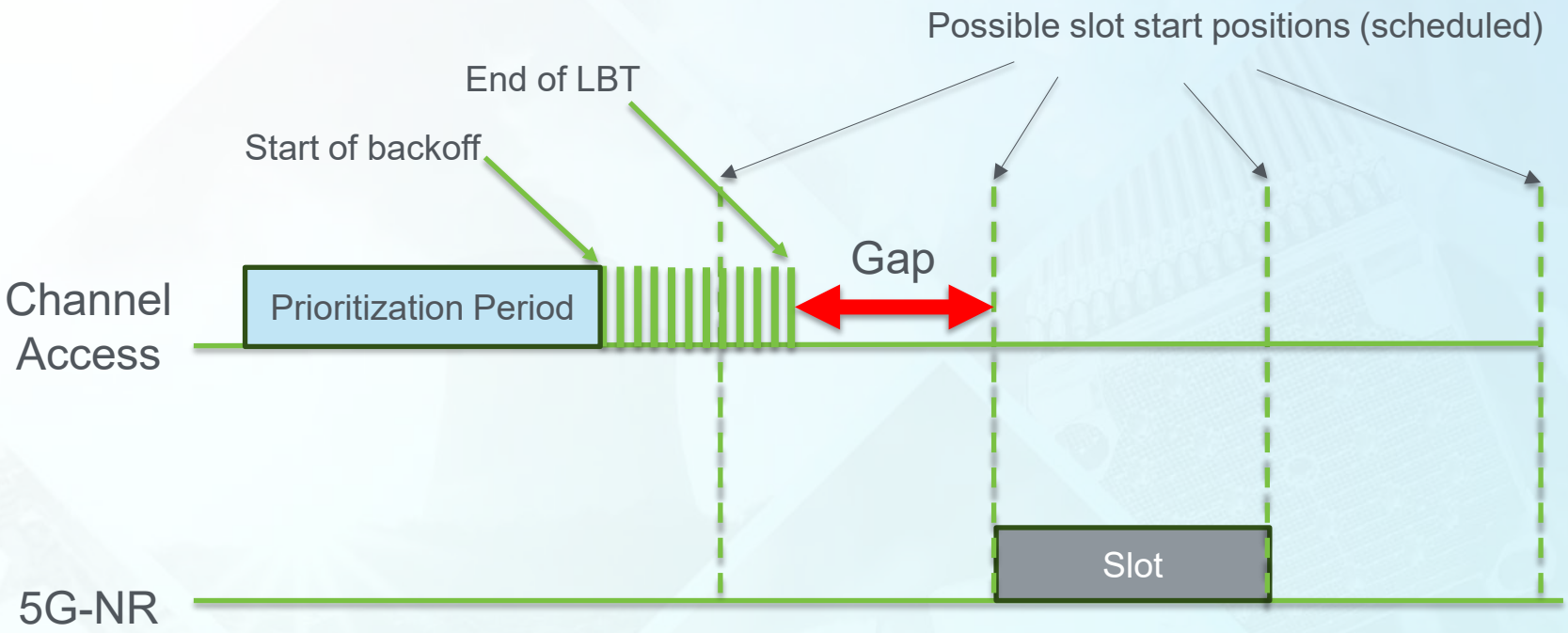


Fig.: 5G-NR : Gap between Slot start boundary and End of LBT procedure

Concluding Remarks:

- Experiments were performed to evaluate co-existence of wireless technologies (Wi-Fi and 5G-NR) in 5 GHz unlicensed band.
- A simulator is developed in Python to evaluate co-existence performance of these networks. This provides **flexibility** in changing parameters like distance between nodes, transmit power level and apply different channel models.
- **Simulations** revealed both Wi-Fi and 5G-NR throughput may degrade based on position and transmit power of the nodes.
- Proposed as part of FY25 scope:
  - Utilize the knowledge gained from experiment/simulation.
  - Develop machine learning (ex. Reinforcement learning) to optimize networks.

Thank You

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