U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

Development of a Technical Basis for a Multi-band Heterogeneous Wireless Network for Nuclear Applications

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
October 29 – November 02, 2023

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Idaho National Laboratory

Project Overview: Purpose

- A multi-band heterogeneous wireless architecture is required for streamlining the data
  - to control systems
  - to digital twin
  - for optimizing maintenance strategies, irrespective of reactor technologies
  - In-pile monitoring under high fluence and high temperature
  - remote center for operation and monitoring.
- This multi-band heterogeneous wireless architecture research and development effort would explore three types of wireless technologies (900 MHz, 2.4 GHz, and 5GHz), their co-existence, strategies to optimize their deployment to ensure coverage and connectivity and perform analysis to support their co-existence and optimal performance.

Project Overview

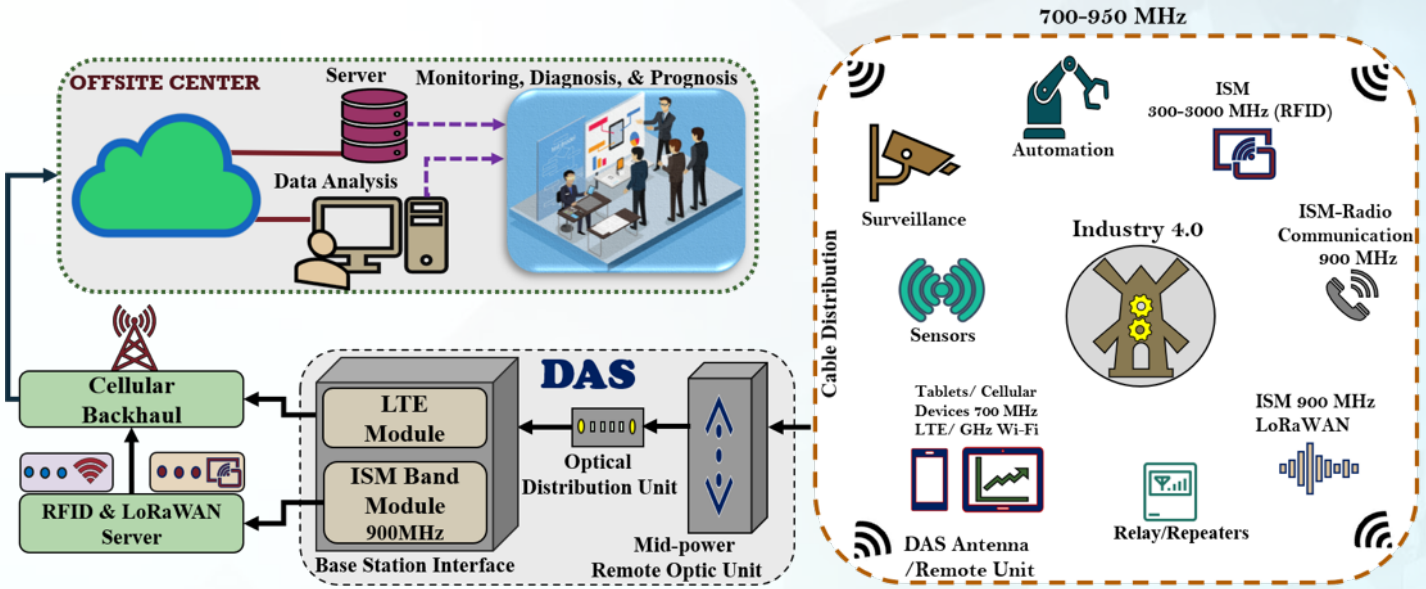
Project Schedule

- March – September 2023

Participants

- **Idaho National Laboratory**
  - Vivek Agarwal (PI)
  - Imtiaz Nasim (New Hire)
- **University of Utah (UoU)**
  - Sneha Kasera
  - Mingyue Ji
  - Syed Ayaz Mahmud (PhD Student)

Technology Impact: Multi-band Heterogeneous Architecture?



Existing Reactors **Advanced Reactors**

Opportunity

- ✓ Wireless communication in Nuclear Power Plant (NPP)
  - ✓ reduces operational risk and industrial hazards
  - ✓ continuous access to plant information
  - ✓ enhance operational efficiency and effectiveness
  - ✓ Achieve connectivity and coverage across the area of interest

Challenges

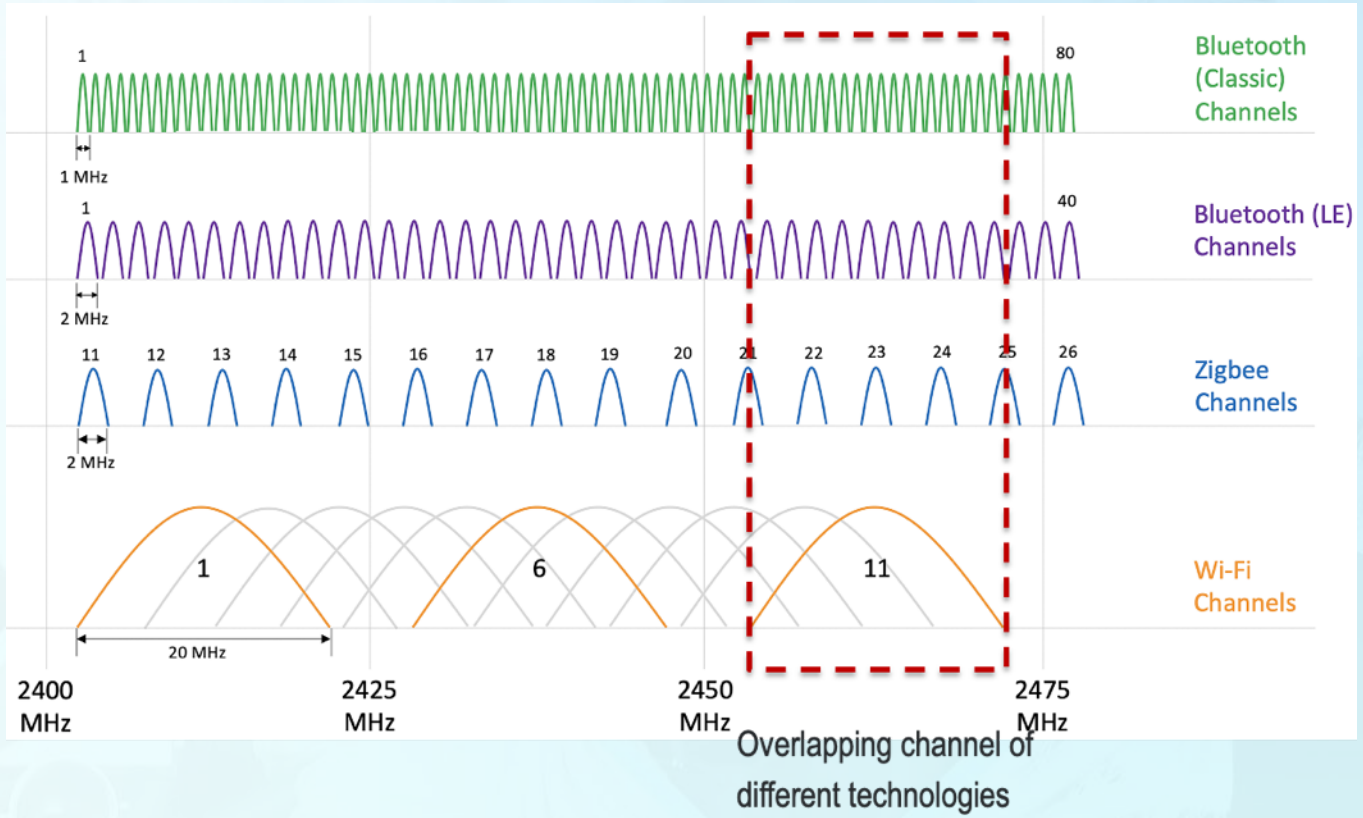
- Heterogeneous applications
  - One-size-fits-all is not applicable
  - Radio frequency (RF) interference
- Stakeholders have less access to wireless information
- Validating received data:
  - Confidentiality, Integrity, and Availability (C-I-A)

Few Networks Used in Nuclear Applications

- Distributed Antenna System, DAS
  - Supports wide range of frequency applications (kHz to GHz) deployment
- Industrial, Scientific, and Medical (ISM) band
  - Operates at wide range of frequencies (MHz to GHz)
  - Used in monitoring, tracking and supervising industrial assets
- Long Range Wide Area Network (LoRaWAN)
  - Low power wide area networking protocol and Works in unlicensed ISM Band

Coverage and Connectivity via Co-existence Wireless Technologies in ISM (2.4GHz) Band

- ZigBee (IEEE 802.15.4)
  - 16 channels (each 2 MHz)
  - Channels can co-exist in same area
- Bluetooth (IEEE 802.15.2)
  - Classic: 80 channels (each 1 MHz).
  - Low Energy: 40 channels (each 2 MHz).
  - Frequency hoping spread spectrum
  - Channels co-exist in same area
- Wi-Fi (IEEE 802.11)
  - Versions a, b, g, n, ac, ax,….
  - 11 channels (each 20 MHz)
  - Channel 1,6,11 are non-overlapping channels



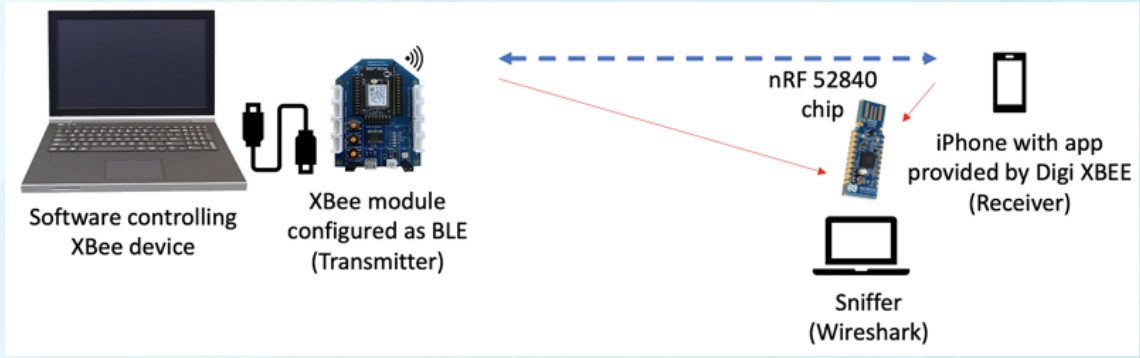
Challenges of Co-existence 2.4 GHz Wireless Protocols

- Interference and frame collision:
  - Supports wide range of frequency applications (kHz to GHz) deployment
- Channel overlap
  - Low power wide area networking protocol and Works in unlicensed ISM Band
- Power levels
  - Operates at wide range of frequencies (MHz to GHz)
  - Used in monitoring, tracking and supervising industrial assets
- Coexistence mechanism
- Quality of service

Results and Accomplishments: Experimental Set-up

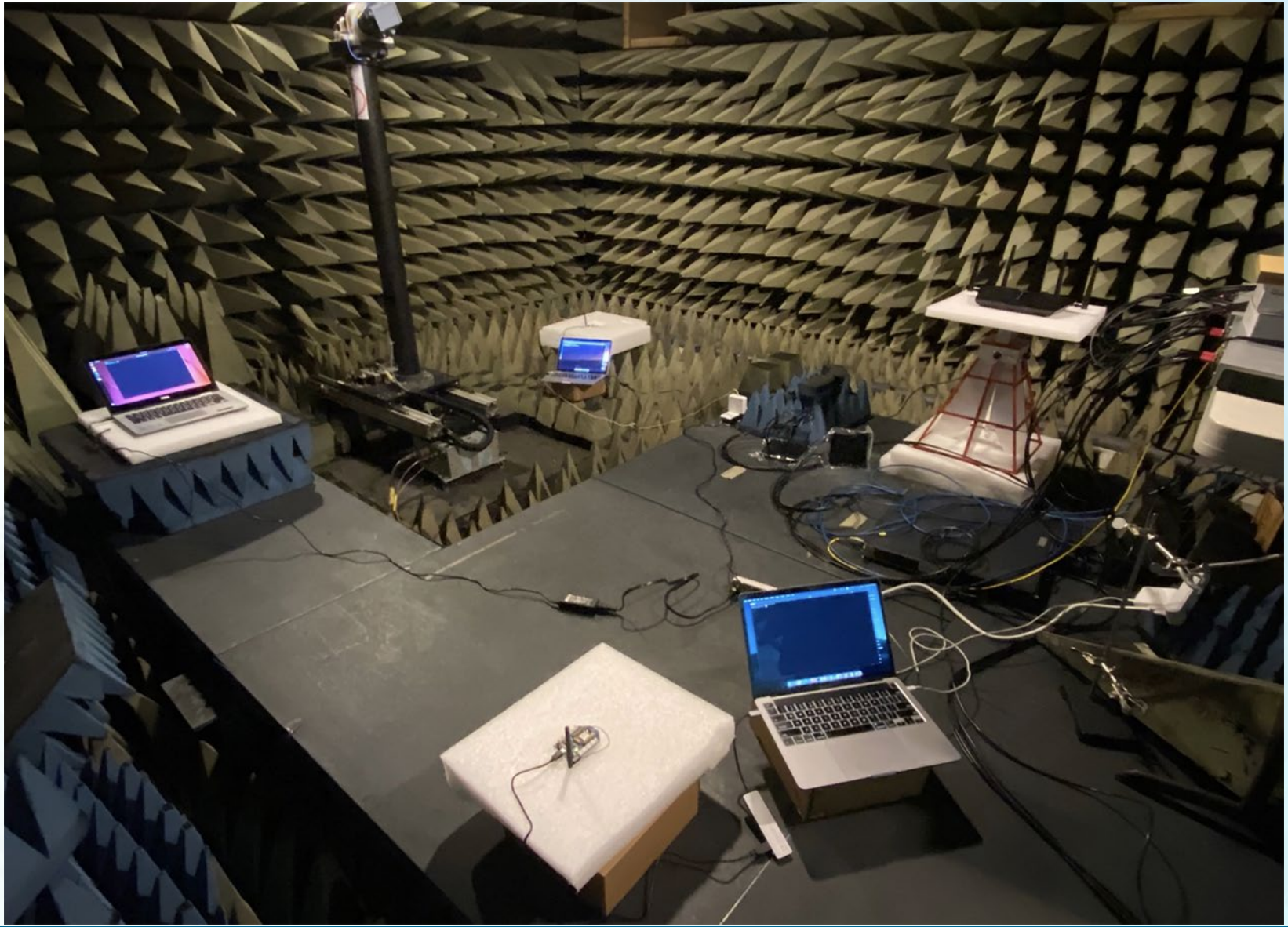
Wi-Fi

Bluetooth



ZigBee

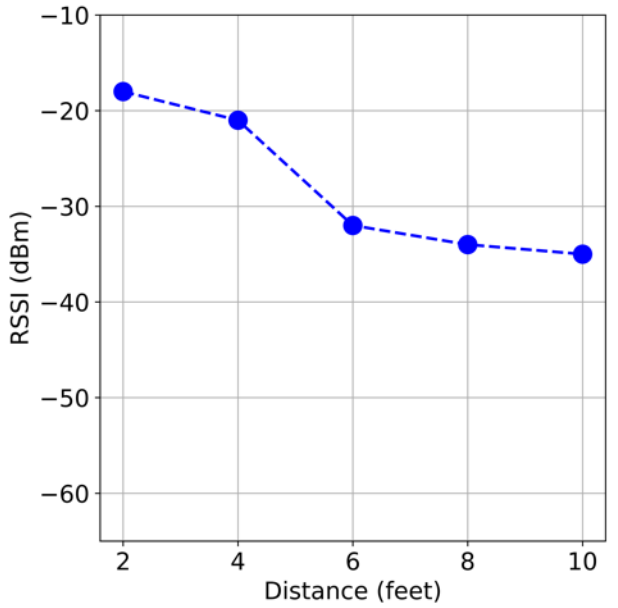
Results and Accomplishments: Experimental Set-up

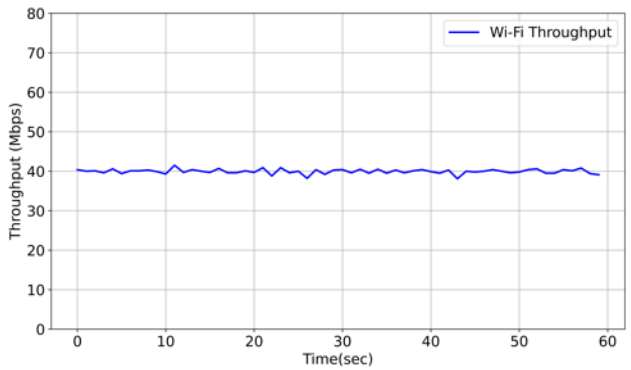


Results and Accomplishments: Baseline Performance

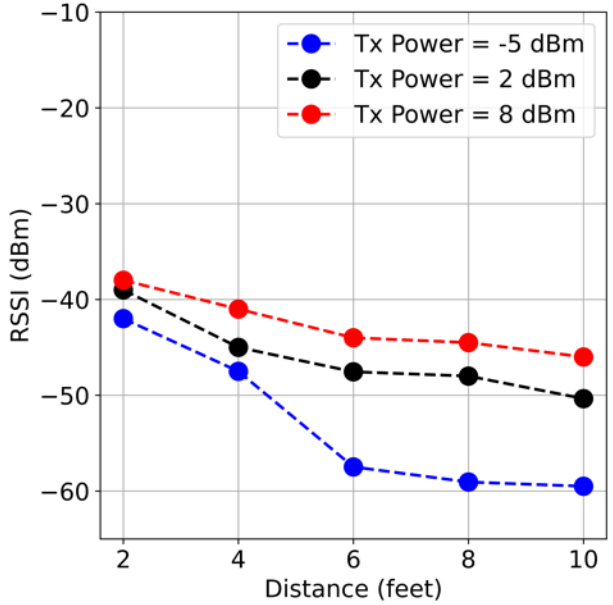
Measuring relative signal strength indication (RSSI) and throughput.

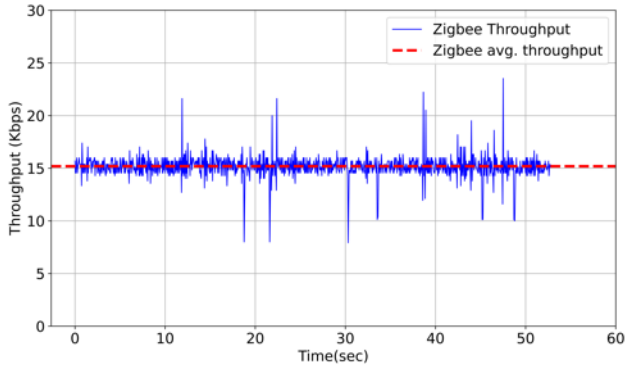
Wi-Fi



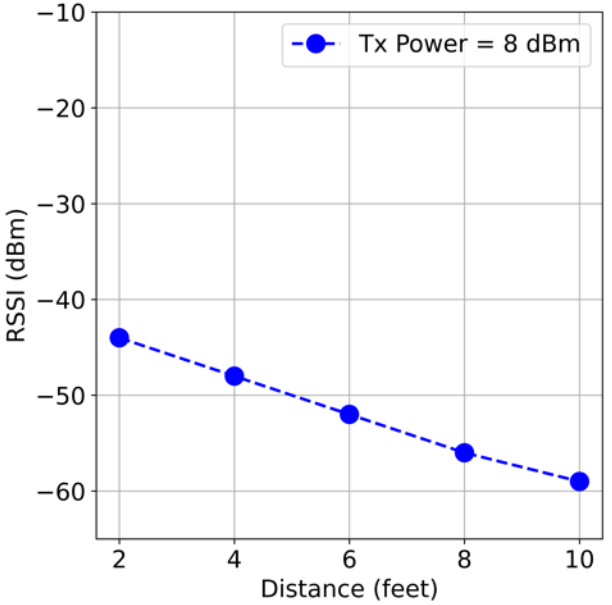


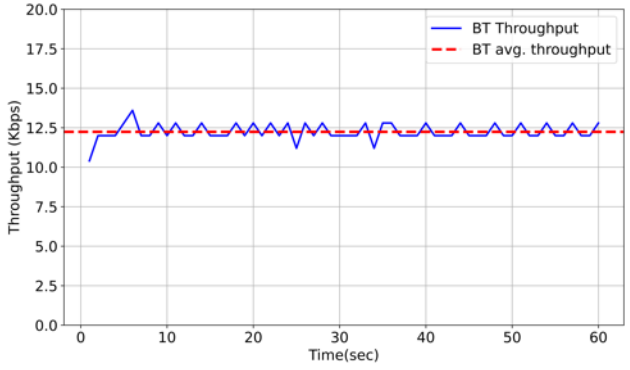
ZigBee





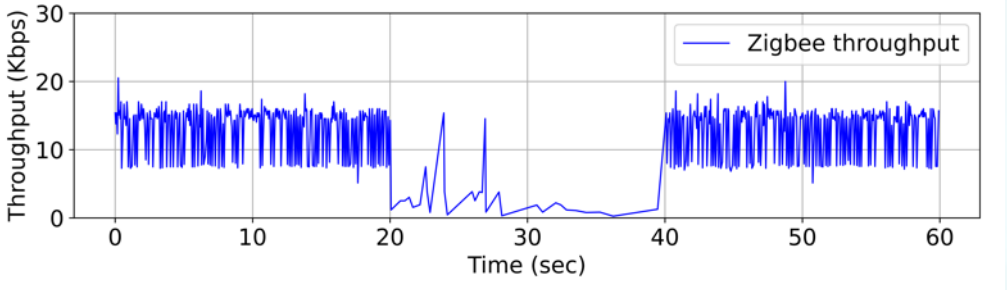
Bluetooth

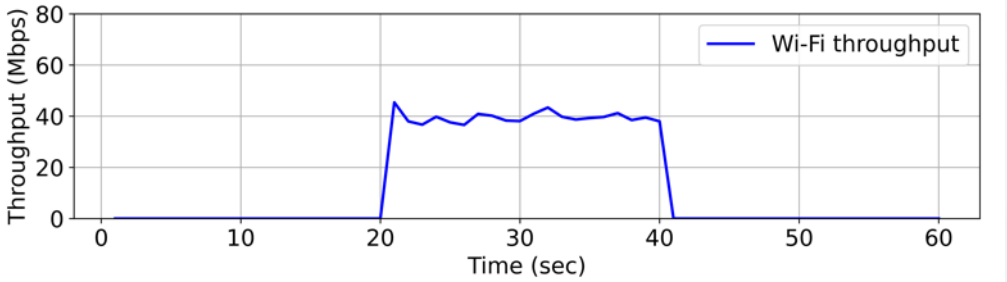


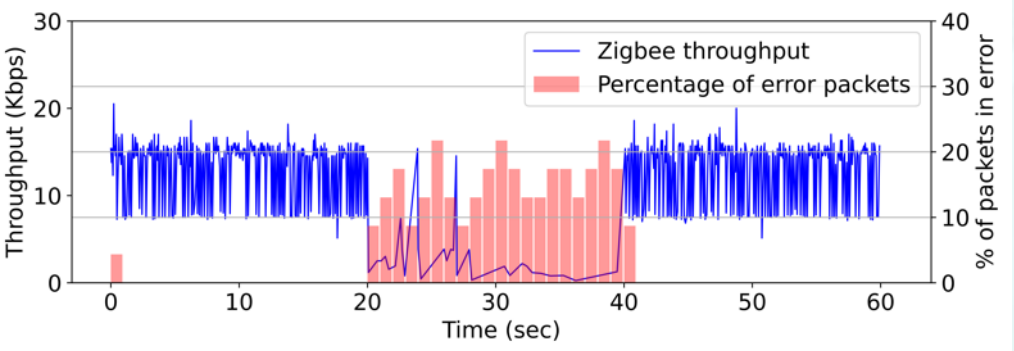


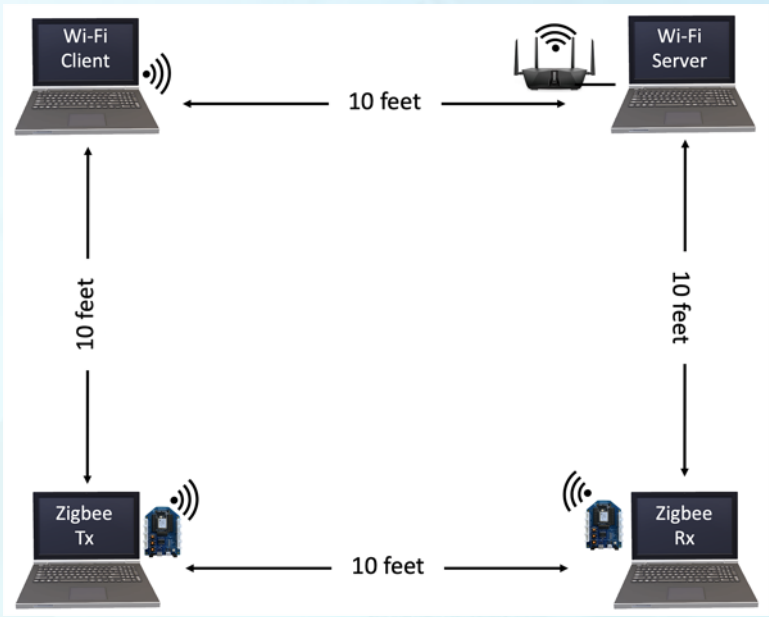
Results and Accomplishments: Wi-Fi and ZigBee Coexistence

Wi-Fi transmission was initiated between 20 and 40 seconds for different transmission rate. Throughput and packet error rate (PER) were measured.





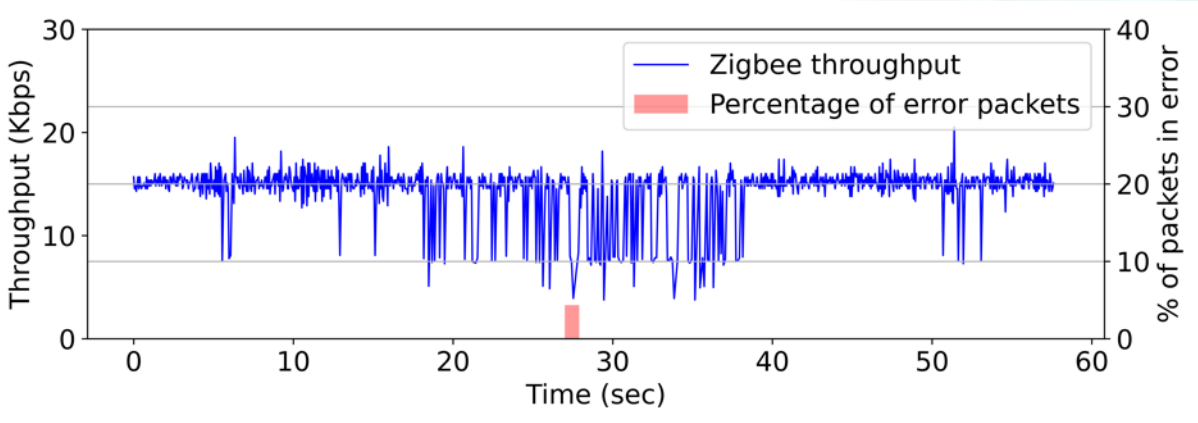




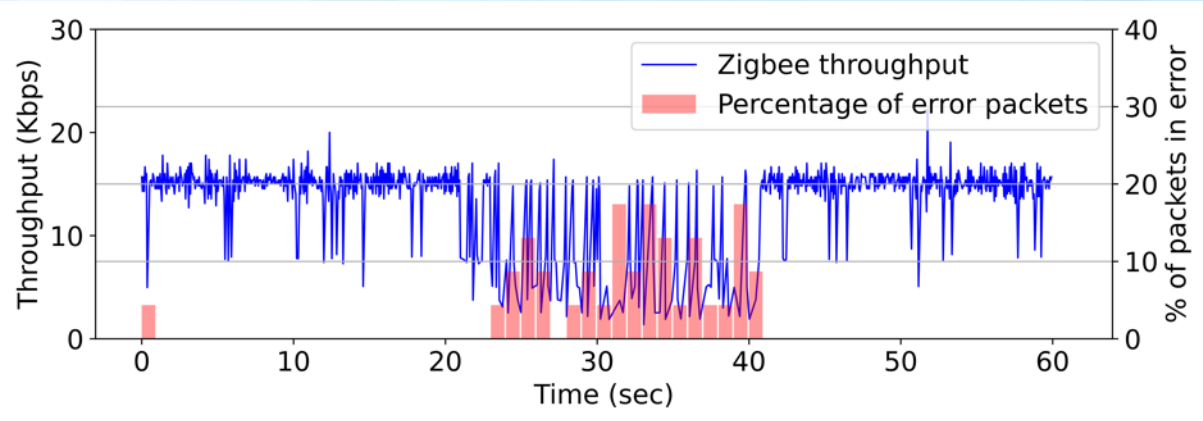
	Wi-Fi Data Rate			
	10 Mbps	20 Mbps	30 Mbps	40 Mbps
ZigBee average throughput	13.17 Kbps	9 Kbps	7.33 Kbps	5.14 Kbps
ZigBee average PER	0.19%	7.31%	10.27%	15.61%

Results and Accomplishments: Wi-Fi and ZigBee Coexistence Varying Data Rate

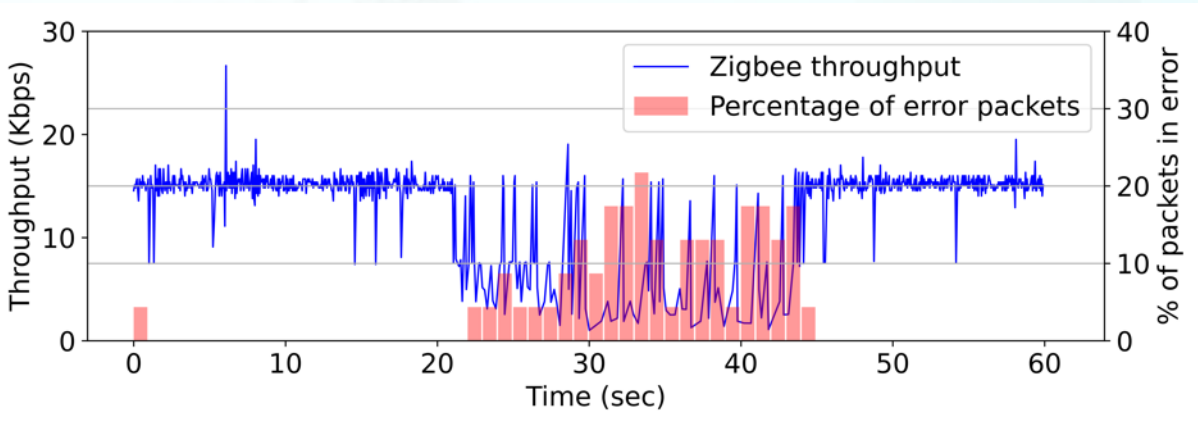
10 Mbps



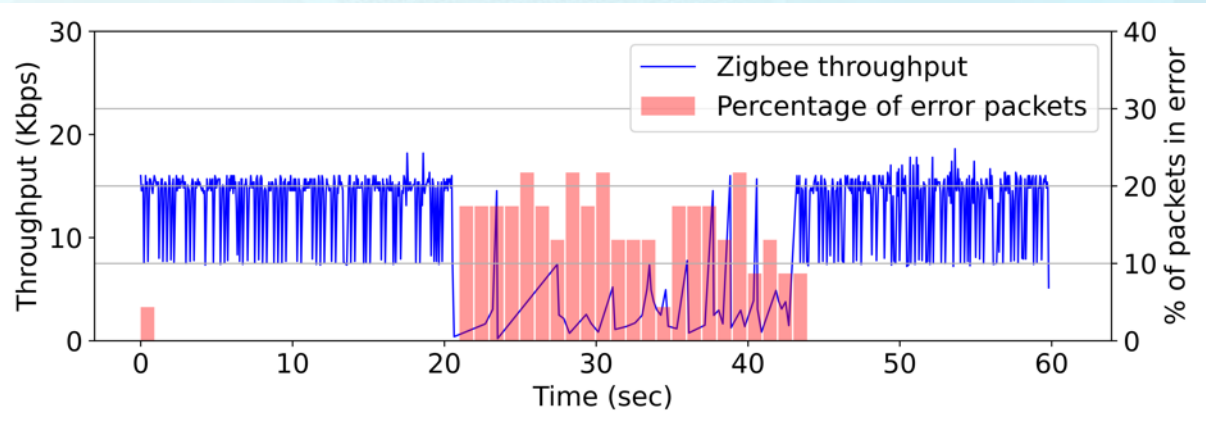
20 Mbps



30 Mbps

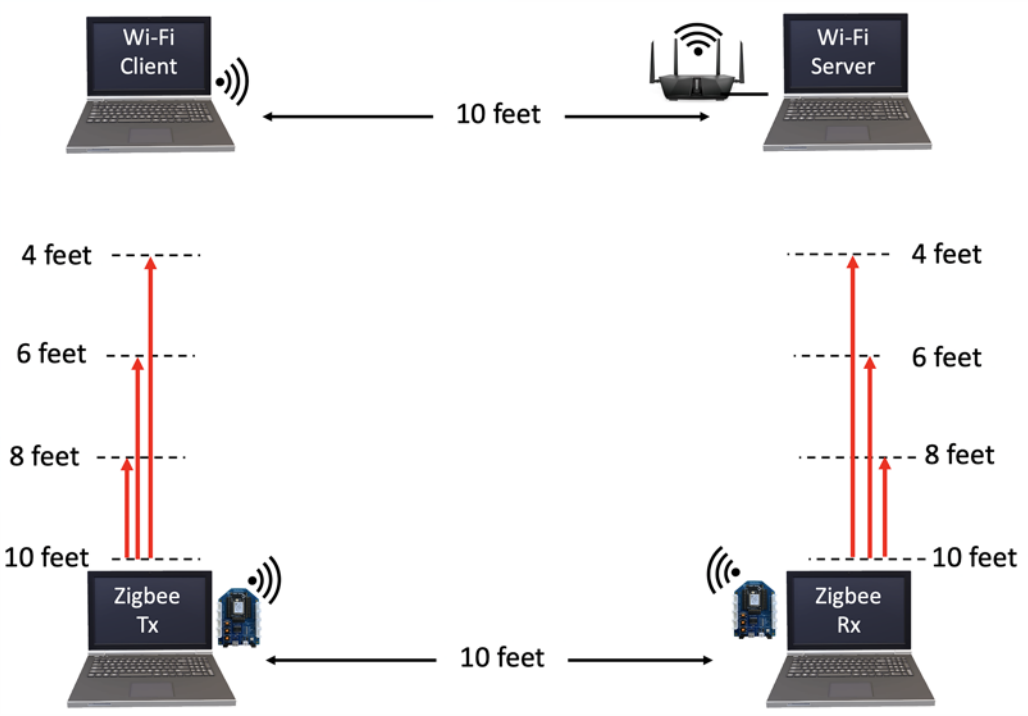


40 Mbps



Results and Accomplishments: Wi-Fi and ZigBee Coexistence Varying Distance and ZigBee Transmission Power

- The distance between Wi-Fi and ZigBee setup was varied.
- The ZigBee transmission power was varied.

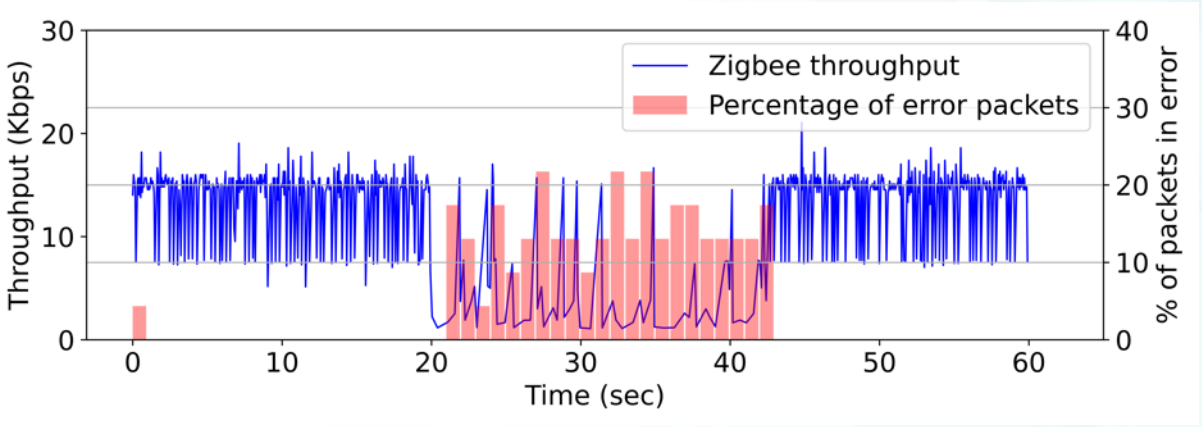


	Distance between Wi-Fi and ZigBee			
	4 feet	6 feet	8 feet	10 feet
ZigBee average throughput	5.37 Kbps	7.18 Kbps	6.86 Kbps	5.14 Kbps
ZigBee average PER	14.42 %	10.86 %	12.64 %	15.61 %

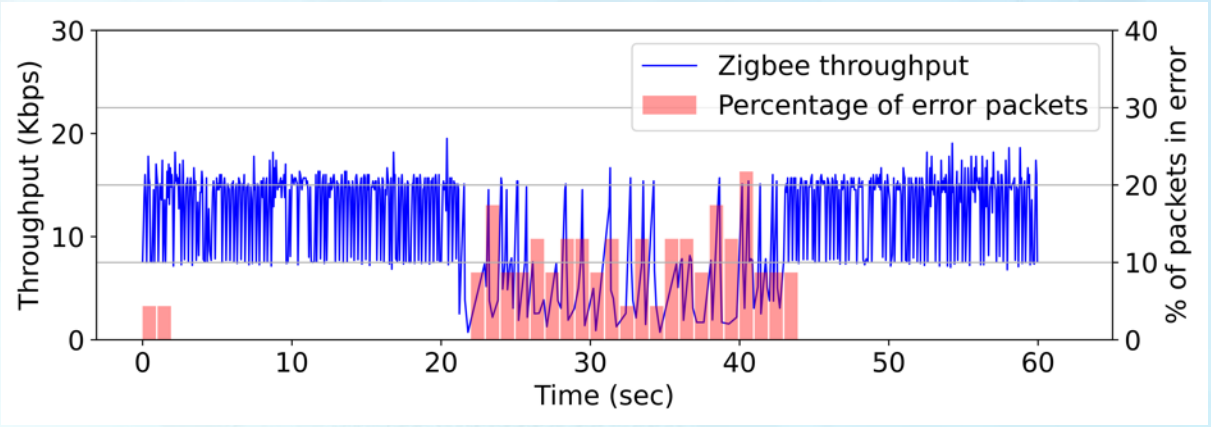
	ZigBee transmit power		
	−5 dBm	2 dBm	8 dBm
ZigBee average throughput	6.14 Mbps	6.10 Mbps	6.15 Mbps
ZigBee average PER	14.42%	14.82%	15.01%

Results and Accomplishments: Wi-Fi and ZigBee Coexistence Varying Distance

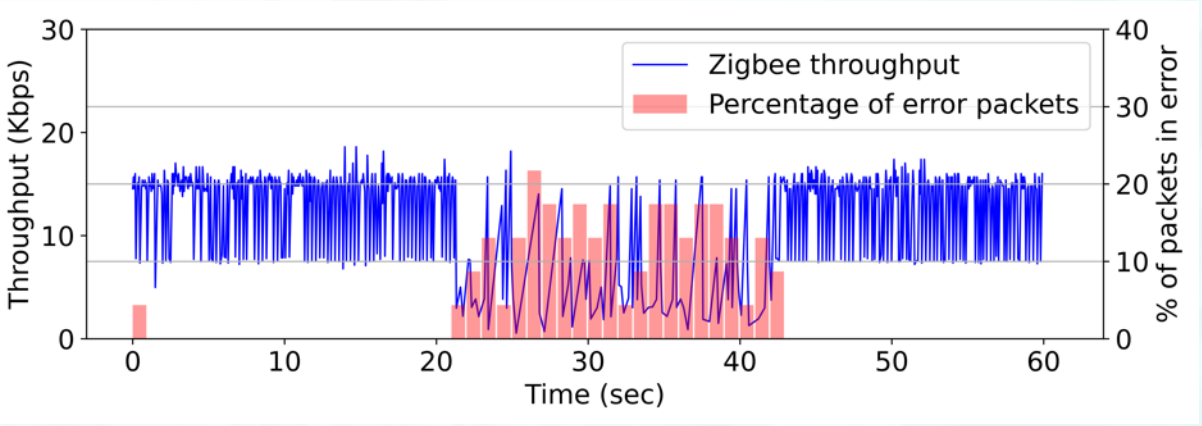
4 feet



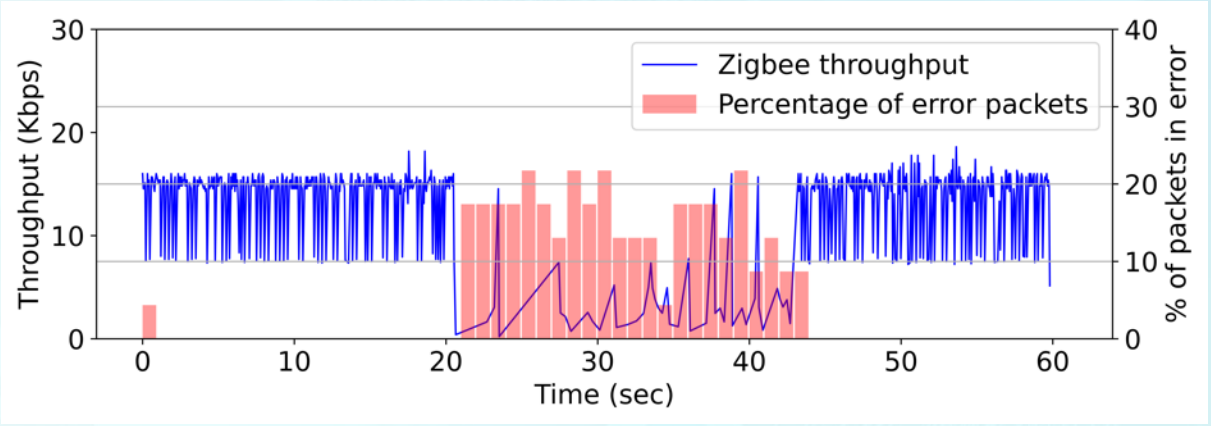
6 feet



8 feet

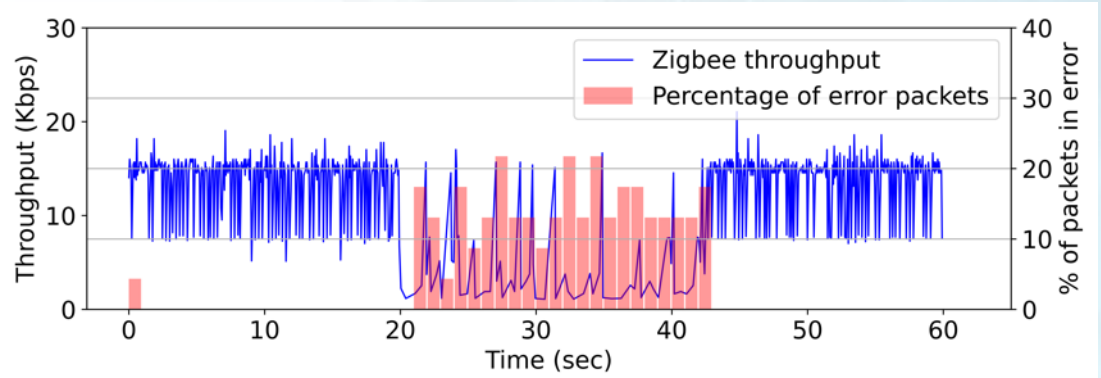


10 feet

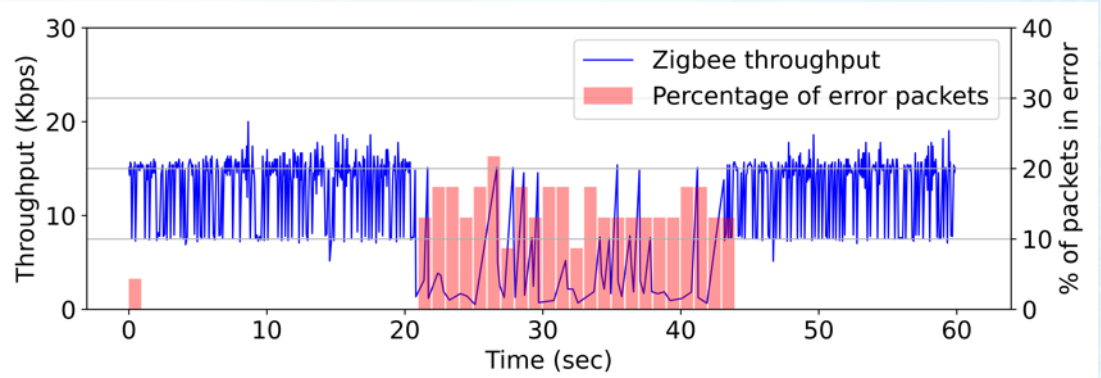


Results and Accomplishments: Wi-Fi and ZigBee Coexistence Varying ZigBee Transmission Power

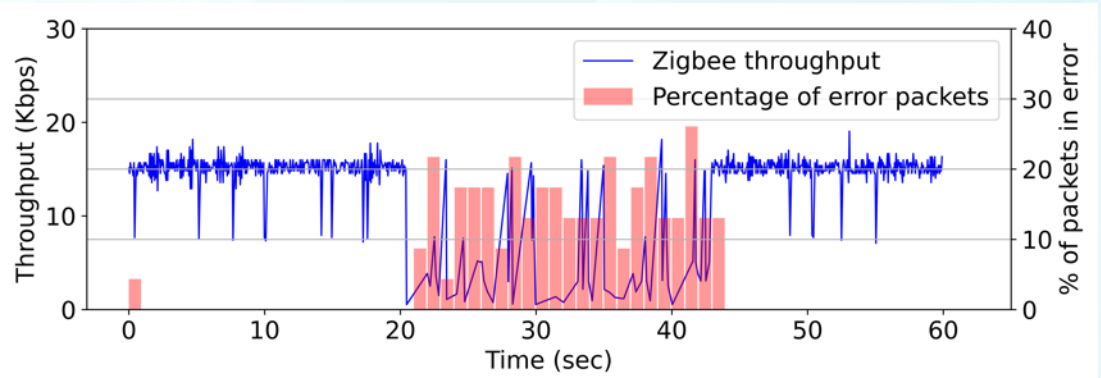
-5 dBm



2 dBm

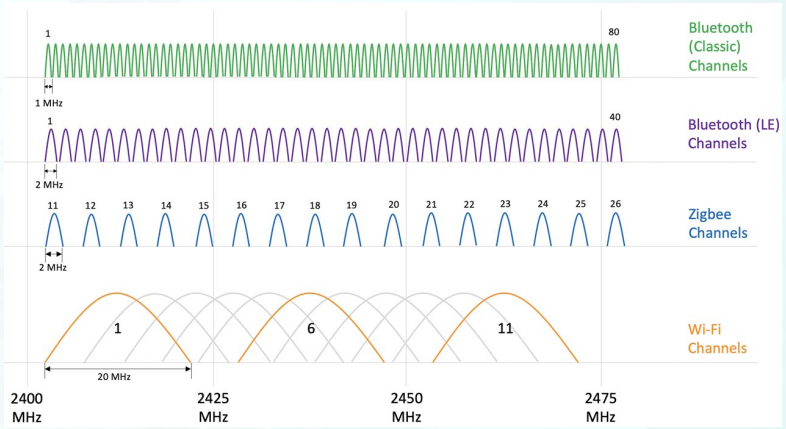


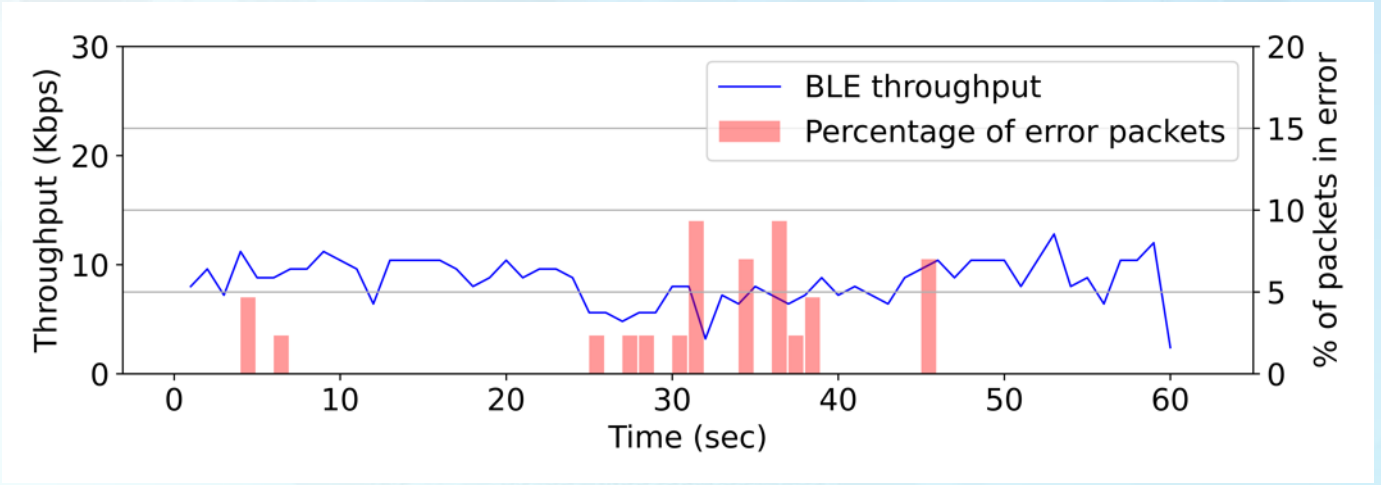
8 dBm

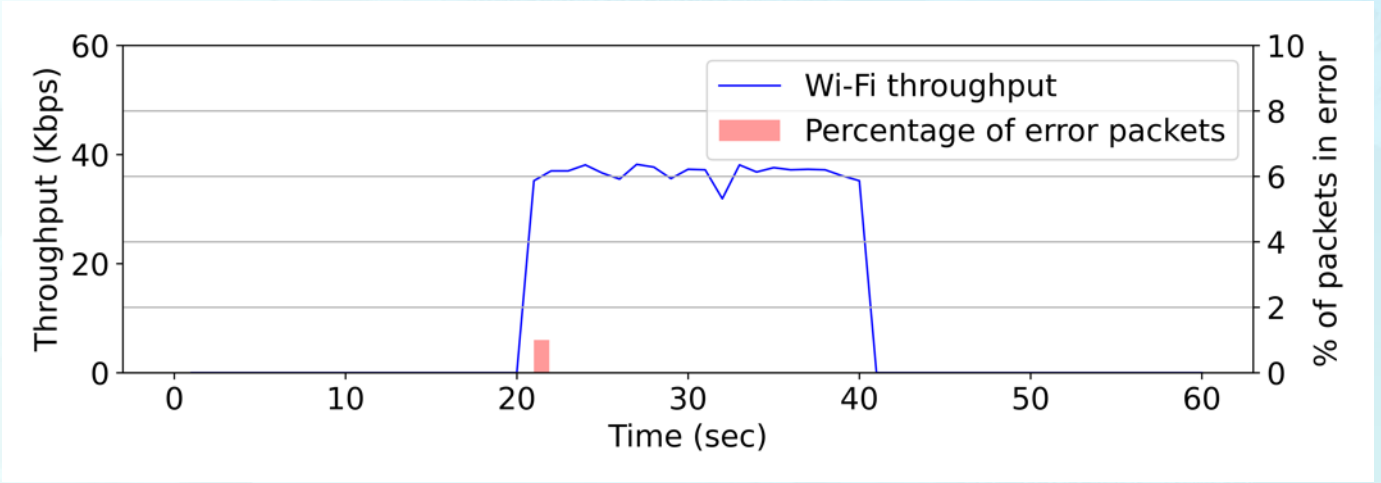


Results and Accomplishments: Wi-Fi and Bluetooth Coexistence

- Wi-Fi channel 6 is selected.
- When Wi-Fi is turned on, Bluetooth low energy (BLE) throughput drops by ~ 41% and PER is observed.
- Alternatively, Wi-Fi performance is robust.

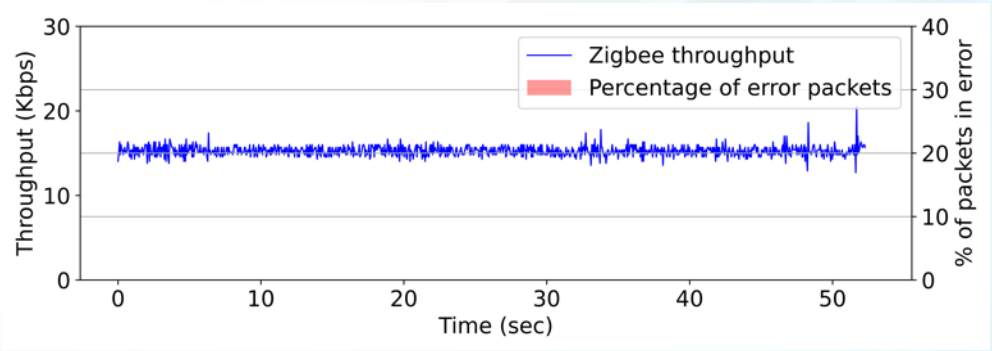


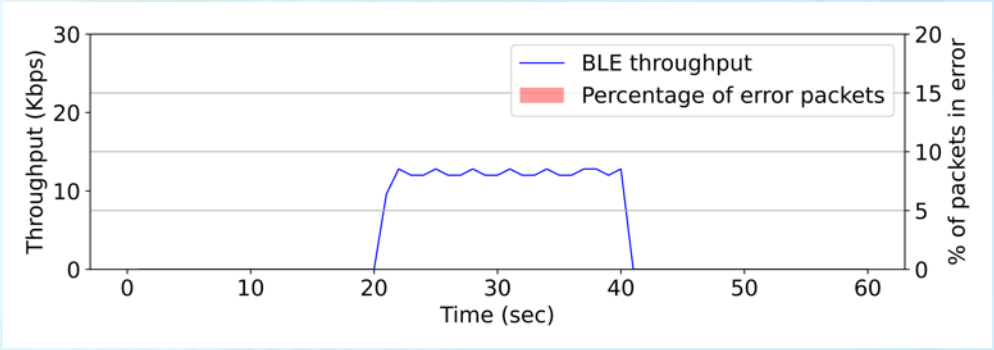




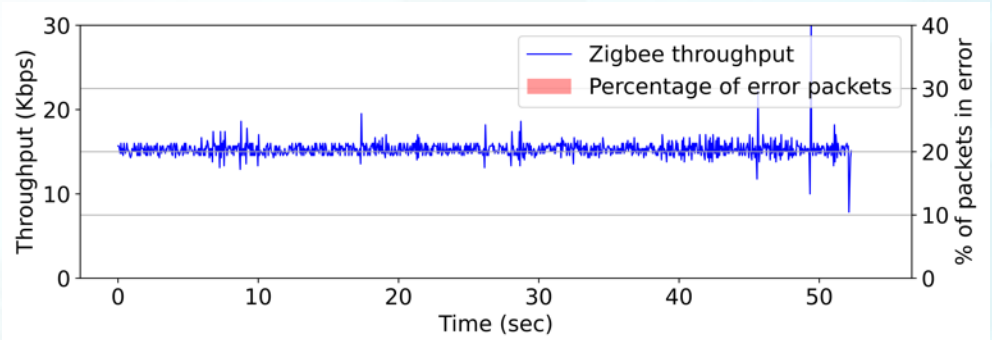
Results and Accomplishments: ZigBee and Bluetooth Coexistence

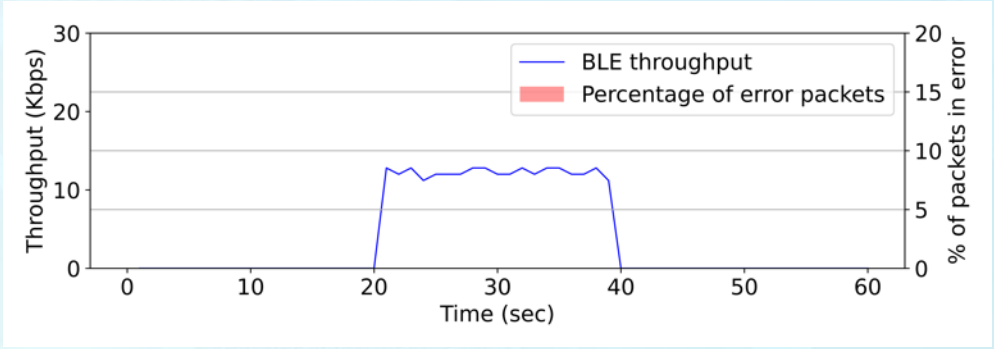
-5 dBm



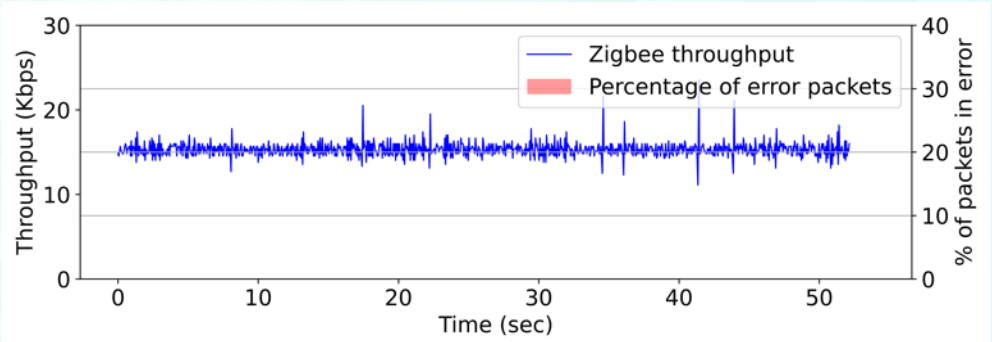


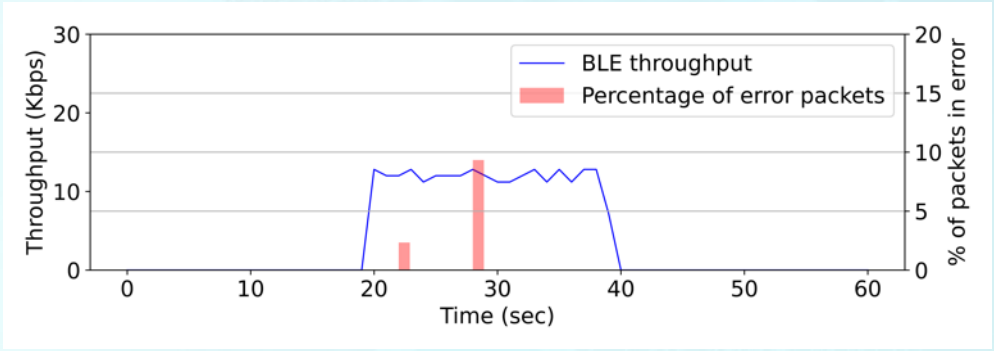
2 dBm





8 dBm





Concluding Remarks: FY24 Research Activities

- Details of the experimental analysis are discussed in detail in the report INL/EXT-23-74719.
- A controlled set of experiments were performed to evaluate co-existence wireless technologies in ISM (2.4GHz) band.
- Wi-Fi interference was observed on ZigBee and Bluetooth low energy performance in terms of throughput and packet error rate when co-existed.
- ZigBee and Bluetooth low energy showed minimal interference and could co-exists.

Concluding Remarks: FY24 Research Activities

- Continue to experimentally evaluate different wireless technologies in different representative environment settings: indoor (controlled) and outdoor (uncontrolled) operating within the 2.4 GHz and 5GHz.
- A series of experiments will be performed for both indoor and outdoor transmission scenarios using commercial-off-the-self wireless sensor nodes and software defined radios operated on the Platform for Open Wireless Data-driven Experimental Research (POWDER) at UoU.
- Utilizing the data obtained from experiments, a learning-based approach will be used to optimize network performance to ensure complete coverage and connectivity within a representative nuclear area.
- The wireless multiband heterogeneous network performance metrics such as packet error rate, throughput, latency, power consumption, and relative signal strength, and others would be evaluated and optimized.

Thank You

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