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

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Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants

Advanced Sensors and Instrumentation Annual Webinar

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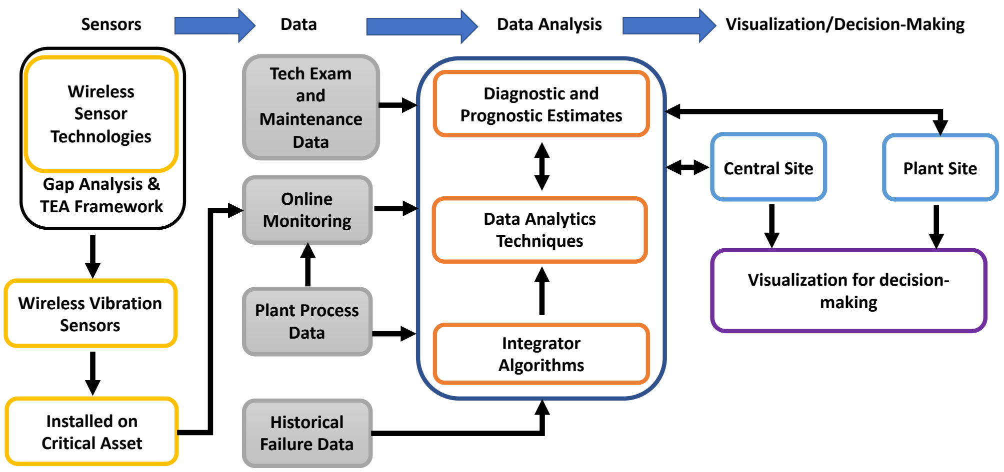
Project Overview—Goals and Objectives

- Goal
  - Advance online monitoring and predictive maintenance in nuclear power plants to enhance plant performance (i.e., efficiency gain and economic competitiveness)



- Objectives
  - Develop a general methodology for techno-economic analysis (TEA) of wireless infrastructure installed at a plant site and used for equipment monitoring
  - Develop diagnostic and prognostic models for an identified balance of plant asset using machine learning techniques
  - Develop visualization algorithms to support informed decision-making
  - Validate developed models and TEA methodologies

Project Overview—Team

- Vivek Agarwal, PhD
- Koushik A. Manjunatha
- Ahmad Al Rashdan, PhD
- Ronald L. Boring, PhD

Idaho National Laboratory INL

- Pradeep Ramuhalli, PhD

Oak Ridge National Laboratory

- Michael Taylor

EPRI ELECTRIC POWER RESEARCH INSTITUTE

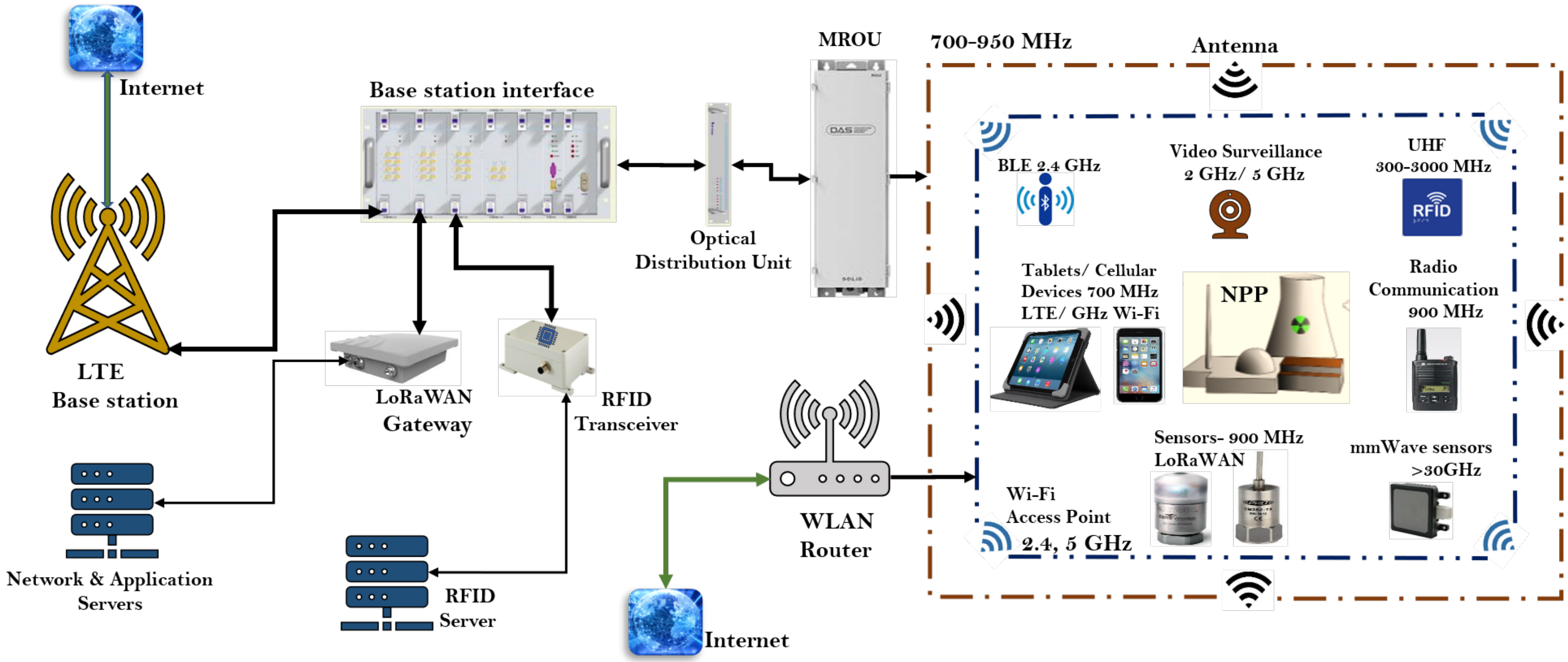
- Scot A. Greenlee
- Richard Weisband

Exelon®

Project Overview—Schedule

- Period of Performance: 10/1/2018 to 9/30/2021
  - **Year 1 (10/1/2018 – 9/30/2019)**
    - **Review of TEA methodologies of wireless infrastructure (INL)**
    - **Identification of balance of plant asset (INL)**
    - **General framework for TEA of wireless infrastructure (INL)**
  - Year 2 (10/1/2019 – 9/30/2020)
    - Wireless sensor modality at a plant site to collect new set of data (INL)
    - Development of integration algorithms and diagnostic models (INL)
    - Development of prognostic models (ORNL)
  - Year 3 (10/1/2020 – 9/30/2021)
    - Visualization tools and development of visualization guidance (INL)
    - Validation and verification of developed models (Team)
    - Development of end state vision on predictive maintenance strategy (Team)

Accomplishments – Envisioned Wireless Infrastructure at a Nuclear Power Plant



MROU : Mid-power Remote Optic Unit
UHF : Ultra High Frequency
mmWave: millimeter Wave

LTE : Long Term Evolution
WLAN : Wireless Local Area Network
BLE : Bluetooth Low Energy

LoRaWAN : Long Range Wide Area Network
NPP : Nuclear Power Plant
RFID : Radio Frequency Identification

- Enable collection, transmission, storage, and usage of plant asset data across different frequency spectrum
- Online equipment monitoring
- Enhance plant performance and situation awareness

Accomplishments – Network Elements

- The whole network topology is predominantly driven by Distribute Antenna System (DAS) or Wireless Local Area Network (WLAN) system

- **Distributed Antenna System, DAS**
  - Use of several antennas as opposed to one antenna
  - Provides wireless coverage to specific area with reduced total power
  - Combination of wireless amplifiers, fiber optic cables and co-axial cables to distribute wireless signals to antennas
  - Supports wide range of frequency applications (KHz to GHz)
  - Supports both indoor and outdoor deployment

- **Wireless Local Area Network (WLAN/WiFi)**
  - Low coverage and limited capacity access points (APs)
  - Works in unlicensed spectrums 2.4GHz and 5GHz
  - Supports bandwidth up-to 160MHz (WiFi-6)
  - Distributes the network capacity by distributing wireless APs

Accomplishments – Network Elements

- **Long Range Wide Area Network (LoRaWAN)**
  - Low power wide area networking protocol
  - Wirelessly connects battery operated low bit rate devices to network
  - Works in unlicensed Industrial, Scientific, and Medical (ISM) Band
  - LoRaWAN signal ranges up-to 10km
- **Bluetooth**
  - Bluetooth operates in the 2.4 GHz unlicensed band
  - Transmits at low power (0 dBm or lower) with a high data rate (up to 2 Mbps)
  - Wirelessly connects battery-operated short-range (up-to 10m) devices to network
  - BLE can connect to the internet through LTE-Cellular or WiFi
- **Radio Frequency Identification, RFID**
  - An automatic identification and data acquisition technology
  - Operates in low frequency(Hz) to ultra-wide band (GHz) frequency
  - Signal coverage between 1m to 100m
  - RFID is used in monitoring, tracking and supervising industrial assets

Accomplishments – Network Features

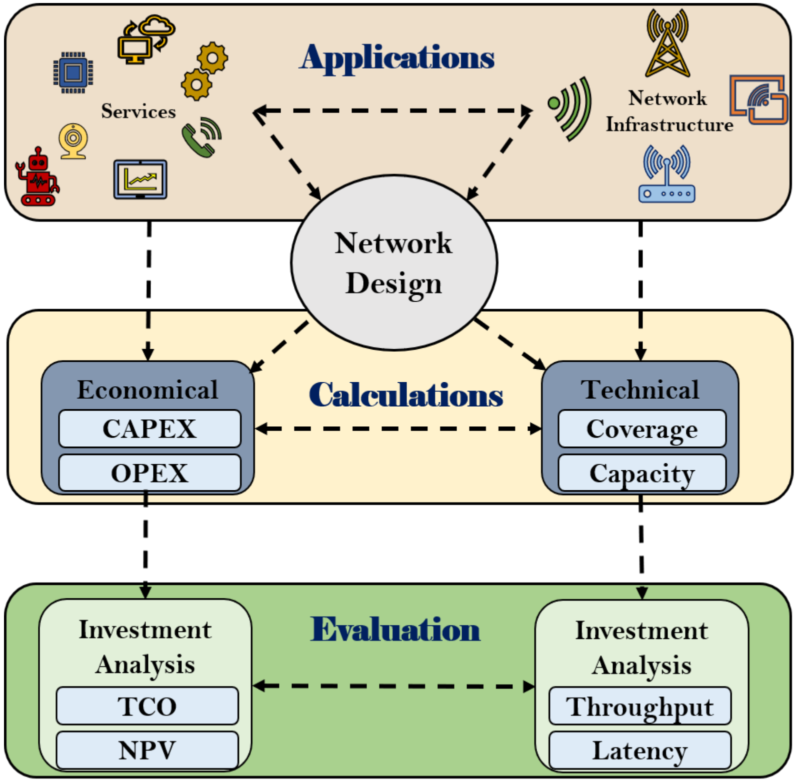
- Applications from
  - low power to high power,
  - low frequency range to high frequency range,
  - short range to long range communication
- LTE-DAS or WiFi can act as a bridge between end-device/other wireless technologies(Bluetooth, LoRaWAN etc.) and the internet or outside network
- Easy network maintenance by bringing all the networking technologies under one network architecture
- High bandwidth and data transmission rate with low latency
- Prioritized data transmission based on required Quality of Service
- Customized security and networking protocols development

Accomplishments – TECHNO-ECONOMIC FRAMEWORK

- Techno-economic analysis framework is used to examine
  - feasibility of proposed network technology
  - cost effective way of traffic offloading and uploading
- Network modelling
  - The number of APs/DAs estimated using
    - Required network capacity
    - Coverage area

$$\max\{\#(AP/DA)_{Area}, \#(AP/DA)_{Capacity}\}$$

- Cost estimations
  - Capital expenditure (CAPEX) on installation and deployment
  - Operation expenditure (OPEX) on network maintenance

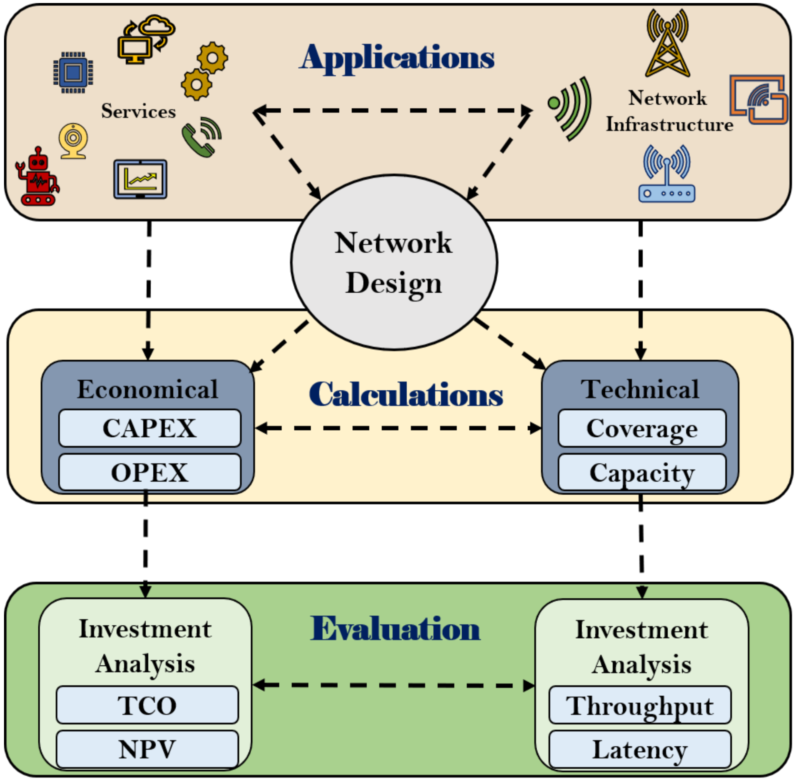


Accomplishments – TECHNO-ECONOMIC FRAMEWORK

- Investment analysis
  - Total Cost of Ownership, TCO
  - Net Present Value, NPV
- Total Cost of Ownership, TCO
  - Defines total network deployment expenditure

$$TCO = CAPEX + OPEX$$

- Net Present Value, NPV
  - ***NPV = Profit - CAPEX***
  - Estimate of cost of an investment in present value terms
  - Indication of profitable deployment
- Performance evaluation
  - Network throughput
  - Average packet delay



Accomplishments – TECHNO-ECONOMIC EVALUATION

- DAS deployment
  - LTE cellular with base station (BS)
  - LoRaWAN with LoRa-gateway
  - RFID with RFID-gateway

- CAPEX includes costs related to
  - DAS equipments (for example: Number of Das)
  - Cellular BS and evolved packet core (optional)
  - LoRa-gateway and RFID-gateway

- OPEX includes costs related to
  - Power consumption of network components
  - Cellular back-hauling
  - Network component repair and replacement

Accomplishments – TECHNO-ECONOMIC EVALUATION

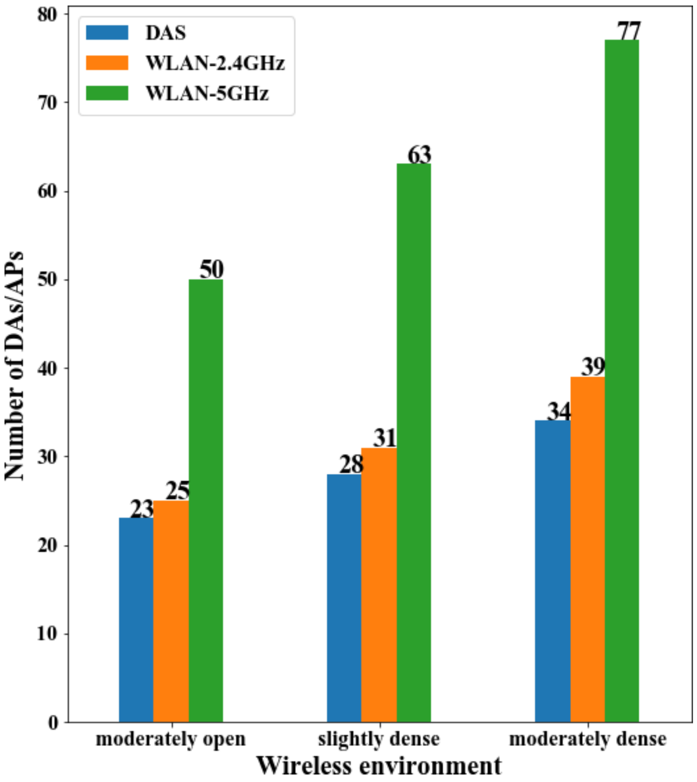
- WLAN deployment
  - Cost model mainly depends on number of APs

- CAPEX consists
  - Cost of an access point and number of access points
  - Network backhauling
  - Network equipment cost such as routers and switches

- OPEX consists
  - Power consumption of network components
  - Network component repair and replacement

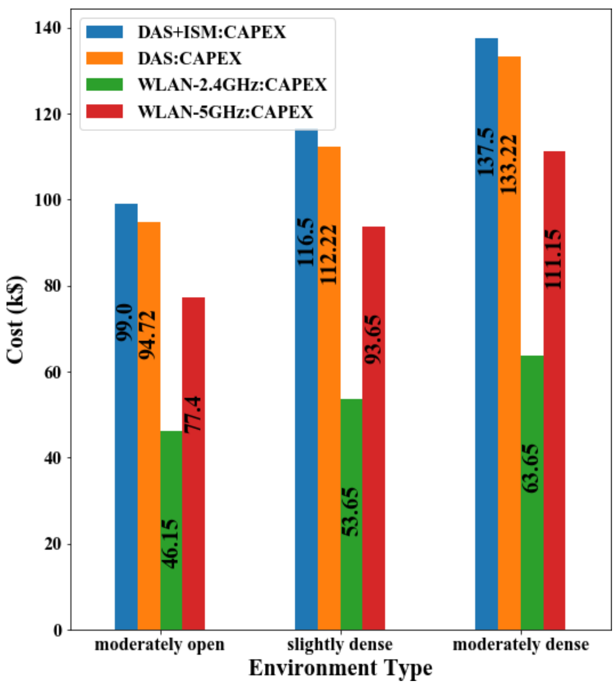
Accomplishments – TECHNO-ECONOMIC EVALUATION

- Number of WLAN access points and DAS antennas based on different environment conditions
  - Moderately open
  - Slightly dense
  - moderately dense
- WLAN with 5GHz requires more number of APs due to fast signal degradation
- Dual band WLAN can give better coverage at the edge location and capacity close to APs
- WLAN with 2.4GHz gives approximately similar coverage compared to DAS

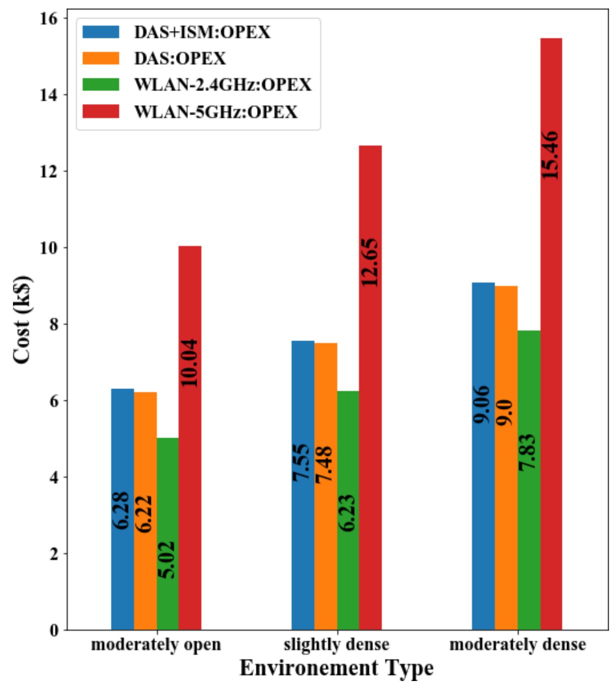


Accomplishments – Cost Analysis

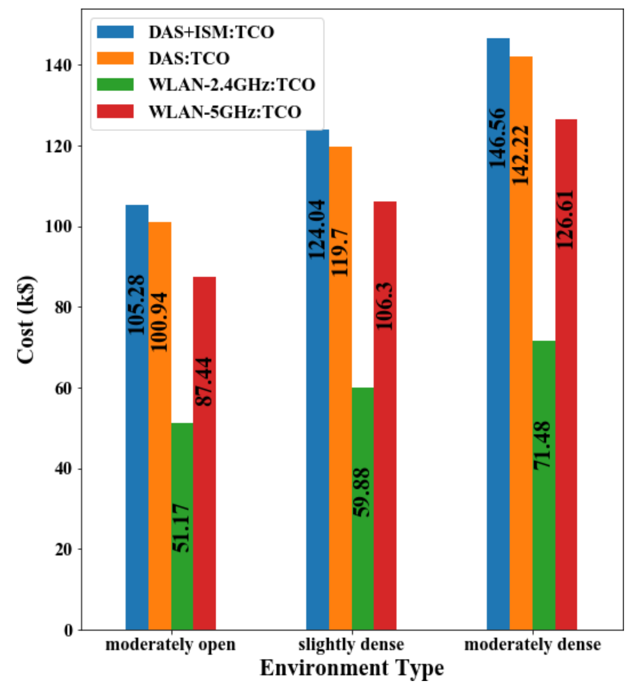
- DAS CAPEX is expensive due to expensive DAS components
- OPEX is estimated on annual basis
- Very thin cost margin between DAS with and without ISM band



CAPEX



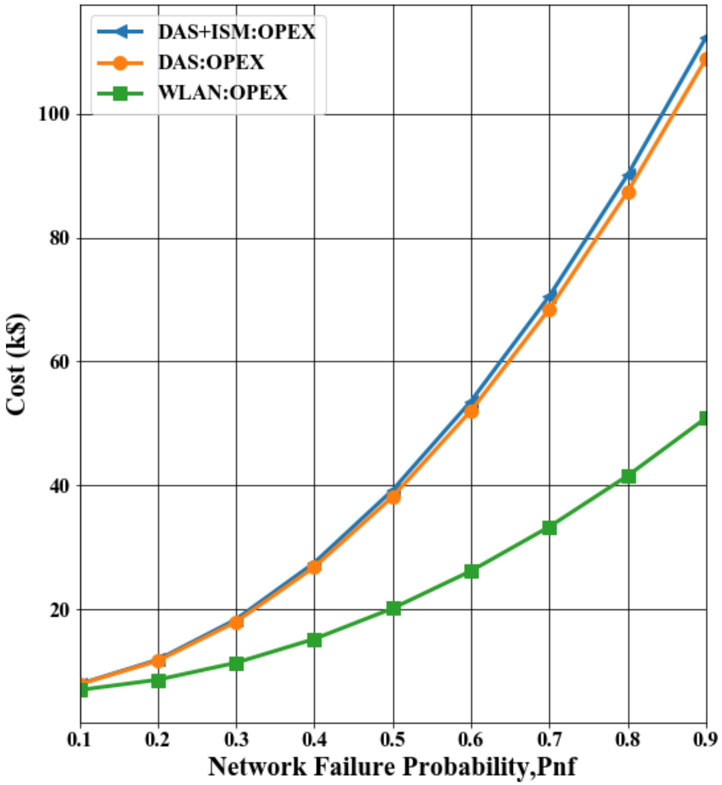
OPEX



TCO

Accomplishments – Cost Analysis

- Network Component repair and replacement cost
  - Failure probability equal to 0 : Component is perfect (minimal maintenance)
  - Failure probability equal to1 : Component need to be replaced



Accomplishments – Network Performance

- Network throughput
  - The rate of successful data transmission
    - number of bits sent through the network per second
  - Depends on channel condition, number of users and data transmission mechanism such as modulation, bandwidth etc.

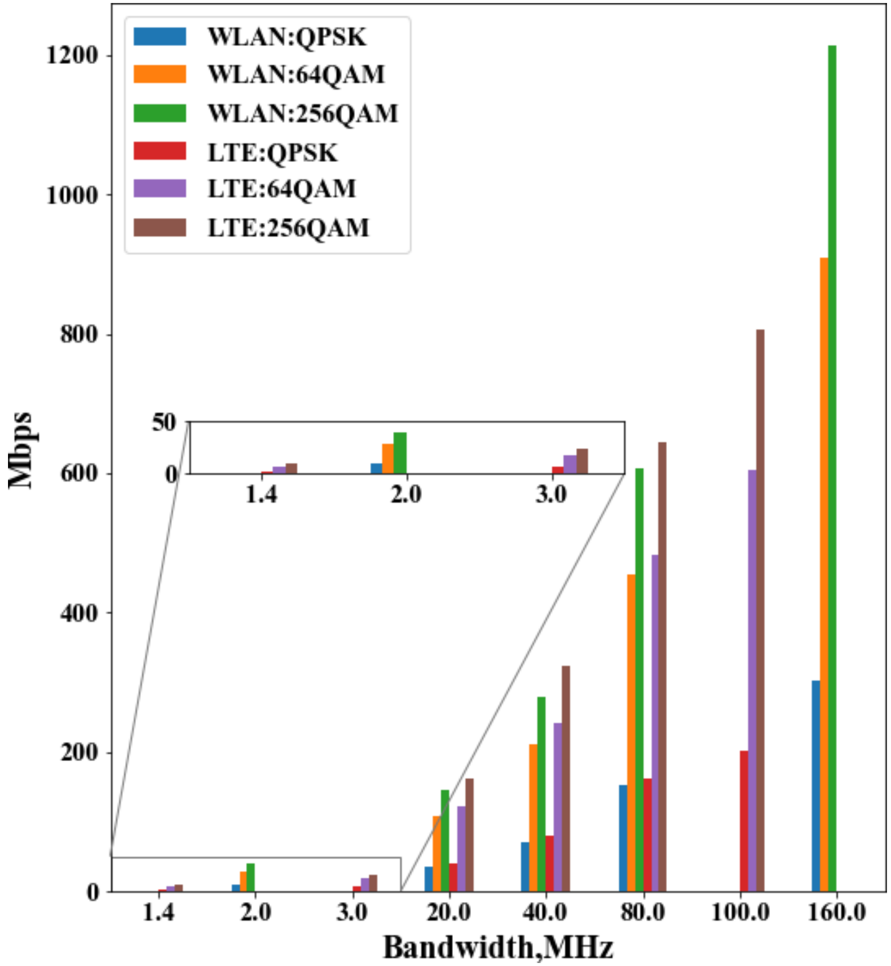
- Higher the throughput better the Quality of Service

- Latency
  - Delay, $\boldsymbol{E}[\boldsymbol{W}]$ experienced by the data to be sent over the network
  - Depends on network throughput, number of users
  - Also depends on channel access mechanism (MAC protocols)

- If $\boldsymbol{E}[\boldsymbol{W}] > \boldsymbol{W}_{\boldsymbol{delay,th}}$, the data will be discarded

Accomplishments – Network Performance

- Throughput per AP and DAS structure is determined for
  - Modulation: QPSK, 64-QAM and 256-QAM
  - Bandwidth:
    - 1.4MHz and 3 MHz (for low power and low data rate IoT applications)
    - 20MHz and 40MHz low data rate applications (ex. Skype)
    - 80 MHz and 160 MHz for high data rate applications(ex. 4K video)
- Both WLAN and DAS can support up to 9-Gbps data rate under high modulation



Accomplishments – Network Performance

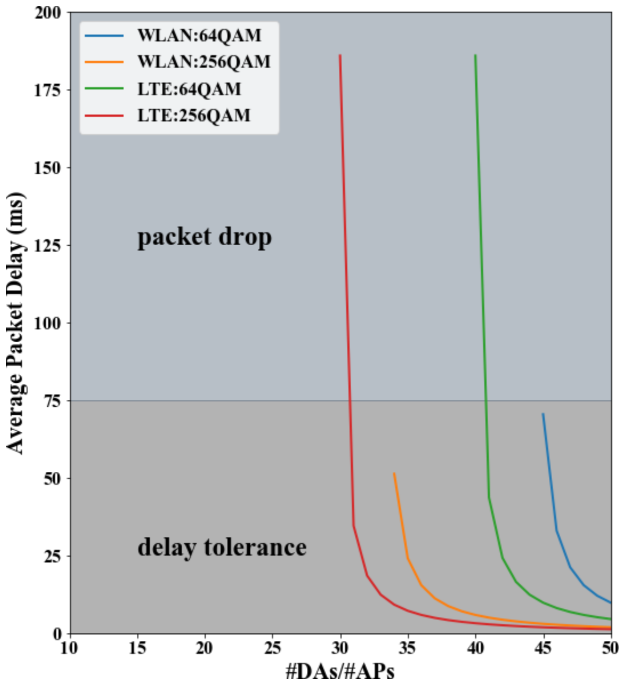
- Network latency is determined for following types of data transmissions
- To increase the capacity of network for low latency, the number of DAs/APs should be increased.

Application	Required data-rate	Required latency
HD Video	8Mbps	75ms
Real-time video conference	1Mbps	100ms
Machine to Machine (M2M) communication	50kbps	1ms

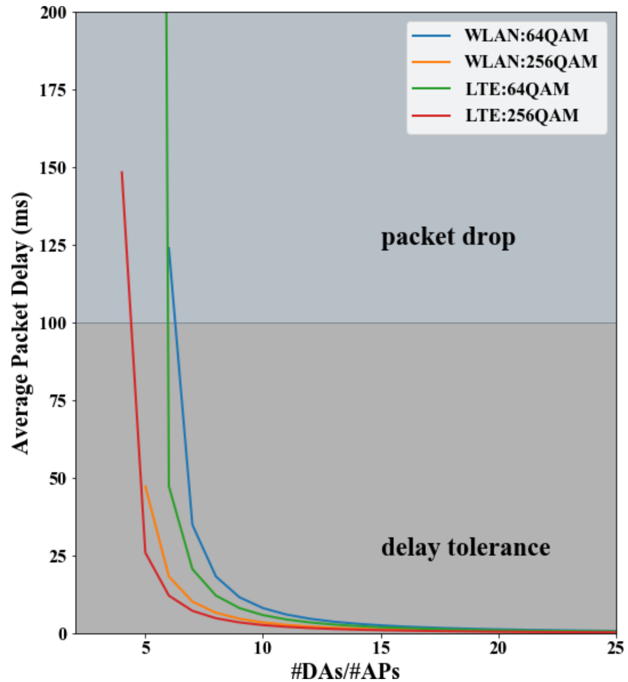
- Higher bandwidth per application can decrease network latency but spectral efficiency also decreases

Accomplishments – Network Performance

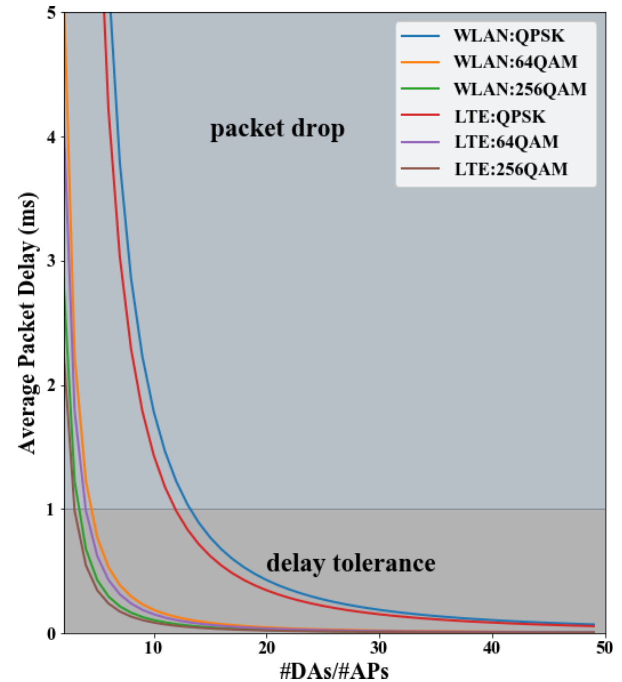
- Latency calculation under different number of DAs/APs
- High-definition video requires large bandwidth



HD-Video



Real-Time Video



M2M Communication

Accomplishments – Feedwater and Condensate System

- Exelon identified Feedwater and Condensate system as a target plant asset for this project
  - Calvert Cliff Nuclear Power Plant (Pressurized Water Reactor)
  - Dresden Generating Station (Boiling Water Reactor)

- Data to be shared with project team for past 10 years
  - Plant process computer data
  - Maintenance records
  - Notification logs and work orders
  - Diagrams and procedures

- Focus is on condensate pumps, booster pumps, feedwater pumps, and main condenser

Technology Impact (1)

- *Advances the state of the art for nuclear application*
  - Advances online monitoring at a nuclear plant site for different plant assets
  - Provides machine learning approaches to integrate and analyze heterogeneous structured and unstructured data (i.e., analytics-at-scale)
  - Visualization of information to make informed decision-making
- *Supports the DOE-NE research mission*
  - Enhance reliability and economic operation of domestic existing fleet
  - Research outcomes can be utilized to develop maintenance strategy for next generation of advanced reactors
  - Develop talent pipeline (interns, post doctoral researchers) to support future nuclear work force

Technology Impact (2)

- *Impacts the nuclear industry*
  - Enable industry to transition from preventive maintenance strategy to predictive maintenance strategy
  - Provide a framework to perform TEA evaluation of the wireless infrastructure at a nuclear plant site with different network elements, if not all.
- *Will be commercialized*
  - **The outcomes of this research will be scaled to facilitate commercialization** because the research is focused on single plant asset.
  - Project team will develop a transition plant to enable transfer of research outcomes to an industrial partner

Conclusions

- Presented an envisioned wireless infrastructure with different network elements
- Performed review of TEA methodology for different wireless communication protocols
- Developed a general TEA framework for the envisioned wireless infrastructure
  - Simulation analysis was performed
- Identified Feedwater and Condensate System as a target balance of plant asset for development of predictive maintenance
- Working with Exelon to gain access to plant process computer data, maintenance records, and other relevant information on the feedwater and condensate system for past 10 years
  - Calvert Cliff Nuclear Power Plant
  - Dresden Generating Station
- *Vivek.Agarwal@inl.gov any additional questions that may not be answered during the webinar.*

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