

# Performance Estimation, Testing, and Control of Cyber-Physical Systems Employing Non-Ideal Communications Networks

Richard Candell

PhD Thesis

28 September 2020

# About Me



Richard Candell has over twenty years of experience in telecommunications system engineering with extensive experience in the design and evaluation of wireless communications systems. Mr. Candell spent twelve years developing, testing, and deploying secure wireless technologies for commercial and defense applications. He served as the lead systems engineer in developing spread spectrum interference cancellation and performance evaluation strategies for satellite ground stations and mobile phased array beam steering transceivers. He holds patents in successive interference cancellation and transmission burst detection applied to spread-spectrum satellite communications signals. Mr. Candell holds a BS and MS degree in Electrical Engineering from The University of Memphis. He joined the NIST in 2014. His current research interests include the performance impacts of wireless networks on industrial sensing and actuated control applications for mobile robotic, manufacturing, and safety applications. Mr. Candell was the primary contributing author of the Guide to Industrial Wireless Systems Deployments (NIST AMS 300-4) and the chair of the NIST Industrial Wireless System technical working group.

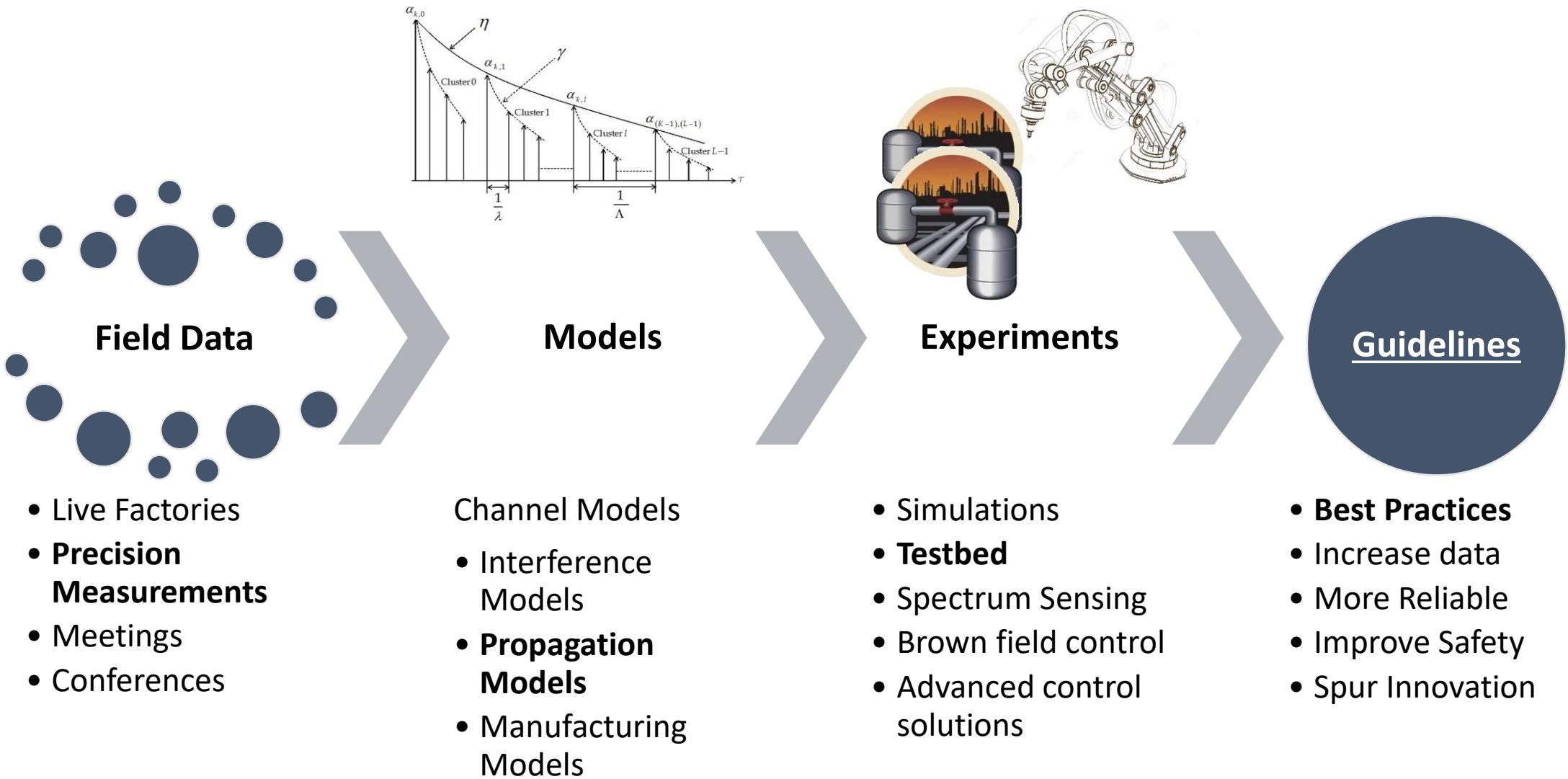
# The NIST Industrial Wireless Project – A Context for Research

*Performance Estimation, Testing, and Control of Cyber-Physical Systems Employing Non-Ideal Communications Networks*

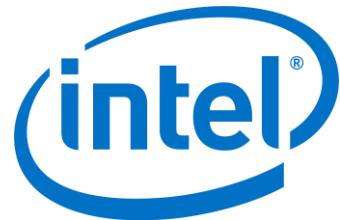
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# Historical Approach



# Collaborators: Past and Present



Honeywell

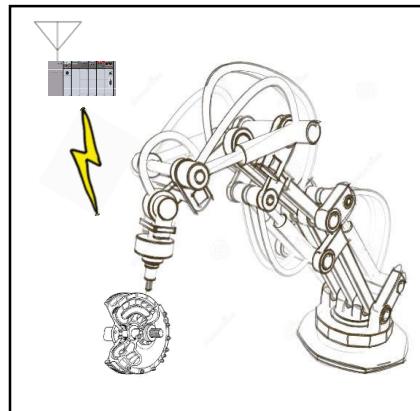
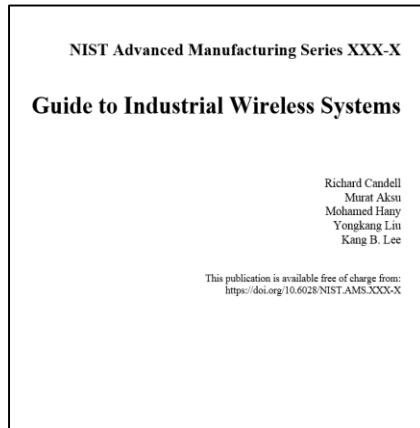


# Technical Working Group Established

- IEEE Sensors Applications Symposium
- Established March 13, 2017
- Key Participants at the time
  - Boeing
  - ABB
  - IEEE
  - ISA
  - NIST

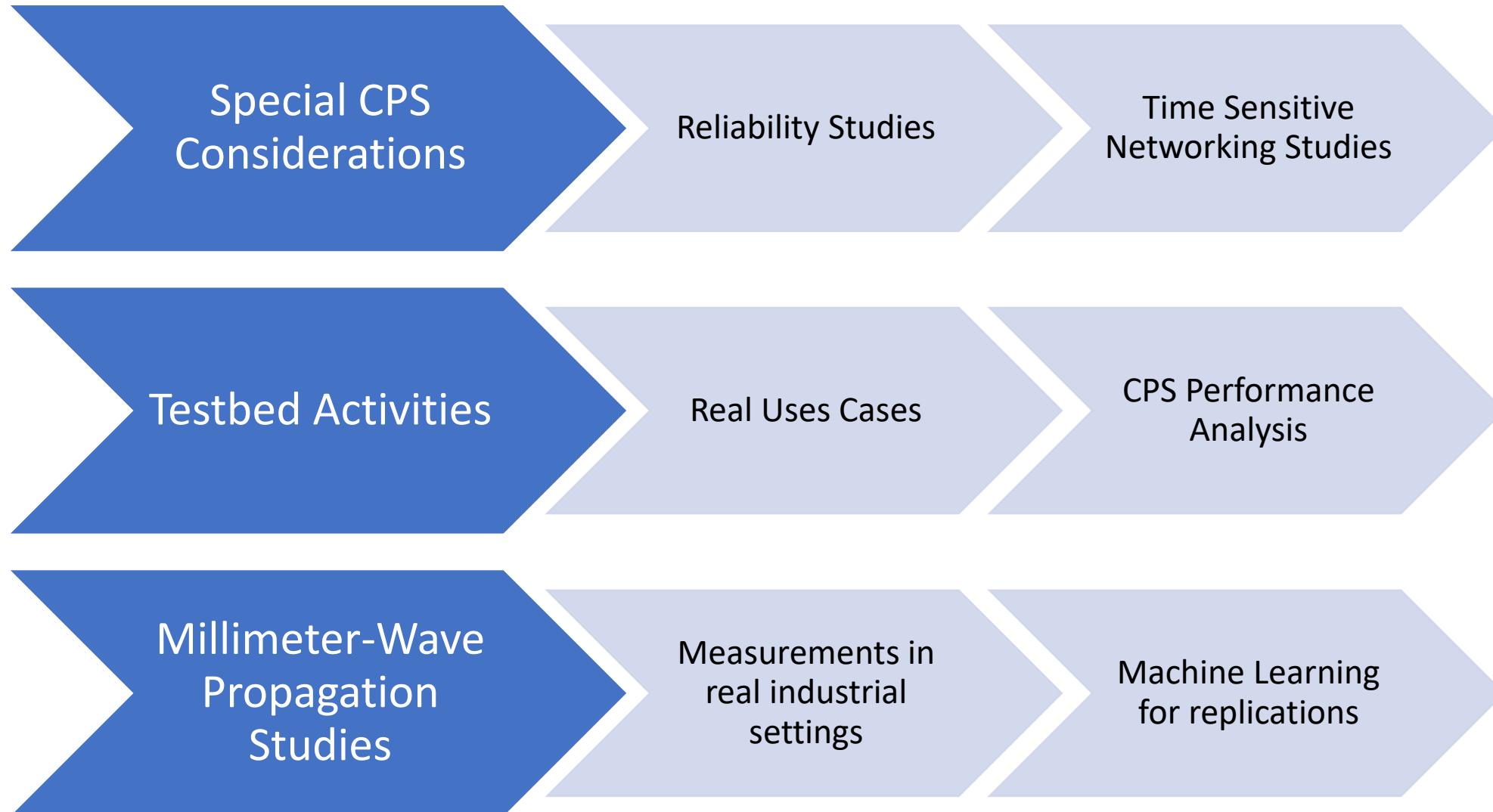


# Current Project Objectives: Two Tracks



- **Track 1: Provide Guidance to Industry**  
Deliver comprehensive, measurement science-based guidelines in the selection, deployment, and optimization of the wireless technologies in specific manufacturing environments.
- **Track 2: Address Emerging Needs**  
Conduct research that advances the state of technology of wireless-based automation systems in which time, reliability, energy, and scale are joint considerations.

# Addressing Emerging Needs



# The NIST Industrial Wireless Testbed

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# Key Capability: *RF Channel Emulator*

- Transmission Delay
- Path loss
- Multipath
- Fading
- Interference
- Mobility Radios
- Mobile Surroundings



Recreates the Factory's Radio  
Environment in the Lab

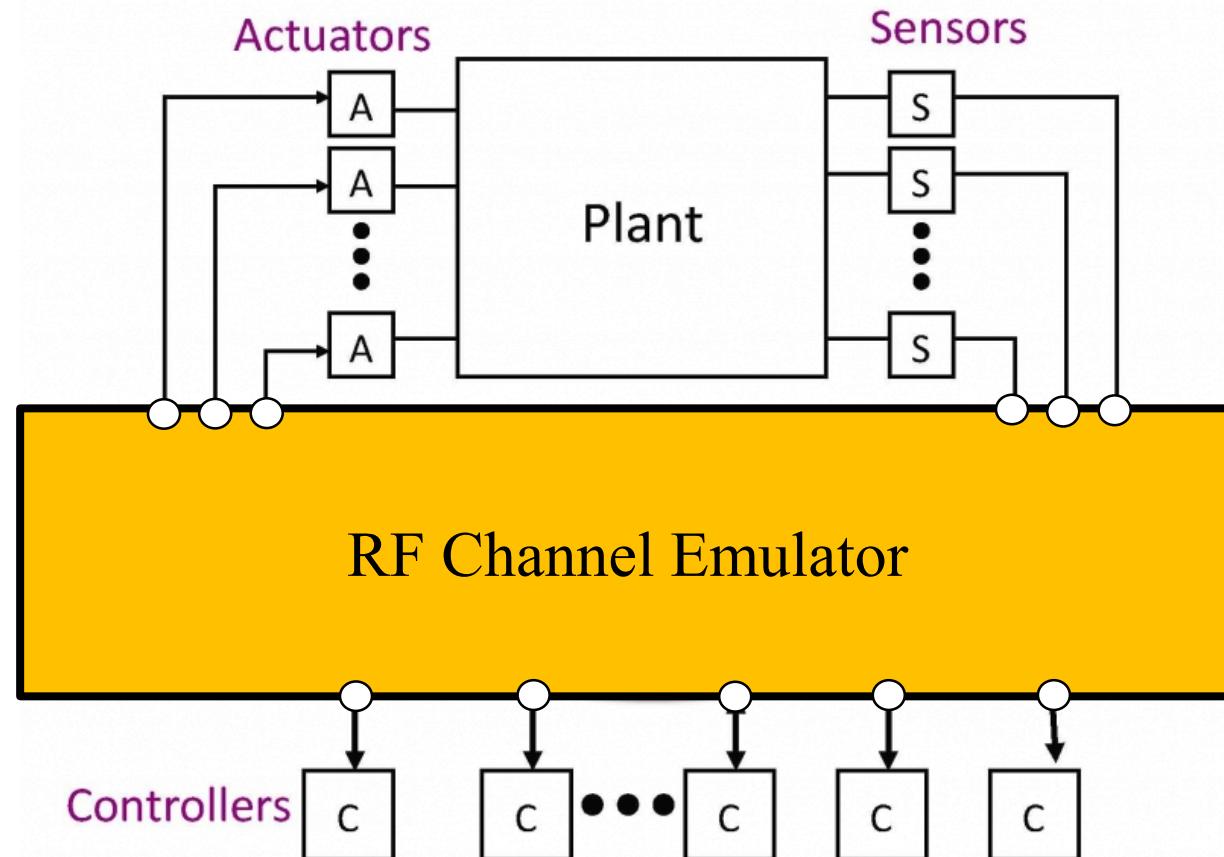
# Recreating the Factory RF Environment in the Lab

## Radio Environment

- Metal, Conduits, Pipes
- Absorptives
- Path loss & reverb.
- Machine Noise
- “Friendly” interference
- Jamming (security)

## Possible Focus Areas

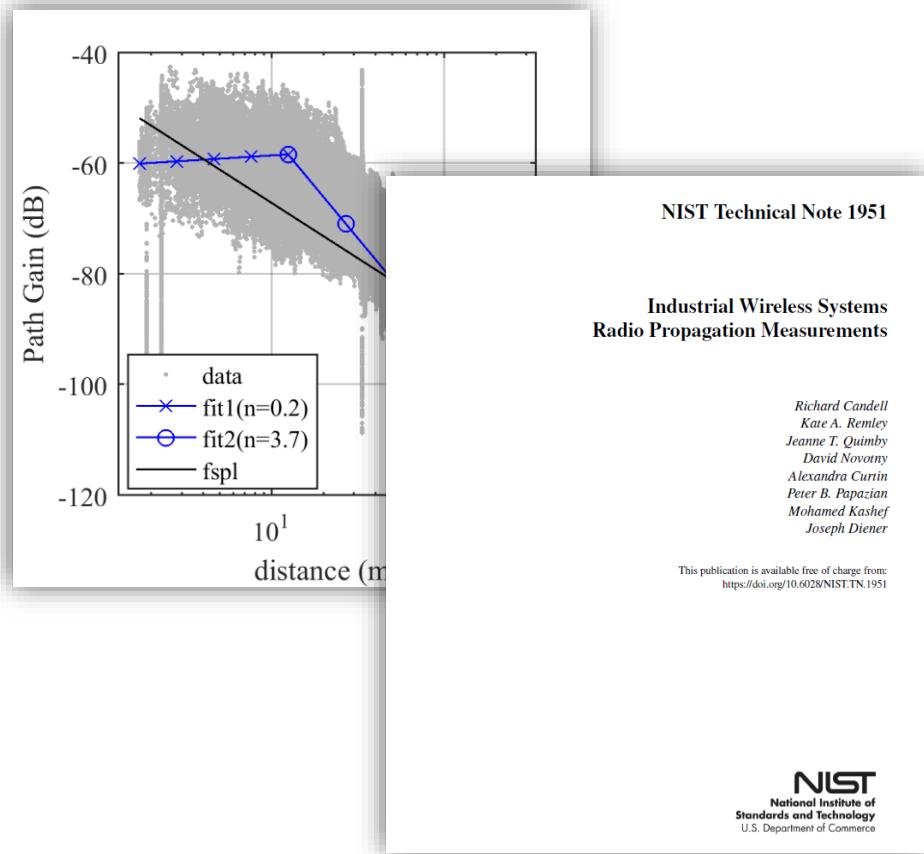
- Improved wireless standards
- Wireless Reliability
- Better Control strategies
- Interference cancellation
- Time Synchronization



# Measurement Campaigns



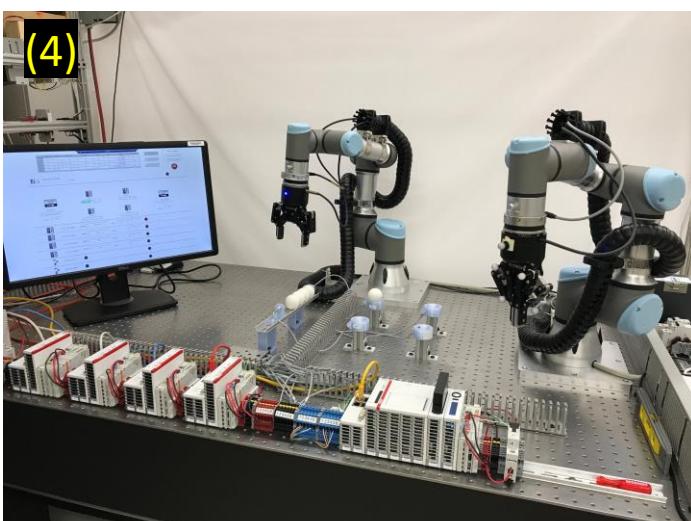
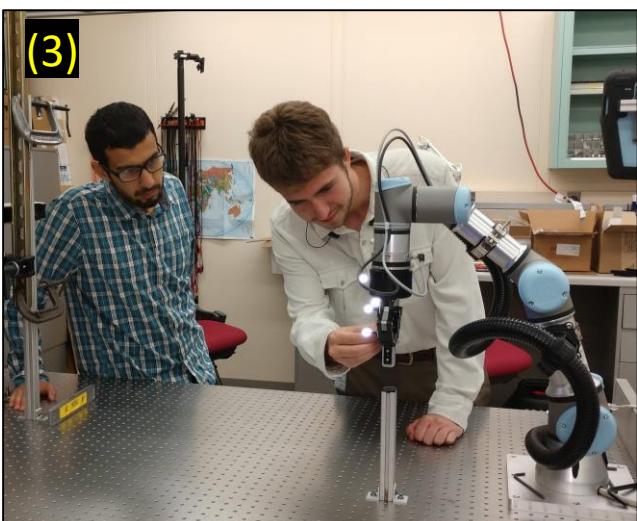
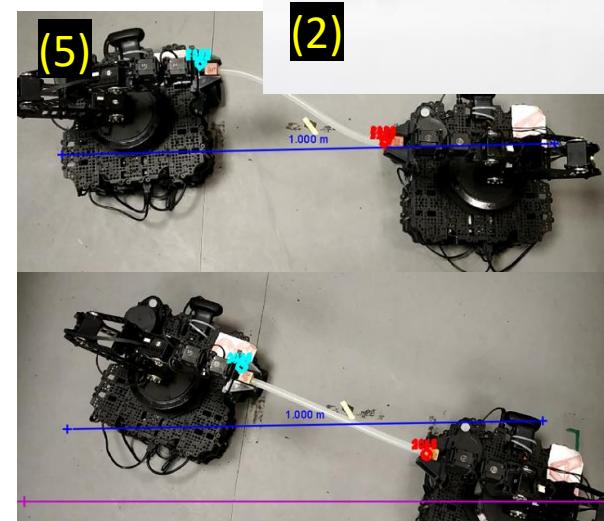
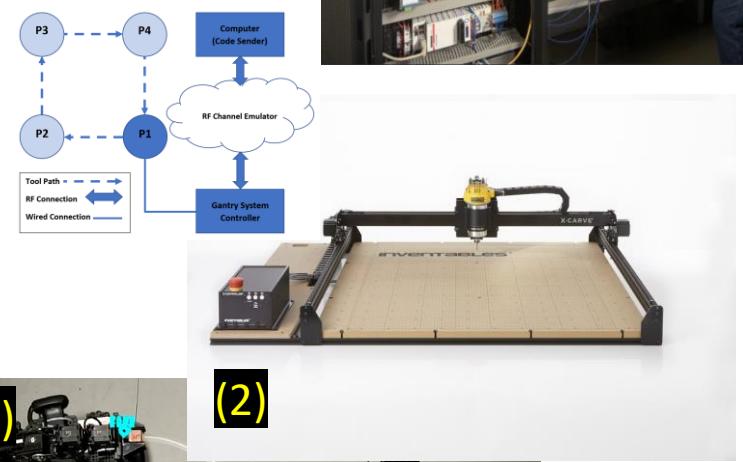
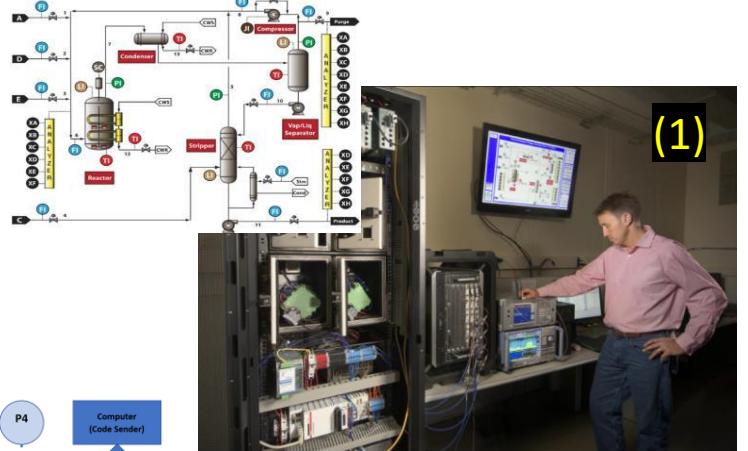
# Mobile Cart-based Measurements



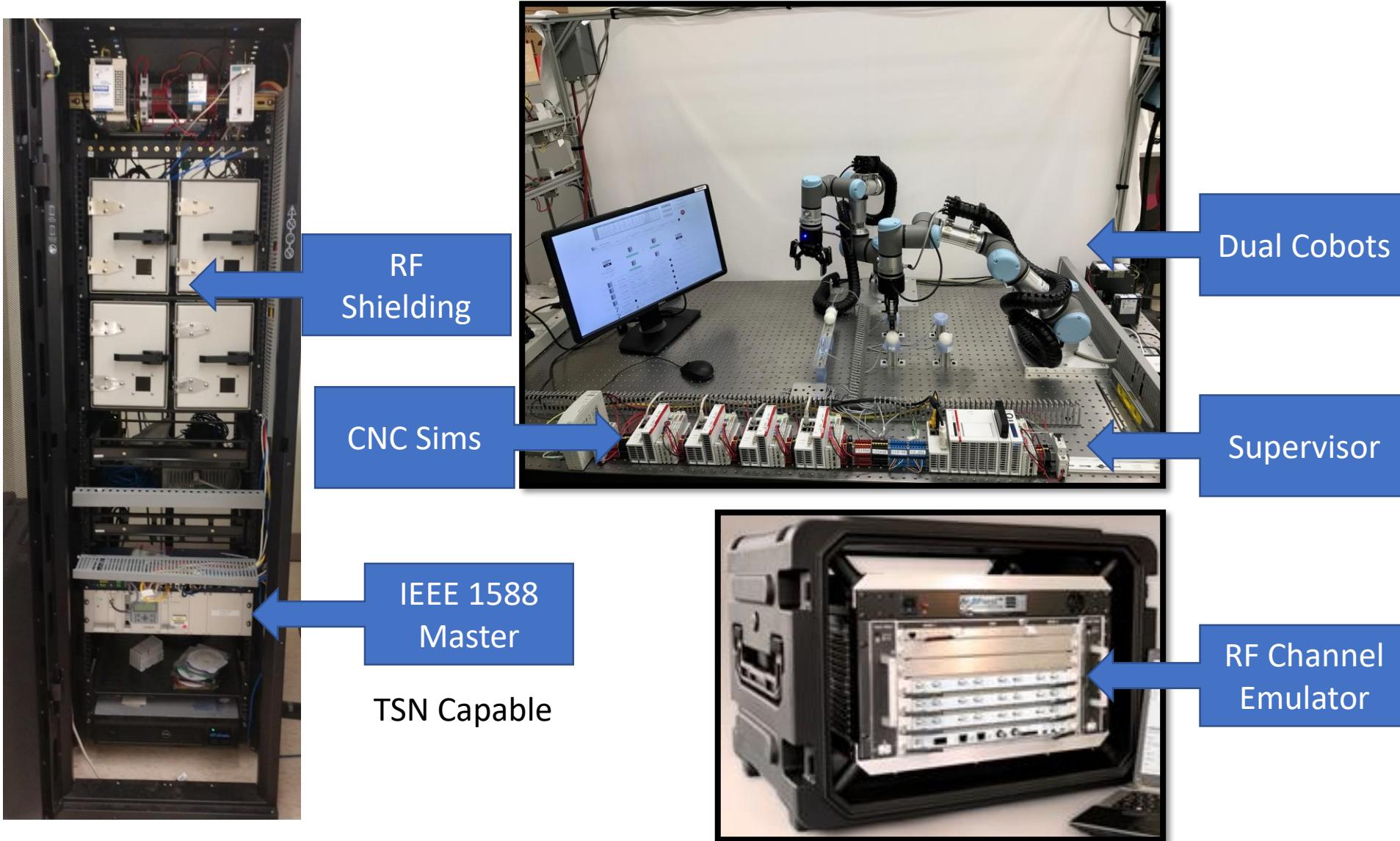
**Candell, R., Remley, K. A., Quimby, J. T., Novotny, D., Curtin, A., Papazian, P. B., Kashef, M., & Diener, J. (2017). *Industrial wireless systems radio propagation measurements*. <https://doi.org/10.6028/nist.tn.1951>**

# Past Testbed Incarnations

- 1 - NIST - Tennessee Eastman chemical plant simulator
- 2 - NIST - 3D gantry system
- 3 - NIST - Force seeking apparatus
- 4 - NIST - Dual-robot machine tending with inspection
- 5 - Intel Dual-robot tether apparatus using TSN



# Current Demonstration Platform



# Thesis

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# Thesis Motivation

Discover practical test and evaluation methods for assessing performance of an industrial workcell thereby helping control systems implementers to improve security, safety, and reliability.



# Research Objectives

- **Exploration of Requirements:**
  - Understand industrial wireless user requirements space
  - Remove hype due to marketplace and speculation
  - Provide validated requirements
- **Architectural Decomposition:**
  - Decompose the factory workcell into components, interfaces, and information flows
  - Identify constraints affecting cyberphysical performance
  - Make the resulting finding reusable and publicly accessible
- **Discovery by Prototyping:**
  - Use data from real-world experiments to drive research
- **Non-traditional Analysis:**
  - Apply learning algorithms to explore data resulting from experimentation
  - Produce novel methods that can help identify problems during operation

# Contributions

- **Requirements** [1]–[4] An examination of the wireless technology landscape is conducted. Existing and future wireless technologies are assessed for their appropriate applicability to industrial use cases.
- **Modeling** [5], [6] In an effort to better understand the architectural composition of the workcell using industrial wireless communication, modeling techniques are used to identify and decomposed the parts, interfaces, and data flows. SysML is adopted for this process and a proposed modeling library is created and presented. The model with conceptual diagram is made publicly available independent of the tool that was used to create the model.
- **Application of Graph Databases** [7], [8] A method is developed for collecting, cleaning, organizing, and presenting the cyberphysical performance indicators of experiments run within the NIST Industrial Wireless Testbed. The method developed utilizes the Neo4j graph database and is presented as a novel approach as compared to traditional approaches using relational database, spreadsheets, and raw file processing.
- **Machine Learning** [9], [10] A machine learning technique is developed and applied to the prediction of signal-to-interference levels within a wireless factory workcell network employing a robot arm within a force-seeking apparatus. The machine learning method allows a trained network to accurately determine the signal-to-interference level using the physical state of the robot arm rather than the state of the wireless link itself.

# Publication List

- [1] **R. Candell** and M. Kashef, “Industrial wireless: Problem space, success considerations, technologies, and future direction,” in *2017 Resilience Week (RWS)*, Sep. 2017, pp. 133–139, doi: 10.1109/RWEEK.2017.8088661.
- [2] K. Montgomery, **R. Candell**, Y. Liu, and M. Hany, “Wireless User Requirements for the Factory Work-cell,” 2019. doi: <https://doi.org/10.6028/NIST.AMS.300-8>.
- [3] **R. Candell**, M. Kashef, Y. Liu, K. B. Lee, and S. Foufou, “Industrial Wireless Systems Guidelines: Practical Considerations and Deployment Life Cycle,” *IEEE Ind. Electron. Mag.*, vol. 12, no. 4, pp. 6–17, 2018.
- [4] **R. Candell**, M. Hany, K. B. Lee, Y. Liu, J. Quimby, and K. Remley, “Guide to industrial wireless systems deployments,” Gaithersburg, MD, Apr. 2018. doi: 10.6028/NIST.AMS.300-4.
- [5] **R. Candell**, M. Kashef, Y. Liu, and S. Foufou, “A SysML representation of the wireless factory work cell,” *Int. J. Adv. Manuf. Technol.*, vol. 104, no. 1–4, pp. 119–140, Sep. 2019, doi: 10.1007/s00170-019-03629-x.
- [6] **R. Candell**, “A Model of a Wireless Factory Work-Cell Using the Systems Modeling Language,” *J. Res. Natl. Inst. Stand. Technol.*, vol. 123, p. 123018, Oct. 2018, doi: 10.6028/jres.123.018.

# Publication List (2)

- [7] **R. Candell**, M. Kashef, Y. Liu, K. Montgomery, and S. Foufou, “A Graph Database Approach to Wireless IIoT Work-cell Performance Evaluation,” in *Proceedings of the 2020 IEEE International Conference on Industrial Technology*, Feb. 2020.
- [8] M. Kashef, Y. Liu, K. Montgomery, and **R. Candell**, “Wireless Cyber-Physical Systems Performance Evaluation through a Graph Database Approach,” *J. Comput. Inf. Sci. Eng.*, pp. 1–19, 2020, doi: 10.1115/1.4048205.
- [9] **R. Candell**, K. Montgomery, M. Kashef, Y. Liu, and S. Foufou, “Wireless Interference Estimation Using Machine Learning in a Robotic Force-Seeking Scenario,” in *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*, Jun. 2019, pp. 1334–1341, doi: 10.1109/ISIE.2019.8781418.
- [10] **R. Candell**, K. Montgomery, M. Kashef, Y. Liu, and S. Foufou, “Machine Learning Based Wireless Interference Estimation in a Robotic Force-Seeking Application,” *ISA Trans.*, 2020, doi: pending.
- [11] **R. Candell** and S. Foufou, “Smart Manufacturing Testbed for the Advancement of Wireless Adoption in the Factory,” in *Proceedings of the 17th International Conference on Product Lifecycle*, 2020, [Online]. Available: <https://www.plm-conference.org/>.
- [12] M. Kashef, **R. Candell**, and S. Foufou, “On the Impact of Wireless Communications on Controlling a Two-Dimensional Gantry System,” in *ASME 2019 14th International Manufacturing Science and Engineering Conference*, 2019, vol. Volume 1:, doi: 10.1115/MSEC2019-2896.

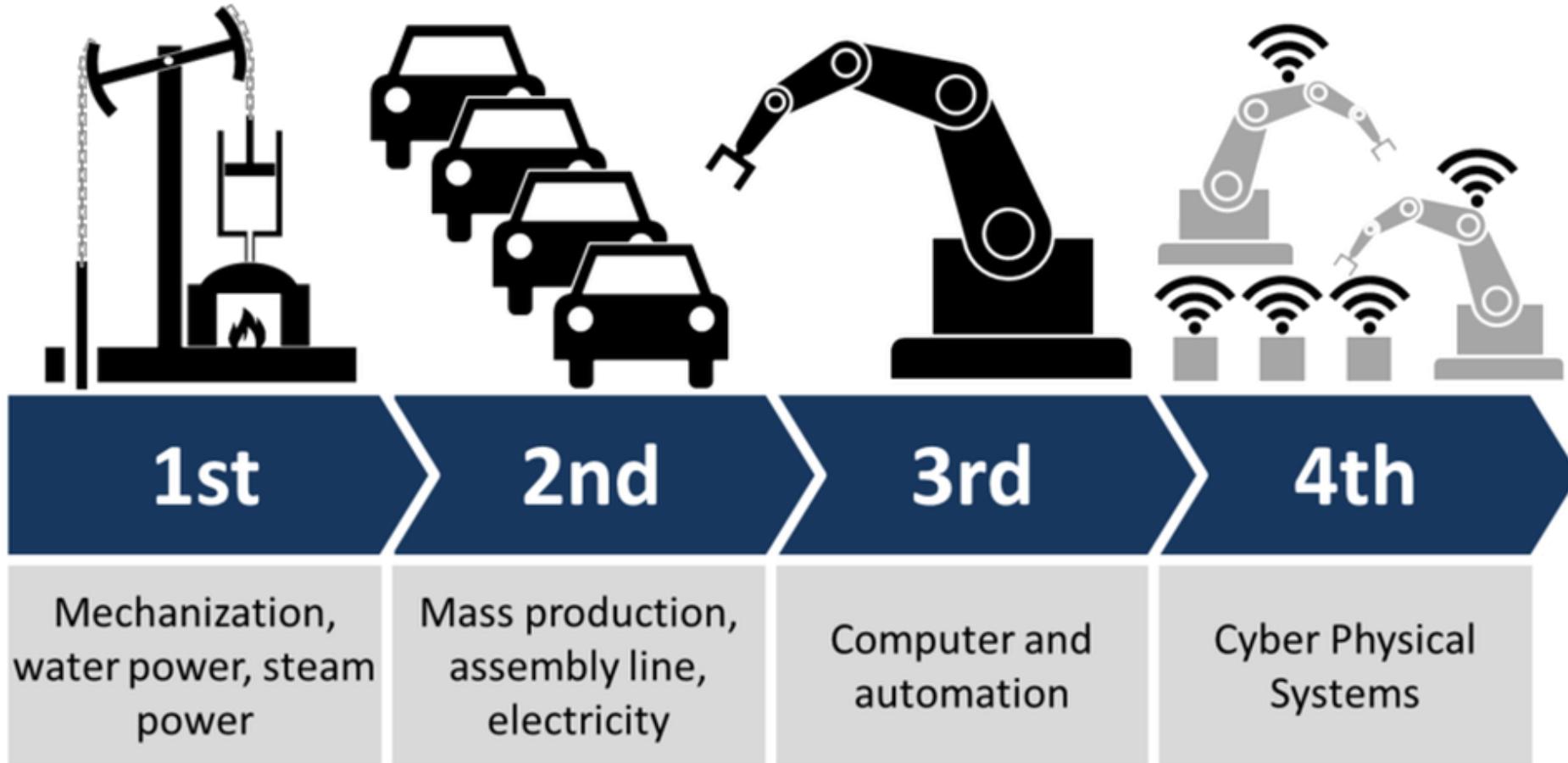
# Introduction to Cyberphysical Systems in Smart Manufacturing

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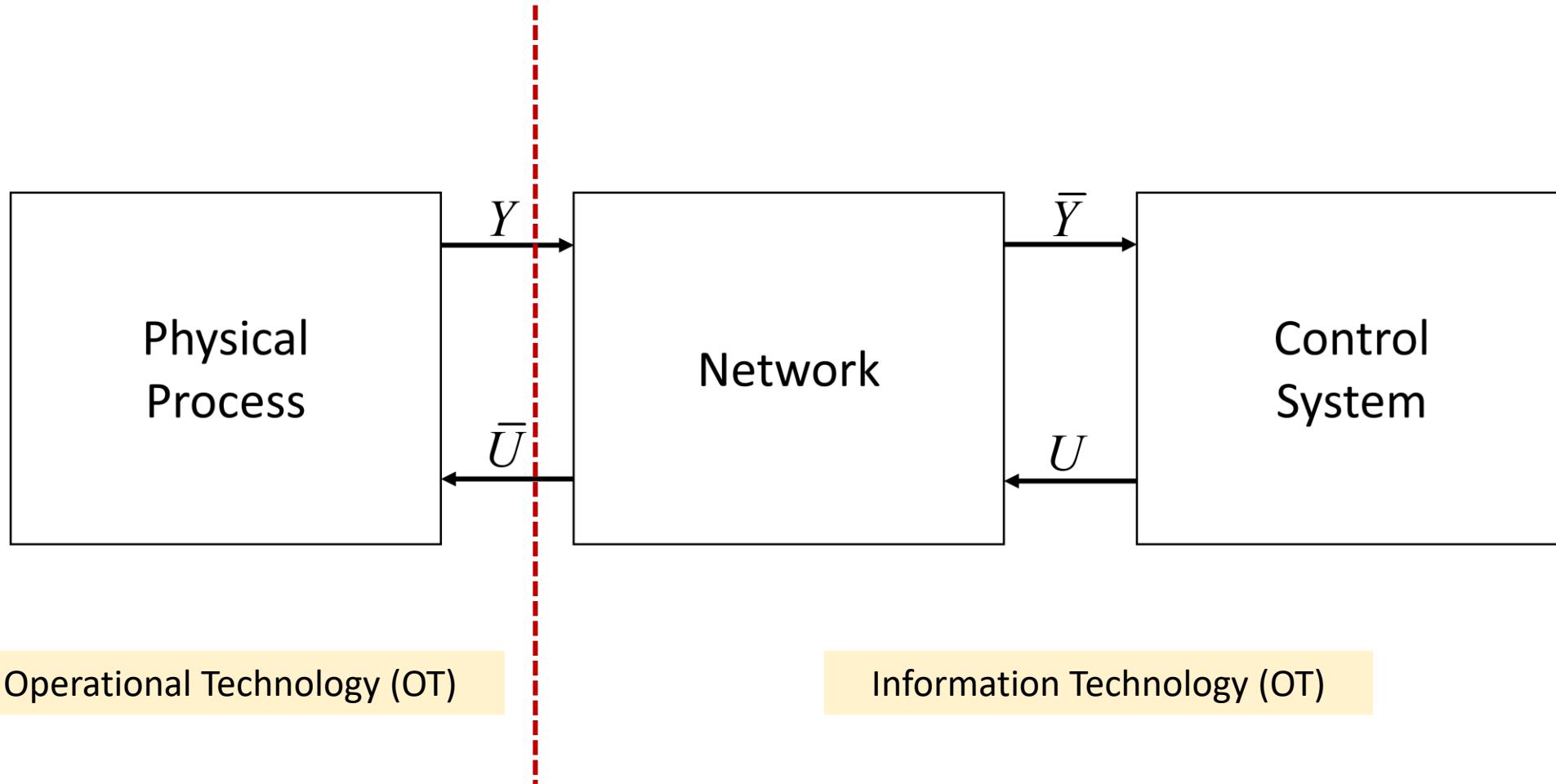
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# History of Industrialization



# What is a Cyberphysical System? (CPS)



# CPS Needs for Smart Manufacturing

- ❖ Situationally-aware automation systems
- ❖ Intelligence closer to the edge devices (or in the devices)
- ❖ Better test methods that include holistic perspective
- ❖ Better communications protocols (for wireless)
- ❖ Maintain security

# Industrial Wireless Technologies

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# Objectives

- Better understand the landscape of wireless within industrial systems
- Create a mapping of use case classes to wireless technologies
- Encourage discussion of wireless solutions in industrial systems

# Wireless Applicability to Industrial Systems

Legend: ●: Technology fully supports problem domain, ○: Supports problem domain with practicality, throughput, latency, reliability, or energy limitations, ↗: Energy requirements of assumed battery-powered devices prevent applicability, ⊕: Latency prevent applicability, ▼: Throughput prevents applicability, ✖: Emerging technology or evolution may support problem domain, ○: Not recommended, -: Not considered by authors.

	Latency, $l$ ms	Pr. Loss, $r$	Scale, $s$
Monitoring	$l < 1000$	$r < 10^{-5}$	$s < 10,000$
Supervisory Control			
Flow-based	$l < 1000$	$r < 10^{-6}$	$s < 30$
Job-based	$l < 100$	$r < 10^{-7}$	$s < 10$
Feedback Control			
Flow-based	$l < 1000$	$r < 10^{-6}$	$s < 100$
Job-based	$l < 10$	$r < 10^{-7}$	$s < 10$
Safety	$l < 10$	$r < 10^{-7}$	$s < 10$

**R. Candell** and M. Kashef, Industrial wireless: Problem space, success considerations, technologies, and future direction, in 2017 Resilience Week (RWS), Sep. 2017, pp. 133139.

# SysML: Workcell Architectural Decomposition and Analysis

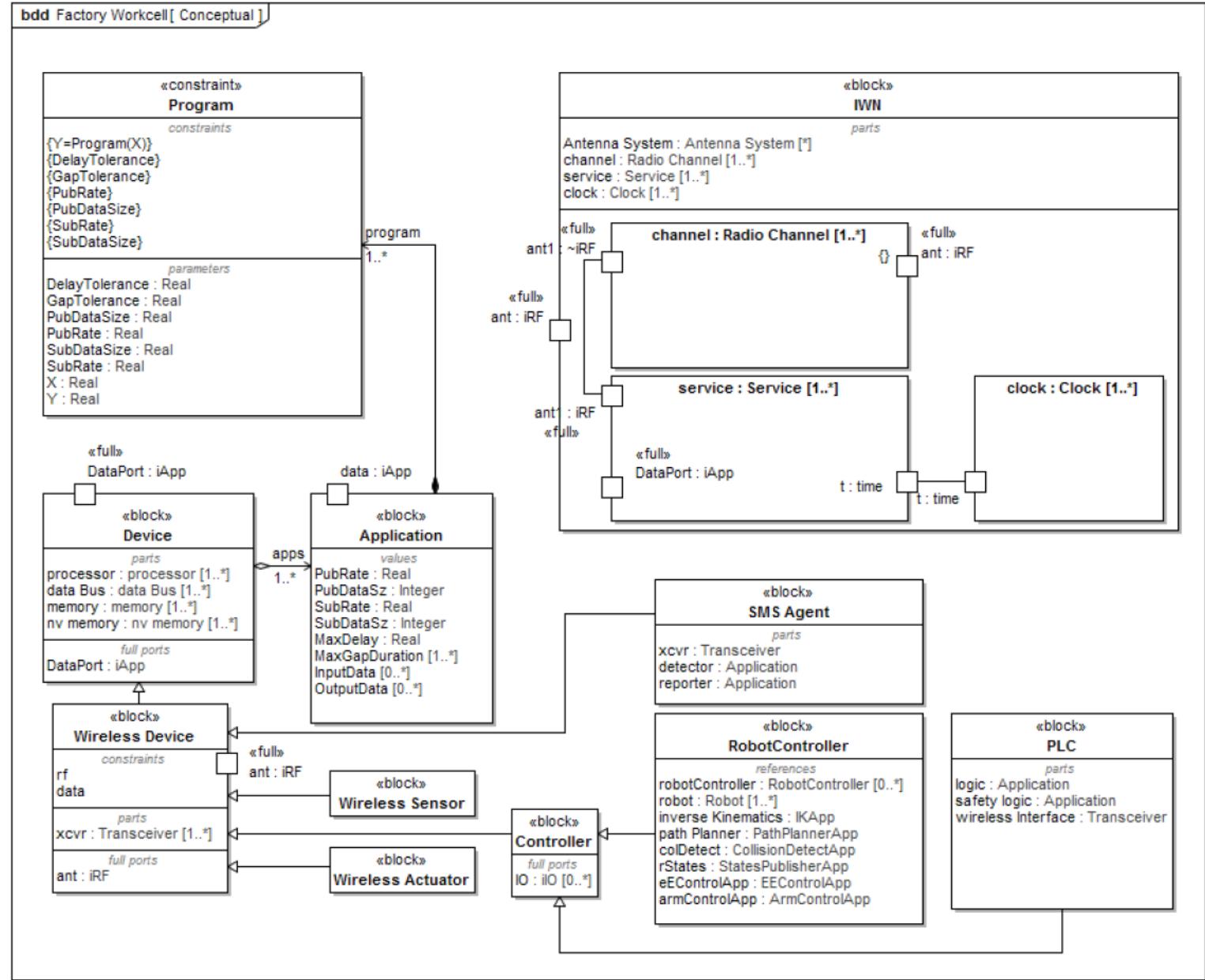
*Performance Estimation, Testing, and Control of Cyber-Physical Systems Employing Non-Ideal Communications Networks*

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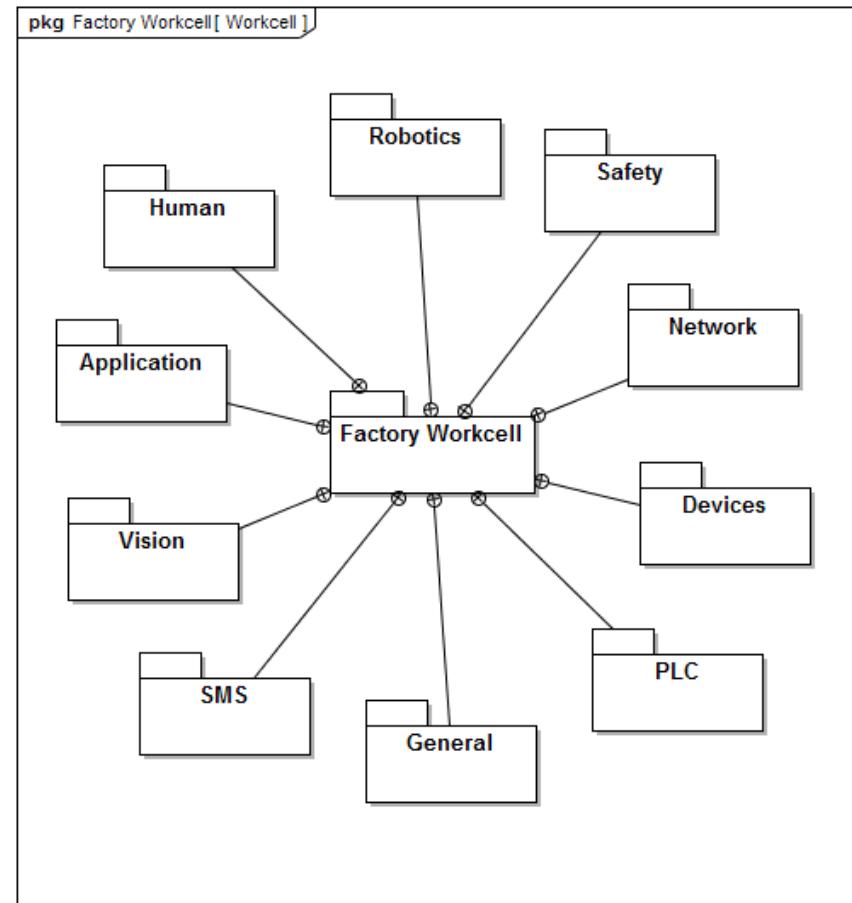
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# Conceptual Diagram

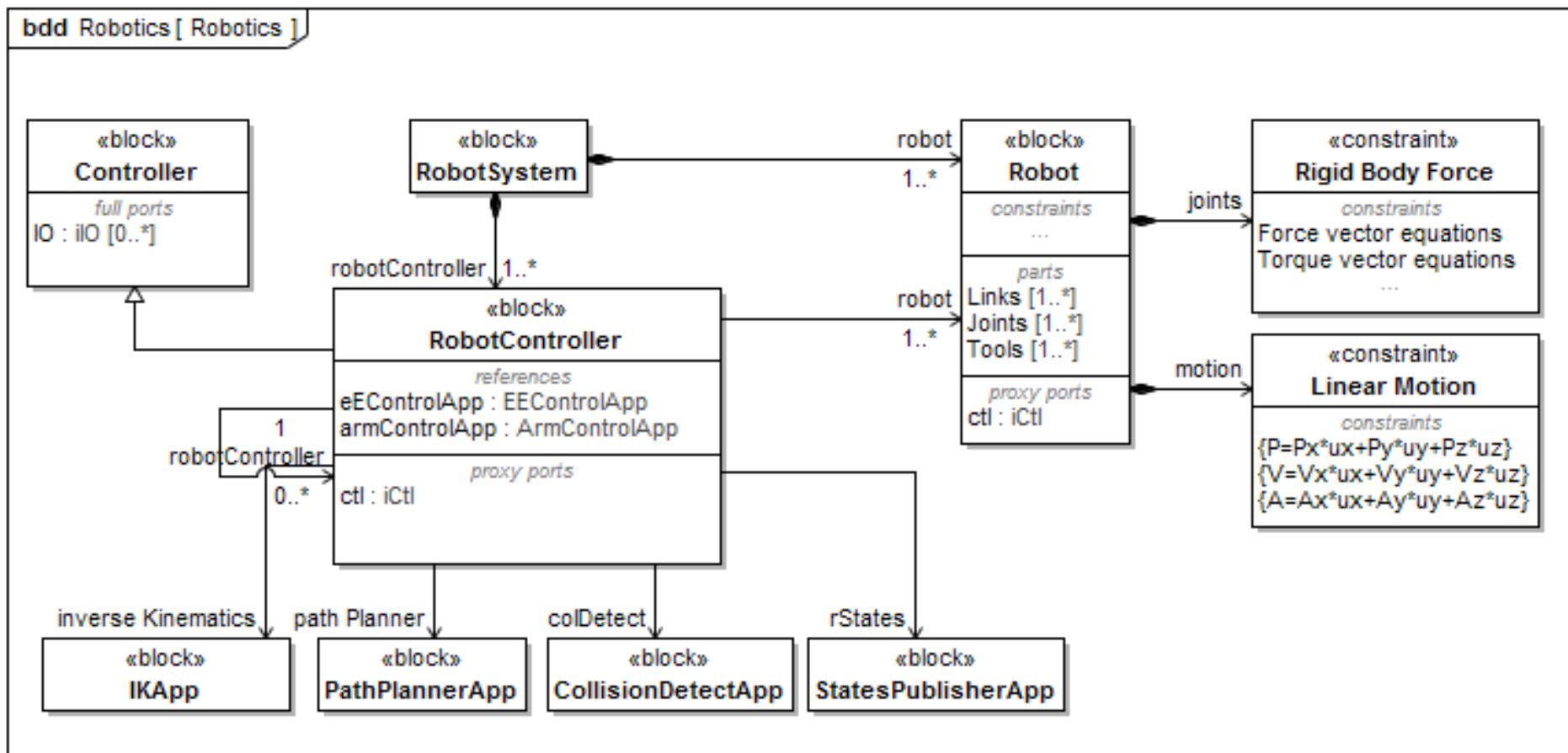
- Device
    - Wireless Device
    - Controller
  - Controller
    - Robot Controller
    - PLC
  - Applications
  - IWN
  - Radio Channel
  - Service
  - Constraints



# Packages

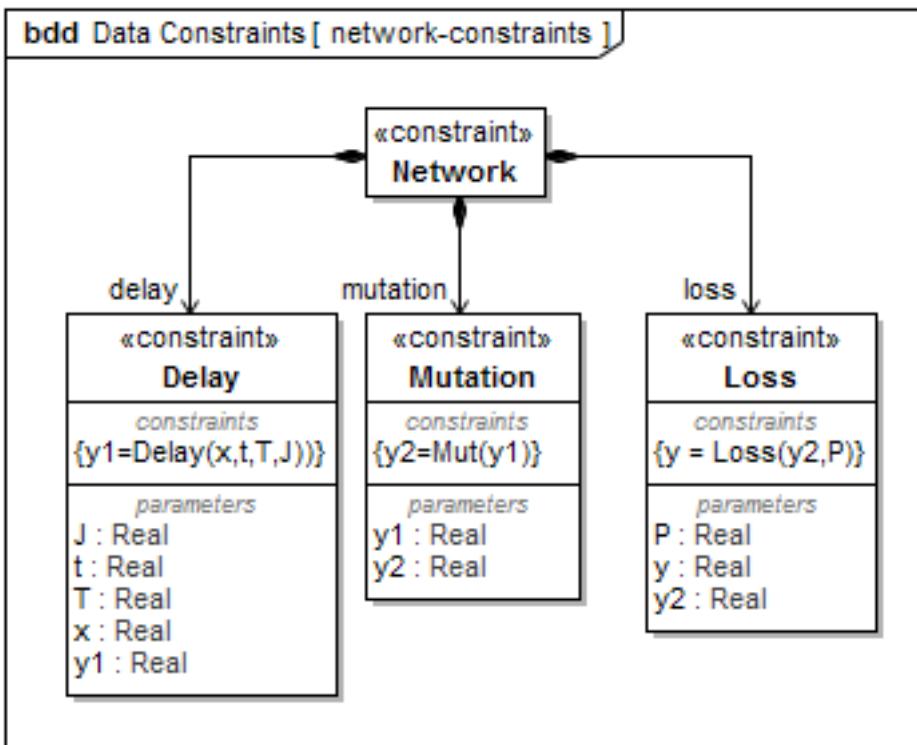
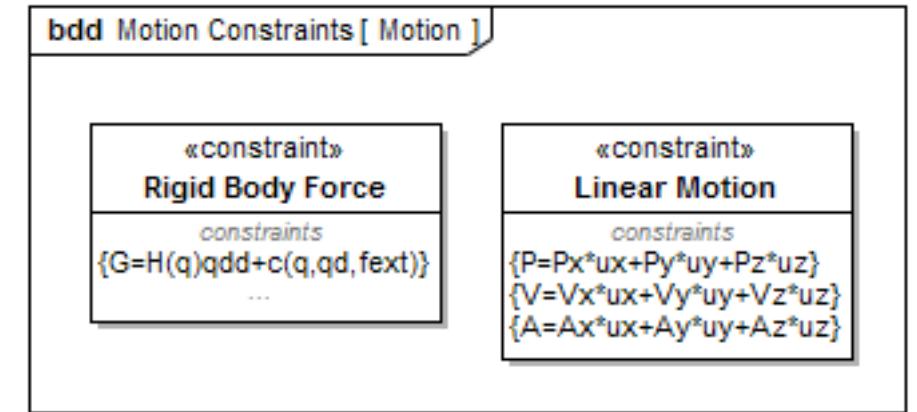
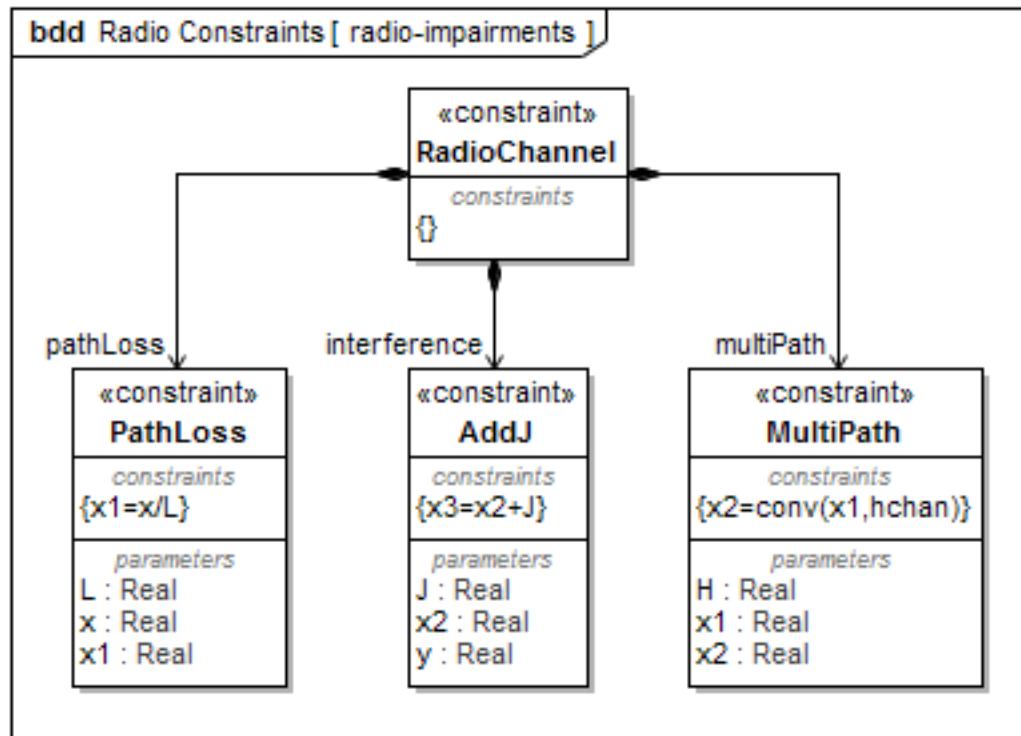


# Robotics

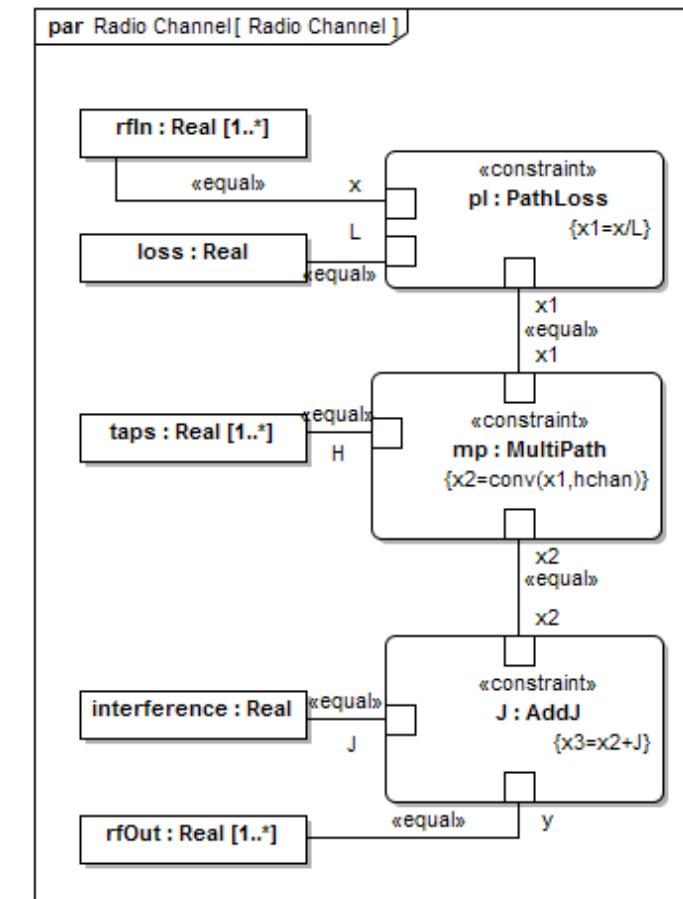
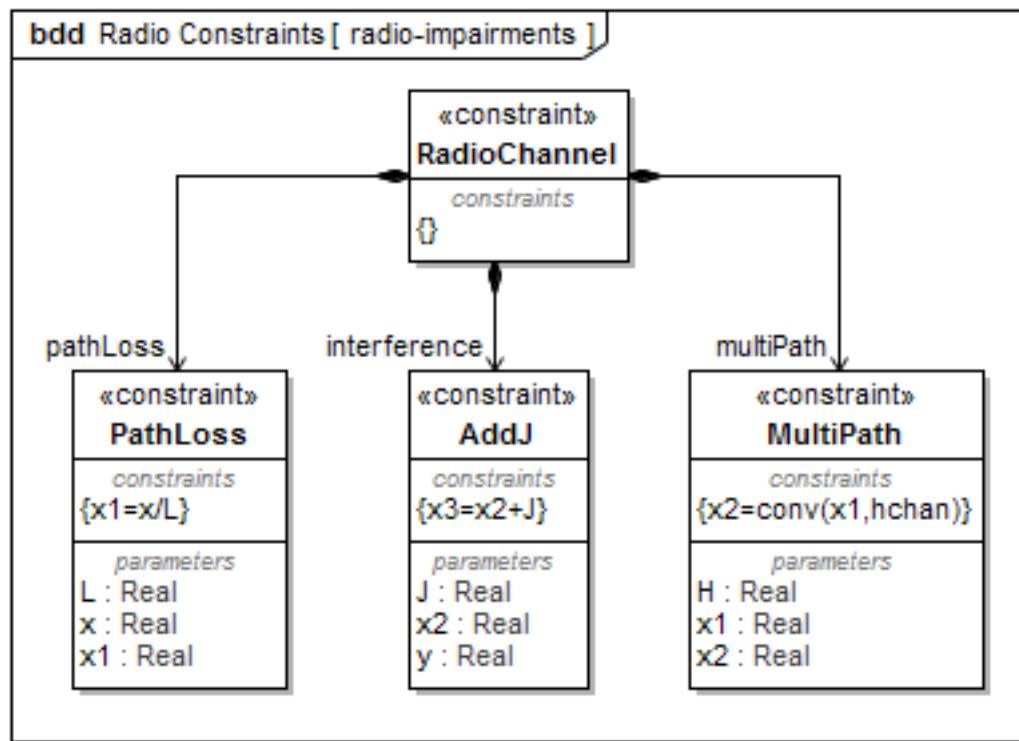


# Constraints

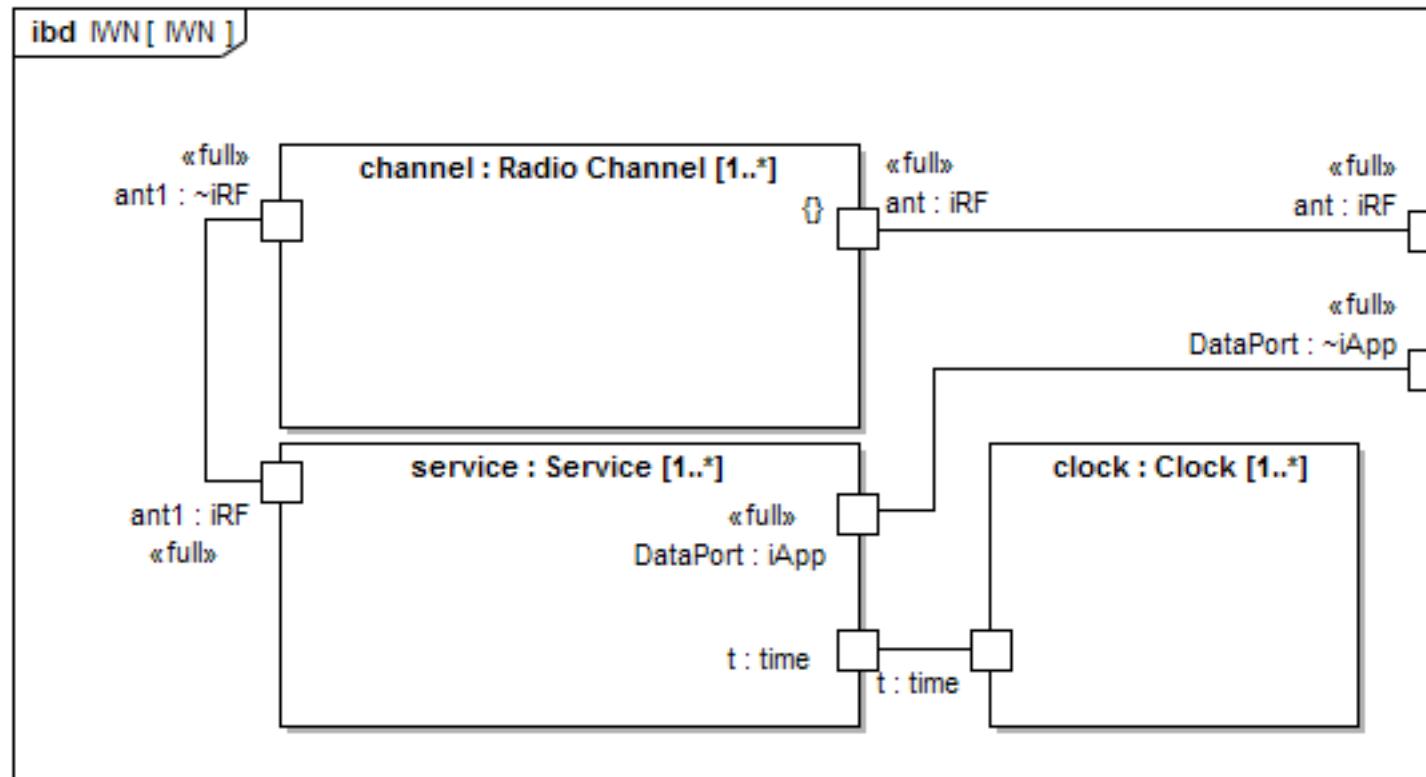
Allows us to model mathematically or programmatically effects of behavior within a block.



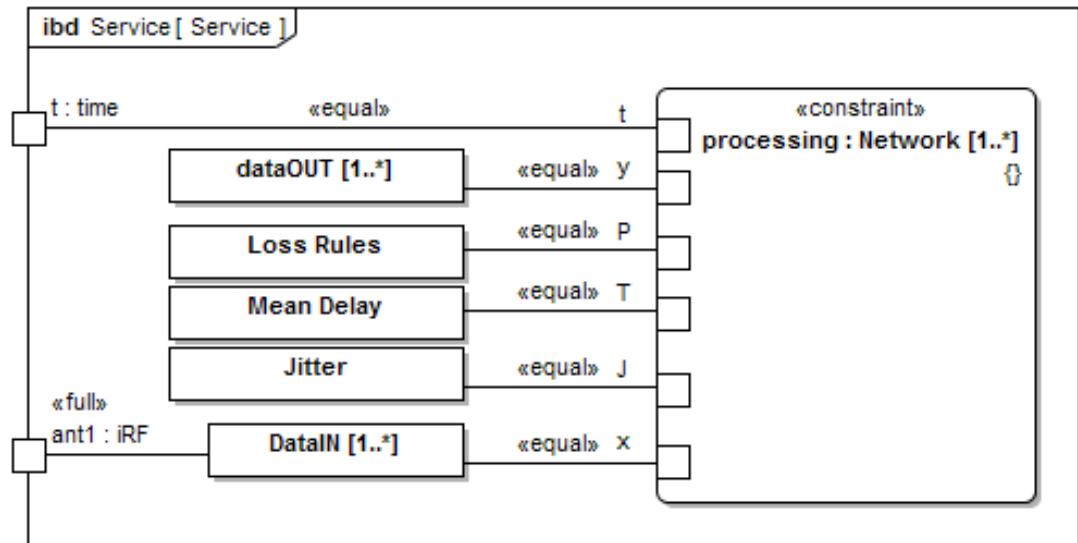
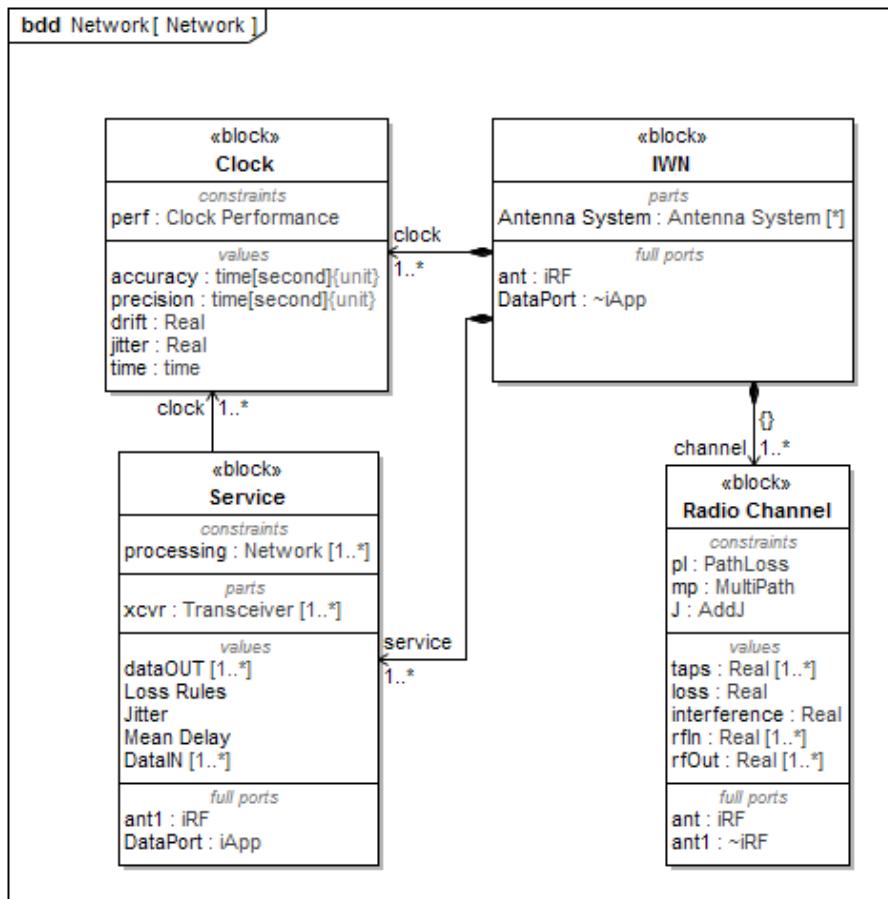
# Radio Channel Constraints



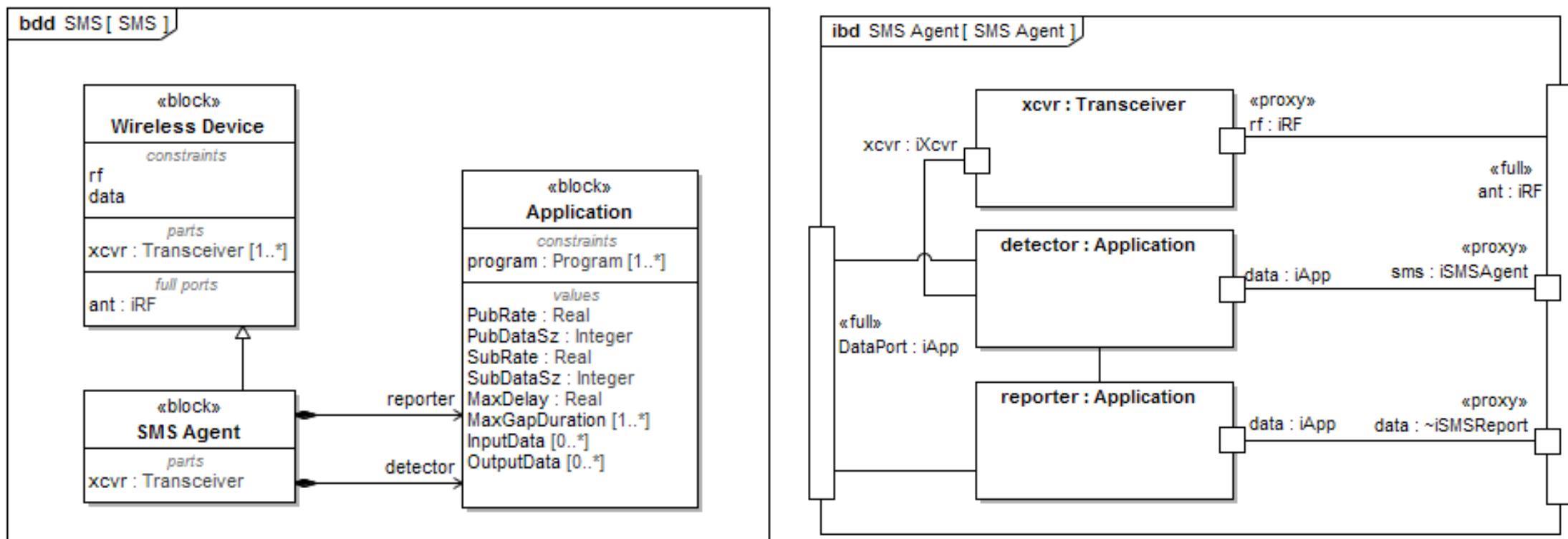
# Industrial Wireless Network (IWN)



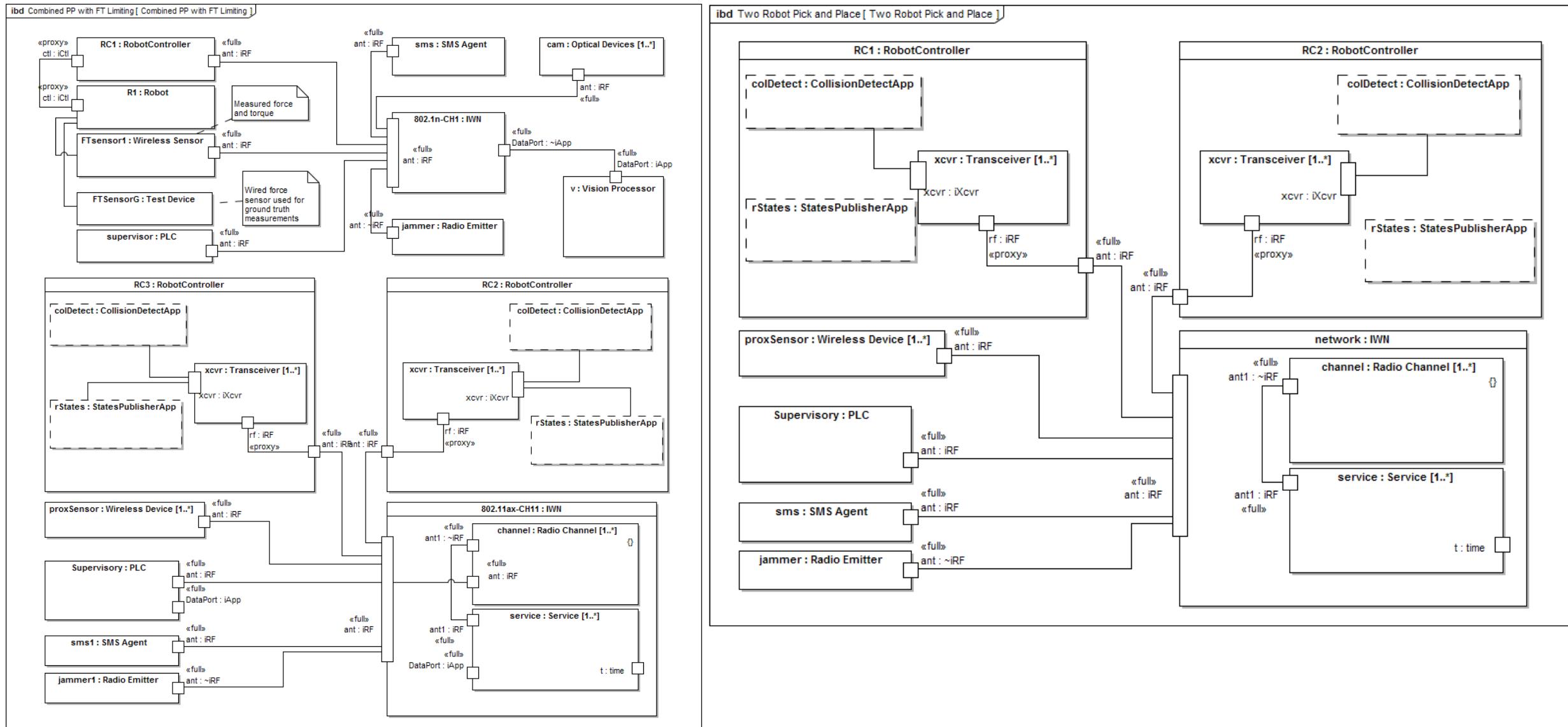
# Service (of an IWN)



# Spectrum Monitoring System (SMS)



# Example IBDs of Factory Workcells



# Application of the Graph Database to CPS Discovery

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Employing Non-Ideal Communications Networks

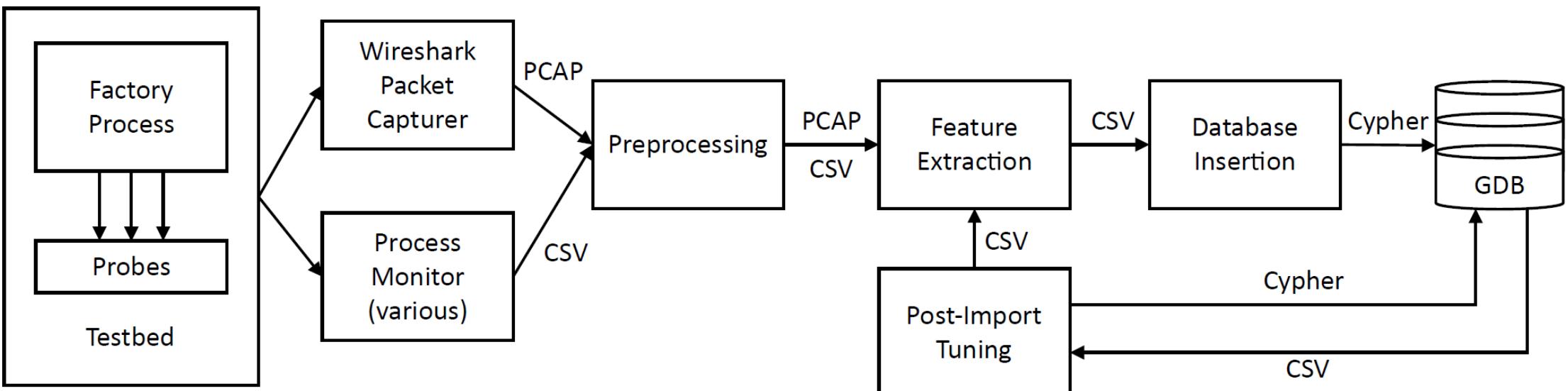
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# Introduction & Motivation

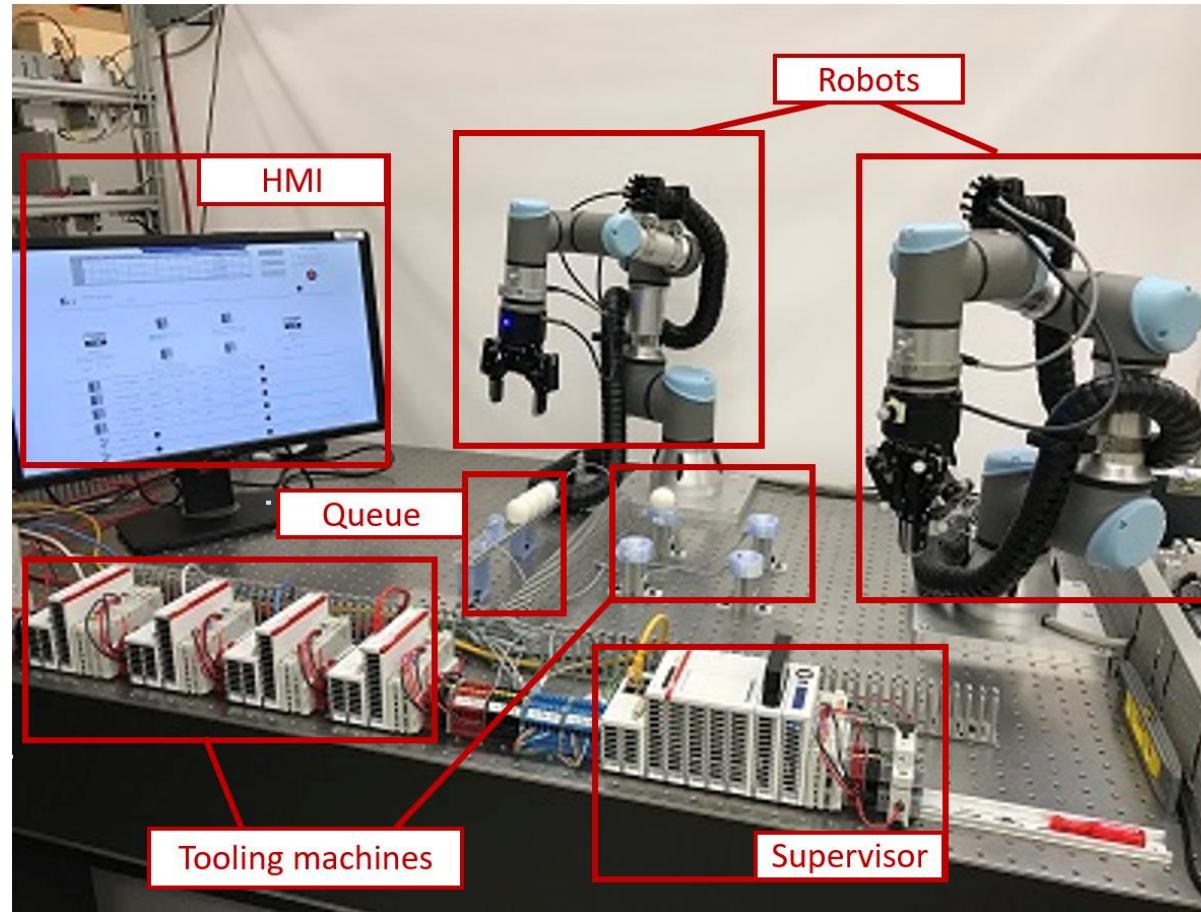
- Motivation:
  - Address the difficulty of organizing data collected from a CPS.
- Graph Database Advantages
  - Inherently capture data and relationships
  - No need to perform complex joins
- Outputs
  - Used the GDB to study the impacts of the IWN on the physical system

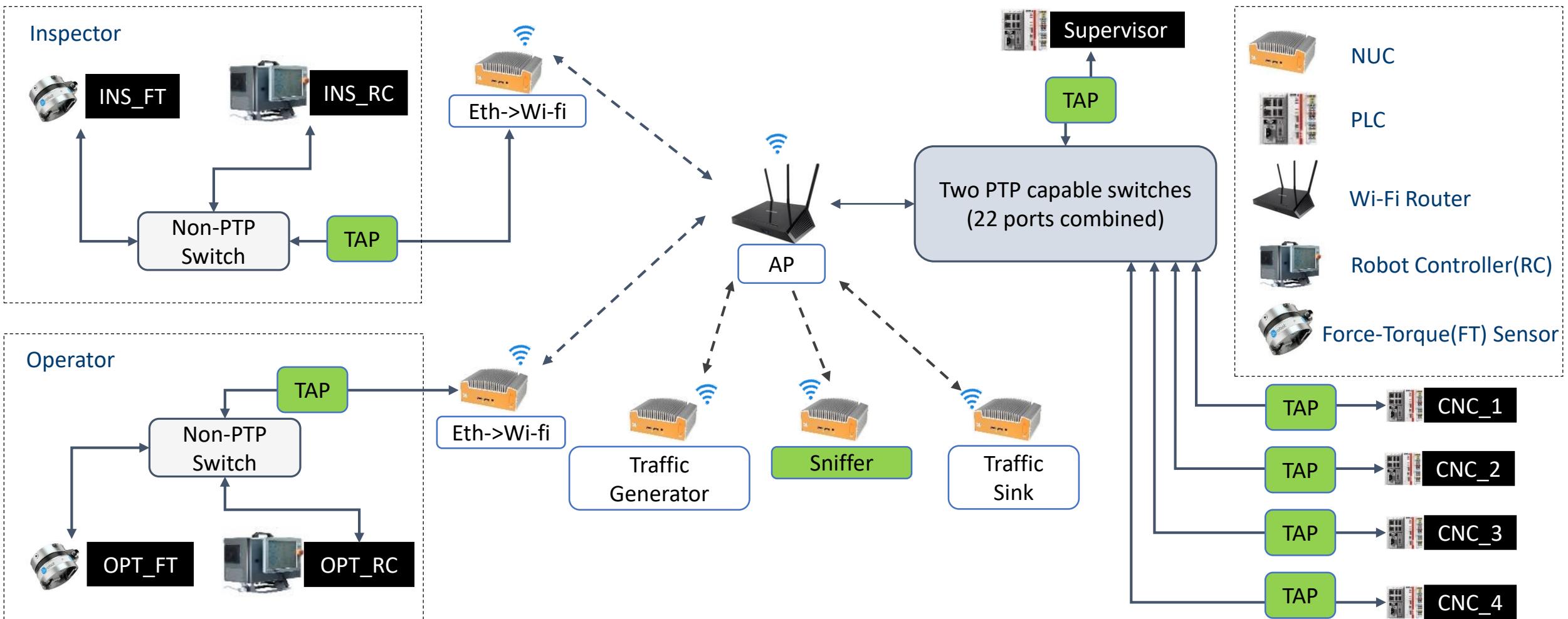


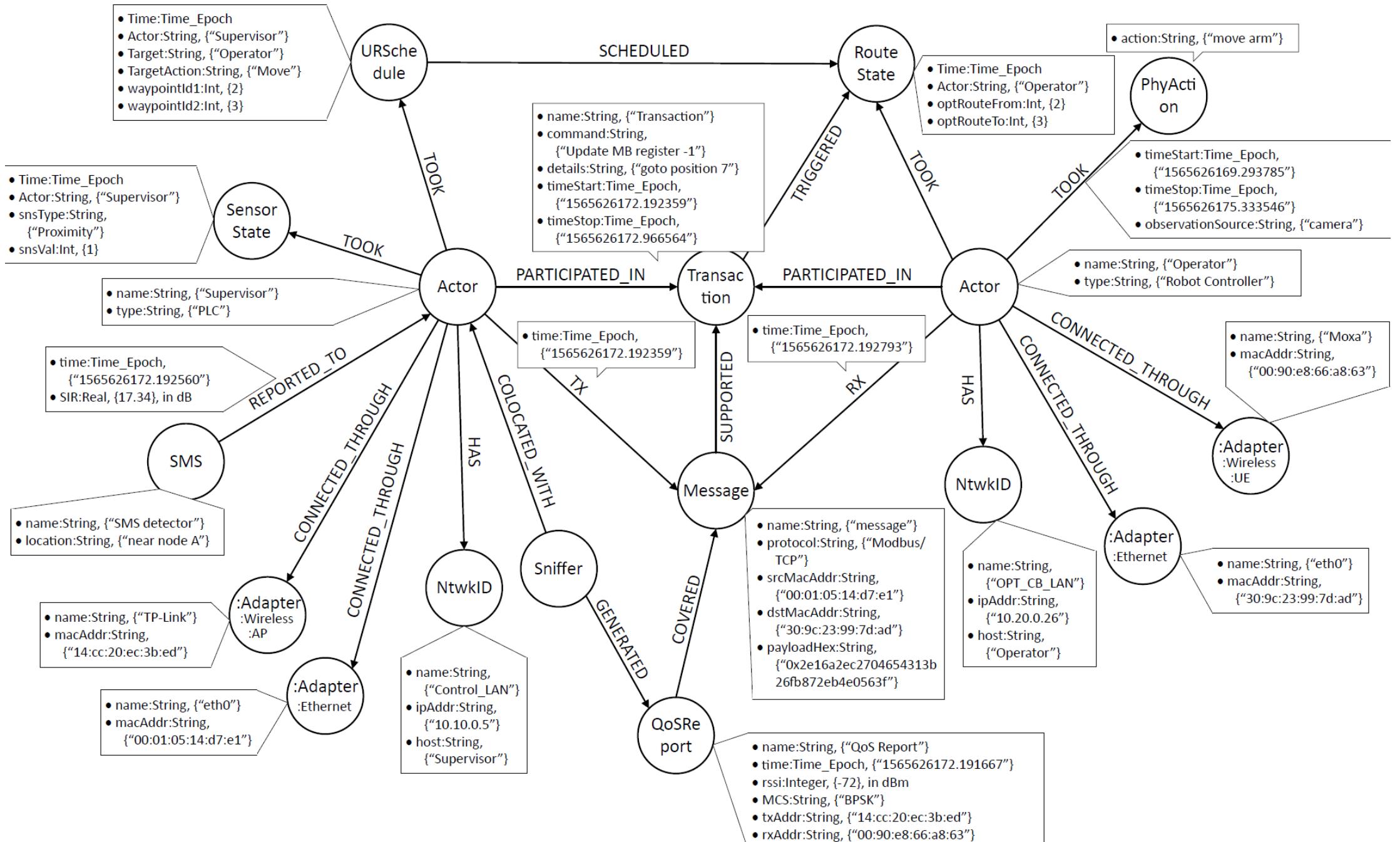
# Graph Database Process Flow



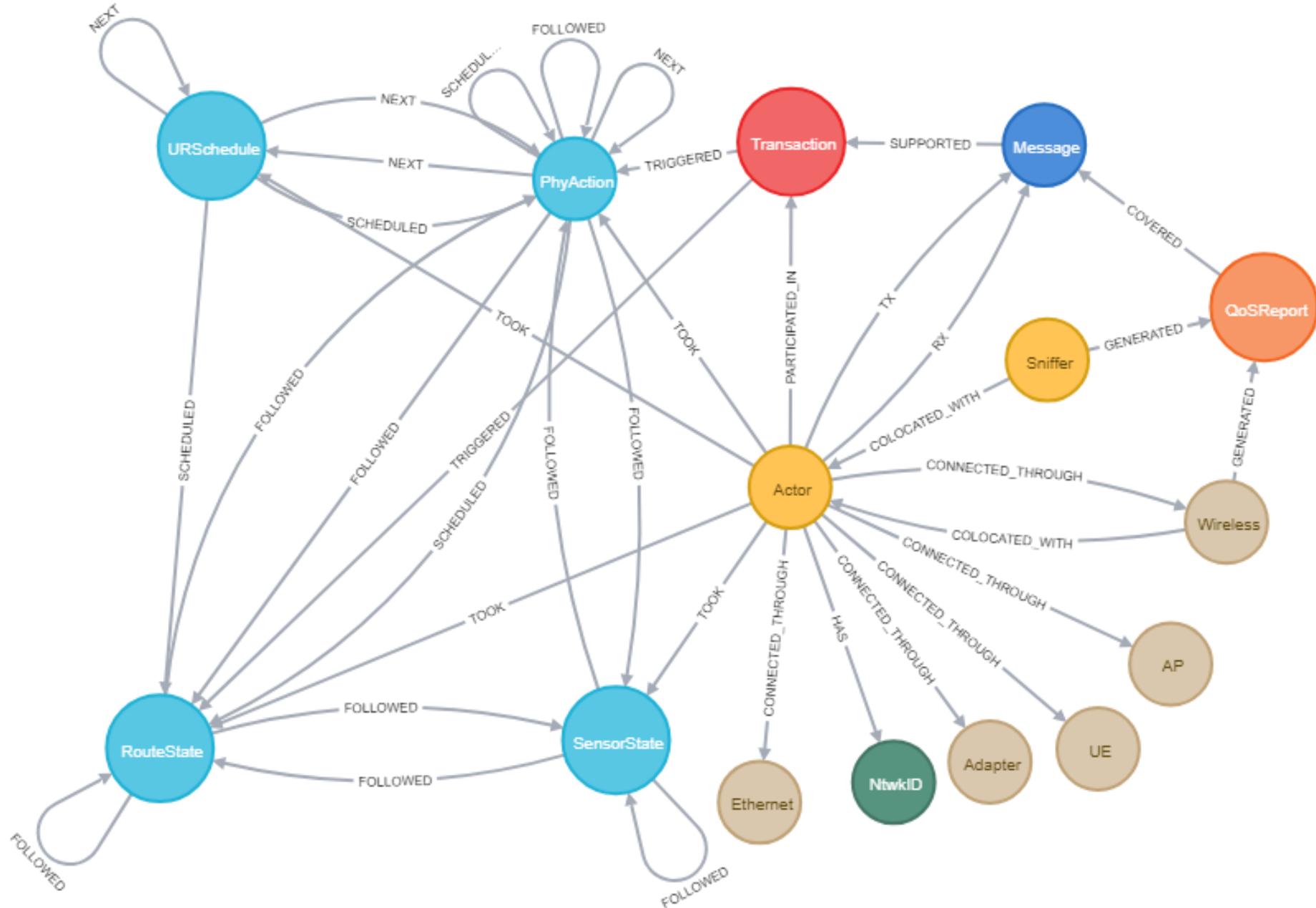
# Testbed Configuration







Designed schema



Realize schema: Only the visualization is different from designed schema

# Example Query Using Cipher

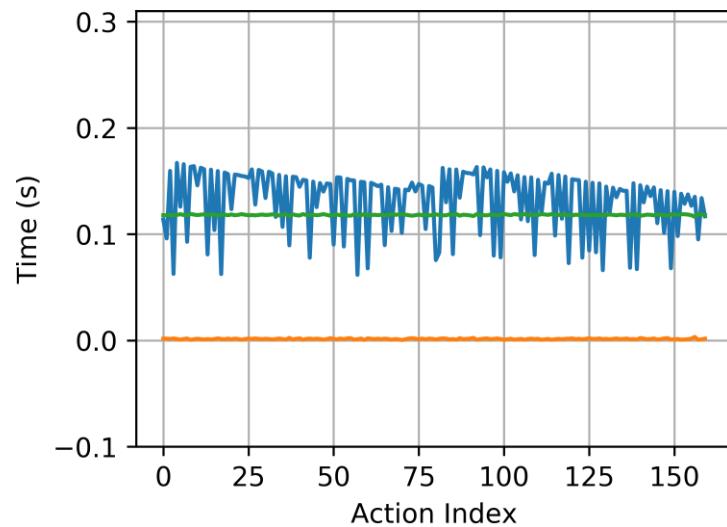
```
MATCH p=(a:Actor {  
    name:'Supervisor'  
})--(t:Transaction)--(b:Actor) , p2=(m:Message)-->(t)  
WHERE t.timeStart>T AND t.timeStop<T+1  
RETURN p, p2
```

This query searches for all Supervisor-based Transactions and associated Messages where the Transaction start and stop times fall within a certain interval.

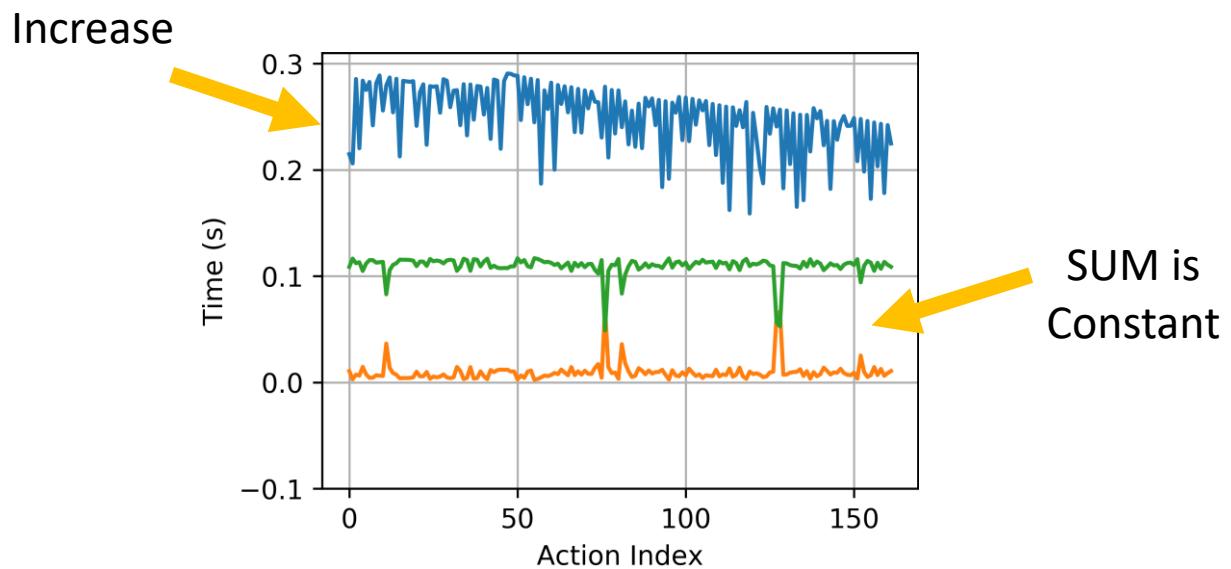
The query will return the Supervisor node with connected messages.

# Sample Results from Query

## Wired Performance Baseline



## Wireless with 2-Stream Interference



The supervisor PLC processing time in **blue** appears unchanged by the IWN latencies. The transaction latency in **orange** is clearly impacted by the wireless channel; however, the robot controller shown in **green** appears to compensate for transaction latency variance such that the sum of transaction latency and robot processing time remains constant. This indicates that wireless should be a good candidate for this control system as physical latencies do not increase under these scenarios.

# Machine Learning in a Robotic Force Seeking Application

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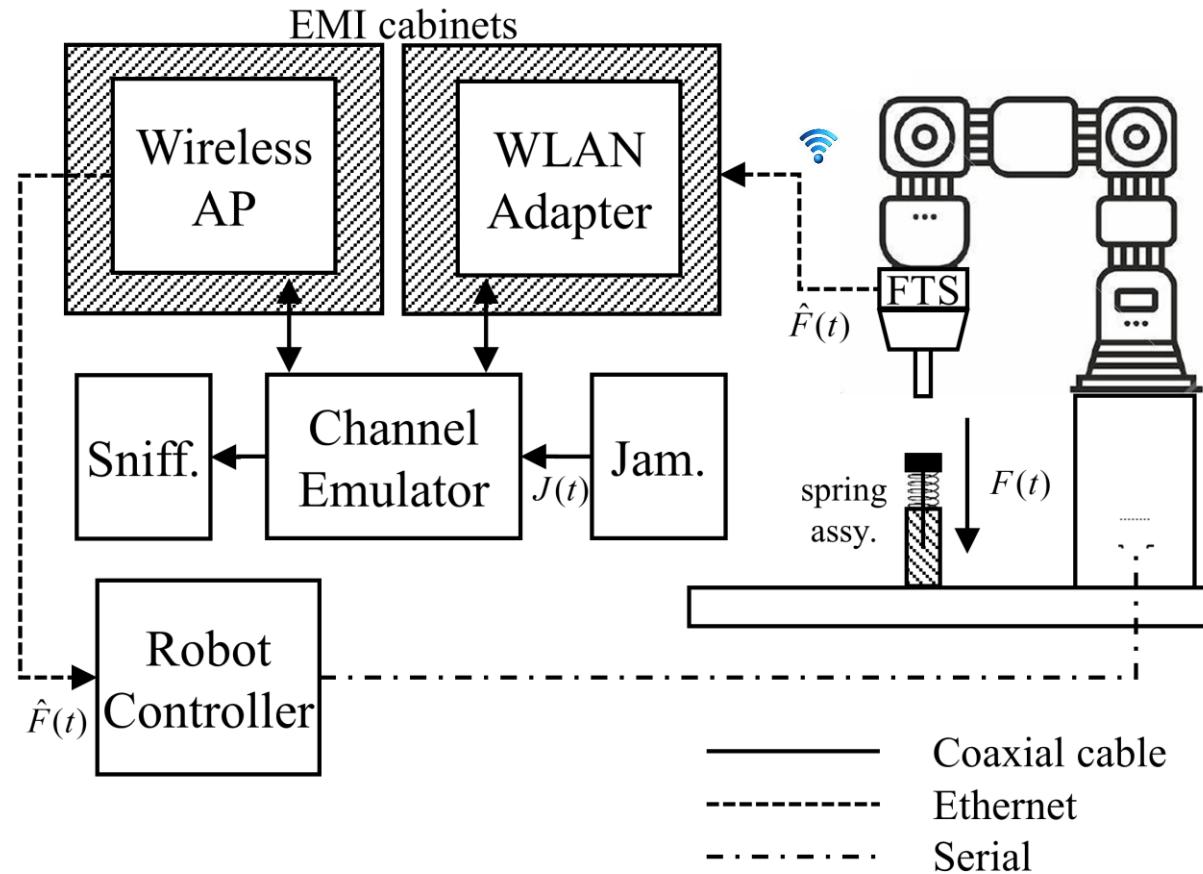
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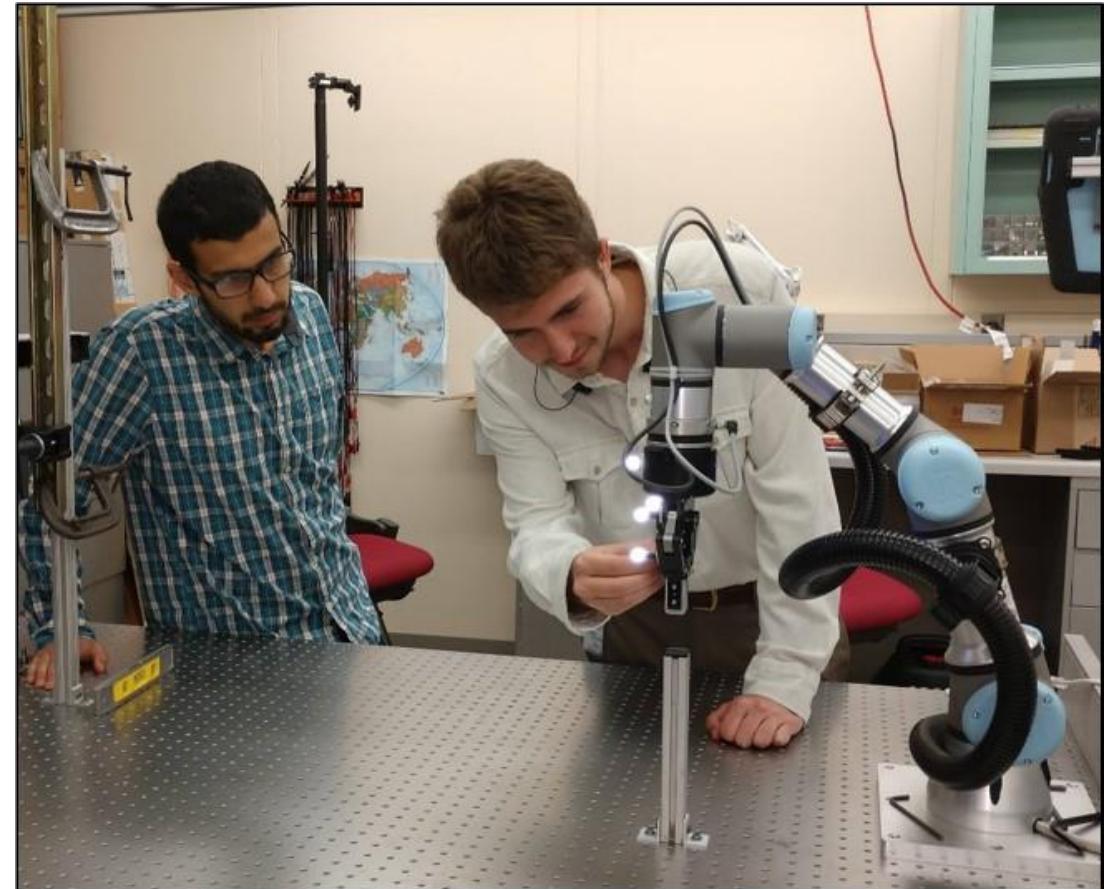
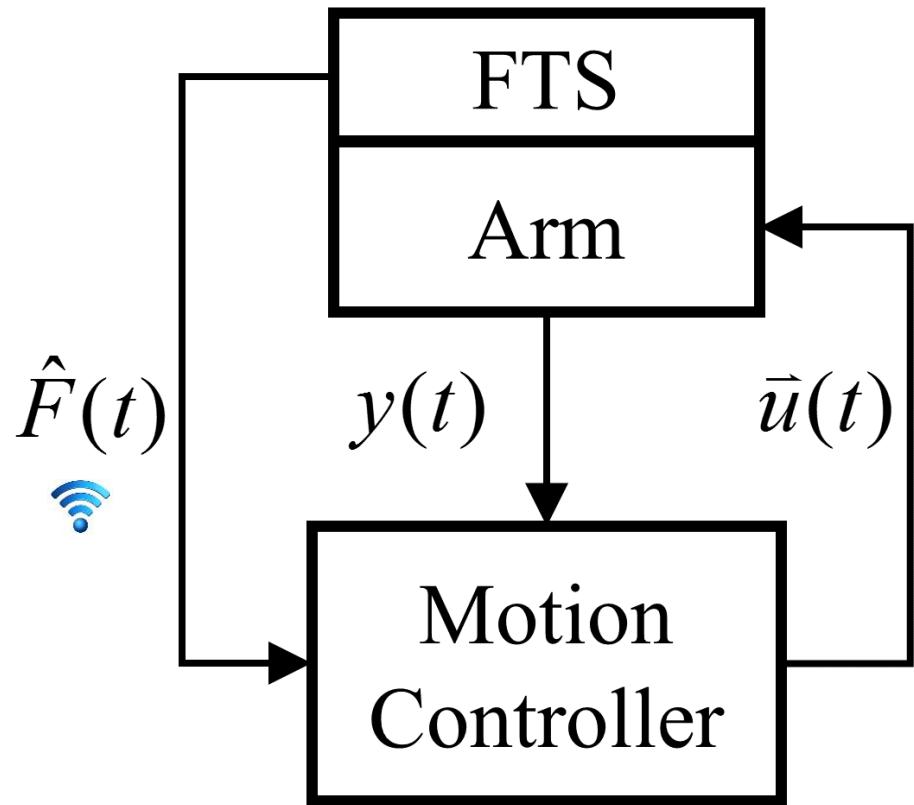
# Introduction and Motivation

- Goals
  - Predict link quality indirectly using measurements of the operational system
  - Eliminate the expense of RF equipment for LQE measurement in the factory
- Results
  - Measured LQE using empirical data from the operational system
  - Accuracy of LQE prediction within  $\pm 0.5$  dB

# Force seeking spring system apparatus

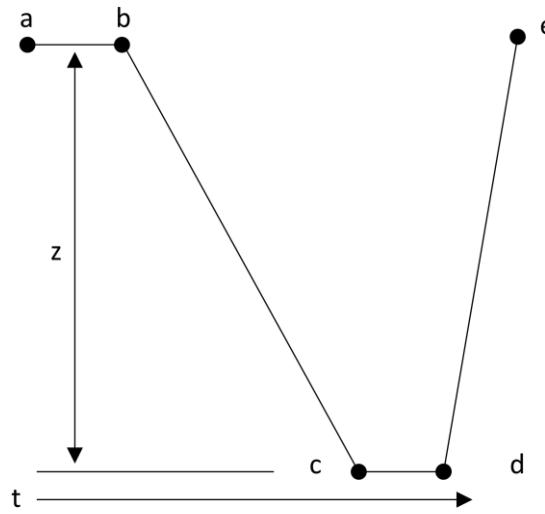


# Apparatus Model

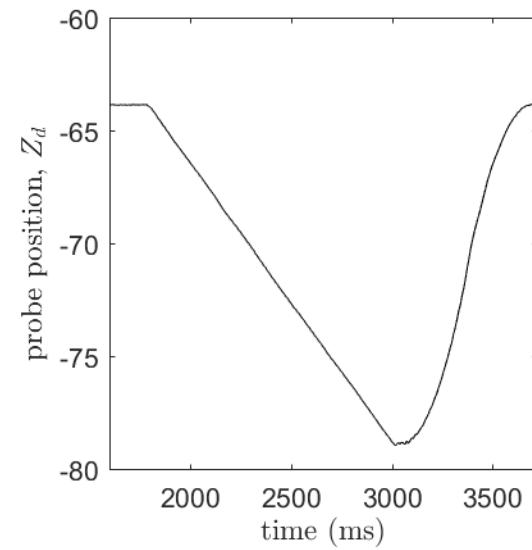


# Depression force search model

**Z-axis Movement Model**

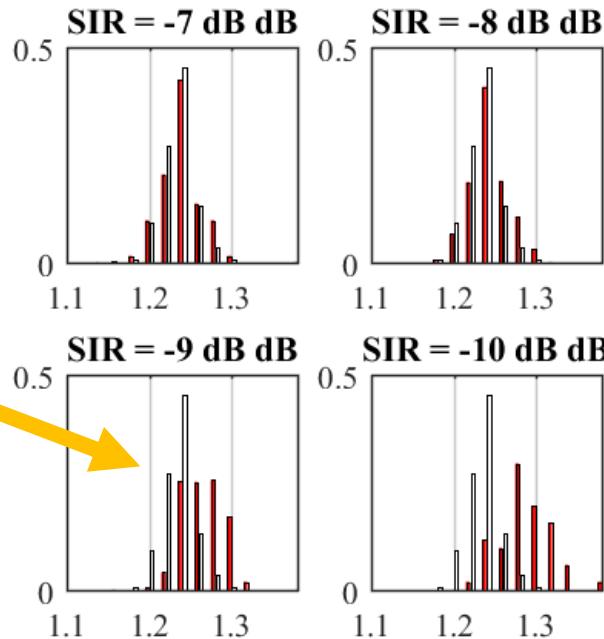


**Sample Z-axis Movement**

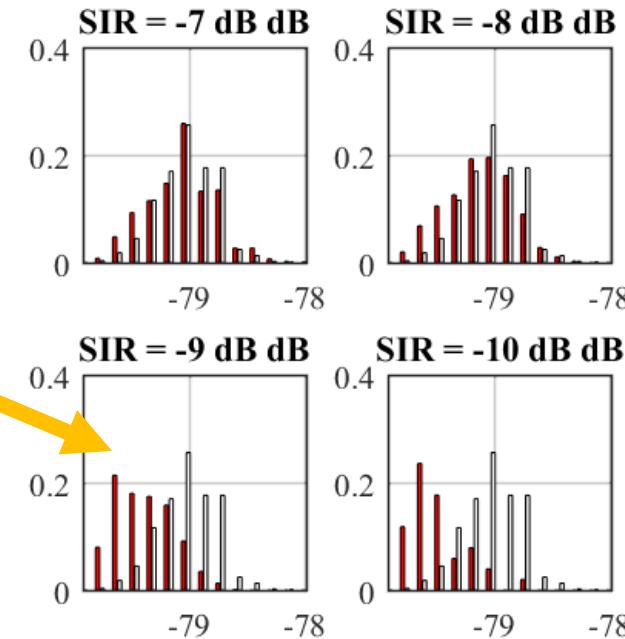


# Learning candidacy statistics

## $Z_{bc}$ Plunge Time



## Z-axis Deflection



Searching for before/after variations. The before and after variations show good candidacy for application of machine learning.

# Feature Independence Check

Table 6.1: Correlation Coefficients for  $-9\text{ dB}$  SIR

	$\Delta t_{ab}$	$\Delta t_{bc}$	$Z_d$	$\Delta t_{cd}$	$\Delta t_{ae}$
$\Delta t_{ab}$	1	0.04	0.04	0	0.56
$\Delta t_{bc}$	0.04	1	-0.96	-0.08	0.18
$Z_d$	0.04	-0.96	1	0.03	-0.01
$\Delta t_{cd}$	0	-0.08	0.03	1	0
$\Delta t_{ae}$	0.56	0.18	-0.01	0	1

Table 6.2: Correlation Coefficients for  $-8\text{ dB}$  SIR

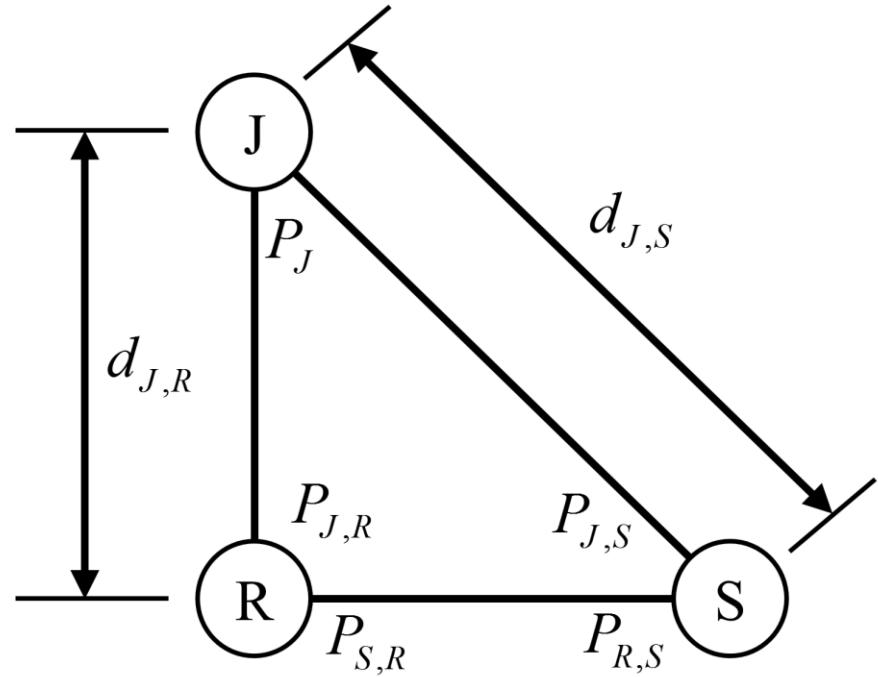
	$\Delta t_{ab}$	$\Delta t_{bc}$	$Z_d$	$\Delta t_{cd}$	$\Delta t_{ae}$
$\Delta t_{ab}$	1	0.01	-0.05	-0.06	0.58
$\Delta t_{bc}$	0.01	1	-0.99	-0.13	0.1
$Z_d$	-0.05	-0.99	1	0.07	-0.1
$\Delta t_{cd}$	-0.06	-0.13	0.07	1	-0.03
$\Delta t_{ae}$	0.58	0.1	-0.1	-0.03	1

Table 6.3: Correlation Coefficients for  $-7\text{ dB}$  SIR

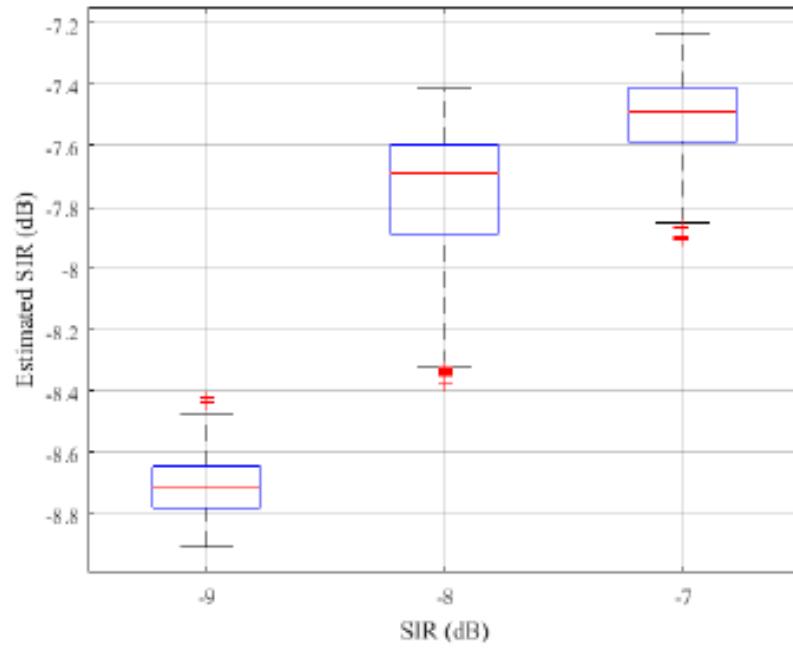
	$\Delta t_{ab}$	$\Delta t_{bc}$	$Z_d$	$\Delta t_{cd}$	$\Delta t_{ae}$
$\Delta t_{ab}$	1	-0.05	-0.04	0.09	0.01
$\Delta t_{bc}$	-0.05	1	-0.93	-0.17	0.05
$Z_d$	-0.04	-0.93	1	0.08	-0.05
$\Delta t_{cd}$	0.09	-0.17	0.08	1	-0.02
$\Delta t_{ae}$	0.01	0.05	-0.05	-0.02	1

Verification of non-correlation between features.  
Machine learning works best when features are mostly independent. A first look shows that the features are mostly independent from one another. This does not mean that each one has importance, but rather they will not interfere or be redundant.

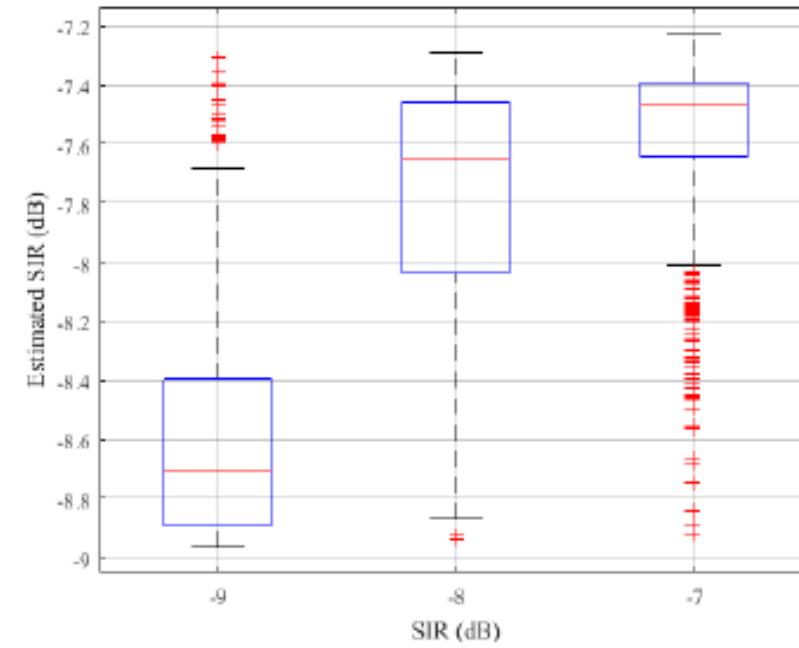
# Model for Radio Path loss and Interference Emulation



# Test set prediction performance



(a)  $M = 100$



(b)  $M = 1$

Figure 6.7: Predicted SIR versus actual SIR for the cases of (a)  $M = 100$  and (b)  $M = 1$ . The box plots show the median value while the bottom and top edges of the box indicate the 25th and 75th percentiles. Statistical outliers are shown as red + signs.

# Initial Results Against Segment Size, M

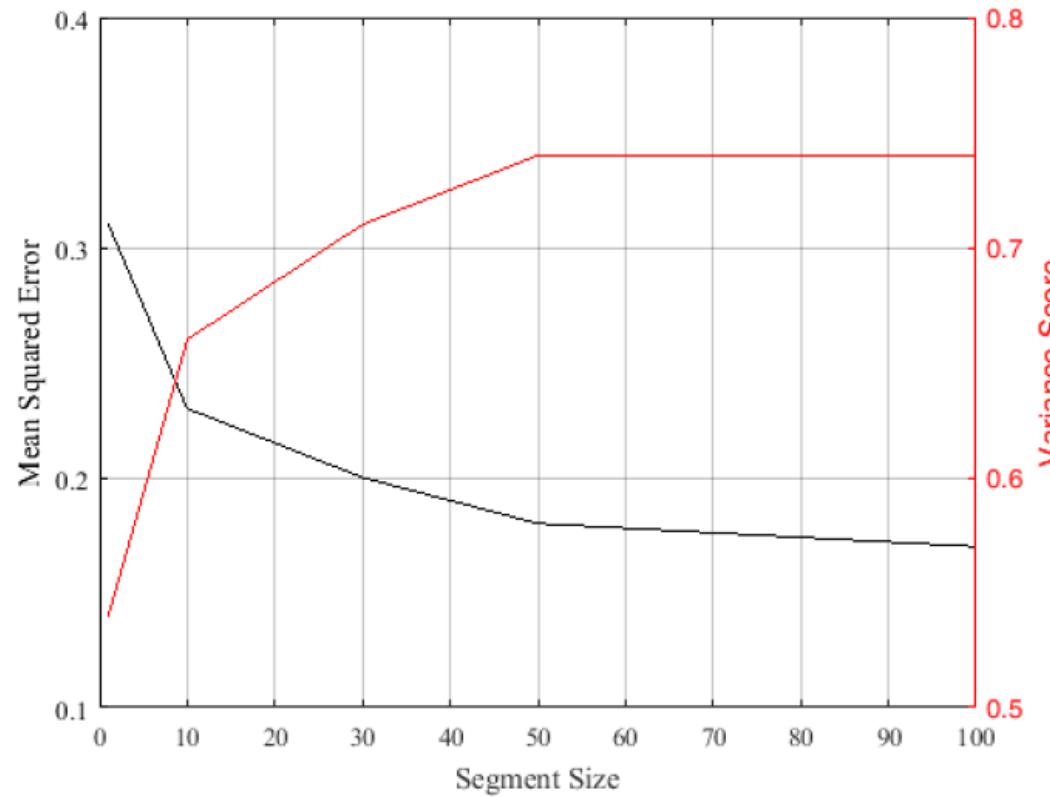


Figure 6.8: The performance of the random forest regression model against segment size,  $M$ . As  $M$  increases, error is reduced but variance increases shown a tendency to over-fit as the training window is increased.

# Subsequent Regressor Comparisons

- Random Forest (RnF) – randomized decision regression trees are formed based on random, and a joint result from all trees are calculated. Overfitting is achieved by limiting leaves and features in each tree constructed although full coverage is guaranteed by the sheer number of trees constructed.
- Gradient Boosting Machine (GBM) – Similar to RnF except that tree size is limited, and trees are iteratively made by minimizing the residual errors of the previous trees until convergence is achieved.
- Extreme Gradient Boosting Machine (XGBM) – Like GBM but uses similarity score (mean sum error + regularization  $\lambda$ )
- Linear Ridge – first-order linear regression model (as a comparison)

# Variance and MSE of Various Regressors

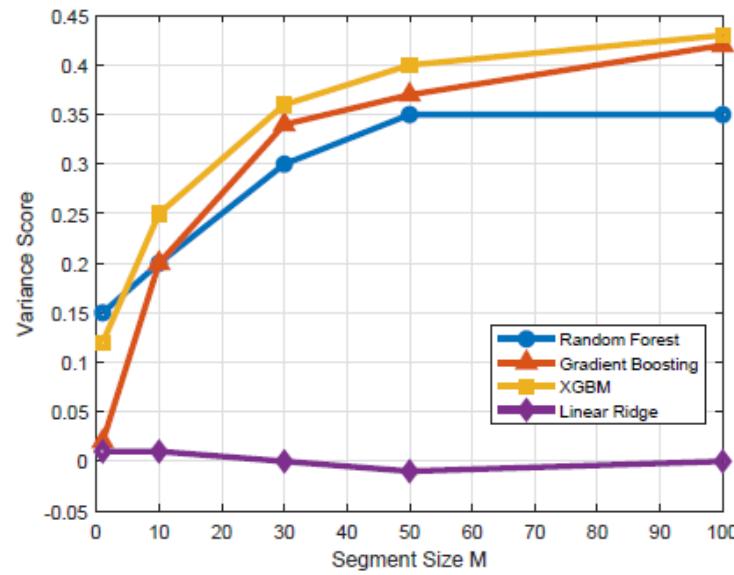


Figure 6.10: The variance score performance with jamming imposed on b/g-Router of various algorithms against segment size,  $M$ .

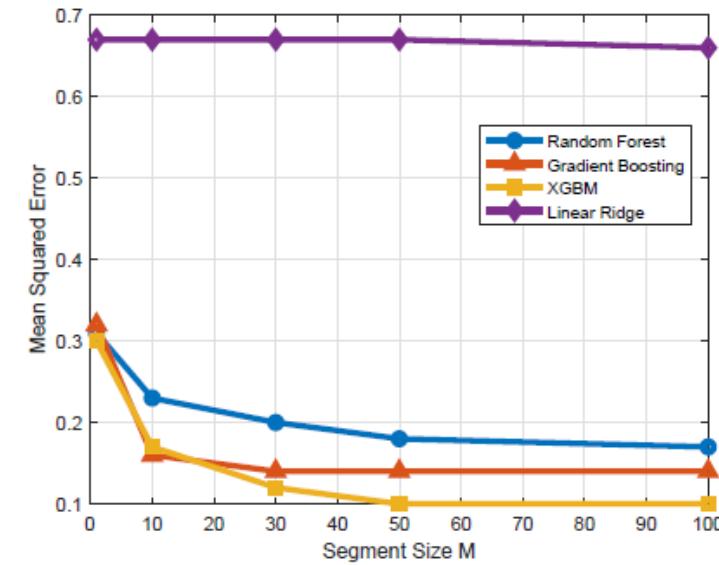


Figure 6.11: The mean squared error performance with jamming imposed on b/g-Station of various algorithms against segment size,  $M$ .

# Comparison of Feature Importance

- Using XGBM as basis
- Comparison of impact of each feature one-at-a-time and then all together.
- Dwell time before descent ( $\Delta t_{ab}$ ) was found to be the most impactful feature
  - Due to zeroing message between robot controller and FT sensor compute box

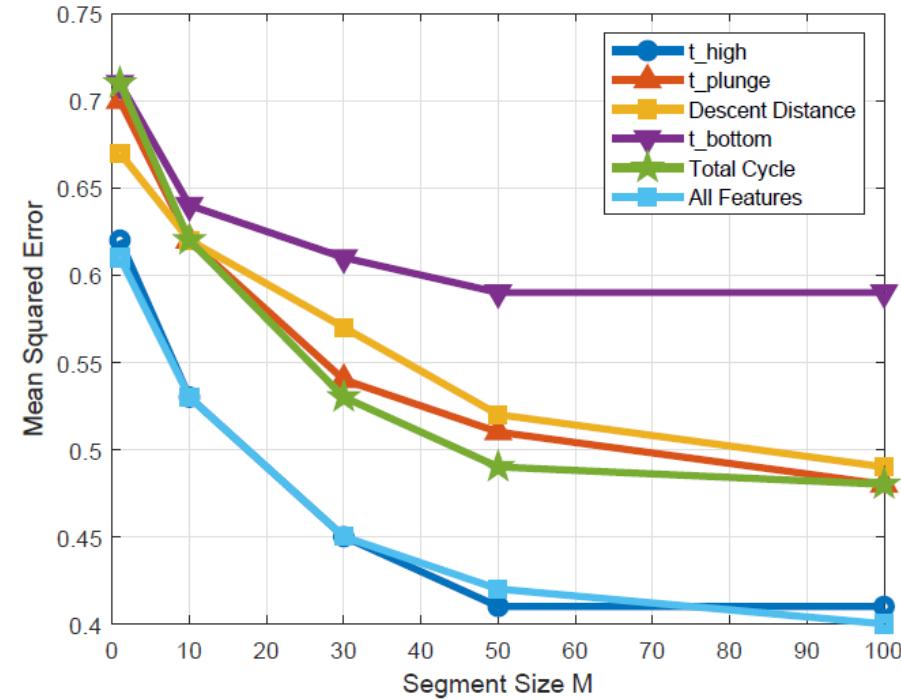


Figure 6.14: The MSE performance for jamming setting b/g-Router of XGBM algorithm against  $M$  including individual features impact. As indicated in the figure, the feature  $\Delta t_{ab}$  is most predictive of the SIR level as compared to all of the features together. It appears that the only the dwell time before REEF plunge is required to predict SIR in this scenario.

# Conclusions and Future Direction

*Performance Estimation, Testing, and Control of Cyber-Physical Systems Employing Non-Ideal Communications Networks*

Thesis Presentation 28 September 2020

Richard Candell

# Conclusions

## Requirements and wireless landscape

- Surveyed the wireless technology landscape
- Made the requirements realistic and validated

## Modeling Approach

- Produced a reusable model using SysML
- Include both structure of the IWN and the Physical System

## Graph Database Approach

- Demonstrated use of a GDB for CPS performance evaluation
- Use of GDB to reveal performance correlations between IT and OT

## Machine learning approach

- Use of decision trees to estimate link quality (SIR) using OT measurements

# Future Work

- SysML
  - Modeling Enhancements
  - Integration with CPS simulation
- Graph Database
  - Make the GDB real-time or near-real-time with on-the-go queries
  - Improve the GDB Schema to avoid Cartesian product explosions
- Machine Learning
  - Increase dimensionality of the machine learning approach to address considerations of larger systems and concerns
  - Integrate the machine learning approach with a control system to allow the control system to adapt to changes in the RF environment
  - Add spectrum monitoring system as an input to the machine learner

# Thank You

A circular word cloud centered on the words "Thank You". The words are repeated in many different languages, including English, Spanish, French, German, Italian, Portuguese, Dutch, Swedish, Danish, Norwegian, and others. The background is white, and the words are in various shades of blue and grey.

$$\text{Bias} = E[\hat{\theta}] - \theta.$$

$$\text{Var}(\hat{\theta}) = E[(E[\hat{\theta}] - \hat{\theta})^2].$$

MSE is mean of square errors between estimate and actual

