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

Field Data

- Live Factories
- **Precision Measurements**
- Meetings
- Conferences

Models

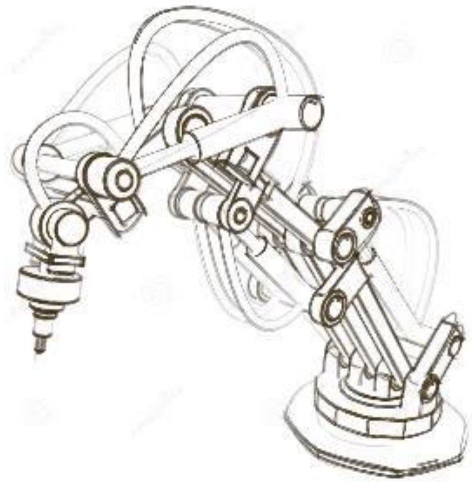
- Channel Models
  - Interference Models
  - **Propagation Models**
  - Manufacturing Models

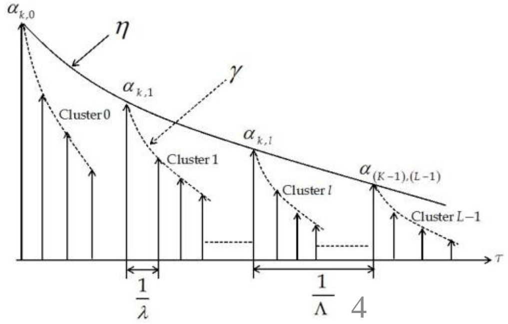
Experiments

- Simulations
- **Testbed**
- Spectrum Sensing
- Brown field control
- Advanced control solutions

<u>Guidelines</u>

- **Best Practices**
- Increase data
- More Reliable
- Improve Safety
- Spur Innovation



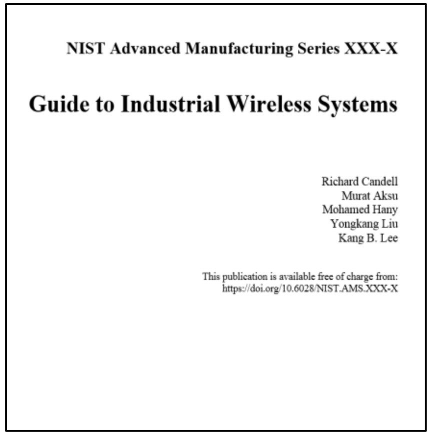


Collaborators: Past and Present

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

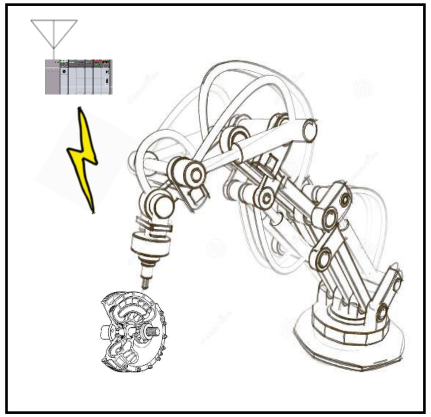

NIST Advanced Manufacturing Series XXX-X

Guide to Industrial Wireless Systems

Richard Candell
Murat Aksu
Mohamed Hany
Yongkang Liu
Kang B. Lee

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.XXX-X

- **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.

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

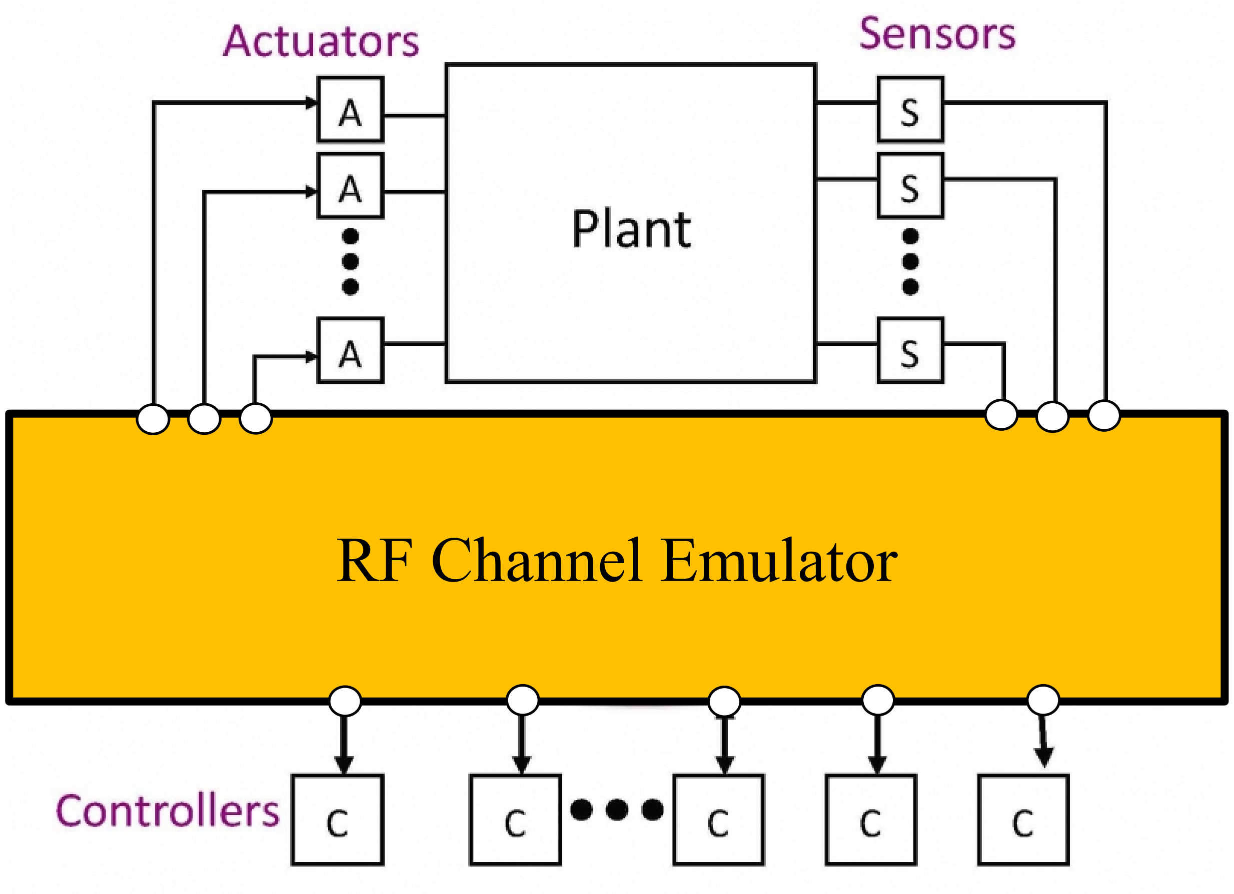
Recreating the Factory RF Environment in the Lab

<u>Radio Environment</u>

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

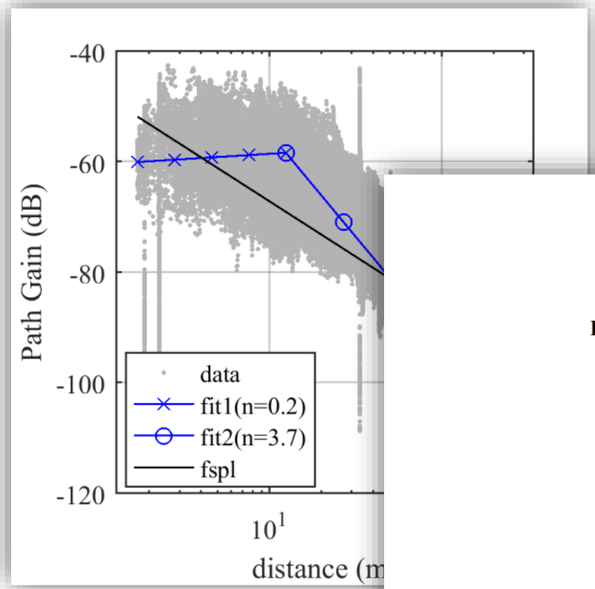
<u>Possible Focus Areas</u>

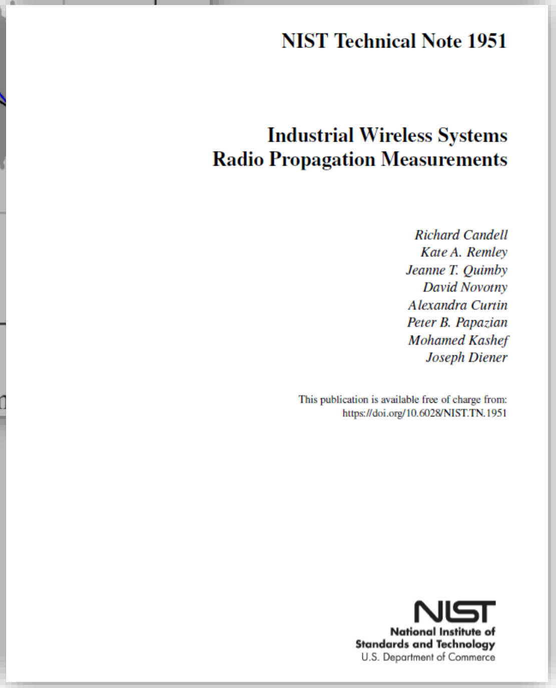
- Improved wireless standards
- Wireless Reliability
- Better Control strategies
- Interference cancellation
- Time Synchronization



Measurement Campaigns

Mobile Cart-based Measurements




NIST Technical Note 1951

Industrial Wireless Systems
Radio Propagation Measurements

Richard Candell
Kate A. Remley
Jeanne T. Quimby
David Novotny
Alexandra Curtin
Peter B. Papazian
Mohamed Kashef
Joseph Diener

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.1951

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

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

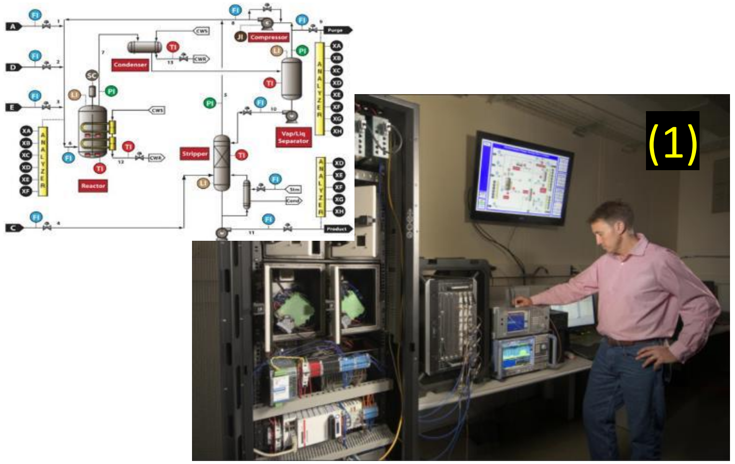
Past Testbed Incarnations

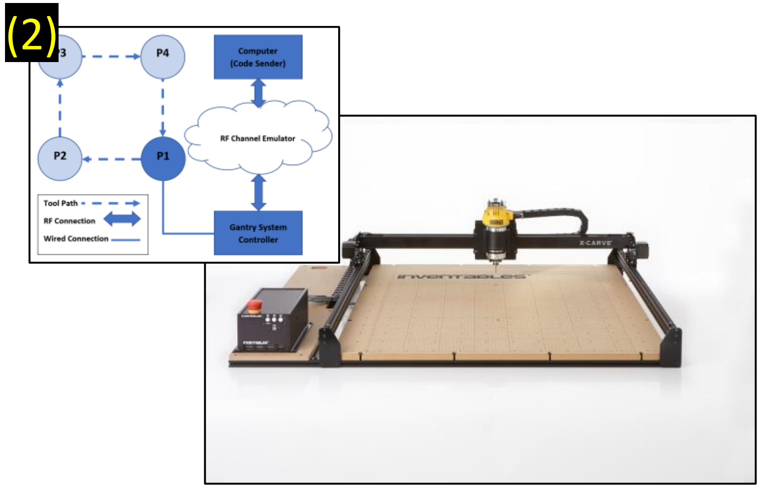
1 - NIST - Tennessee Eastman chemical plant

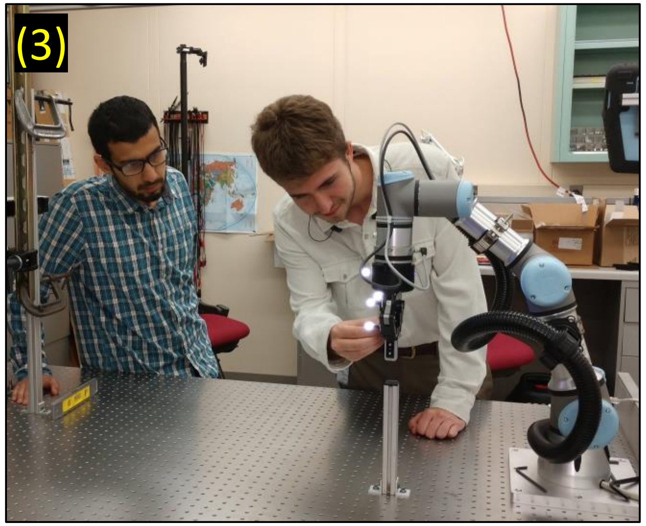
2 - NIST - 3D gantry system

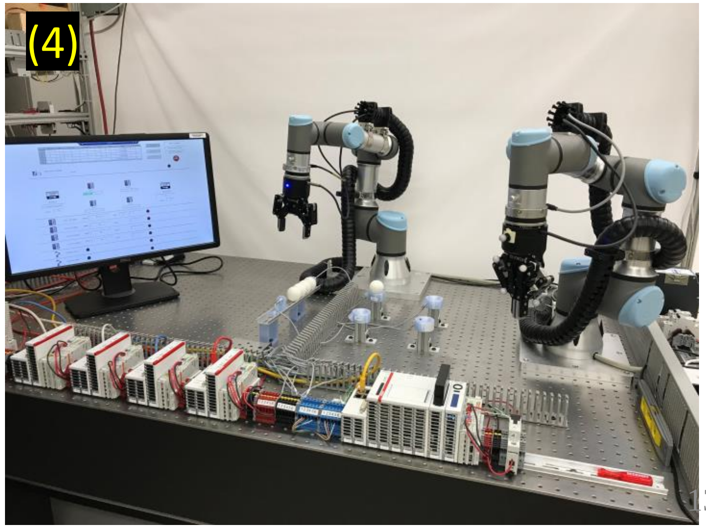
* 3 - NIST - Force seeking apparatus

* 4 - NIST - Dual-robot machine tending with inspection









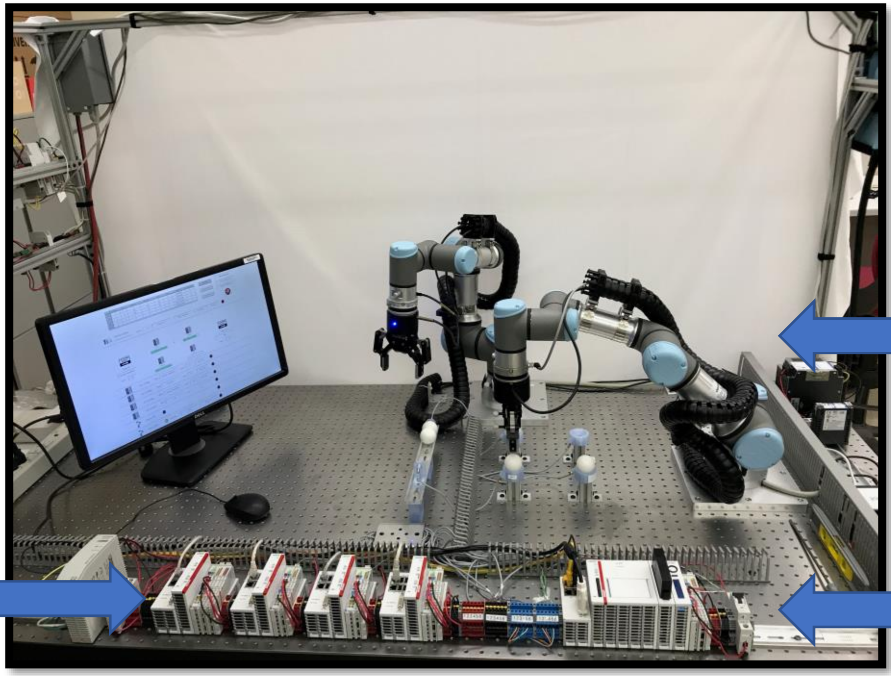
Current Demonstration Platform

RF Shielding

CNC Sims

IEEE 1588 Master

TSN Capable



Dual Cobots

Supervisor

RF Channel Emulator

Thesis

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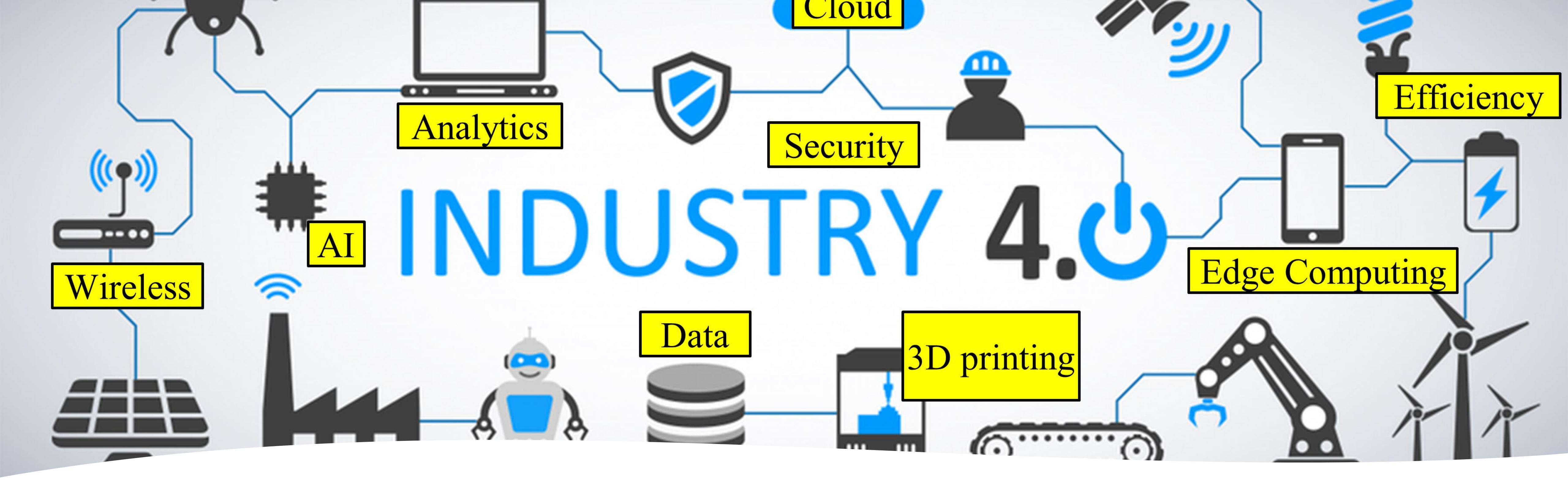

Thesis Motivation

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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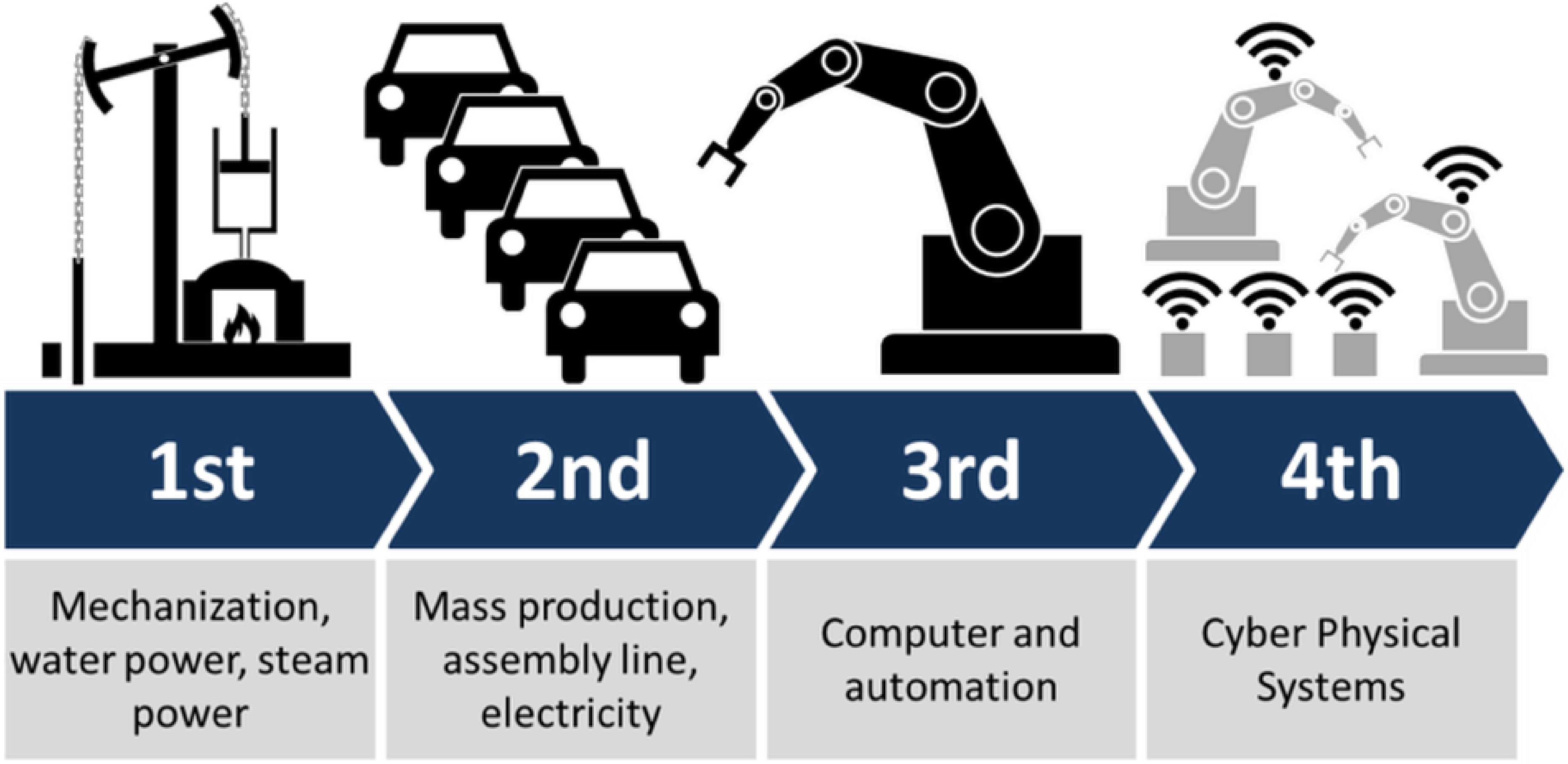
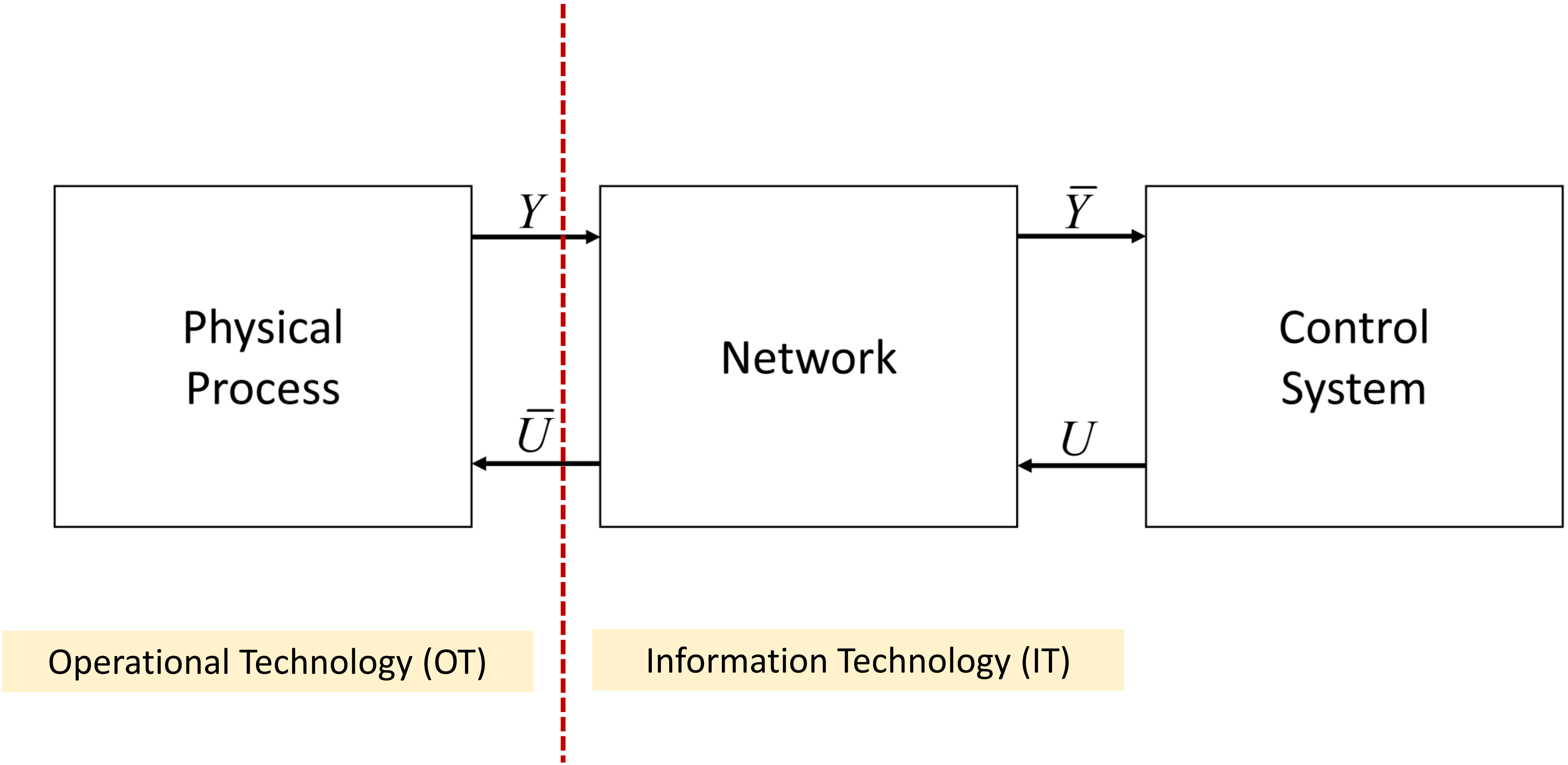
History of World Industrialization



What is a Cyberphysical System? (CPS)



CPS Concepts in Smart Manufacturing

- ❖ Situationally-aware and state-aware automation systems
- ❖ Move intelligence closer to the edge devices (or in the devices)
- ❖ Better test methods that include holistic perspective
- ❖ Better communications protocols (esp. for wireless)
- ❖ Requires high reliability and security

Industrial Wireless Requirements

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Research 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

Mapping Wireless to Automation Systems

- Flow-based
- Job-based
- Safety
- Back-haul
- Tracking
- Security
- Remote Control
- Maintenance

		Flow-based					Job-based					
		Process Monitoring	Supervisory Control	Feedback Control	Alarm Conditions	In-situ Inspection	Factory Monitoring	Assembly: Sensing	Assembly: Actuation	Robots: Supervision	Robots: Feedback Control	Quality Inspection
Home/Office	IEEE 802.11	●	●	◐	◐	-	●	◐	◐	◐	◐	◐
	IEEE 802.15.1	○	○	○	○	○	○	◐	◐	◐	○	●
Industrial	IEEE 802.15.4 TDMA	●	●	◐	◐	-	●	◷	◷	◷	◷	◐
	IEEE 802.15.4 CSMA	◐	◐	○	○	-	●	◷	◷	◷	◷	◐
	IEEE 802.11 TDMA	⚹	⚹	⚹	⚹	-	⚹	⚹	⚹	⚹	⚹	⚹
	VLBR WAN	●	●	○	◐	-	●	◷	◷	◷	◷	◷
Satellite	Geostationary	◐	◐	○	○	○	○	○	○	○	○	○
	Low-earth Orbit	◐	◐	○	○	○	○	○	○	○	○	○
	VLBR WAN	◐	◐	○	◐	○	◷	◷	◷	◷	◷	◷
Tracking	RFID	-	-	-	-	-	-	-	-	-	-	-
Optical	Indoor Dispersive	⚹	⚹	⚹	⚹	○	⚹	⚹	⚹	⚹	⚹	⚹
	Free-space	◐	◐	◐	◐	○	○	○	○	○	○	○
Cellular	Legacy	◐	◐	○	○	-	○	○	○	○	○	○
	4G	◐	◐	○	◷	-	○	○	○	○	○	○
	5G	⚹	⚹	⚹	⚹	-	⚹	⚹	⚹	⚹	⚹	⚹
Land-mobile	All types	○	○	○	○	○	○	○	○	○	○	○
Specialty	Leaky Coax	◐	◐	-	◐	◐	◐	-	-	○	○	-

		Safety				Back-haul				Tracking				
		Fall Prevention	Confined Spaces	Critical Event Detection	Human-Machine Colocation	Nearby or Indoor	Distant: LOS	Distant: BLOS	Geographically Remote	Indoor Machine Localization	Materials in Storage	Materials in Production	Tools	Personnel
Home/Office	IEEE 802.11	○	○	◐	○	●	●	●	-	◐	ϟ	ϟ	ϟ	ϟ
	IEEE 802.15.1	○	◐	○	○	○	○	○	○	○	○	ϟ	●	◐
Industrial	IEEE 802.15.4 TDMA	◷	◐	◐	○	▼	▼	▼	▼	◐	ϟ	ϟ	ϟ	◐
	IEEE 802.15.4 CSMA	◷	◐	◐	○	▼	▼	▼	▼	◐	ϟ	ϟ	ϟ	◐
	IEEE 802.11 TDMA	⚹	⚹	⚹	⚹	-	-	-	-	⚹	-	-	-	-
	VLBR WAN	◷	○	○	○	▼	▼	▼	▼	◐	◐	◐	◐	◐
Satellite	Geostationary	○	○	○	○	○	○	○	◐	○	○	○	○	○
	Low-earth Orbit	○	○	○	○	○	○	◐	◐	○	○	○	○	○
	VLBR WAN	◷	○	○	○	▼	▼	▼	▼	○	○	○	○	◐
Tracking	RFID	-	-	-	-	-	-	-	-	○	●	●	●	●
Optical	Indoor Dispersive	⚹	⚹	⚹	⚹	⚹	○	○	○	⚹	ϟ	ϟ	ϟ	ϟ
	Free-space	○	○	○	○	●	●	●	○	◐	○	○	○	○
Cellular	Legacy	◷	◷	◷	◷	◐	◐	◐	◐	○	○	○	○	○
	4G	◷	◷	◷	◷	◐	◐	◐	◐	○	○	○	○	○
	5G	⚹	⚹	⚹	⚹	●	●	●	○	⚹	⚹	⚹	⚹	⚹
Land-mobile	All types	○	○	○	○	▼	▼	○	○	○	○	○	○	○
Specialty	Leaky Coax	○	◐	◐	-	◐	○	○	○	◐	●	●	○	○

		Security						Remote			Maint.		
		Voice and Video Communication	Video Surveillance	Drone-based Surveillance	Grounds Control	Spectrum Monitoring Data	Personnel Authorization	Well-head Monitoring	Pipeline Monitoring	Tank Level Monitoring	Machine Health Monitoring	Building Automation	Augmented Reality
Home/Office	IEEE 802.11	●	●	●	●	●	●	◐	○	◐	◐	●	●
	IEEE 802.15.1	▼	▼	▼	○	○	◐	○	○	○	◐	○	▼
Industrial	IEEE 802.15.4 TDMA	▼	▼	▼	◐	▼	○	●	●	●	●	●	▼
	IEEE 802.15.4 CSMA	▼	▼	▼	◐	○	○	◐	◐	◐	●	●	▼
	IEEE 802.11 TDMA	-	-	-	⚹	-	-	⚹	⚹	⚹	⚹	⚹	-
	VLBR WAN	▼	▼	▼	◷	○	○	○	○	○	◐	◐	○
Satellite	Geostationary	◐	◐	○	◐	◐	◐	◐	◐	◐	○	○	◐
	Low-earth Orbit	◐	◐	◐	◐	◐	◐	◐	◐	◐	◐	○	◐
	VLBR WAN	▼	▼	▼	◐	○	○	○	○	○	◐	○	▼
Tracking	RFID	-	-	-	-	-	-	-	-	-	-	-	-
Optical	Indoor Dispersive	⚹	⚹	○	○	⚹	○	○	○	○	⚹	○	○
	Free-space	●	●	○	○	○	○	●	○	●	○	○	●
Cellular	Legacy	○	○	○	○	⚹	◐	◐	◐	◐	◐	▼	▼
	4G	●	●	◐	●	●	●	◐	◐	◐	○	○	○
	5G	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹	⚹
Land-mobile	All types	◐	○	○	●	○	◐	○	○	○	○	○	○
Specialty	Leaky Coax	○	○	○	●	○	●	○	○	○	◐	◐	○

Legend: ●: Technology fully supports problem domain, ◐: Supports problem domain with practicality, throughput, latency, reliability, or energy limitations, ϟ: 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.

SysML: Workcell Architectural Decomposition and Analysis

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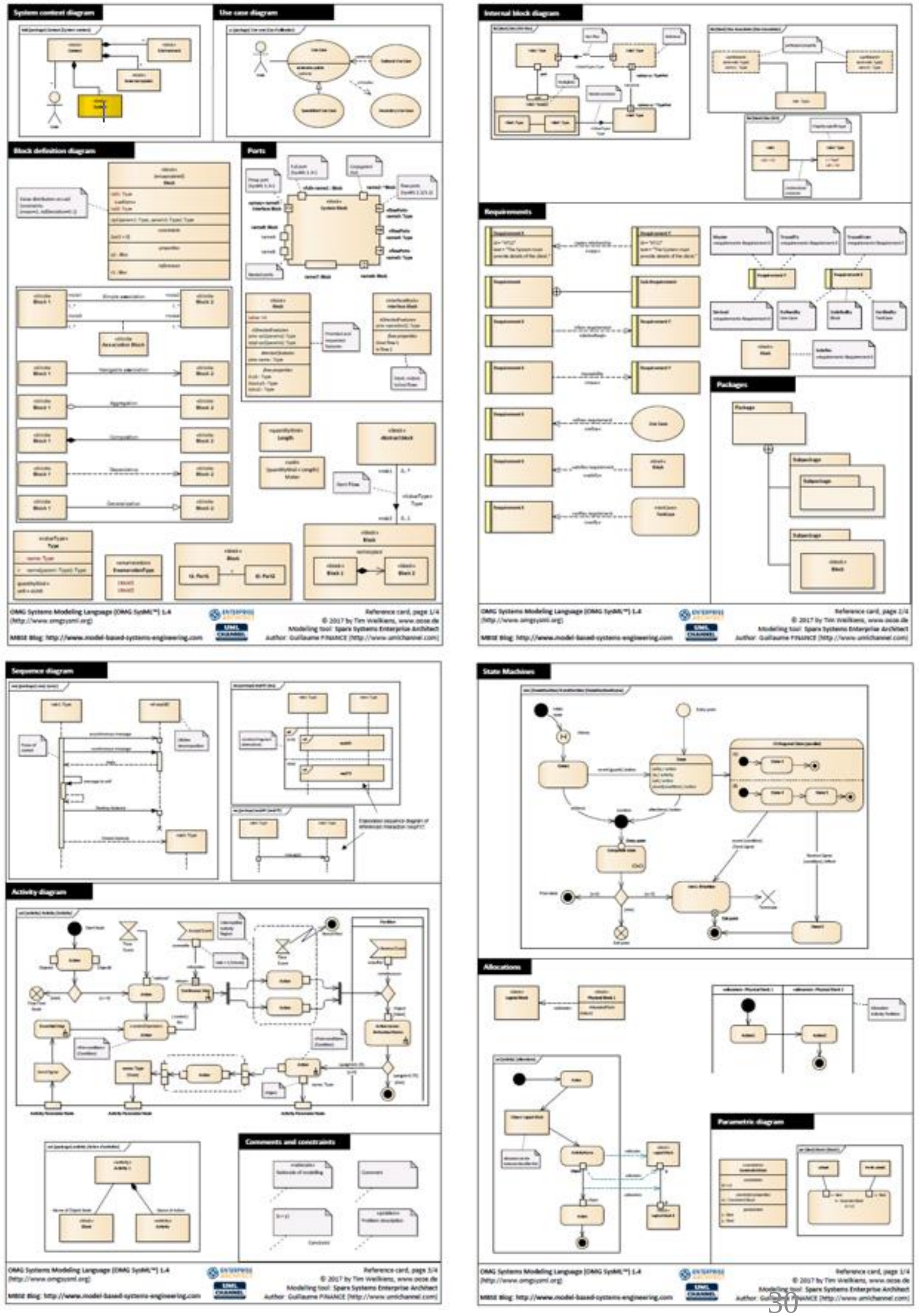
Modeling Objectives

- Decompose the industrial wireless workcell into:
  - Constituent components
  - Identify interfaces
  - Identify information flows
  - Identify constraints to performance
- Construct a re-usable model for other researchers
  - Help improve the understanding of the industrial wireless workcell
  - Communicate designs more effectively
- Make model publicly available

SysML Primer

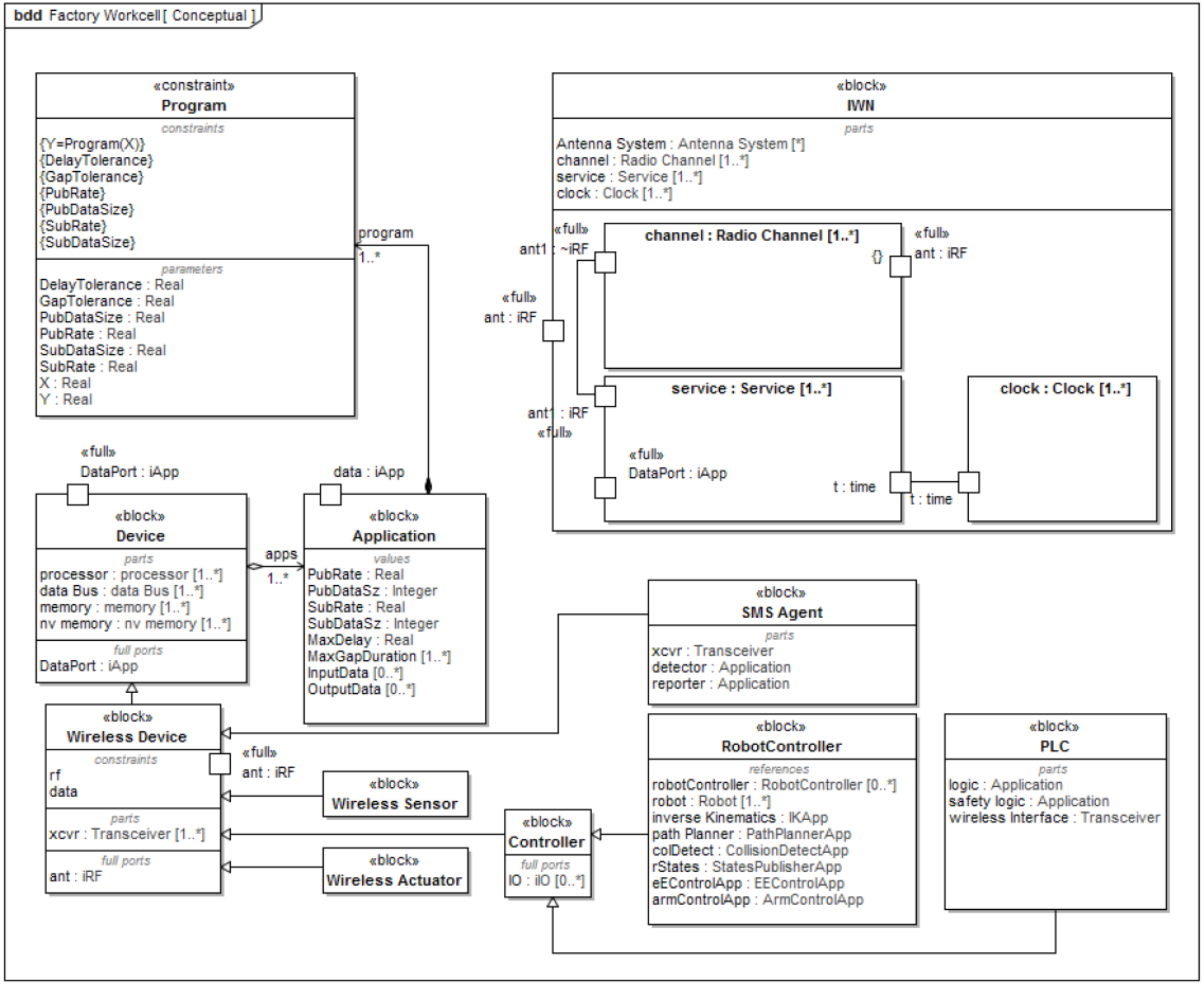
- SysML Components
  - Blocks, Ports, Connections, Associations
- Popularly Used Diagrams
  - Block Definition Diagrams (BDD)
  - Internal Block Diagram (IBD)
  - Parametric diagram (PAR)
  - Use case diagram (UC)
  - Requirements diagram (REQ)
  - Package diagram (PKG)
- Other diagrams



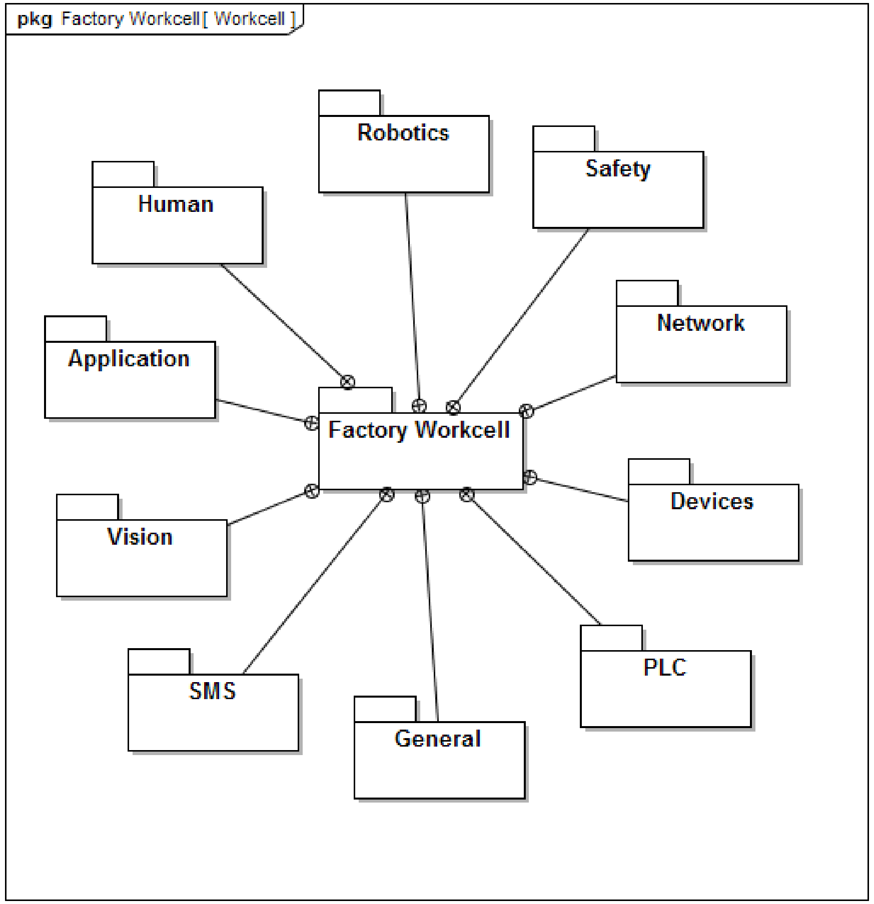
Reference card taken from: https://community.sparxsystems.com/community-resources/1043-sysml-1-4-reference-card

Conceptual Diagram

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

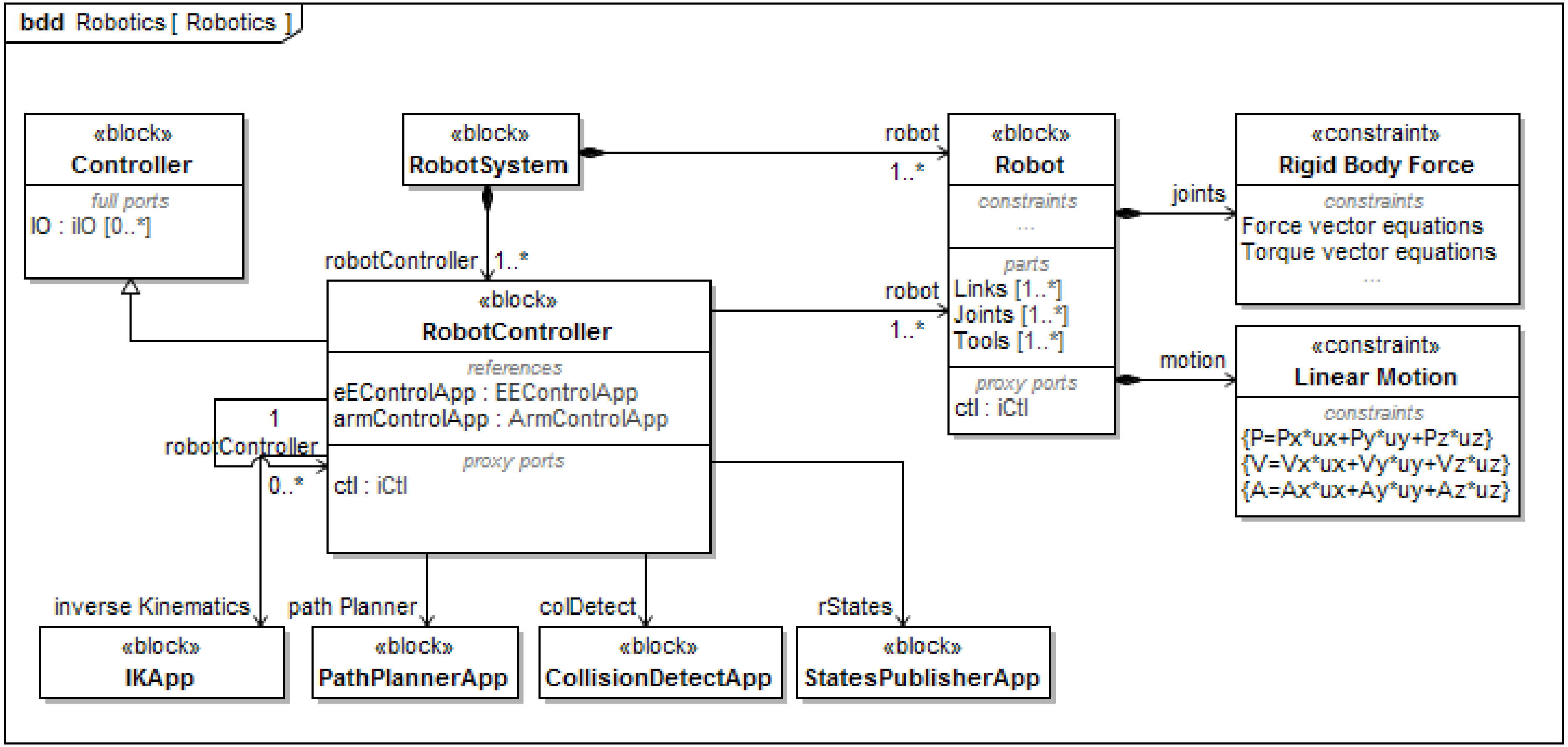


Packages



- General: contains key reusable blocks for constructing other packages
- Devices: describes the generic device blocks within the model
- Network: describes the generic industrial network
- Robotics
- PLC: Programmable Logic Controller
- Safety
- SMS: Spectrum Monitoring System

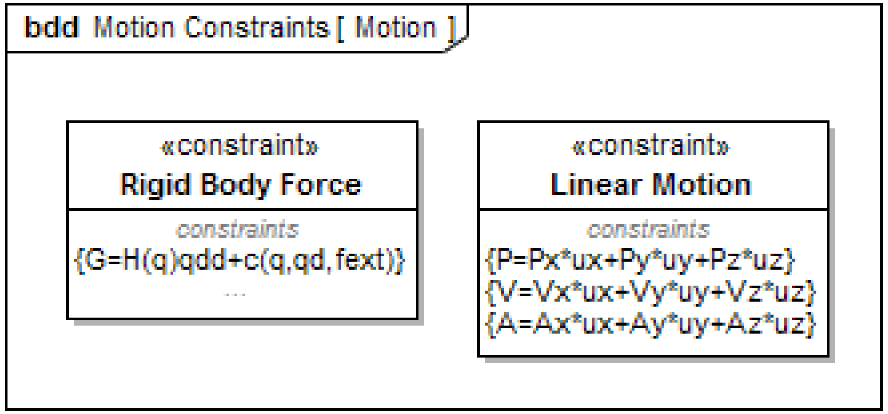
Robotics

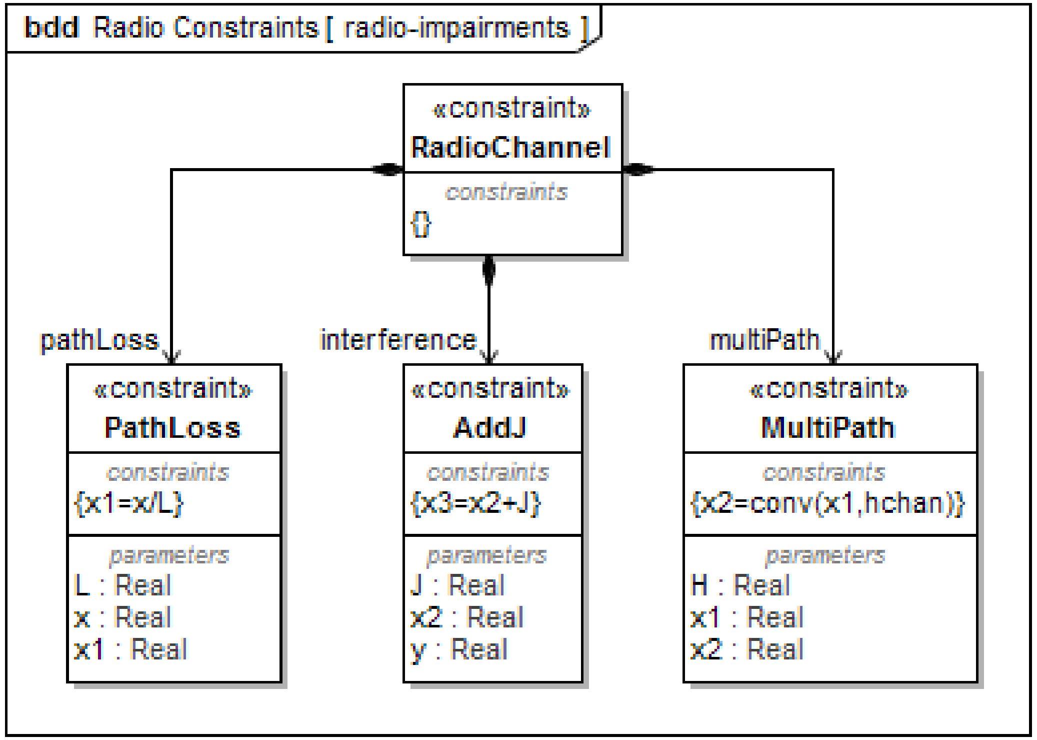


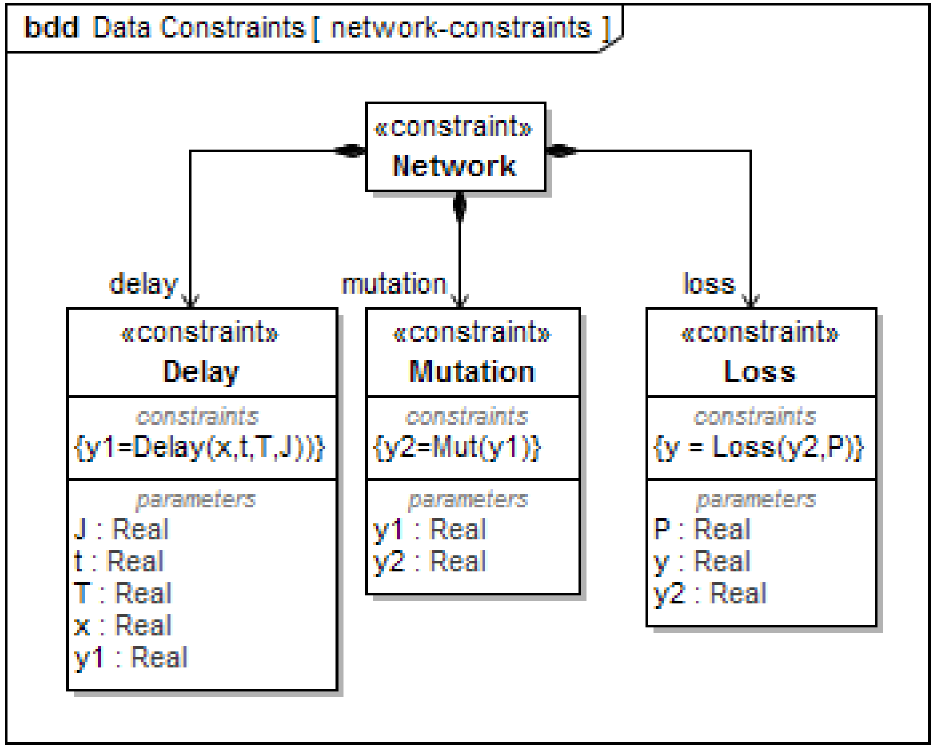
bdd Robotics [Robotics]
«block»
Controller
full ports
IO : iIO [0..*]
«block»
RobotSystem
robot
1..*
«block»
Robot
constraints
...
parts
Links [1..*]
Joints [1..*]
Tools [1..*]
proxy ports
ctl : iCtl
joints
«constraint»
Rigid Body Force
constraints
Force vector equations
Torque vector equations
...
motion
«constraint»
Linear Motion
constraints
{P=Px*ux+Py*uy+Pz*uz}
{V=Vx*ux+Vy*uy+Vz*uz}
{A=Ax*ux+Ay*uy+Az*uz}
robotController
1..*
robot
1..*
«block»
RobotController
references
eEControlApp : EEControlApp
armControlApp : ArmControlApp
proxy ports
ctl : iCtl
1
robotController
0..*
inverse Kinematics
path Planner
colDetect
rStates
«block»
IKApp
«block»
PathPlannerApp
«block»
CollisionDetectApp
«block»
StatesPublisherApp

Constraints

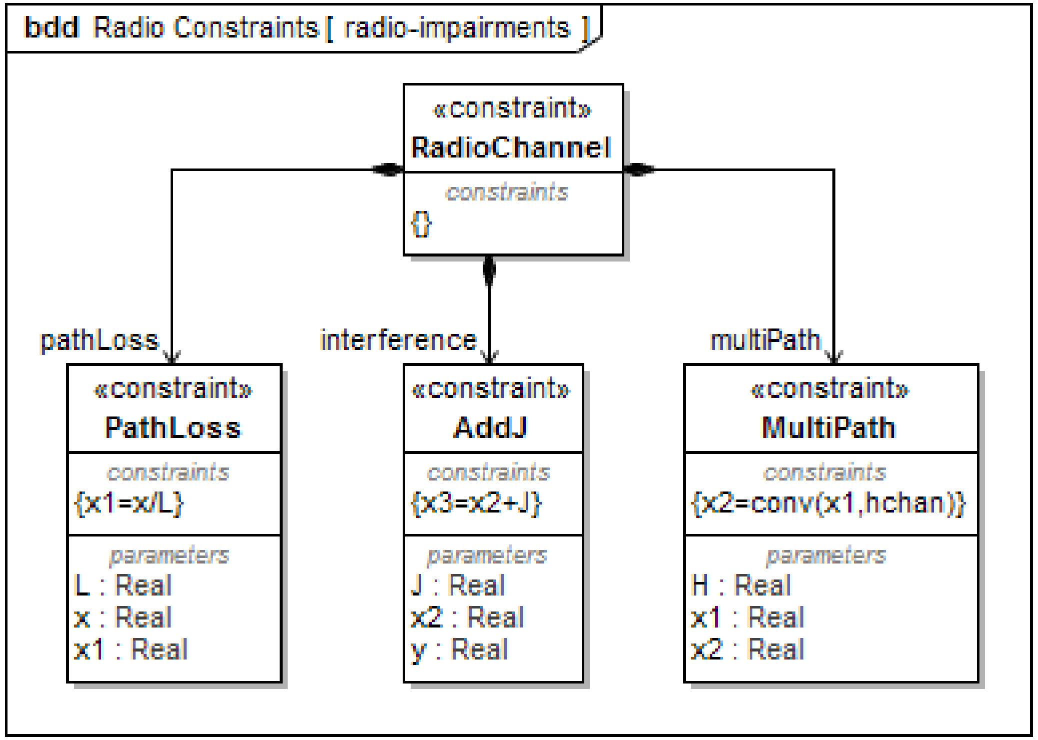
Allows us to model mathematically or programmatically effects of behavior within a block.

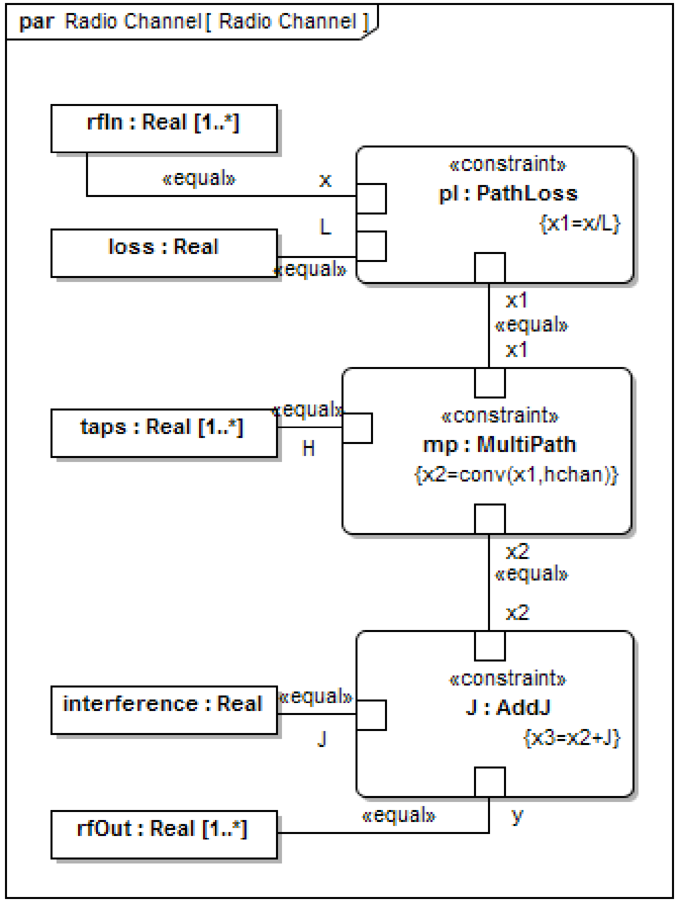




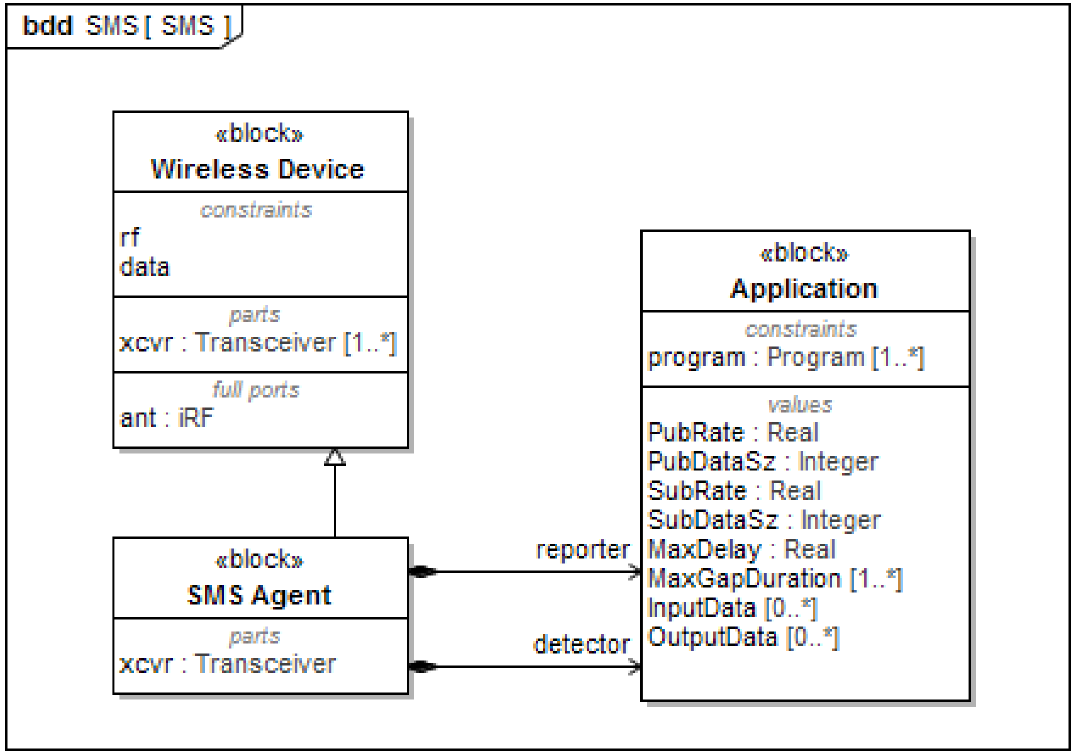


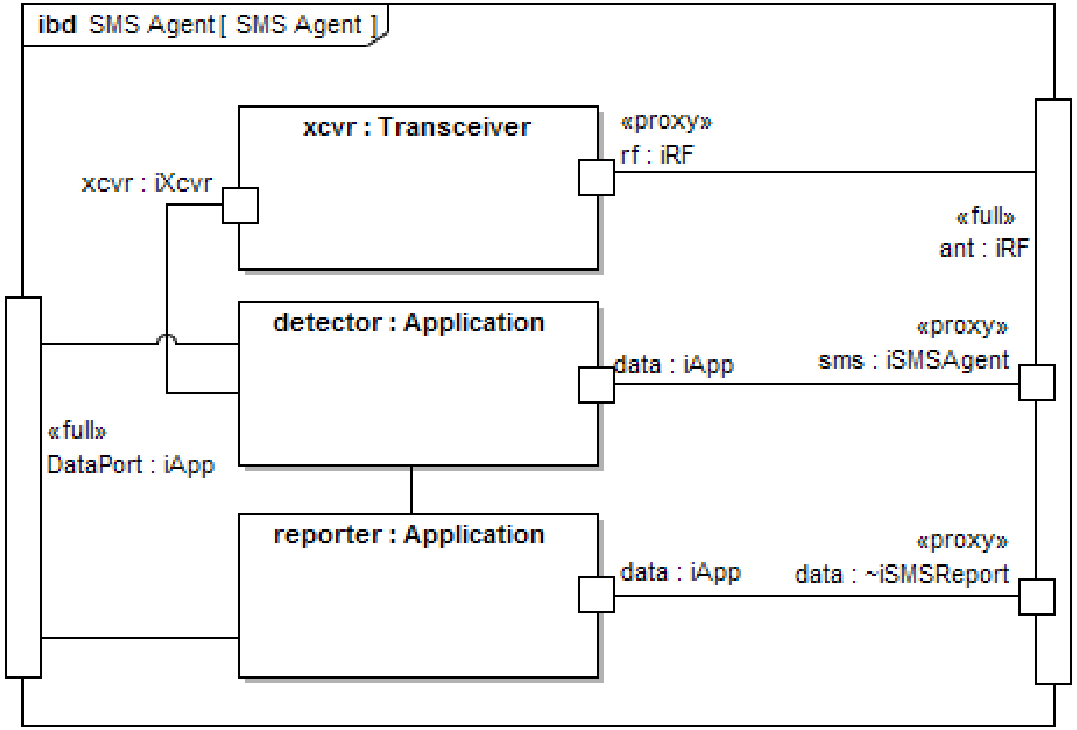
Radio Channel Constraints



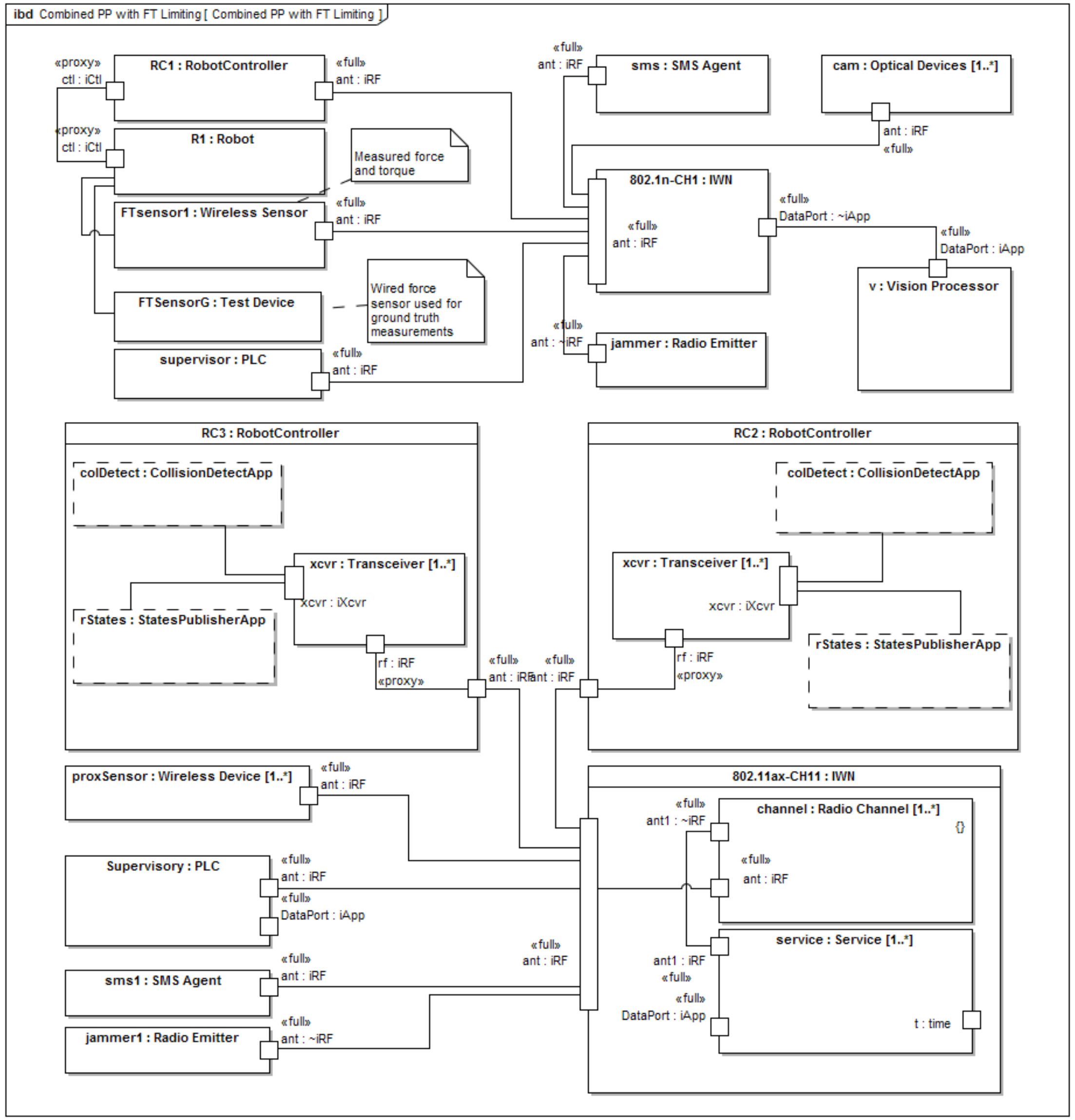


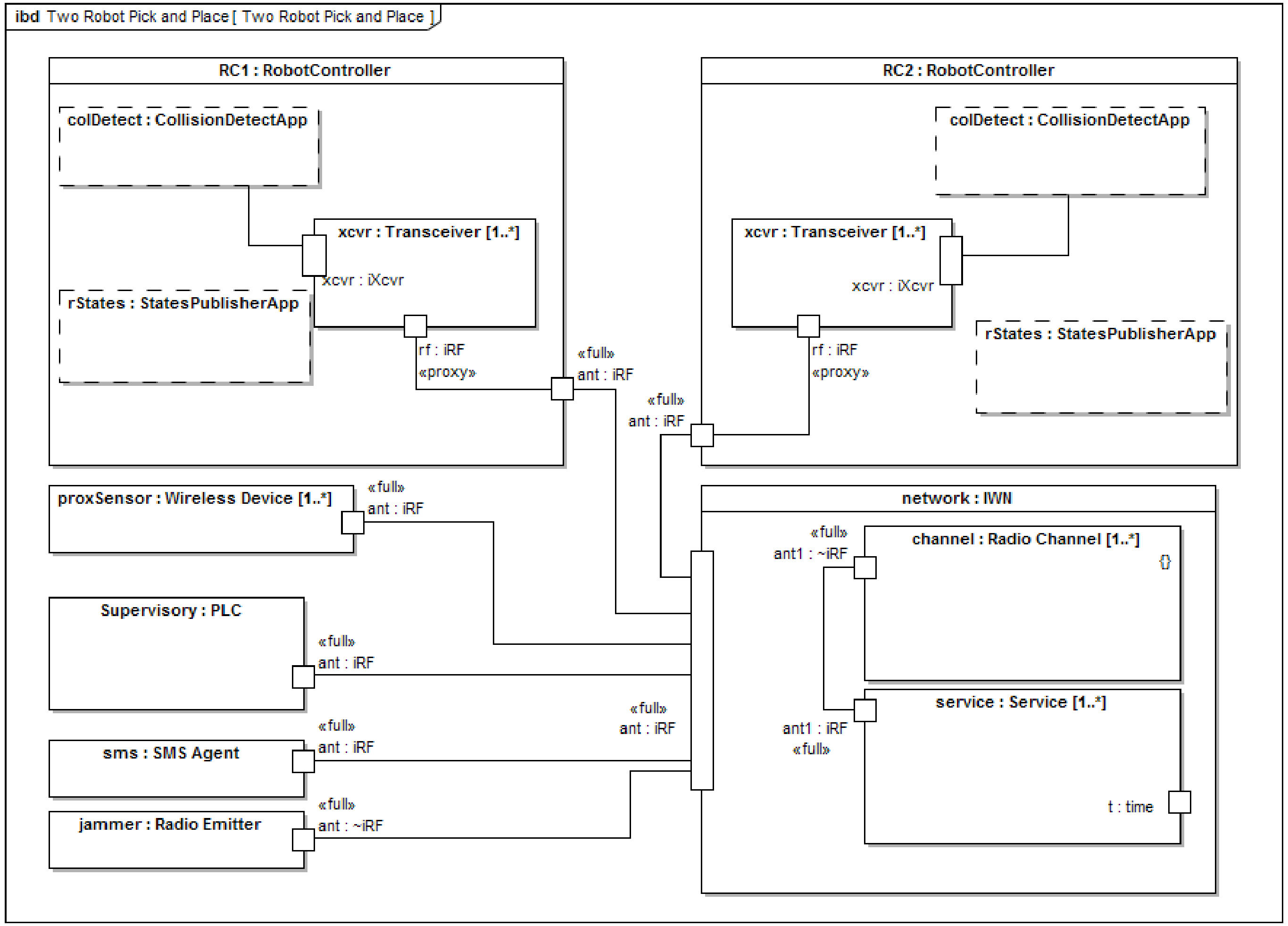
Spectrum Monitoring System (SMS)





Example IBDs of Factory Workcells





Application of the Graph Databases to CPS Experiments

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

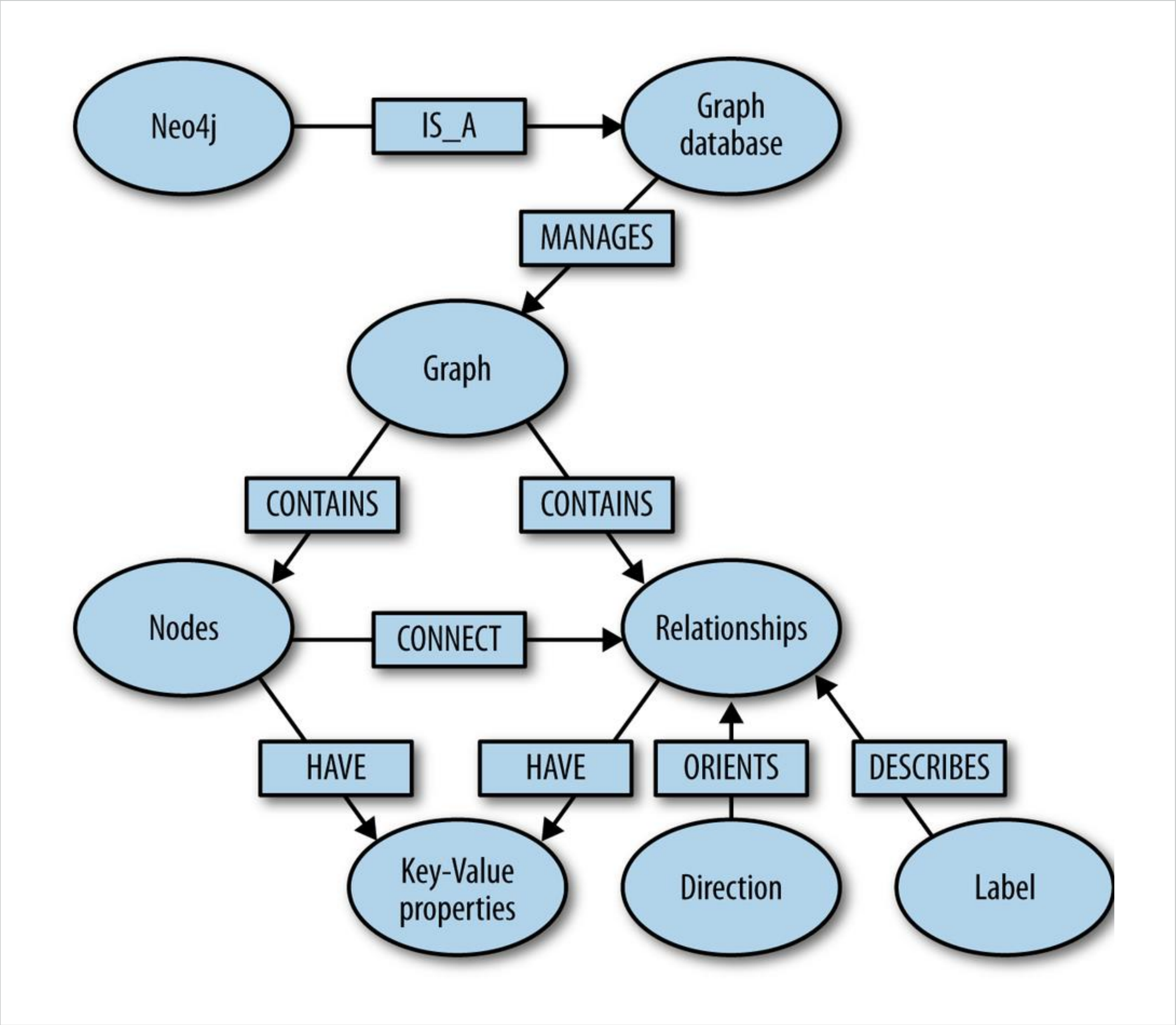
Richard Candell

Introduction & Motivation

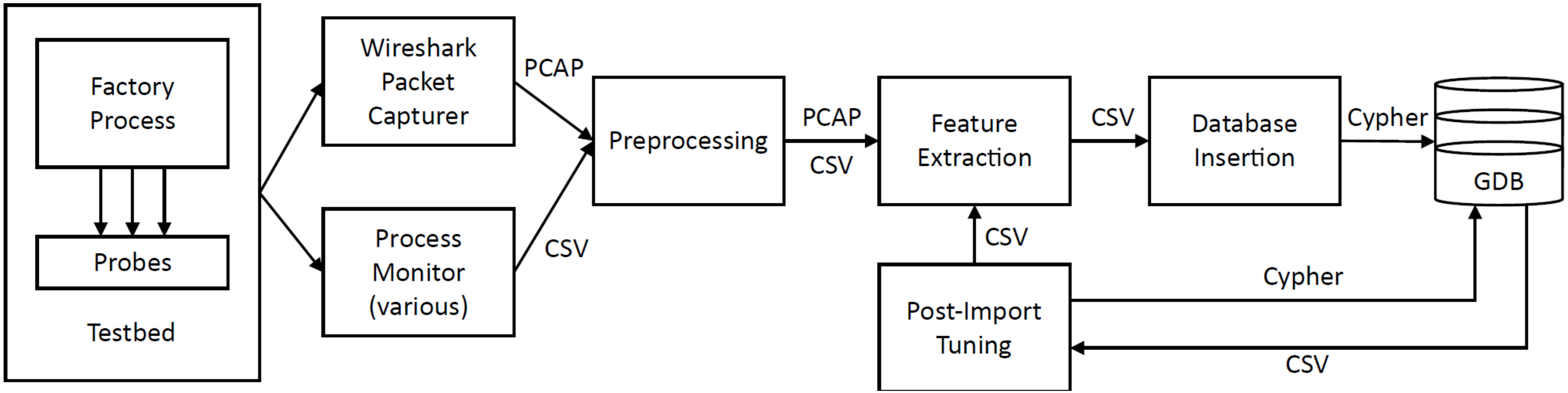
- Motivation:
  - Address the difficulty of organizing IT and OT data and their correlated relationships
- Graph Database Advantages
  - Inherently capture data and relationships
  - No need to perform complex joins
- Outputs
  - Used the GDB to study the impacts of the IWN on the physical system

What is a Graph Database?

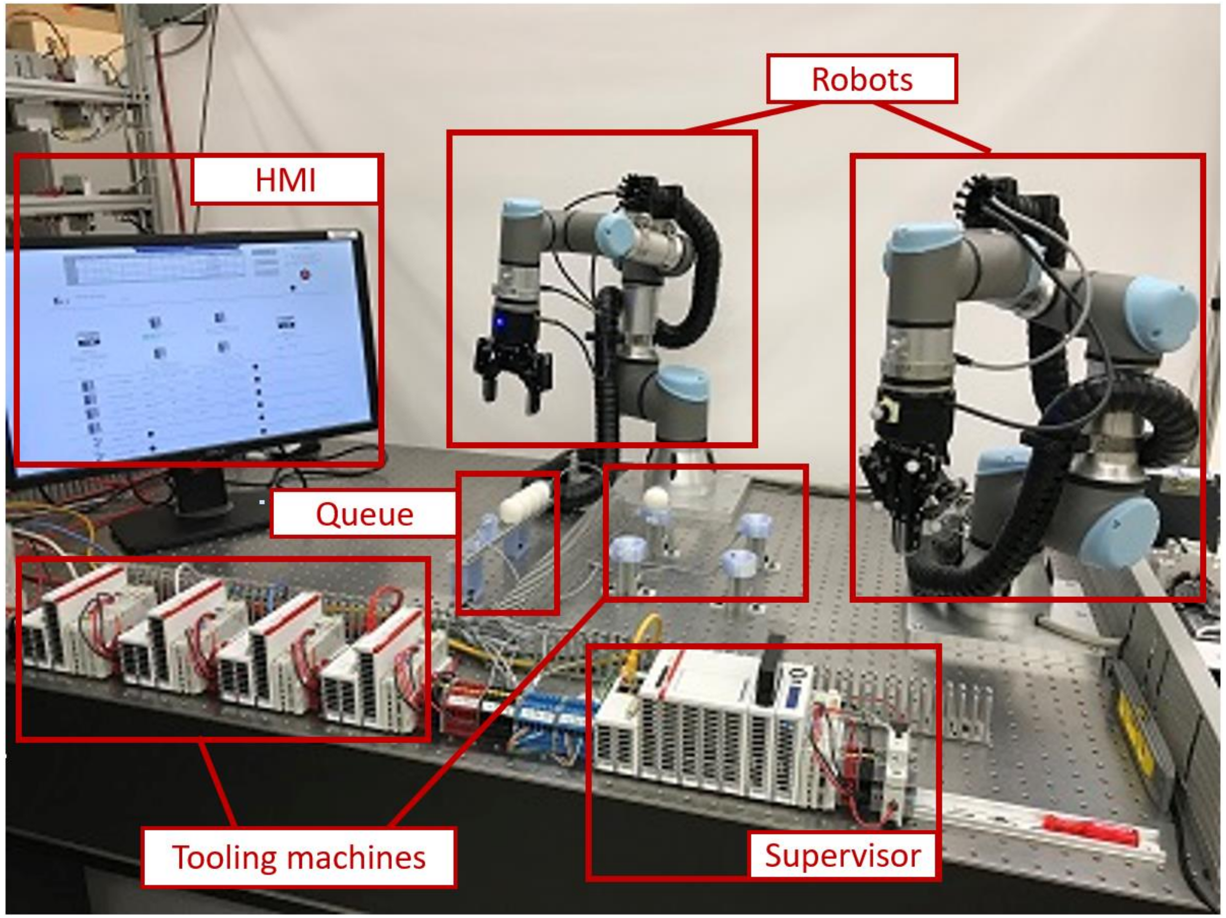
A graph database (GDB) is a database that uses graph structures for semantic queries with nodes, edges, and properties to represent and store data. A key concept of the system is the graph.

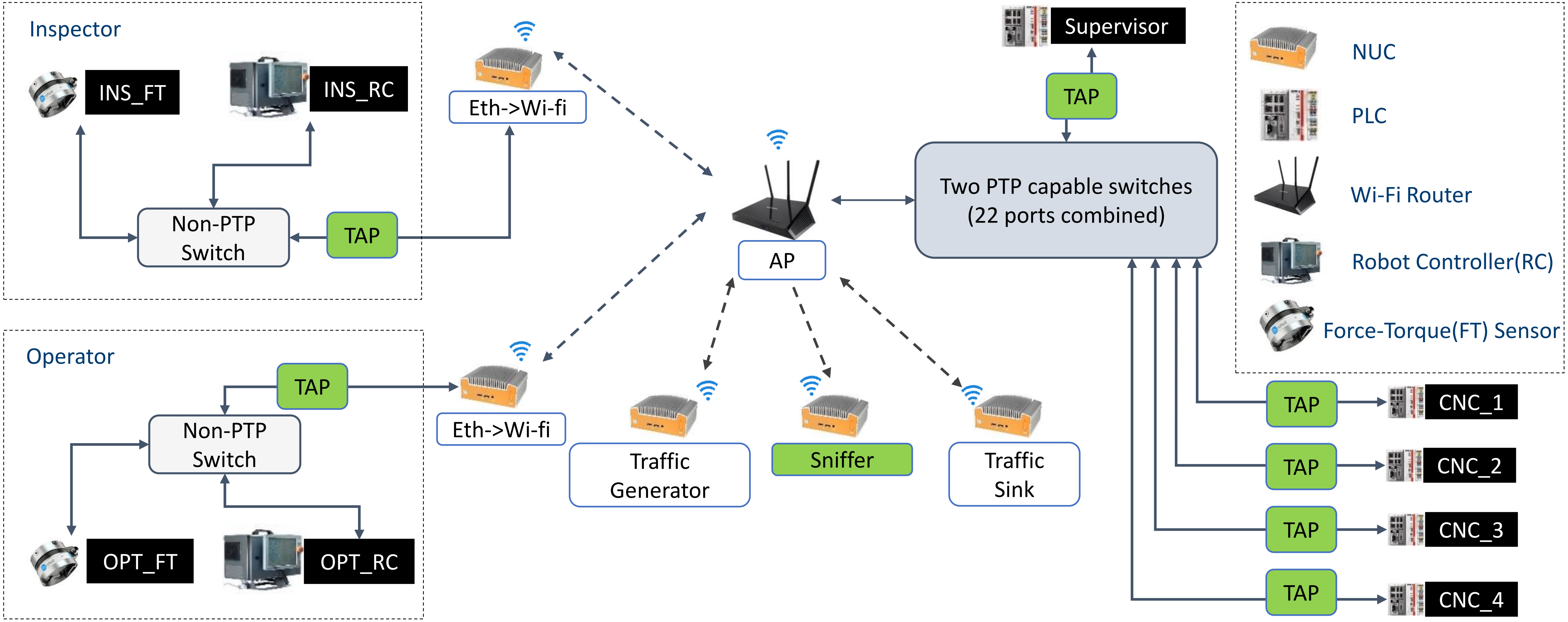


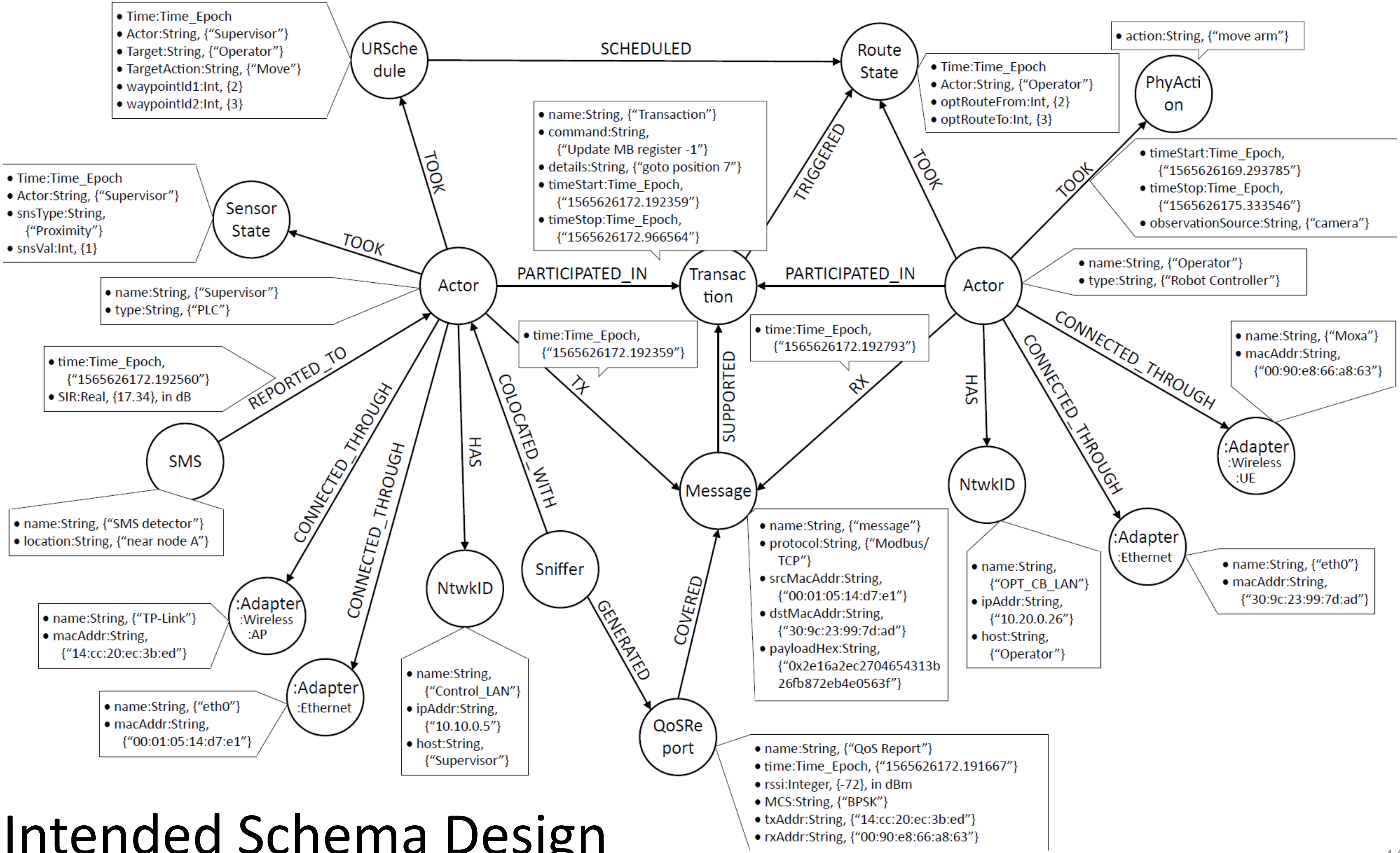
Graph Database Process Flow



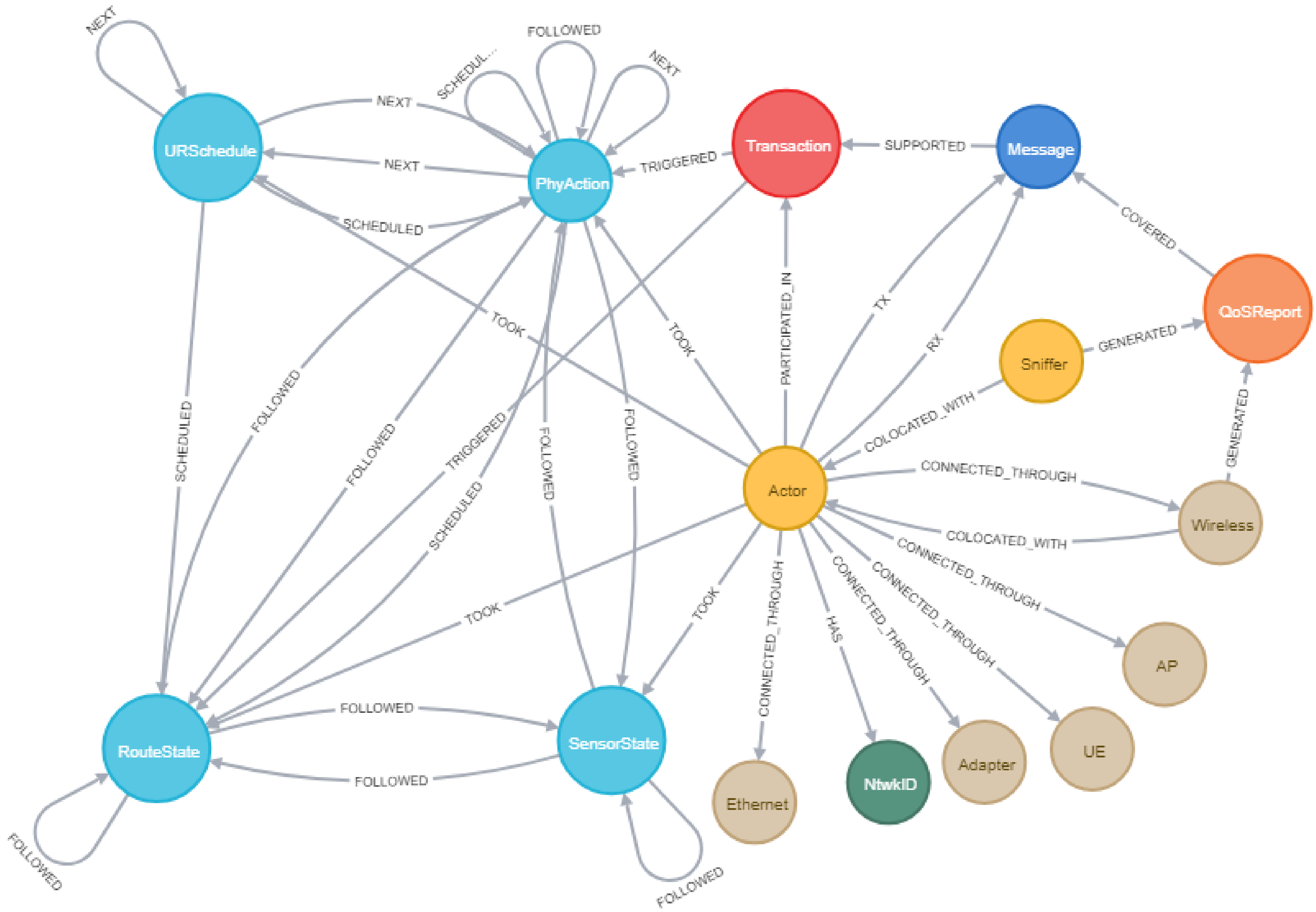
Testbed Configuration




Inspector
INS_FT
INS_RC
Non-PTP Switch
TAP
Eth->Wi-fi
Supervisor
TAP
Two PTP capable switches (22 ports combined)
AP
NUC
PLC
Wi-Fi Router
Robot Controller(RC)
Force-Torque(FT) Sensor
Operator
TAP
Non-PTP Switch
OPT_FT
OPT_RC
Eth->Wi-fi
Traffic Generator
Sniffer
Traffic Sink
TAP
CNC_1
TAP
CNC_2
TAP
CNC_3
TAP
CNC_4



Intended Schema Design



Realized schema: Only the visualization is different from designed schema

Example Query Using Cipher

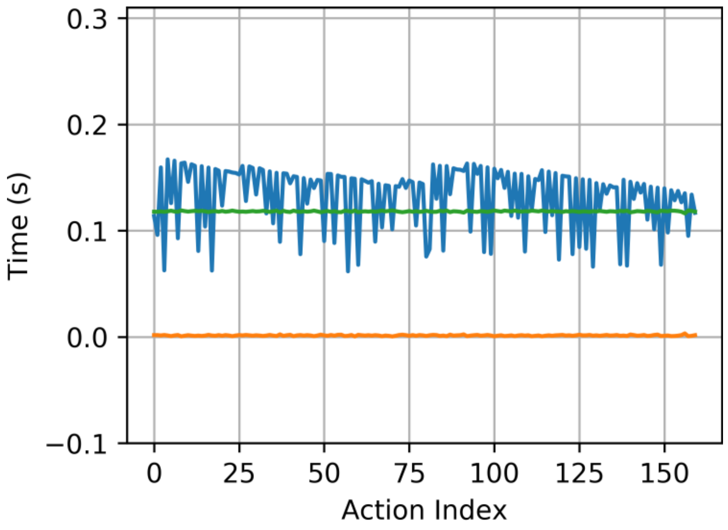
```
MATCH p=(a:Actor {
  name:'Supervisor'
})--(t:Transaction)--(b:Actor) , p2=(m:Message)-->(t)
WHERE t.timeStart>T AND t.timeStop<T+1
RETURN p, p2
```

This query searches for all Supervisor-based Transactions and associated Messages where the Transaction start and stop times fall within the first second of the experiment.

The query will return the Supervisor node with connected messages.

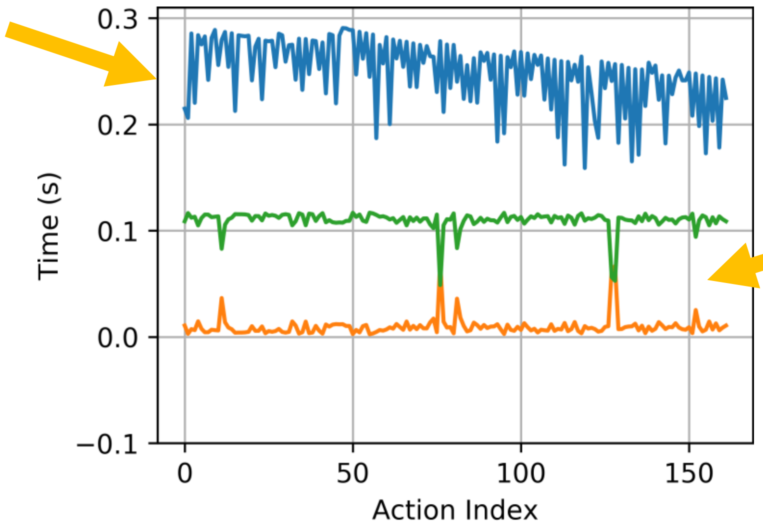
Sample Results from Query

Wired Performance Baseline



Wireless with 2-Streams Interference

Increase



Sum is Constant

The supervisor PLC processing time in blue is shown and appears to have a change in latency bias. 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

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

Thesis Presentation 28 September 2020

Richard Candell

Introduction and Motivation

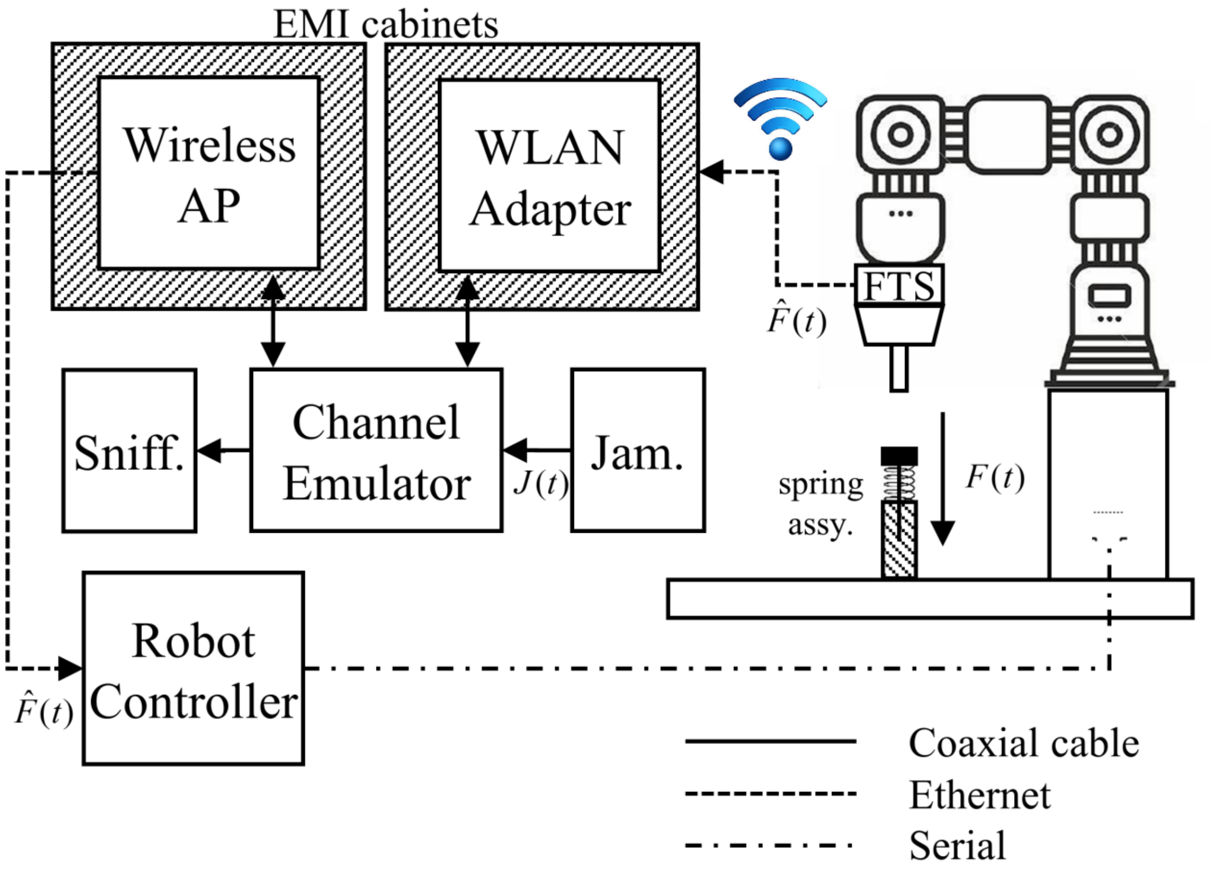
Goals

- Predict link quality indirectly using measurements of the OT (physical) system
- Eliminate the expense of RF equipment for LQE measurement in the factory

Results

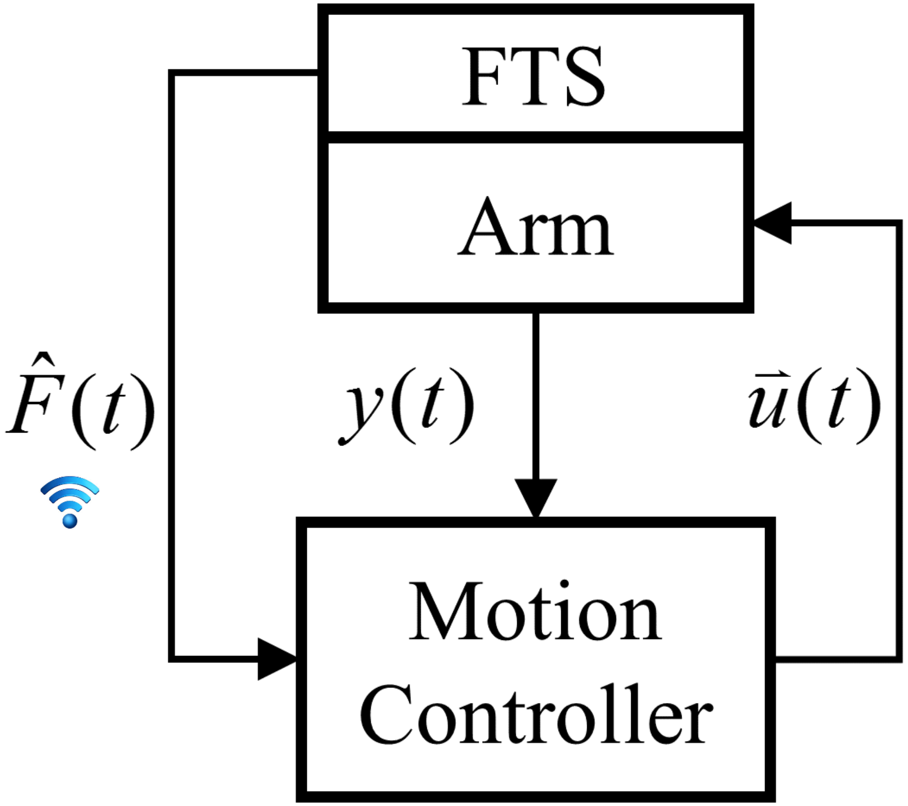
- Measured LQE using measurements data from vision system measuring the movement of a robotic arm depressing a spring
- Accuracy of LQE prediction within ±0.5 dB

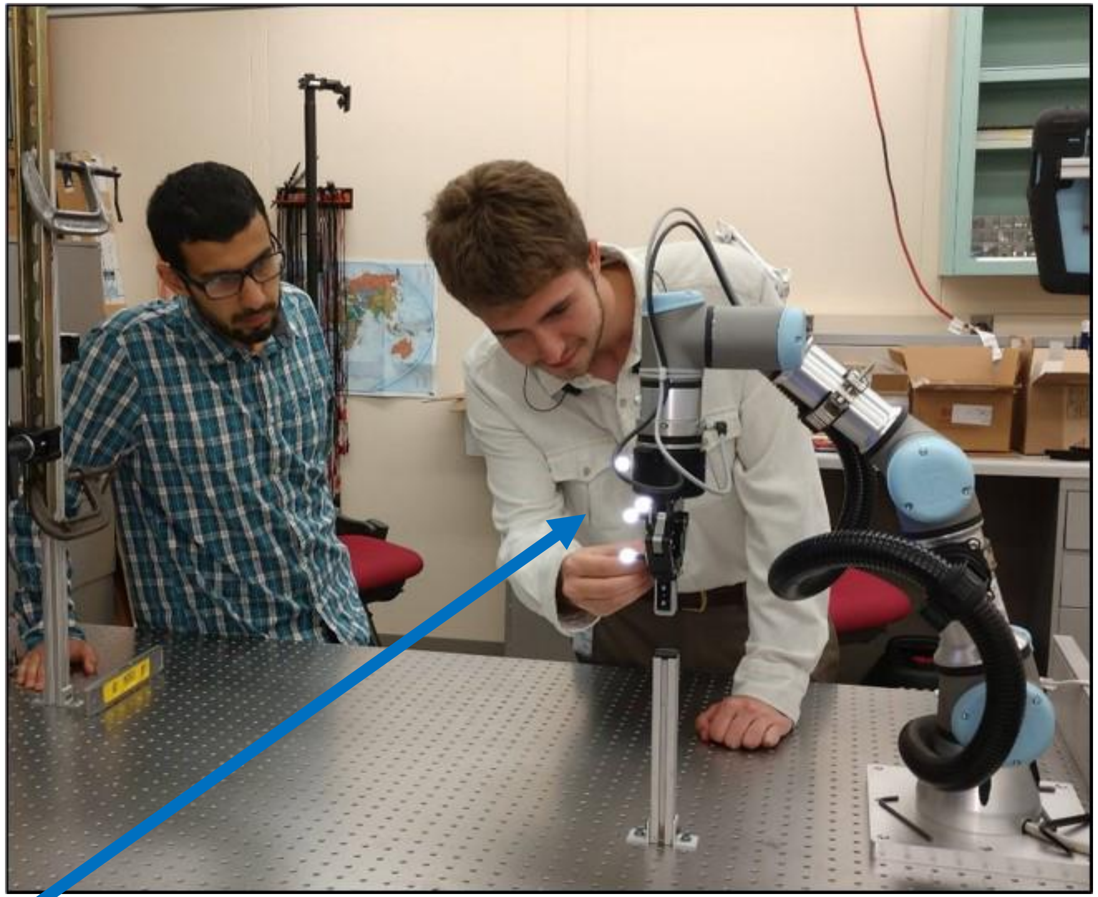
Force seeking spring system apparatus



- Robot depresses a spring until a force of 5 N is sensed
- Force is monitored by a wireless force-torque sensor (FTS)
- Robot Controller is wired thereby isolating the wireless component to the FTS
- Emulator is used to control the effect of a local jammer
- Wireless sniffer is used to monitor network traffic traversing space

Model of the Feedback Control System

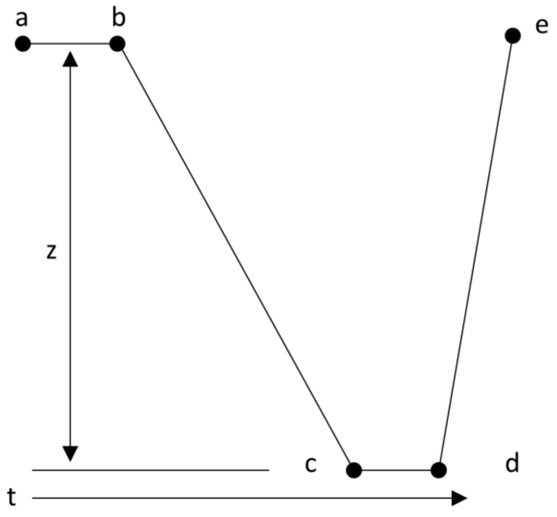




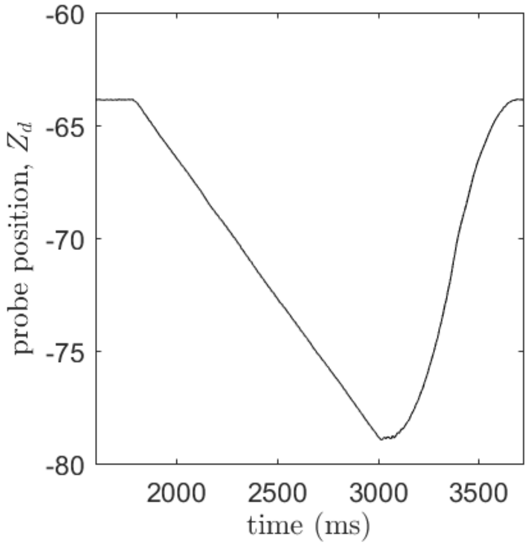
Vision system targets

Depression force search model

Z-axis Movement Model

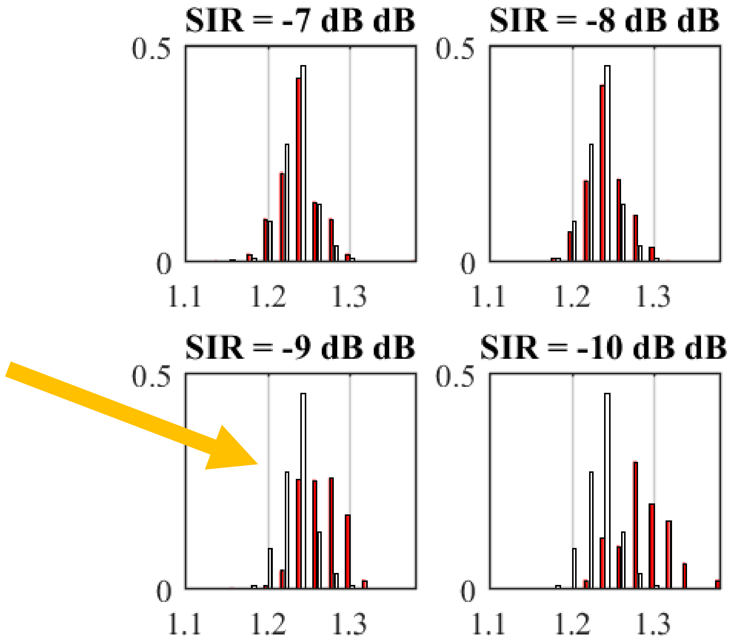


Sample Z-axis Movement

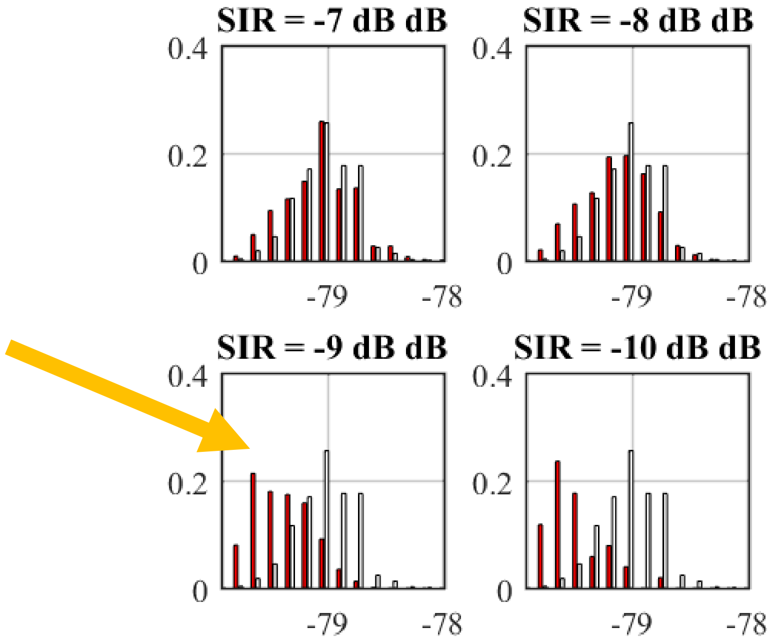


Learning candidacy statistics

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 $-9\ dB$ SIR

	Δt_{ab}	Δt_{bc}	Z_d	Δt_{cd}	Δt_{ae}
Δt_{ab}	1	0.04	0.04	0	0.56
Δt_{bc}	0.04	1	-0.96	-0.08	0.18
Z_d	0.04	-0.96	1	0.03	-0.01
Δt_{cd}	0	-0.08	0.03	1	0
Δt_{ae}	0.56	0.18	-0.01	0	1

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

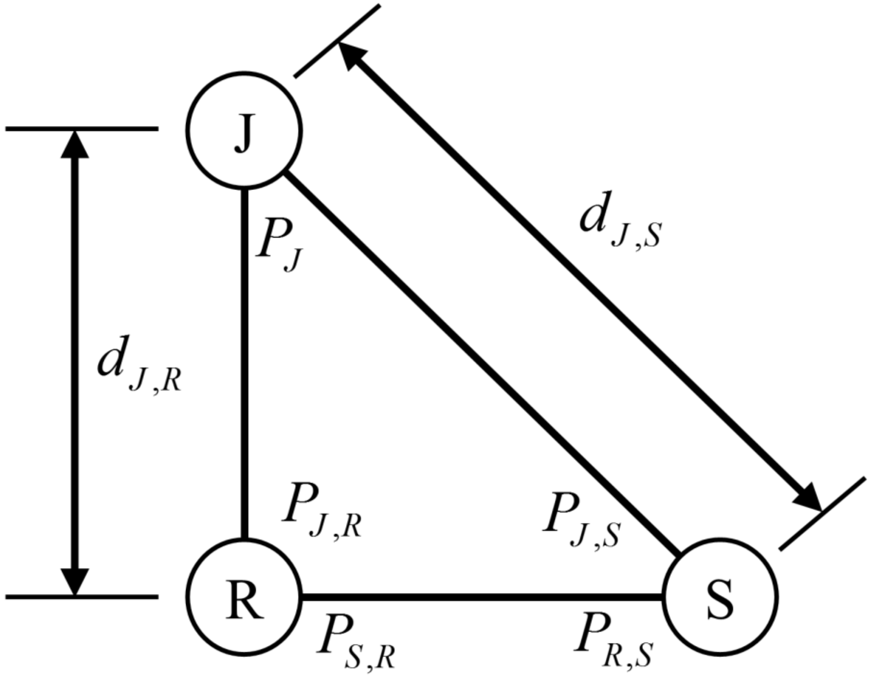
	Δt_{ab}	Δt_{bc}	Z_d	Δt_{cd}	Δt_{ae}
Δt_{ab}	1	0.01	-0.05	-0.06	0.58
Δt_{bc}	0.01	1	-0.99	-0.13	0.1
Z_d	-0.05	-0.99	1	0.07	-0.1
Δt_{cd}	-0.06	-0.13	0.07	1	-0.03
Δt_{ae}	0.58	0.1	-0.1	-0.03	1

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

	Δt_{ab}	Δt_{bc}	Z_d	Δt_{cd}	Δt_{ae}
Δt_{ab}	1	-0.05	-0.04	0.09	0.01
Δt_{bc}	-0.05	1	-0.93	-0.17	0.05
Z_d	-0.04	-0.93	1	0.08	-0.05
Δt_{cd}	0.09	-0.17	0.08	1	-0.02
Δt_{ae}	0.01	0.05	-0.05	-0.02	1

Verification of non-correlation between features. Features work best in ML when they 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



- Vary distance between jammer and router
- Vary distance between jammer and station
- Vary the mode of the router

Test set prediction performance

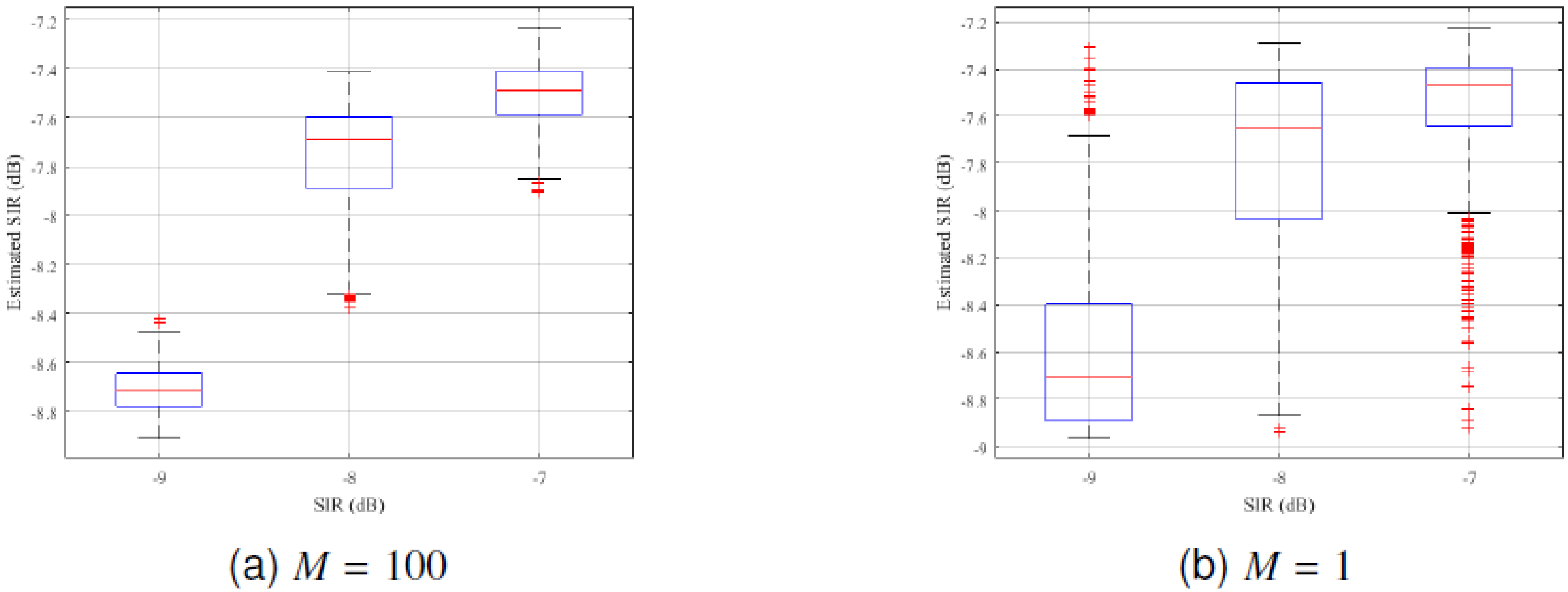


Figure 6.7: Predicted SIR versus actual SIR for the cases of (a) $M = 100$ and (b) $M = 1$. The box plots show the median value while the bottom and top edges of the box indicate the 25th and 75th percentiles. Statistical outliers are shown as red + signs.

Initial Results Against Segment Size, M

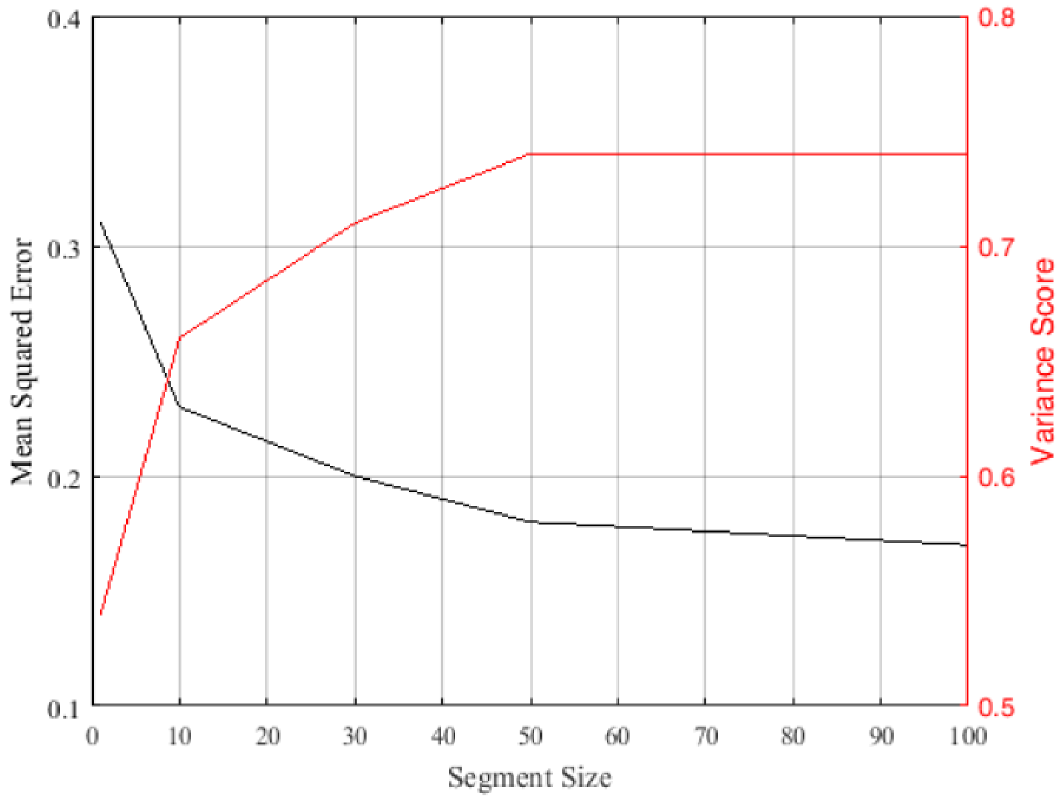


Figure 6.8: The performance of the random forest regression model against segment size, M. As M increases, error is reduced but variance increases shown a tendency to over-fit as the training window is increased.

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 λ)
- **Linear Ridge** – first-order linear regression model (as a comparison)

Variance and MSE of Various Regressors

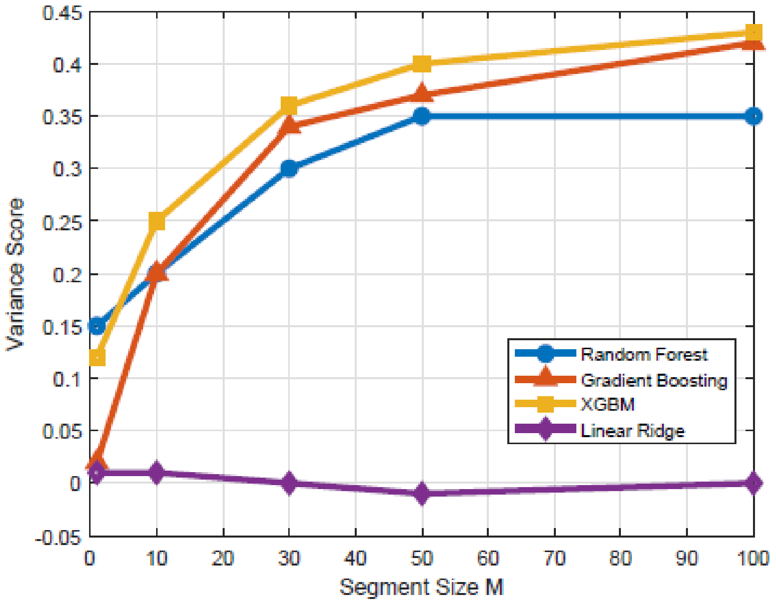


Figure 6.10: The variance score performance with jamming imposed on b/g-Router of various algorithms against segment size, M.

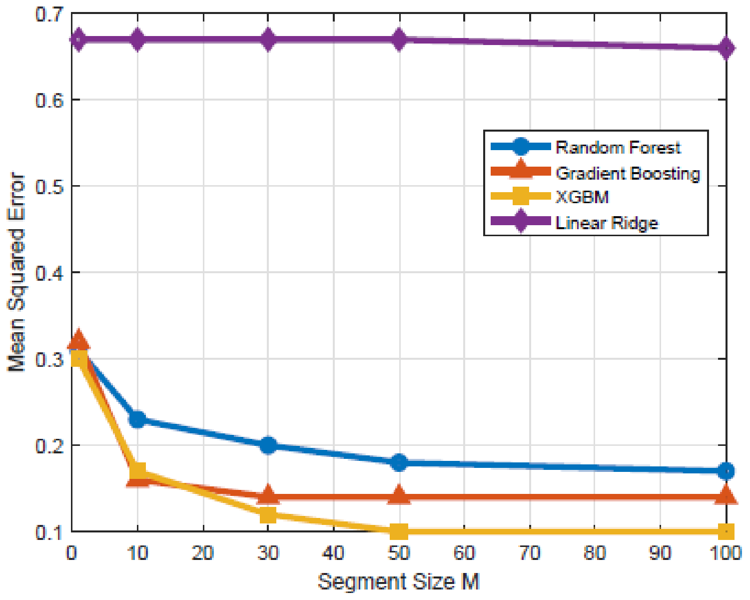
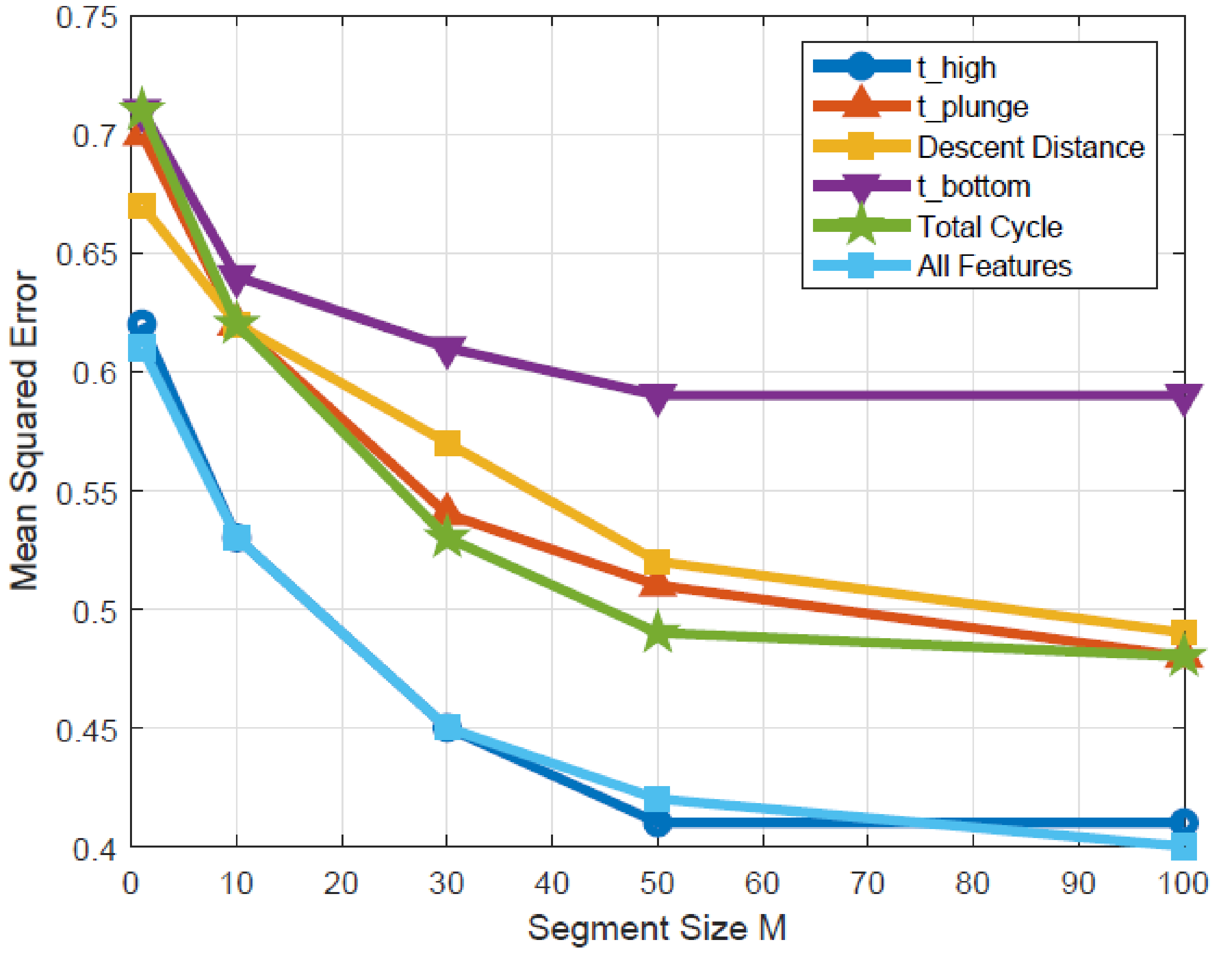


Figure 6.11: The mean squared error performance with jamming imposed on b/g-Station of various algorithms against segment size, M.

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 (Δt_{ab}) was found to be the most impactful feature
  - Due to zeroing message between robot controller and FT sensor compute box



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
Mercé
ありがとう
Gracias
Rahmat
Matondo
Dankjewel
Grazie
Misaotra
Efharisto
Köszönöm
Terima Kasih
Takk
Mahalo
Kiitos
Tak
Merci
Mauruuru
Xièxie
Sagolun
Danke
Toda
Dankie
Faleminderit
Obrigado
Hvala
شكرا
Спасибо

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

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

MSE is mean of squared errors
between estimate and actual value