L2Wireless: Enabling Low-Latency High-Reliability Wireless for Industry Communication Systems

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AGENDA

- **Section I**
  - InfoBeyond R&D
  - NIST's Network Control System Group
- **Section II**
  - Industrial Control System (ICSs)
  - Low-Latency High-Reliability L2Wireless MAC Layer
  - Cost-Efficient L2Wireless PHY Layer
  - Latency And Reliability Analysis
- **Section III**
  - Applications
  - Application Examples

SECTION I

WHO ARE WE?

INFOBEYOND TECHNOLOGY LLC

InfoBeyond Technology is an innovative company specializing in Network, Machine Learning and Data Security within the Information Technology industry.

SR 2017

50

Fastest Growing

Tech Companies

NIST

SBIR SUCCESS STORY:

InfoBeyond Technology LLC

INFOBEYOND

Our Research and Products

R&D Highlights:

- **Network Delay and Reliability:**
  - Ultra-Low Latency and Ultra-high Reliability for Industry Control System (ICS) Communications
  - Secure Personal Wireless Networks
- **Cybersecurity:**
  - Data Security – Fragment-based data cloud
  - Access Control –Security policy verification
- **Big Data:** Data Streaming with Machine Learning

Product Highlights:

National Institute of Standard and Technology

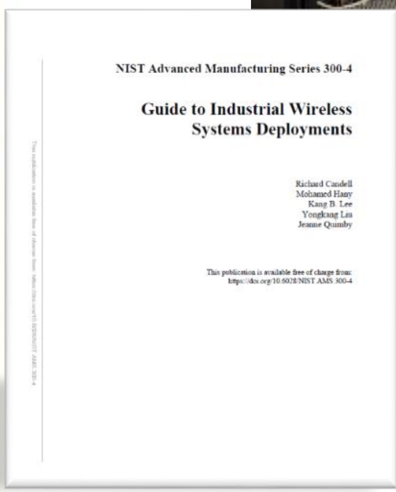
❑ NETWORKED CONTROL SYSTEMS GROUP

- ❑ **Richard Candell**
- ❑ The Networked Control Systems Group develops, advances, and deploys measurement science for sensor networks and control systems used in manufacturing, construction, and other cyber-physical systems applications.
- ❑ Carries out mission-related measurement science research and services to advance:
  - ❑ Predict and optimize real-time performance of networks and systems;
  - ❑ Automation and control system security and safety; and
  - ❑ Site-wide equipment and process in.

Thanks NIST for supporting our L2Wireless project R&D.

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

NIST Industrial Wireless Testbed, Data, and Guidelines


NIST Advanced Manufacturing Series 300-4

Guide to Industrial Wireless Systems Deployments

Richard Candell
Mohamed Hany
Kang B. Lee
Yongkang Liu
Jeanne Quimby

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.300-4

Industrial Wireless Testbed

- Hardware-in-the-loop simulation with real-time spectrum analytics, radio channel emulation, and interference injection.
- Recreate factory radio wave propagation effects in the laboratory.
- Enables the measurement of impacts of wireless systems on factory automation systems.

Industrial Guidelines

- NIST AMS 300-4 *Guide to Industrial Wireless Systems Deployments (release date scheduled for May 2018)*
- Comprehensive overview of industrial wireless systems with guidance on identification, selection, and deployment of industrial wireless systems for process control and factory automation.
- Collaboration between government, industry, and academic

Data Impacts

- ABB: Developed a high-performance wireless system for factory automation/control and specifically collaborative robotic applications.
- Prof. Katia Jaffres-Runser, University of Toulouse, France: Developed coursework centered around the factory measurements and report NIST-TN-1951

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

Wireless Opportunities in Manufacturing

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

Challenges of Wireless in Manufacturing Automation

- **Coexistence**: How should existing wireless technologies be used in discrete manufacturing spaces?
- How can wireless be extended to the factory edge (i.e. instrumentation on the factory floor)? Currently, wireless is used as a backhaul from PLC to automation center in manufacturing.
- What **theoretical models** can be devised for **wireless network realization** in the manufacturing IIoT space? Includes time and coordinate uncertainty.
- How do we address the **reliability-latency-scale** (RLS) trade-space?
- How can wireless accommodate all network scales in the factory? This would include **inside machines** to the **work-cell** to the **entire factory**?
- How should **spectrum awareness** be applied in the factory? i.e. Spectral monitoring, machine learning, and interoperability with automation systems.
- What **test methods** are necessary to wireless networks for manufacturing applications?

Recent Collaborators

Section II

What Are We Doing?

Industrial Control Systems

ROBOTS AND MOTION CONTROL

GASOLINE AND REFINERIES

Wired or Wireless ICS Network

❑ Wired ICS Networks:

- ❖ **High Cost of Cabling/Installation/Maintenance:**
  - ❖ Cable and material cost
  - ❖ Installation of cables could be very difficulty due to a harsh environment, e.g., oil refinery
  - ❖ Labor Costs and Time
- ❖ **Maintenance and Upgrade Difficulty:**
  - ❖ Troubleshooting
  - ❖ Disrupting the operations
- ❖ **Mobility Support:** Operators are hard to move, low productivity caused by movement

❑ Wireless ICS Networks:

- ❖ **Wireless Sensors are installed in the equipment:**
  - ❖ Without the constraints caused by cables
  - ❖ Flexible and scalable
  - ❖ Save the cost and less delay for installation and updating

Can Wireless Satisfy the Delay Requirement?

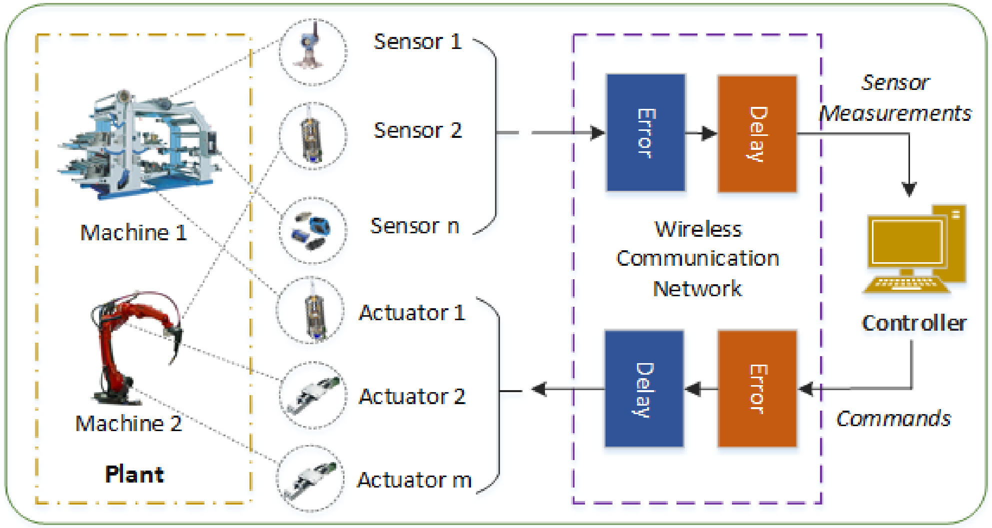
Table 1: Latency Requirement Comparison for ICS and other time-critical Industries

	Description	Latency Requirement
Industry Control Systems	Automation and motion control in warehouse and discrete manufacturing, assembly, robotics, oil and gas refineries, and water and wastewater treatment	$< 1\ ms$
RF remote control	Safety and security control	$1 - 100\ ms$
Intelligent transportation systems	Intelligence of transportation infrastructures (e.g., traffic and vehicular)	$\sim 5\ ms$
Smart grid	Operational and energy measures from smart meters, smart appliances, renewable energy resources, and energy efficient resources	$3 - 5\ ms$
Tactile Internet	The next evolution of the Internet of Things (IoT) in an extremely low latency in combination with high availability, reliability, and security	$\sim 1\ ms$
Processing automation	Factory automation	$< 100\ ms$
Automatic guided vehicles	Portable robots used for picking load from rack, carrying very heavy cargo, and other tasks.	$< 20\ ms$

ICS Delay, Reliability Low Power, and Scalability requirements

Ultra Low Latency: 1 ms

Ultra High Reliability: 10^{-9}



Wireless Control System

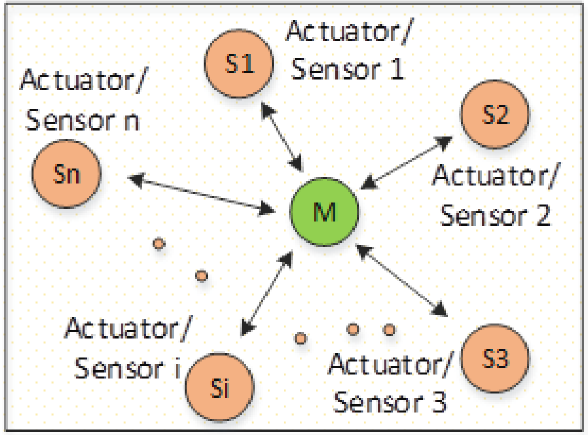
Industrial General Requirements: Latency, Error Rate, and Scalability*

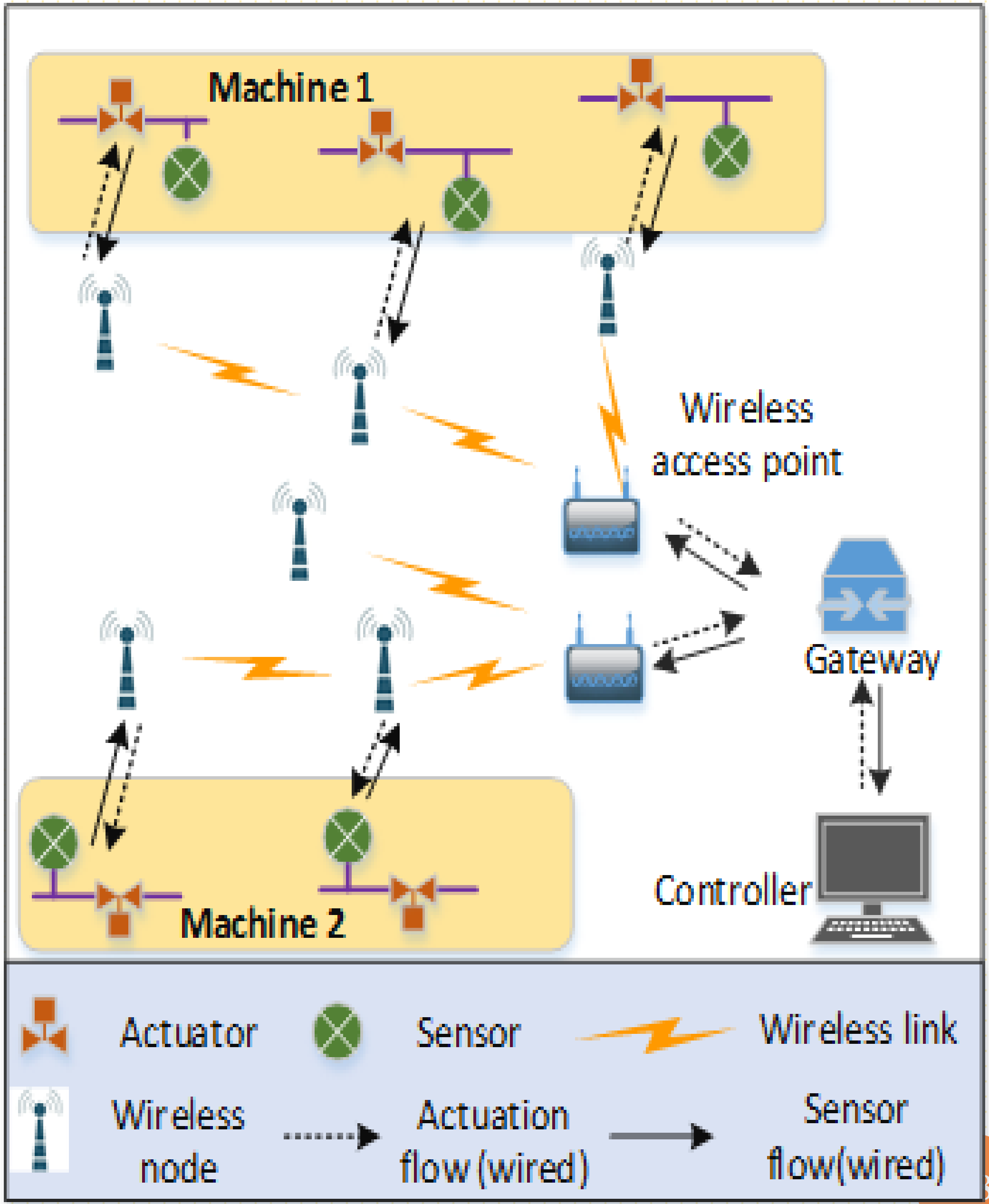
	Latency, l ms	Pr. Loss, r	Scale, s
Monitoring	$l < 1000$	$r < 10^{-5}$	$s < 10,000$
Supervisory Control			
Flow-based	$l < 1000$	$r < 10^{-6}$	$s < 30$
Job-based	$l < 100$	$r < 10^{-7}$	$s < 10$
Feedback Control			
Flow-based	$l < 1000$	$r < 10^{-6}$	$s < 100$
Job-based	$l < 10$	$r < 10^{-7}$	$s < 10$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

*R.Candell, M. Kashe, "Industrial Wireless: Problem Space, Success Considerations, Technologies, and Future Direction" Proceedings of International Symposium on Resilient Communications Systems, 2017

AN TYPICAL ICS WIRELESS NETWORK

If the delay is larger than $20 - 60\%$ of the time constant of the closed loop system, here called the critical delay, the controller cannot respond to changes in the system quickly enough, and the control system fails, resulting in automation and control errors.





Design Requirements for Wireless ICS Networks

Operate in the unregulated ISM (Industrial, Scientific, and Medical) band between 902 MHz and 928 MHz

- **Stringent Latency and Reliability Specification**:

For *advanced manufacturing applications*, the wireless networks need to meet stringent latency and reliability specification (e.g., close-loop sense-to-actuation time <1ms and transaction error rate < 10^{-9} under strong multipath propagation and noise.

- ***Supporting Sufficient Nodes within Each Work Cell***:

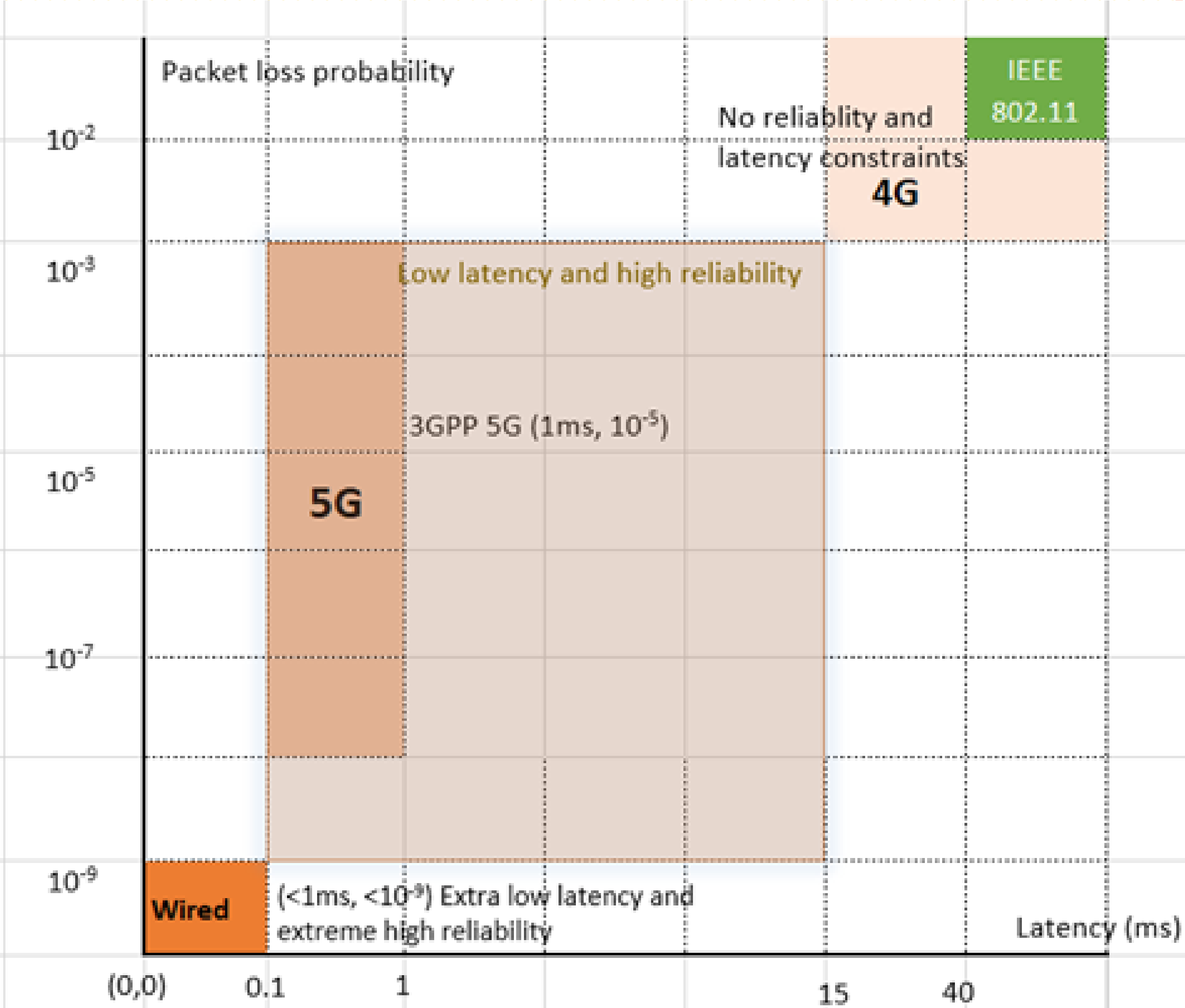
The wireless system should support communications within a factory work cell with at least 10 sensing/actuation devices. The wireless system should be scalable with the amount of wireless nodes (i.e., sensors/actuators).

- **Using Existing Physical Layer Technologies:**

The wireless network of manufacturing control system should reuse as many blocks as possible from one or many current wireless PHYs in order to minimize the development and verification costs.

RELIABILITY AND LATENCY OF VARIOUS NETWORKS

Current wireless network design gives massive attentions to network capability (e.g., throughput per link in a network) while the network latency and reliability are not optimally considered. This is generally referred as throughput-centric design that sacrifices the latency and reliability in order to pursue a high throughput.



A throughput –greedy network protocol optimizes the MAC and PHY design to achieve the network throughput, e.g., maximization of the RF utilization. This degrades the performance of the latency and reliability.

STATE OF ART – WIRELESS FOR MANUFACTURING

		Flow-based					Job-based						Safety			
		Process Monitoring	Supervisory Control	Feedback Control	Alarm Conditions	In-situ Inspection	Factory Monitoring	Assembly: Sensing	Assembly: Actuation	Robots: Supervision	Robots: Feedback Control	Quality Inspection	Fall Prevention	Confined Spaces	Critical Event Detection	Human-Machine Colocation
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	◐	◐	-	◐	◐	◐	-	-	○	○	-	○	◐	◐	-

		Back-haul				Tracking					Security						Remote			Maint.		
		Nearby or Indoor	Distant: LOS	Distant: BLOS	Geographically Remote	Indoor Machine Localization	Materials in Storage	Materials in Production	Tools	Personnel	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	●	●	●	-	◐	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	◐	○	○	○	◐	●	●	○	○	○	○	○	●	○	●	○	○	○	◐	◐	○

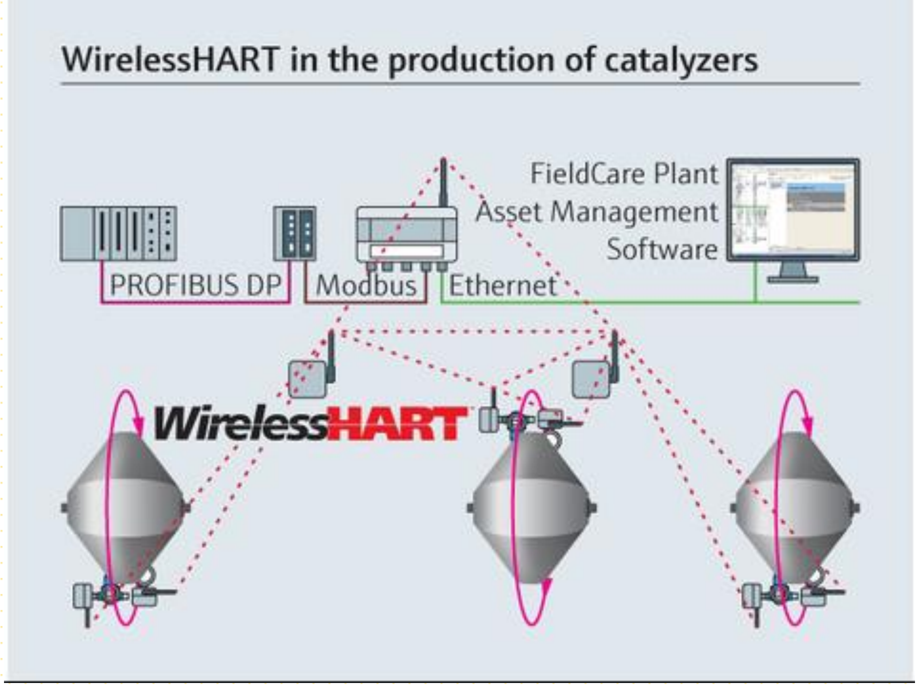
Legend: ●: Technology fully supports problem domain, ◐: Supports problem domain with practicality, throughput, latency, reliability, or energy limitations, ϟ: Energy requirements of assumed battery-powered devices prevent applicability, ◷: Latency prevent applicability, ▼: Throughput prevents applicability,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

Applicability of current wireless solutions for Manufacturing application*

WHY NOT GOOD?

- **WirelessHART**: The WirelessHART protocol was developed based on IEEE802.15.4 standard for low-performance control systems.

- **Limitations**: It can offer reliable communications for industrial applications but sacrifices the latency and network throughput. It can only provide latency on the order of 100ms and transmission rate of 250kbps.



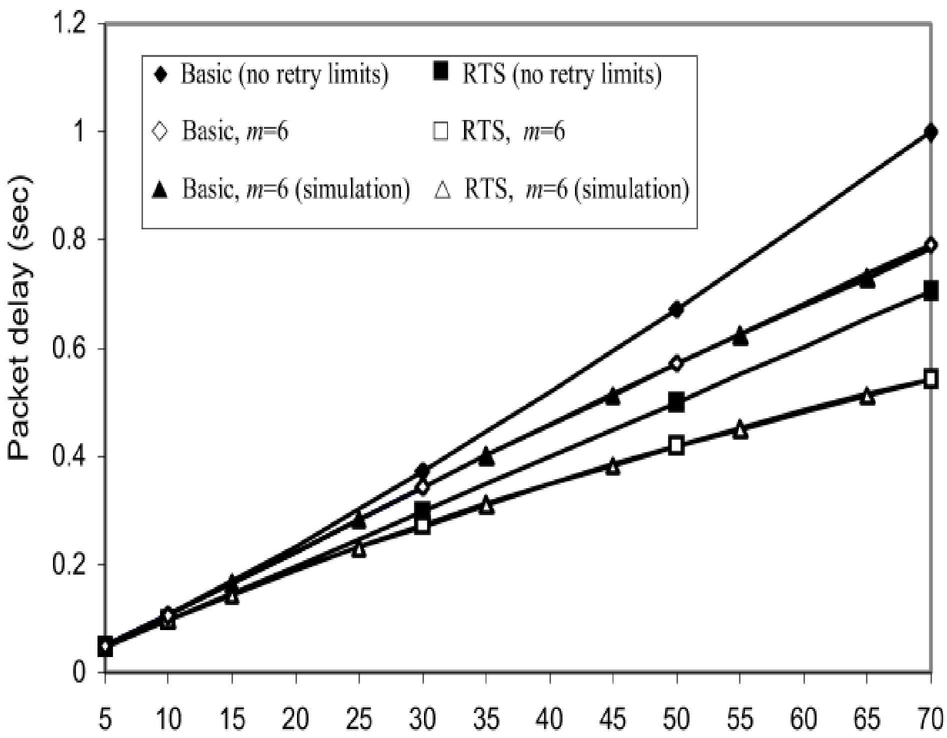
WirelessHART

- **Technical Drawbacks:**
  - **Carrier Sense Multiple Access (CSMA):** Multiple nodes compete with each other to access the wireless channel randomly, which cause large latency.
  - **Low Transmission Rate:** Use narrowband transmission technique, i.e., Direct Sequence Spread Spectrum (DSSS).
  - **No Channel Coding**: Without channel coding for error correction, it depends on unbounded retransmission to ensure the reliability, which results in large latency.

WHY NOT GOOD?

- **IEEE 802.11:** To achieve lower latency, there has been interest in determining the performance of control systems using existing high data-rate wireless standards, such as IEEE 802.11, for manufacturing applications.

- **Technical Drawbacks:**
  - Poor Scalability: Use CSMA. Increasing the number of nodes in the network results in higher random latency .
  - High Error Coding Rate and ARQ: Higher error coding rate means low error correction capability, large number of retransmission latency.
  - Large Packet: Maximum size 2346 bytes, which does not suit well the data communication of the industrial control system (i.e., periodically small amount of data exchange between the controller and sensor/actuation).
  - OFDM Guard Interval: Maximum 800ns, which can not overcome the high multipath propagation RF environments of the manufacturing.



LTE/IEEE 802.11 Latency Analysis: 10 nodes connection results in 0.1s delay. Furthermore ,as the number of nodes increases the network latency largely increase.

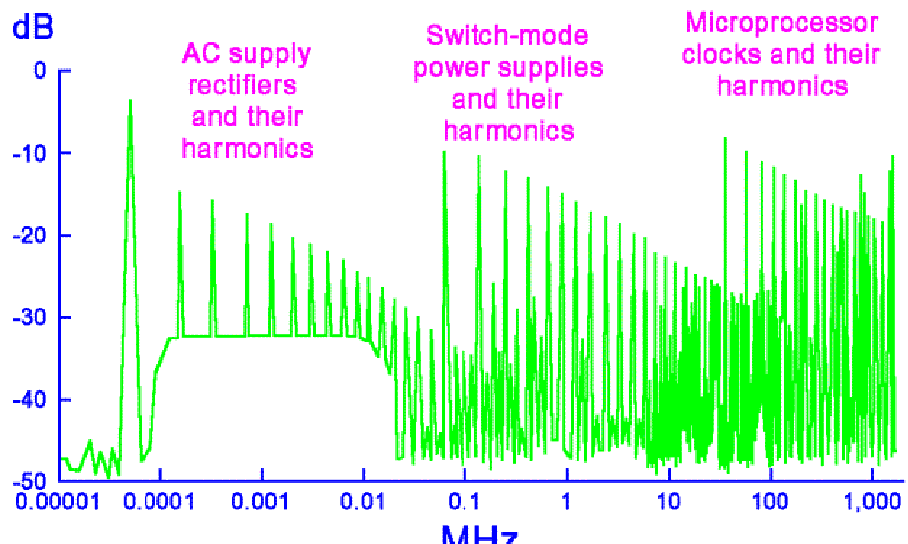
Industry RF Environment

Industrial RF Environment: NIST Engineering Lab has conducted several RF measurements campaigns to assess the characteristics of RF propagation under the factory environments. It shows that the radio environments of manufacturing applications have strong multipath propagation (channel delay spread up to 1,000ns) and strong noise/interference (power up to -50dBm).

NIST Technical Note 1951

Industrial Wireless Systems Radio Propagation Measurements

The high reflective environment s of factories causes strong multipath propagation



The industrial environment suffers from broadband electromagnetic interference from various instruments and devices in the plant.

What is L2Wireless?

L2Wireless is an enhancement of IEEE 802.11 ac with novel wireless protocols to offer ICS communications that achieves ultra low-latency and ultra high-reliability.

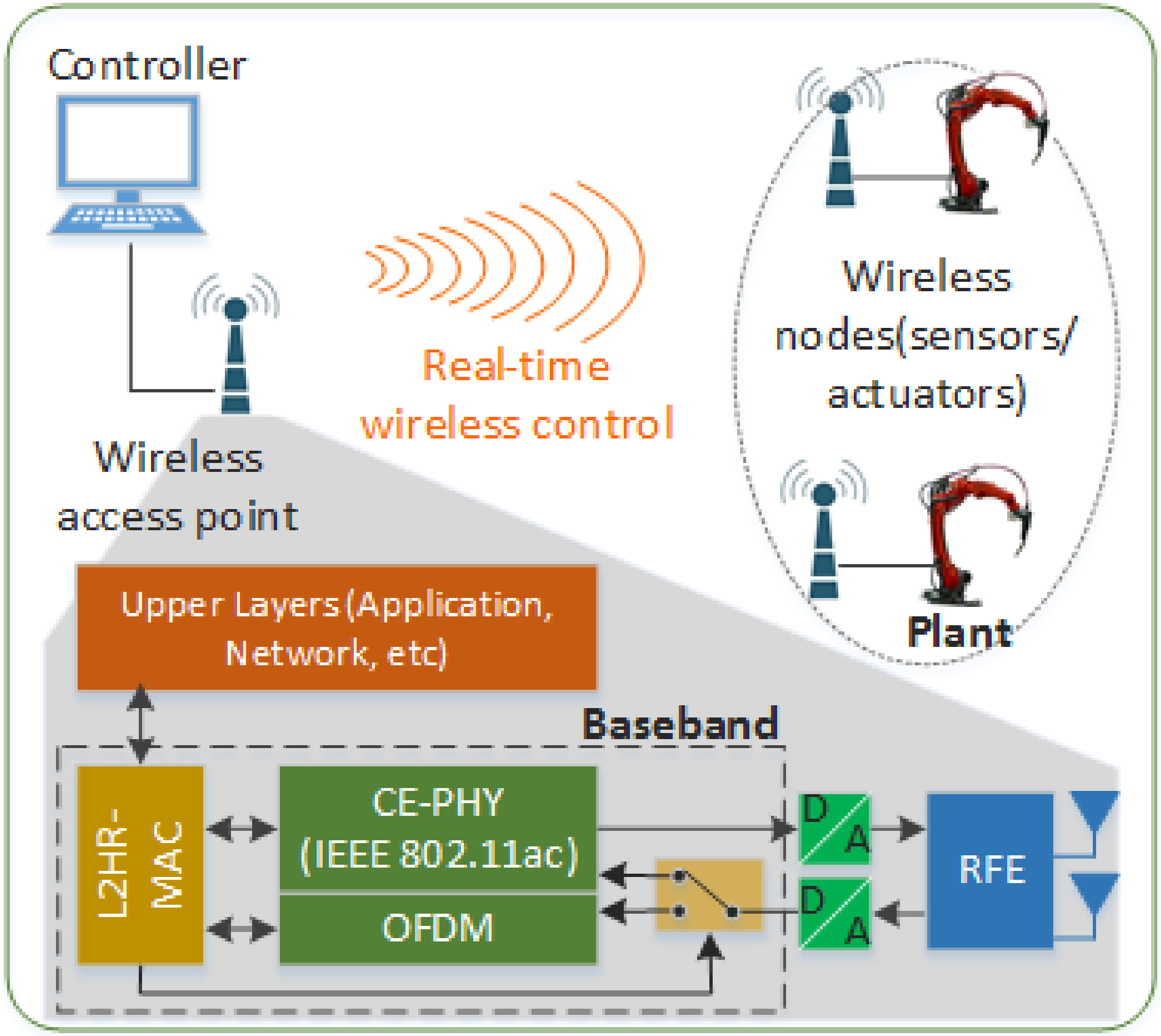
Company	Product	Adopted Solution	Latency	Meet ICS Needs?
InfoBeyond	L2Wirelss	IEEE 802.11ac Enhancement	< 1 ms	Yes
Cisco	Industrial Wireless 3700 Series	IEEE 802.11 ac	150-200 ms	No
	Aironet 1550 Series	802.11n	150-200 ms	No
ICPDAS	GTM-201-USB	2G/3G	60-200 ms	No
	ZT-2005-C8	ZigBee (IEEE 802.15.4)	$7.35 \times N_{node}$ ms	No
	BLE-USB	Bluetooth	$8.75 \times N_{node}$ ms	No
Emerson	Wireless 1420 Gateway	WirelessHART (IEEE 802.15.4)	$7.35 \times N_{node}$ ms	No
Honeywell	Wireless XYR 6000	WirelessHART (IEEE 802.15.4)	$7.35 \times N_{node}$ ms	No
Huawei	OneAir 6000	4G, LTE	$21 \sim 132$ ms	No

Ultra Low Latency: Closed-loop latency < 1 ms
Ultra High Reliability: Packet error rate <10^{-9}
Cost-effective: A Chip-scale solution

L2Wireless is NIST Sponsored R&D Project.

WHAT IS L2WIRELESS

- Low-latency High Reliability MAC Layer
- Cost Efficient L2Wireless PHY Layer (CE-PHY)
- Redesign the OFDM, Error coding, Modulation and synchronization to adapt to the performance (i.e., latency, reliability) requirement in the hash radio environment of manufacturing application.



L2Wireless Technical Features

- **Low Latency and High Reliability**: The L2Wireless protocol is able to achieve the desired latency (sense-to-actuation latency <1ms) and reliability (transaction error < 10^{-9}) for advanced manufacturing applications. Thus it can provide real-time wireless communications for command and control of machines/mobile robotic work agents with rapidity, reliability and timeliness.

- **High Diversity Gain**: The L2Wireless protocol brings together ideas from cooperative communication to exploit multi-user diversity, so that each receiver can harvest a large diversity gain to achieve high-reliability.

- **High Scalability**: The cooperative scheme of the L2Wireless protocol uses simultaneous transmissions by many relays to overcome the bad fading channels, which makes the protocol scalable with the network size. As the number of wireless nodes in the network increases, it can still achieve high reliability without greatly decreasing the throughput or increasing the latency. Only a small amount of additional SNR is required to achieve the desired latency and reliability as the number of wireless nodes increases from 10 to 30.

COMPARISON WITH OTHER SOLUTIONS

	IEEE802.11ac	WirelessHART	L2Wireless
Network Structure	Star	Mesh	Star
Medium Access	CSMA/CA	CSMA/CA	Scheduled
Signaling	OFDM	DSSS	OFDM
Frequency	5GHz	2.4GHz	2.4GHz/5GHz
Bandwidth	20-160 MHz	1.25-20 MHz	20-160 MHz
Error Coding Type	Convolution /LDPC	No coding	Convolution
Code rate	1/2, 2/3, 3/4, 5/6	1	1/2
Modulation	BPSK-64QAM	OQPSK	BPSK,QPSK
Network coding	No	No	Yes
Cooperative relay	No	No	Yes
Multi-hop	No	Yes	Maximum 2 hops
Diversity Sources	Time, beamforming	Time, Muti-user	Time, Multi-user
Latency	150-200ms	150-200ms	<1ms
Relaibility Source	ARQ	HARQ	Cooperative relaying

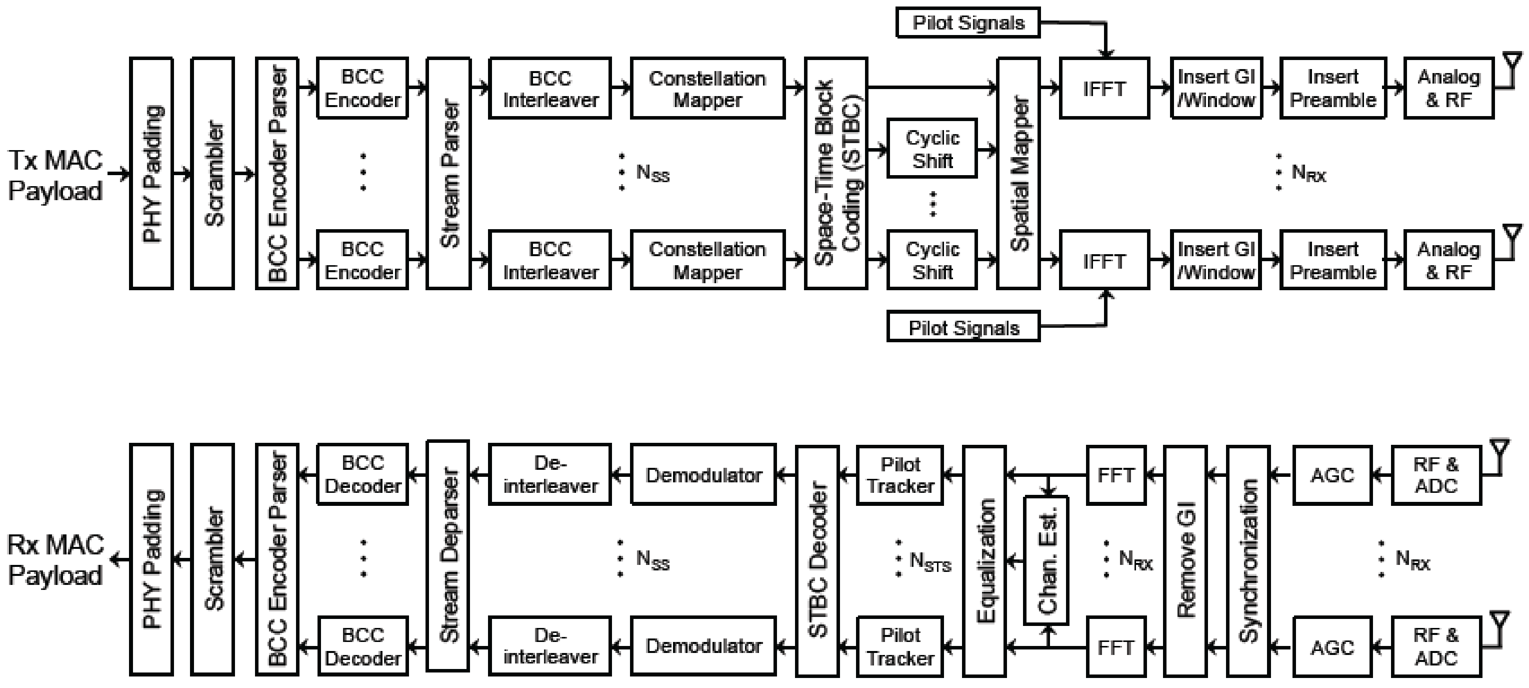
IEEE 802.11 ac/ WirelessHART Drawbacks:

- Carrier Sense Multiple Access (CSMA)： CSMA causes large amount of random delay for accessing the wireless channel.
- High error coding rate and unlimited retransmission (ARQ/HARWQ) to assure high reliability, however, result in unbounded delays.

L2Wireless Technical Benefits:

- Redesign the MAC layer to avoid the latency caused by CSMA and ARQ.
- Two-hop transmission & cooperative RF signal relaying.
- Low error coding rate and low order modulation to simultaneously achieve low-latency and high-reliability.

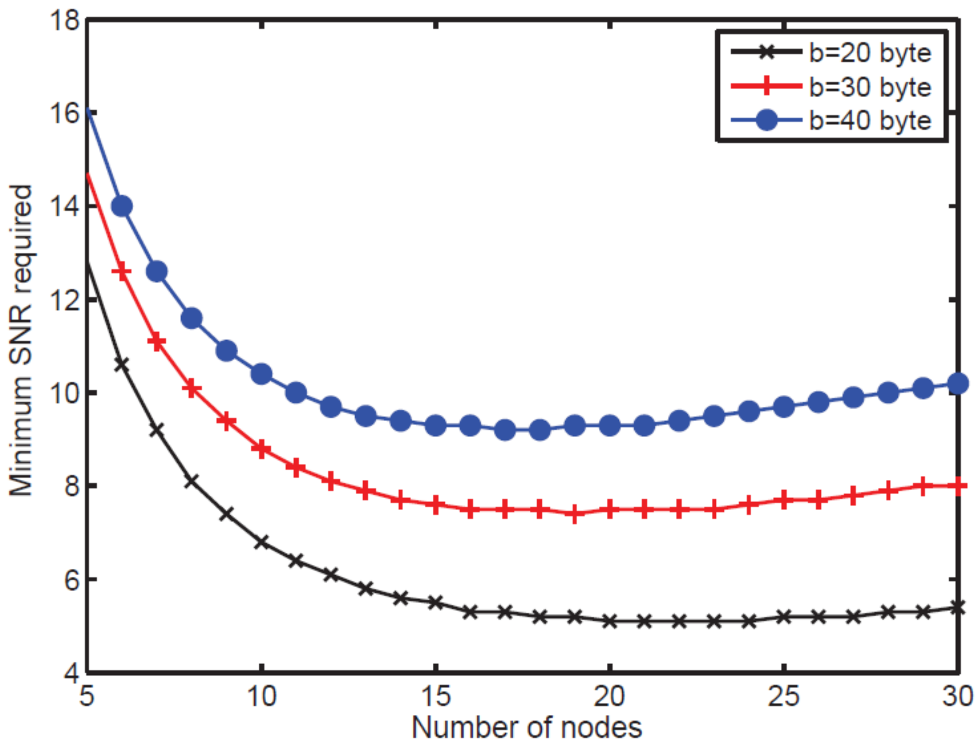
Cost-Efficient L2Wireless PHY Layer



IEEE 802.11ac PHY block should be redesigned to maximize the reliability

FCC CONSTRAINTS AND RELIABILITY

Minimum SNR required to achieve transmission error rate <1e-9) and latency <1ms as the number of slave nodes increasing from 5 to 30 with payload b=20 (black), 30 (red), 40 (blue) bytes.



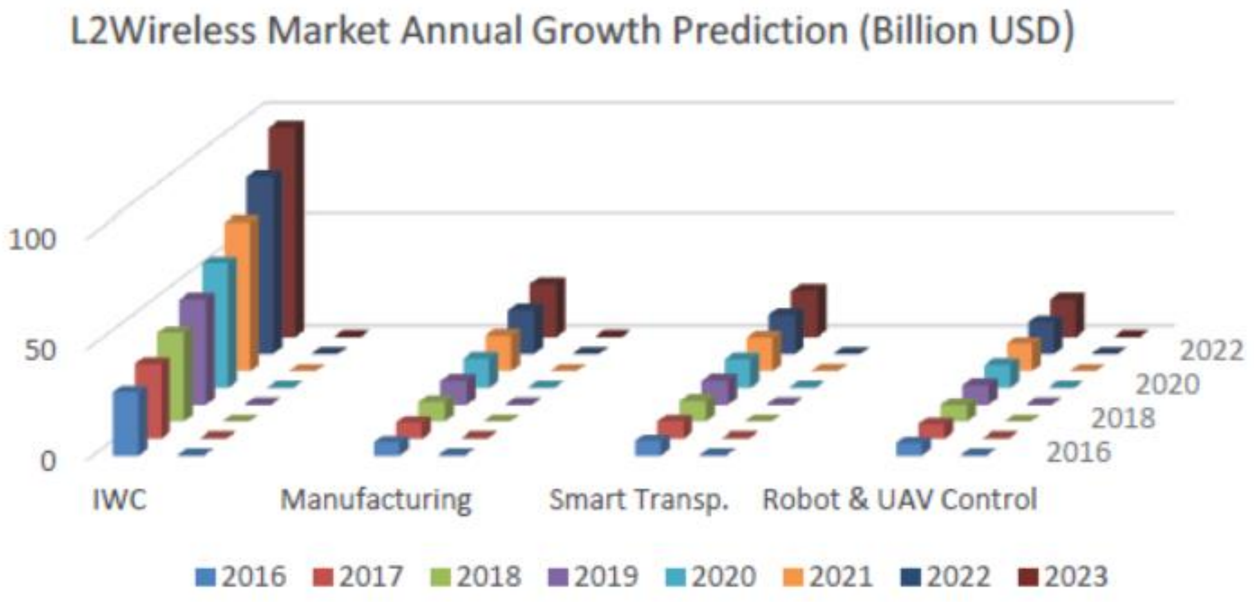
- **Path Gain:** The path gain under a 100 meter transmitter-to-receiver distance in the ISM band of a typical industrial environment is around -90dB.
- **Noise/Interference:** The power of noise- plus-interference is from -50dBm to -100dBm.
- **Maximum Transmission Power:** For point to multipoint transmissions, the maximum equivalent isotropically radiated power (EIRP) allowed by FCC 2.4GHz band rules is 36dBm.

Section III

Where Are We Going?

Applications

National Instruments is intended to develop the next-generation control systems optimized for the Industrial Internet of Things (IIoT) interconnecting tactile devices, equipment, and infrastructure.



- **Discrete Manufacturing plant: Tightly aligned with ICSs for manufacturing applications that require real-time data communication with high reliability in such a way to** improve the manufacturing productivity
- **Automation and motion control:** In the industrial manufactures and automation systems, communications are required to provide a means for controls, monitoring, and cooperation over a number of devices.
- **Tactile Internet:** Tactile Internet ranges from industry automation and transport systems to healthcare, education and gaming, robotics and telepresence, virtual reality, augmented reality, road traffic, remote sensing, monitoring, and control.

Who Uses L2Wireless?

MHS: Material Handling Systems, Inc. Louisville, KY

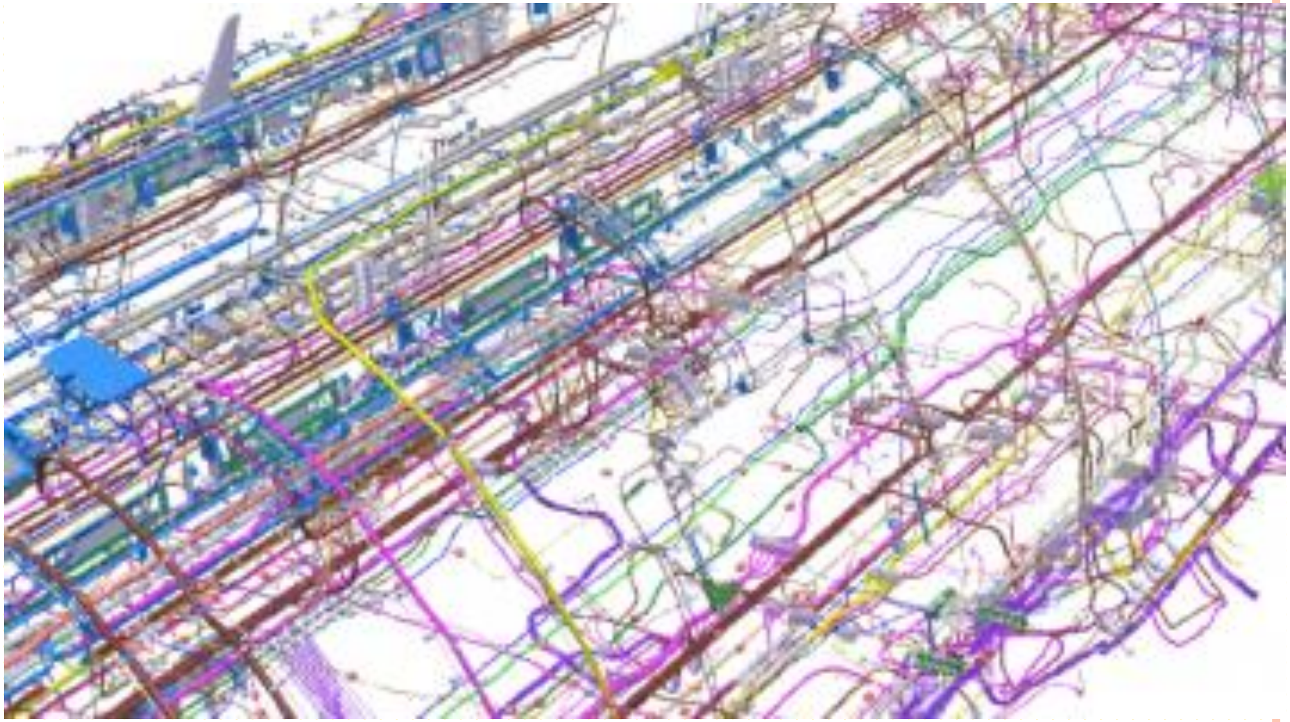
Who Uses L2Wireless?

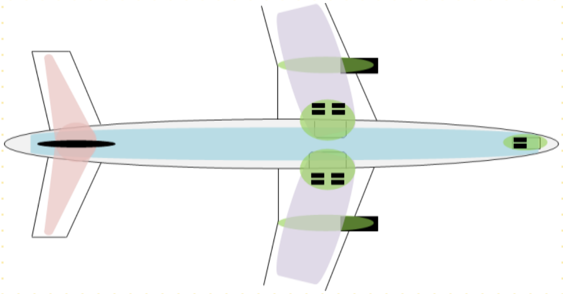
GM Auto Mobile Plant-Louisville

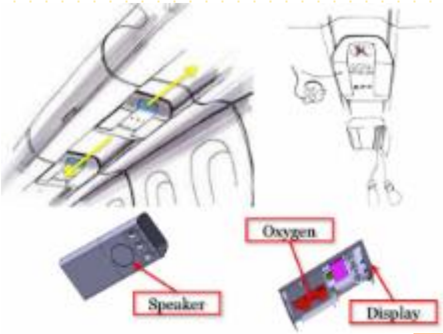
WAIC Alliance: Wireless Avionics Intra-Communications

Wiring in modern aircraft is a highly complex, critical system:

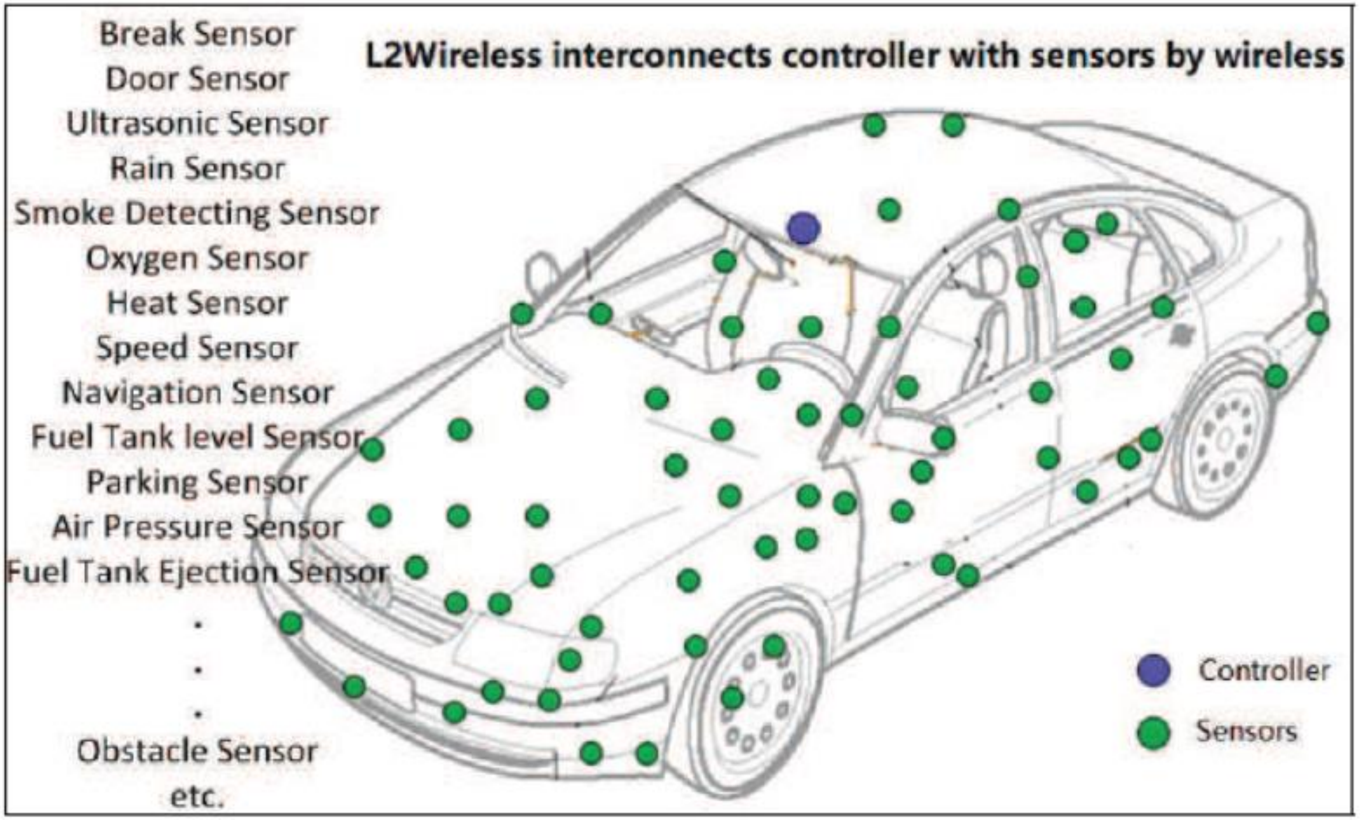
- Total wire count: ~100 000
- Total wire length: 470 km
- Total weight of wires: 5,700 kg
- About 30% of additional weight for harness-to-structure fixation
- About 30% of electrical wires are potential candidates for a wireless substitute!







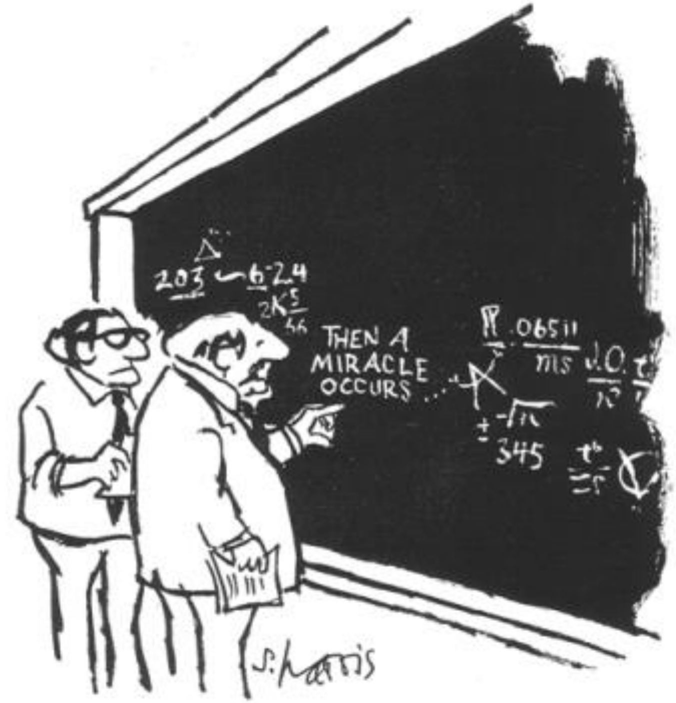
L2WIRELESS CONNECTS SENSORS A IN-VEHICLE NETWORK



The wiring cables used for the transmission of data and power delivery within the current vehicle architecture may have up to 4 000 parts, weigh as much as 40 kg and contain up to 4 km of wiring. Eliminating these wires would additionally have the potential to improve fuel efficiency, greenhouse gas emission, and spur innovation by providing an open architecture to accommodate new systems and applications.

Standardization of Ultra-low Latency and High Reliable Wireless Communications

THANK YOU!



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."