Real–time Wireless Networks for Industrial Control Applications

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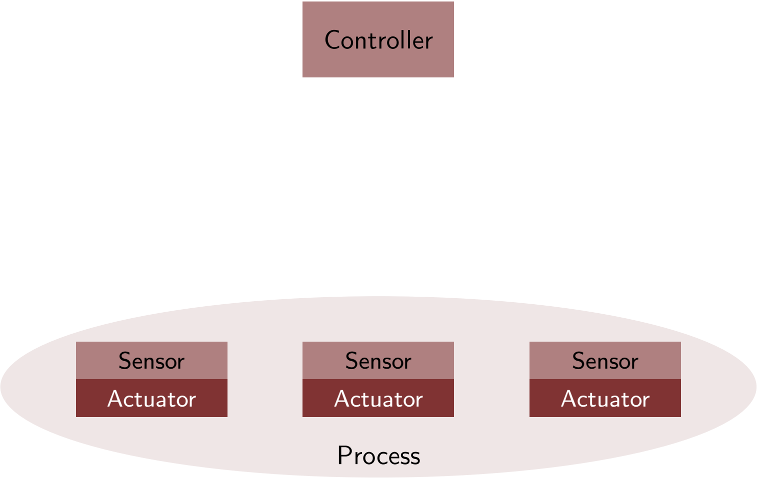
Introduction and background

Networked control systems



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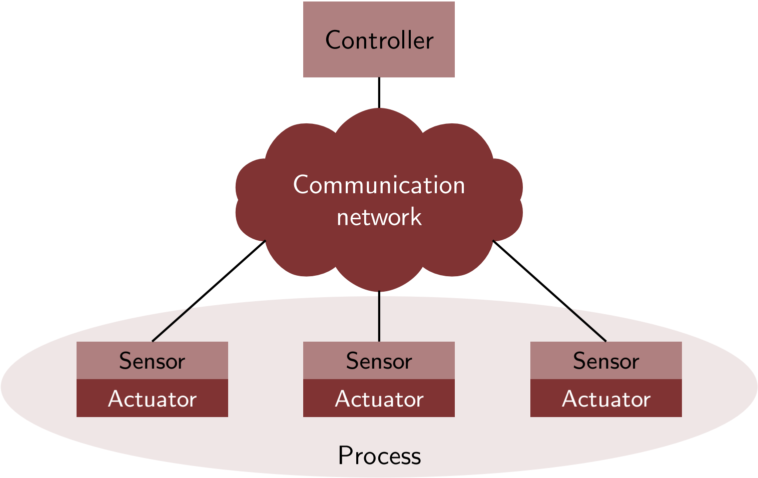
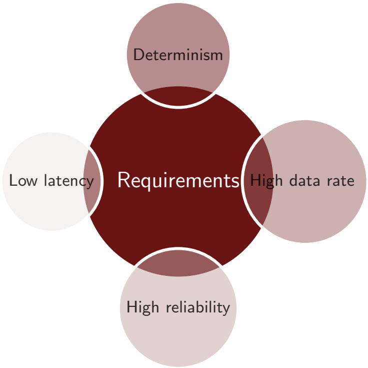


Communication requirements and assumptions



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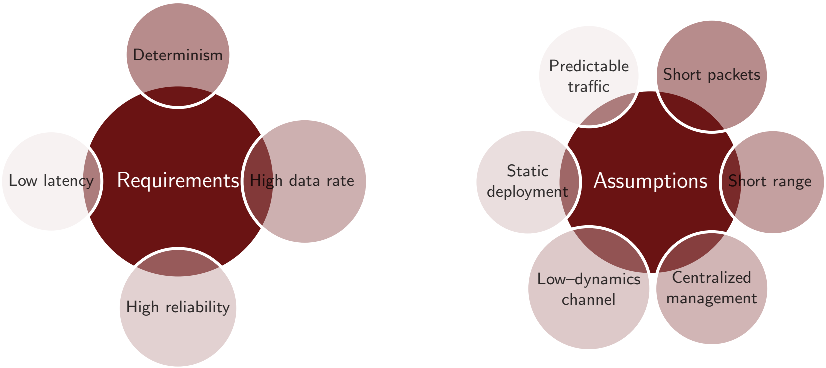

Benefits of wireless communications

Reduced costs

- Material
- Installation & commissioning
- Maintenance

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Difficult to deploy scenarios

- High temperatures
- Large heights
- Mobility & rotating parts




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Long–term reliability

- Aging
- High potentials in PE applications



Challenges of wireless communications

Error–prone channel

- Path loss, fading, shadowing, etc.
- Messages may be retransmitted to ensure reliability
- Retransmissions impair latency and determinism

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- Nodes that share the same space and frequency band can interfere with each other
- Medium access control (MAC) schemes are needed to coordinate access
- Tradeoff between fairness and determinism

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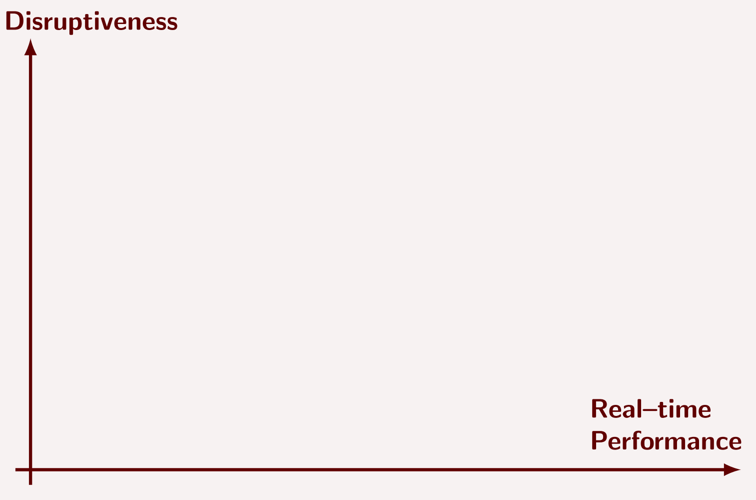
Security concerns

- Shared channel $\rightarrow$ everyone can hear and talk
- Jammers with high transmission powers can block network operations

Research topics



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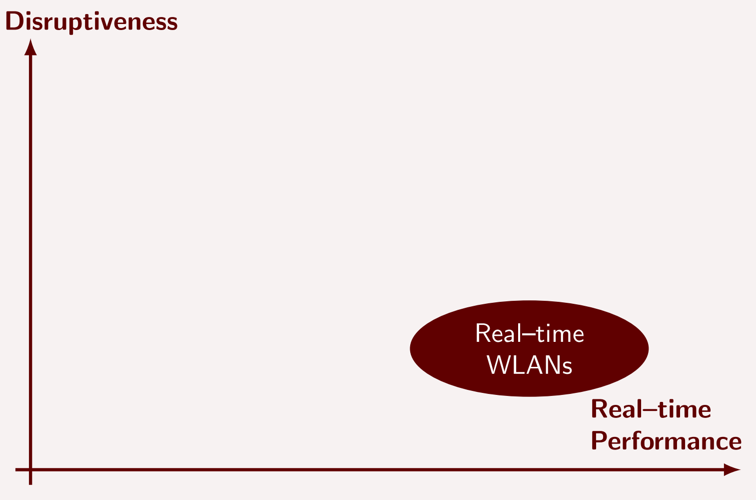

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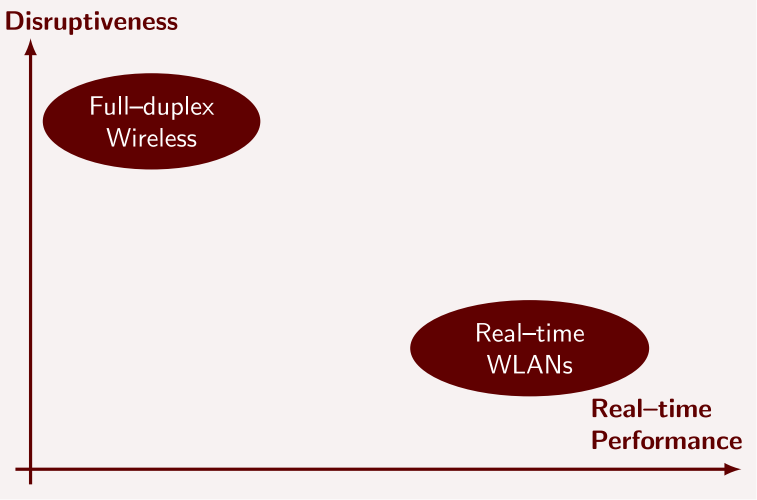

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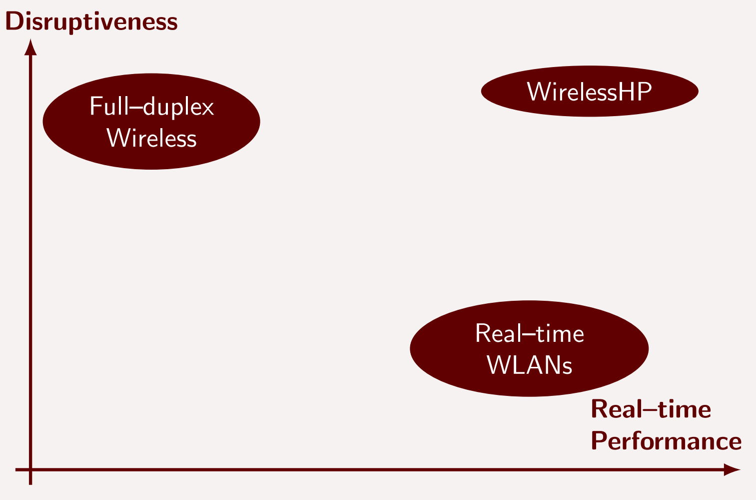

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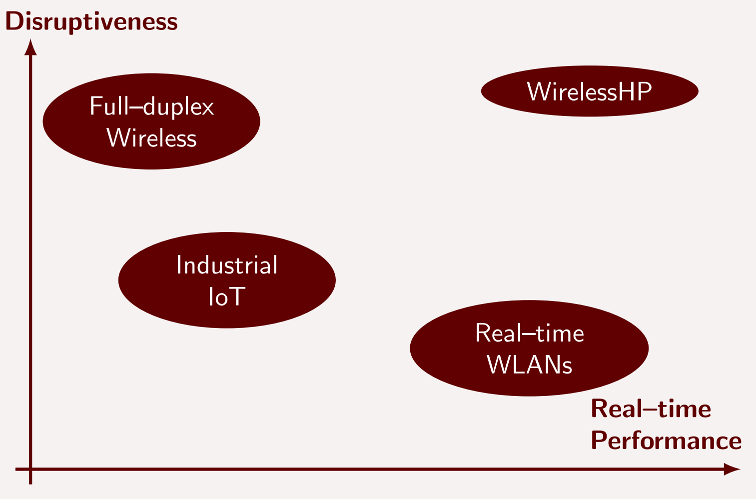
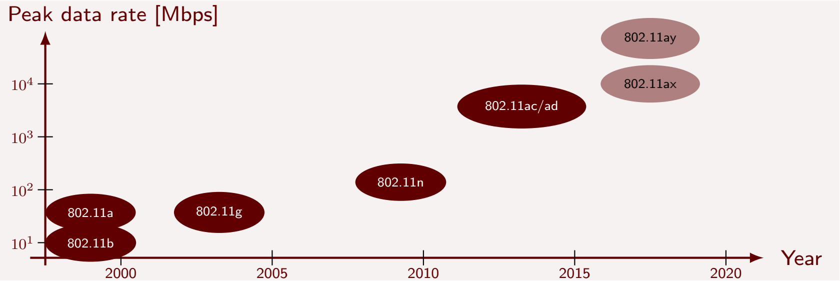


Real–time WLANs

IEEE 802.11 overview

Features

- ✓ High data rates (comparable to Ethernet networks)
- ✕ Random channel access (CSMA/CA + backoff)



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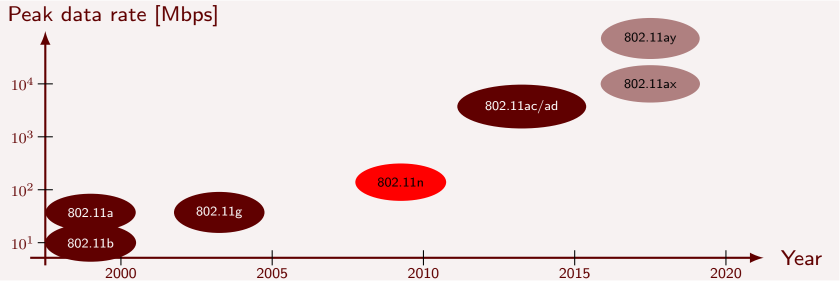

IEEE 802.11n for Industrial Communications

New features

- Multi–antenna architectures (MIMO)
- Channel bonding up to 40 MHz
- Higher order modulations
- More robust channel coding (LDPC)
- QoS–aware MAC enhancements

Configuration for real–time

- MIMO STBC for reliability
- Channel bonding
- LDPC
- No frame aggregation
- No block ACK

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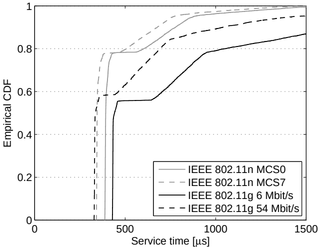

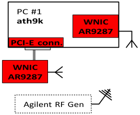

Configuration	No Interference		Interference	
	Mean	Std. Dev.	Mean	Std. Dev.
IEEE 802.11g 6 Mbit/s	434.0 μs	5.8 μs	919.3 μs	961.8 μs
IEEE 802.11n MCS0	391.1 μs	13.4 μs	489.5 μs	212.6 μs
IEEE 802.11g 54 Mbit/s	332.1 μs	3.9 μs	556.4 μs	460.1 μs
IEEE 802.11n MCS7	344.1 μs	8.9 μs	428.4 μs	184.9 μs

Industrial rate adaptation algorithms

Multi–rate support

- Feature of IEEE 802.11: multiple data rates available
- Different speed and reliability levels
- No algorithm defined in the standard

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General–purpose RA algorithms

- ARF: increase/decrease rate after a given number of successes/failures
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Previous industrial RA algorithms

- SARF: drops to lowest rate once after each failure
- FARF: drops to lowst rate permanently after each failure

Rate Selection for Industrial Networks (RSIN)

Features

- Selects both number of transmissions and data rates
- Constrained optimization procedure

$$\underset{N \leq N_{max}, r^{(i)} \in \mathcal{R}}{\arg\min} \mathcal{P}\left(L, s, N, r^{(1)}, \ldots, r^{(N)}\right) \text{ s.t. } \mathcal{D}\left(L, N, r^{(1)}, \ldots, r^{(N)}\right) \leq D$$

- Based on explicit SNR feedback from the receiver

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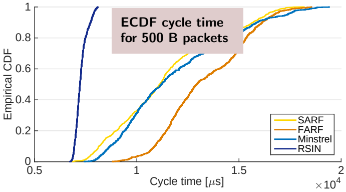
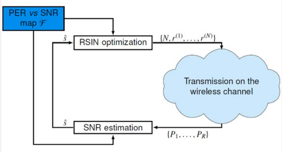


	RSIN	SARF	FARF	Minstrel
Metric	$\mathbf{L_{data}}$**=50 Byte**			
Average cycle time [ms]	2.93	3.00	3.09	3.19
Standard deviation [μs]	45	130	77	333
RTT [Mbit/s]	2.46	2.41	2.33	2.29
	$\mathbf{L_{data}}$**=500 Byte**			
Average cycle time [ms]	7.28	11.47	13.34	11.87
Standard deviation [μs]	364	2883	2440	3001
RTT [Mbit/s]	5.46	3.68	3.07	3.55

RSIN with SNR estimation

Features

- No more need for explicit SNR feedback
- Regularized estimation problem:
  $$\hat{s} = \arg\min_{s \in \mathcal{S}} (1-\lambda)\mathcal{E}(s) + \lambda\mathcal{H}(s)$$
- Dynamic tuning of penalty coefficient λ



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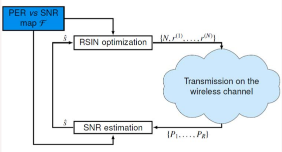
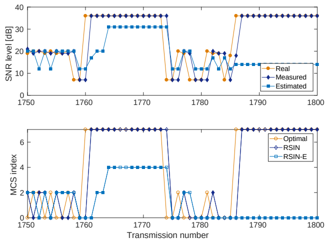
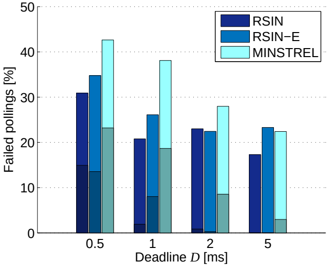






Selected publications

F. Tramarin, S. Vitturi, M. Luvisotto, and A. Zanella, "**On the Use of IEEE 802.11n for Industrial Communications**," *IEEE Transactions on Industrial Informatics*, vol. 12, pp. 1877–1886, Oct 2016

F. Tramarin, S. Vitturi, and M. Luvisotto, "**Improved Rate Adaptation strategies for real-time industrial IEEE 802.11n WLANs**," in *2015 IEEE 20th Conference on Emerging Technologies Factory Automation (ETFA)*, Sept 2015

F. Tramarin, S. Vitturi, and M. Luvisotto, "**A Dynamic Rate Selection Algorithm for IEEE 802.11 Industrial Wireless LAN**," *IEEE Transactions on Industrial Informatics*, vol. 13, pp. 846–855, April 2017

F. Tramarin, S. Vitturi, and M. Luvisotto, "**Performance analysis of IEEE 802.11 Rate Selection for Industrial Networks**," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Oct 2016

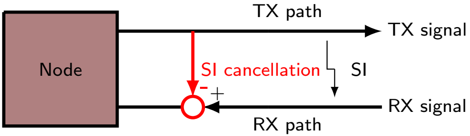
M. Luvisotto, F. Tramarin, and S. Vitturi, "**A learning algorithm for rate selection in real-time wireless LANs**," *Computer Networks*, vol. 126, pp. 114 – 124, 2017

Full–duplex wireless networks

Fundamentals of FD wireless

How to overcome the HD constraint

- Typical wireless networks: no simultaneous TX/RX in the same frequency band
- Main issue: self–interference (SI)
- Several SI cancellation methods proposed since 2010



SI cancellation methods

- Opportune antenna placement
- Analog cancellation ($\sim$ 60 dB)
- Digital cancellation ($\sim$ 50 dB)

RCFD MAC for FD wireless networks

Features

- Combines FD capabilities with frequency–domain channel access
- Nodes transmitting intentions are advertised (RTS) and confirmed/rejected (CTS) by using OFDM subcarriers (SCs)
- Fully distributed and randomized (fairness)
- Fixed channel access delay
- Solves hidden–terminal problem

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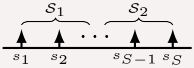
Assumptions

- Ad–hoc wireless network with FD nodes
- Unique maps between nodes and SCs



OFDM subcarriers $\mathcal{S}$

Node n	$\mathcal{F}_1(n)$	$\mathcal{F}_2(n)$
n_1	s_1	$s_{S/2+1}$
n_2	s_2	$s_{S/2+2}$
...	...	...
n_N	$s_{S/2}$	s_S

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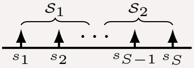

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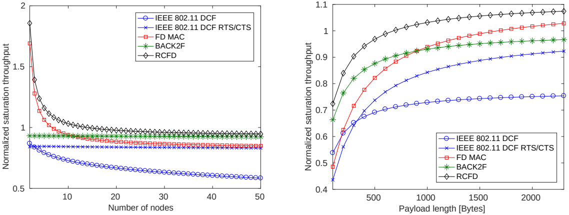
$\cdots$	$\cdots$	$\cdots$
n_N	$s_{S/2}$	s_S

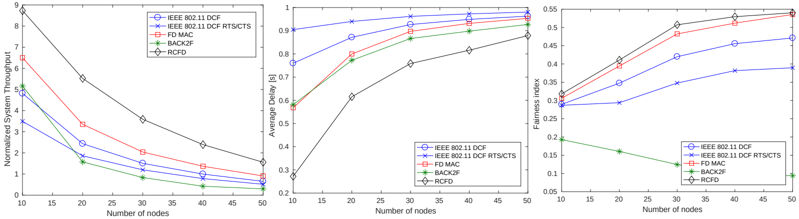
Channel access scheme

- **Round 1:** randomized contention to elect primary transmitters (PTs)
- **Round 2:** PTs advertise intentions (RTS)
- **Round 3:** designed receivers confirm or reject transmission (CTS) and possibly start a simultaneous transmission thanks to FD capabilities

RCFD vs. other MAC protocols



Theoretical saturation throughput (R=6 Mbps, L=1000 B, N=10 nodes when fixed)



Simulations with different number of nodes (R=18 Mbps, L=1000 B)

Selected publications

M. Luvisotto, A. Sadeghi, F. Lahouti, S. Vitturi, and M. Zorzi, "**RCFD: A frequency-based channel access scheme for full-duplex wireless networks**," in *2016 IEEE International Conference on Communications (ICC)*, May 2016

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High–performance Wireless Networks for Critical Control Applications (WirelessHP)

Critical industrial control applications

Reference scenarios

Building Aut. (BA)

Process Aut. (PA)

Factory Aut. (FA)

Power Sys. Aut. (PSA)

PE Control (PEC)

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Typical system–level performance

Scenario	No. of nodes	Cycle time	Reliability level
BA	1000	10 s	medium
PA	10000	100 ms	medium
FA	100	1 ms	high
PSA	100	100 μs	high
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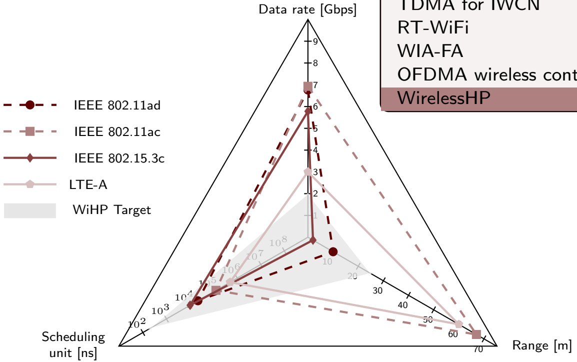
Corresponding link–level performance

Scenario	Data rate	Scheduling unit	Link range
Baseline	500 Mbps	1 μs	3 m
Target	2 Gbps	500 ns	10 m

Performance of current standards



Solution	PHY standard	Scheduling unit
WirelessHART/ISA100	802.15.4	10 ms
WISA/PNO WSAN	802.15.1	2 ms
TDMA for IWCN	802.15.4	1 ms
RT-WiFi	802.11	200 μs
WIA-FA	802.11	100 μs
OFDMA wireless control	802.11	66.7 μs
WirelessHP	Custom	<1 μs

Design directions

Goal

Design a low–latency PHY layer aimed at reducing as much as possible the packet transmission time when transmitting short amount of data

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Strategy

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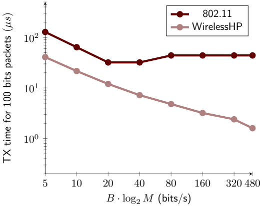
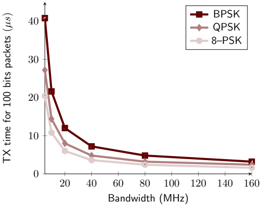
Validation

Test the reliability of the proposed PHY on SDR platforms

Current results





Theoretical TX time for 100 bits packet

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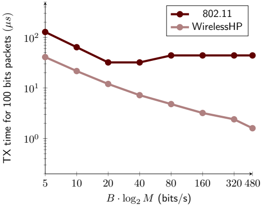

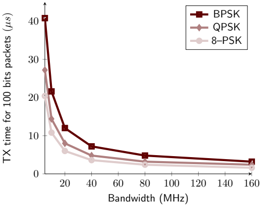

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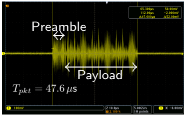
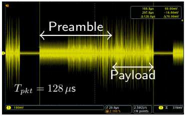
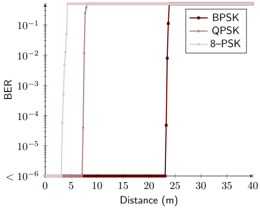


(a) WirelessHP BPSK



(b) 802.11 BPSK



Experimental results with USRP N210

Selected publications

M. Luvisotto, Z. Pang, and D. Dzung, "**Ultra High Performance Wireless Control for Critical Applications: Challenges and Directions**," *IEEE Transactions on Industrial Informatics*, vol. 13, pp. 1448–1459, June 2017

M. Luvisotto, Z. Pang, D. Dzung, M. Zhan, and X. Jiang, "**Physical Layer Design of High Performance Wireless Transmission for Critical Control Applications**," *IEEE Transactions on Industrial Informatics (accepted for publication)*, 2017

Z. Pang, M. Luvisotto, and D. Dzung, "**High Performance Wireless Communications for Critical Control Applications**," *Industrial Electronics Magazine (accepted for publication)*, 2017

LoRaWAN for Industrial IoT

IIoT overview

IoT and Industrial IoT

- IoT: network of networks with massive number of connected devices
- IoT paradigm applied to the productive sector (industrial IoT):
  - Increased efficiency and new concepts (e.g., outcome economy)
  - Impact on 2/3 of global GDP

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Communication technologies for IIoT

- Short–range: NFC, Bluetooth, etc.
- Long–range: WiMAX, mobile networks (2G/3G/4G), etc.
- WLANs: IEEE 802.11g/n/ac/ad, etc.
- WPANs: IEEE 802.15.4–based (ZigBee, Thread, 6LoWPAN, etc.)
- LPWANs: LoRaWAN, SigFox, Ingenu, Weightless, etc.

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Focus on LoRaWAN

PHY layer

- Proprietary modulation (LoRa) by Semtech
- Based on CSS modulation
- Different spreading factors (SFs) available
- Deployed in the ISM 900 MHz band (power and duty–cycle limited)

SF	Req. SNR	Data rate
7	-7.5 dB	5.47 Kbps
8	-10 dB	3.13 Kbps
9	-12.5 dB	1.76 Kbps
10	-15 dB	0.98 Kbps
11	-17.5 dB	0.44 Kbps
12	-20 dB	0.25 Kbps

MAC layer and topology

- End Devices (EDs) $\leftrightarrow$ Gateways (GWs) $\leftrightarrow$ Network Server (NS)
- Different class of EDs (A, B, C)
- Class A devices access the channel according to ALOHA and open receive windows at fixed intervals after transmission $\rightarrow$ lowest energy consumption

LoRaWAN for indoor industrial monitoring

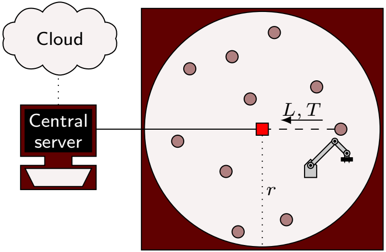
Scenario

- Uplink communications only: end nodes to sink (unconfirmed)
- Technologies: LoRaWAN vs. IEEE 802.15.4
- Metrics: probability of success, interpacket time, energy consumption
- Methodology: ns3 simulations with realistic industrial channel model

LoRaWAN for indoor industrial monitoring

Scenario

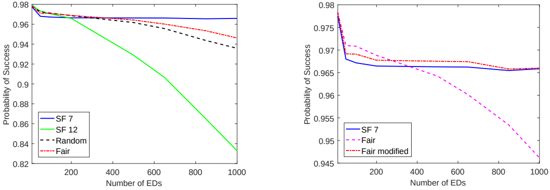
- Uplink communications only: end nodes to sink (unconfirmed)
- Technologies: LoRaWAN vs. IEEE 802.15.4
- Metrics: probability of success, interpacket time, energy consumption
- Methodology: ns3 simulations with realistic industrial channel model



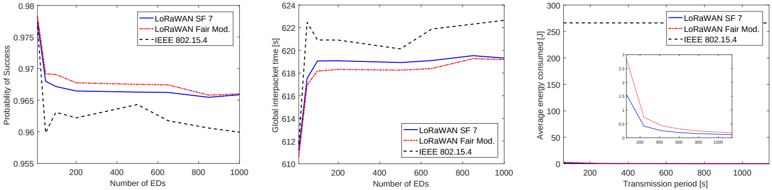
Sink
End node
Wireless link
Backhaul link

Parameter	Description	Value
N	Number of nodes	$\{10, \ldots, 1000\}$
r	Coverage radius	200 m
L	Message length	50 Bytes
T	Transmission period	$\{60, \ldots, 1800\}$ s

Simulation results



PoS for different LoRaWAN SF allocation strategies: constant, random, optimal (T=600 s)



LoRaWAN vs. IEEE 802.15.4 (T=600 s, N=500 when fixed)

Conclusions

Conclusions

Background

- Wireless technologies can have a great impact on industrial applications
- Requirements and assumptions of industrial networks are quite different from those of general–purpose communications
- Currently available standards/solutions do not meet all the requirements

Research findings

- RT performance of WLANs can be greatly improved through opportune configuration (e.g., MIMO, rate adaption)
- Full–duplex wireless can help significantly if equipped with proper MAC schemes
- Customized PHY layer is needed for extremely demanding applications (WirelessHP)
- Innovative IoT technologies (e.g. LPWANs) can be used in industrial applications bringing several advantages

Thanks for your attention

For any comment or question:

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