

FINAL REPORT

Student name: Michele Luvisotto

Cycle: XXX

Curriculum: ICT

Supervisor name: Prof. Stefano Vitturi

Thesis title (final): Real-time Wireless Networks for Industrial Control Systems

PART 1 - COURSES, CONFERENCES AND MOBILITY

Courses for Ph.D. students

1. Real-Time Systems and Applications (20 hours)
2. Applied Linear Algebra (20 hours)
3. Statistical Methods (24 hours)
4. Applied Functional Analysis and Machine Learning (28 hours)

Seminars

1. 06/10/14: Sandro Zampieri, *DEI Padova*
“On the existence and linear approximation of the power flow solution in power distribution network”
Automatica Group Seminars
2. 07/11/14: David Yau, *SUTD Singabore*
“Cyber-Physical Security in Future Cities”
SIGNET Meeting

3. 13/11/14: Florian Dörfler, *ETH Zürich*
“Plug and Play Operation of Microgrids”
Automatica Group Seminars
4. 27/11/14: Luigi Colangeli, *European Space Agency (ESA)*
“Rosetta rendez-vous with the 67P/Churyumov-Gerasimenko comet”
DEI Distinguished Lecture
5. 23/03/15: Walter Snoeys, *PH department, CERN*
“How chips helped discover the Higgs boson at CERN”
DEI Distinguished Lecture
6. 26/03/15: Federico Boccardi, *OFCOM*
“Shaping 5G”
Telecommunications Group Seminars
7. 24/04/15: Luigi Palopoli, *Univ. Trento*
“When multimedia meets control: use of soft real-time techniques for control design”
Automatica Group Seminars
8. 24/04/15: Federico Tramarin, *CNR*
“The IEEE 802.11n wireless LAN for real-time industrial communications”
SIGNET Meeting
9. 03/06/15: Mérouane Debbah, *Huawei France R&D Center*
“Mathematical Scientific Challenges of 5G”
DEI Distinguished Lecture
10. 18/06/15: Rodolphe Sepulchre, *Univ. Cambridge*
“Do brains compute?”
DEI Distinguished Lecture
11. 29/07/15: Felipe Gomez Cuba, *Univ. Vigo*
“Wireless Network Evolution: New Architectures and Resources”
SIGNET Meeting
12. 03/11/15: Horst Uwe Keller, *University Braunschweig*
“From Halley Multicolour Camera on Giotto to OSIRIS on Rosetta: the first and the latest images of cometary nuclei”
OSIRIS Team Meeting
13. 06/11/15: Fabrizio Luccio, *Università di Pisa*
“Arithmetic for Rooted Trees”
DEI Colloquia

14. 10/12/15: Francesca A. Lisi, *Università degli Studi di Bari*
“Lovelace Test: Verso macchine creative”
DEI Colloquia
15. 20/01/16: Pierpaolo Salvo, *Università La Sapienza*
“LTE Floating Car Data Application Off-Loading via VANET-driven Clustering Formation”
SIGNET meetings
16. 03/11/16: Kasim Sinan Yildirim, *TU Delft*
“Research Challenges for Intermittently Powered Wireless Embedded Systems”
Automatica Group Seminars
17. 05/04/17: Giulia Prando, *University of Padova*
“Introduction to Deep Learning”
Automatica Group Seminars
18. 26/04/17: Giulia Prando, *University of Padova*
“Recurrent and Convolutional Neural Networks”
Automatica Group Seminars
19. 11/05/17: Guenter Pfeifer, *Rohde & Schwarz*
“5G Technology Introduction, Market Status Overview and Worldwide Trials”
5G & IoT Seminar
20. 11/05/17: Lothar Walter, *Rohde & Schwarz*
“IoT System Design Challenges and Testing Solutions”
5G & IoT Seminar
21. 11/05/17: Christian Mazzucco, *Huawei Technology Italia*
“Engineering Antenna Arrays for mmWave 5G Systems”
5G & IoT Seminar
22. 16/05/17: Dacfe Dzong, *ABB Corporate Research*
“5G and Industrial Automation?”
ABB CRC Seminars
23. 17/05/17: Giulia Prando, *University of Padova*
“Training Strategies for Deep Neural networks”
Automatica Group Seminars
24. 31/05/2017: Giulia Prando, *University of Padova*
“Deep Learning Applications in Supervised Learning”
Automatica Group Seminars

25. 21/06/17: Reza Arghandeh, *Florida State University*
“From Data Mining to Knowledge Mining in Smart Infrastructure”
Automatica Group Seminars

Participation to International Conferences and Workshops

1. *IEEE World Conference on Factory Communication Systems (WFCS 2015)*, Palma de Mallorca (Spain), 27-29 May 2015
2. *IEEE International Conference on Communications (ICC 2016)*, Kuala Lumpur (Malaysia), 23-27 May 2016
3. *IEEE International Conference on Industrial Informatics (INDIN 2017)*, Emden (Germany), 24-26 July 2017
4. *International Conference on Enterprise Systems (ES 2017)*, Beijing (China), 22-24 September 2017

Mobility periods

1. ABB Corporate Research, Västerås (Sweden), March 23rd 2016 - September 30th 2016, *Ultrahigh Performance Wireless Networks for Critical Control Applications: study and prototyping*
2. ABB Corporate Research, Västerås (Sweden), June 26th 2017 - August 4th 2017, *Real-time FPGA Prototyping of a Low-Latency PHY Layer for Wireless Networks employed in Critical Control Applications*
3. ABB Corporate Research, Västerås (Sweden), October 1st 2017 - October 31st 2017, *Real-time FPGA Prototyping of PHY and MAC layers for Wireless Networks employed in Critical Control Applications*

PART 2 - RESEARCH ACTIVITY

The research during my PhD in Information Science and Technology has been developed in five main directions:

- *Real-time IEEE 802.11 industrial WLANs*, with Prof. Stefano Vitturi and Dr. Federico Tramarin. We have studied an optimal configuration of IEEE 802.11n WLANs

deployed in industrial applications and we have experimentally assessed the performance gains with respect to the older IEEE 802.11g standard. We have investigated and tuned several rate adaptation algorithms for IEEE 802.11 WLANs deployed in industrial applications. We have developed an original rate adaptation algorithm for real-time industrial networks, that optimally selects the transmission rate based on feedback on the channel conditions, aiming at maximizing the success probability of transmission while ensuring the observation of a deadline on packet delivery time. The algorithm has been implemented on commercial WiFi chipsets, together with other reference rate adaptation algorithms, and evaluated through numerical simulations.

- *Distributed clustering strategies in industrial wireless sensor networks*, with Giulia Michieletto and Prof. Angelo Cenedese. We have developed an original algorithm to partition a network of sensors in non-overlapping clusters based on connectivity and similarity of measurements. Both a centralized and a distributed version of the algorithm have been designed and tested via numerical simulations on practical industrial use cases.
- *Medium access control for full-duplex wireless networks*, with Alireza Sadeghi, Prof. Farshad Lahouti, Prof. Stefano Vitturi and Prof. Michele Zorzi. We have developed an original protocol for shared channel access in full-duplex wireless networks, able to guarantee fast and deterministic access to the medium. We have also created an analytical framework to investigate statistical quality-of-service requirements in full-duplex heterogeneous cellular networks.
- *High-performance wireless networks for critical industrial control applications*, with Dr. Zhibo Pang and Dr. Dacfe Dzong. I have taken part in the “Wireless HP” project at ABB Corporate Research Center. This industrial research project aims at developing wireless networks to be deployed in the most challenging industrial automation applications, from factory automation to power electronics control. I have first conducted a thorough analysis of the state-of-the-art, including both standards and scientific literature. Subsequently, I have proposed a cross-layer design aimed at achieving deterministic, low-latency and high-reliability wireless communications with short packets. Finally, I have developed two experimental prototypes, the first one on a low-performance software-defined radio platform (USRP N210), the second one on a more performing setup (Xilinx Zynq + ADI 9361). These setups allowed to demonstrate the feasibility of the proposed design principles.
- *Industrial Internet-of-Things*, with Prof. Stefano Vitturi, Dr. Federico Tramarin and Prof. Lorenzo Vangelista. We have considered the use of low-power wide-area networks (LPWANs), and in particular of LoRaWAN, for indoor industrial monitoring applications. Starting from an already developed network simulator for LoRaWAN

networks, additional modules were added to accurately reproduce industrial environments. Subsequently, different strategies for the selection of spreading factors in a LoRaWAN network have been compared, including an original strategy specifically designed for industrial applications. Finally, the performance of LoRaWAN and IEEE 802.15.4 in indoor industrial monitoring scenarios have been compared, showing that the former offered slightly better performance and also a significantly lower energy consumption.

PART 3 - PUBLICATIONS

List of publications on international journals

- J1. Tramarin, F. and Vitturi, S. and Luvisotto, M. and Zanella, A., *On the Use of IEEE 802.11n for Industrial Communications*, IEEE Transactions on Industrial Informatics, vol.12, no.5, pp.1877-1886, October 2016, DOI: 10.1109/TII.2015.2504872
- J2. Michieletto, G. and Luvisotto, M. and Cenedese, A., *Distributed Clustering Strategies in Industrial Wireless Sensor Networks*, IEEE Transactions on Industrial Informatics, vol.13, no.1, pp.228-237, February 2017, DOI: 10.1109/TII.2016.2628409
- J3. Tramarin, F. and Vitturi, S. and Luvisotto, M., *A Dynamic Rate Selection Algorithm for IEEE 802.11 Industrial Wireless LAN*, IEEE Transactions on Industrial Informatics, vol.13, no.2, pp.846-855, April 2017, DOI: 10.1109/TII.2016.2616327
- J4. Luvisotto, M. and Pang, Z. and Dzung, D., *Ultra High Performance Wireless Control for Critical Applications: Challenges and Directions*, IEEE Transactions on Industrial Informatics, vol.13, no.3, pp.1448-1459, June 2017, DOI: 10.1109/TII.2016.2617459
- J5. Luvisotto, M. and Tramarin, F. and Vitturi, S., *A learning algorithm for rate selection in real-time wireless LANs*, Computer Networks, 2017, vol.126, pp.114-124, October 2017, DOI: 10.1016/j.comnet.2017.07.002
- J6. Luvisotto, M. and Pang, Z. and Dzung, D. and Zhan, M. and Jiang, X., *Physical Layer Design of High Performance Wireless Transmission for Critical Control Applications*, IEEE Transactions on Industrial Informatics, vol.PP, no.99, pp.1-1, 2017, DOI: 10.1109/TII.2017.2703116
- J7. Pang, Z. and Luvisotto, M. and Dacfe, D., *High Performance Wireless Communications for Critical Control Applications*, IEEE Industrial Electronics Magazine, 2017 [Accepted for publication]

- J8. Luvisotto, M. and Sadeghi, A. and Lahouti, F. and Vitturi, S. and Zorzi, M., *RCFD: A Novel Channel Access Scheme for Full-Duplex Wireless Networks Based on Contention in Time and Frequency Domains*, IEEE Transactions on Mobile Computing, 2017 [Submitted for publication]
- J9. Sadeghi, A. and Luvisotto, M. and Lahouti, F. and Zorzi, M., *Analysis of Statistical QoS in Half Duplex and Full Duplex Dense Heterogeneous Cellular Networks*, IEEE Transactions on Mobile Computing, 2017 [Submitted for publication]

List of publications on conference proceedings

- C1. Tramarin, F. and Vitturi, S. and Luvisotto, M. and Parrozzani, R., *Performance assessment of an IEEE 802.11-based protocol for real-time communication in agriculture*, 2014 IEEE Conference on Emerging Technology and Factory Automation (ETFA), DOI: 10.1109/ETFA.2014.7005304
- C2. Tramarin, F. and Vitturi, S. and Luvisotto, M. and Zanella, A., *The IEEE 802.11n wireless LAN for real-time industrial communication*, 2015 IEEE World Conference on Factory Communication Systems (WFCS), DOI: 10.1109/WFCS.2015.7160568
- C3. Tramarin, F. and Vitturi, S. and Luvisotto, M., *Enhancing the real-time behavior of IEEE 802.11n*, 2015 IEEE World Conference on Factory Communication Systems (WFCS), DOI: 10.1109/WFCS.2015.7160580
- C4. Bianchin, G. and Cenedese, A. and Luvisotto, M. and Michieletto G., *Distributed fault detection in sensor networks via clustering and consensus*, 2015 IEEE Annual Conference on Decision and Control (CDC), DOI: 10.1109/CDC.2015.7402814
- C5. Tramarin, F. and Vitturi, S. and Luvisotto, M., *Improved Rate Adaptation strategies for real-time industrial IEEE 802.11n WLANs*, 2015 IEEE Conference on Emerging Technology and Factory Automation (ETFA), DOI: 10.1109/ETFA.2015.7301481
- C6. Tramarin, F. and Vitturi, S. and Luvisotto, M., *An innovative approach to rate adaptation in IEEE 802.11 real-time industrial networks*, 2016 IEEE World Conference on Factory Communication Systems (WFCS), DOI: 10.1109/WFCS.2016.7496498
- C7. Luvisotto, M. and Sadeghi, A. and Lahouti, F. and Vitturi, S. and Zorzi, M., *RCFD: A frequency-based channel access scheme for full-duplex wireless networks*, 2016 IEEE International Conference on Communications (ICC), DOI: 10.1109/ICC.2016.7511361
- C8. Sadeghi, A. and Luvisotto, M. and Lahouti, F. and Vitturi, S. and Zorzi, M., *Statistical QoS analysis of full duplex and half duplex heterogeneous cellular networks*, 2016 IEEE International Conference on Communications (ICC), DOI: 10.1109/ICC.2016.7511332

- C9. Tramarin, F. and Vitturi, S. and Luvisotto, M., *Performance Analysis of IEEE 802.11 Rate Selection for Industrial Networks*, 2016 Annual Conference of the IEEE Industrial Electronics Society (IECON), DOI: 10.1109/IECON.2016.7794033
- C10. Tramarin, F. and Vitturi, S. and Luvisotto, M., *IEEE 802.11n for Distributed Measurement Systems*, 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), DOI: 10.1109/I2MTC.2017.7969670
- C11. Luvisotto, M. and Tagliapietra, A. and Romagnolo, S. and Tramarin, F. and Vitturi, S., *Real-Time Wireless Extensions of Industrial Ethernet Networks*, 2017 IEEE International Conference on Industrial Informatics (INDIN) [Presented at the conference]
- C12. Zhu, H. and Pang, Z. and Xie, B. and Luvisotto, M., *Real-time and Non-intrusive On-site Diagnosis for Commissioning Wireless Sensor and Actuator Networks in Building Automation*, 2017 International Conference on Enterprise Systems (ES) [Accepted for publication]
- C13. Xie, B. and Pang, Z. and Zhu, H. and Luvisotto, M., *Location aided commissioning of building automation devices enabled by high accuracy indoor positioning*, 2017 International Conference on Enterprise Systems (ES) [Accepted for publication]

Date

15/09/2017

Signature (PhD student)

Michele Luvisotto

Signature (Supervisor)

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