

Final Report

Student name Marco Centenaro

Cycle XXX

Curriculum ICT

Supervisor name Prof. Lorenzo Vangelista

Thesis title (final) “On the Support of Massive Machine-to-Machine Traffic in Heterogeneous Networks and Fifth-Generation Cellular Networks”

Part 1 – Courses, Conferences and Mobility

Courses for Ph.D. students

I attended and passed the following courses:

- “Information-Theoretic Methods in Security” (20 hours), Prof. Laurenti;
- “Real-Time Systems and Applications” (20 hours), Prof. Manduchi;
- “Applied Linear Algebra” (20 hours), Prof. Picci;
- “Internet of Things” (20 hours), Prof. Vardanega and Prof. Beghi;
- “Statistical Methods” (24 hours), Prof. Finesso;
- “Bayesian Machine Learning” (20 hours), Prof. Di Nunzio;
- “English for Academic Purposes” (30 hours), Prof. Davies.

I also attended two further courses as an auditor:

- “Network Programming Languages” (24 hours), held at the Politecnico di Milano, Milan, Italy, by Prof. Soule.
- “Applied Machine Learning in Biomedicine” (16 hours), Prof. Grisan.

All courses were held at the Department of Information Engineering (DEI), University of Padova, Italy, unless otherwise specified.

Summer schools, short courses, tutorials

I attended the summer school entitled “Computational Complex and Social Systems” held at the Aktea Conference Center of Lipari, Italy, from July 10 to July 17, 2016.

Seminars

- *Brain-Machine-Interfaces in Complete Paralysis, Stroke, and Neuropsychiatric Disorders*, N. Birbaumer, November 5, 2014;
- *On the Geometry of Maximum Entropy Problems*, M. Pavon, March 13, 2015;
- *Shaping 5G*, F. Boccardi, March 26, 2015;
- *Learning with Computational Regularization*, L. Rosasco, March 27, 2015;
- *Mathematical Scientific Challenges of 5G*, M. Debbah, June 3, 2015;
- *Do Brains Compute?*, R. Sepulchre, June 18, 2015;
- *Development of Sensory Feedback System for Stroke Patients with Sensory Disturbance and Neural Basis of Musician's Dystonia*, K. Kita, September 24, 2015;
- *Bitcoin, an Attempt at a Separation of Money and State*, P. Pattnaik, September 25, 2015;
- *Autonomous Mobile Robot Research*, J. Miura, October 5, 2015;
- *Building Heterogenous Systems: A View from the Trenches*, R. Kastner, January 12, 2016;
- *Neuroscience Day @ DEI*, workshop, February 2, 2016;
- *Luce da Nobel*, workshop, March 3, 2016;
- *LTE Floating Car Data application off-loading via VANET driven clustering formation*, P. Salvo, March 4, 2016;
- *Development of Wide-Angle Liquid Crystal Fovea Lens*, S. Shimizu, March 31, 2016;
- *Low Power Wide Area Networks for the IoT*, M. Kelly, May 4, 2016;
- *Rohde&Schwarz Research & Education Seminar*, workshop, May 17, 2016;
- *Tactile Internet, the ultimate case of low latency, reliable communications*, T. Mahmoodi, May 18, 2016;
- *When is Big Data Sufficiently Big? When is it Too Big? Sample Complexity, Uniform Convergence, and Generalization Error*, E. Upfal, June 6, 2016;
- *Cross layer Sensing, Estimation & Control in Wireless Networks*, N. Michelusi, June 10, 2016;
- *Computational Thinking, Inferential Thinking and Data Science*, M. I. Jordan, June 21, 2016.
- *Lo straordinario percorso dell'informatica*, F. P. Preparata, June 24, 2016;
- *CyPhy Detective: Learning Based Events Detection in Power*, R. Arghandeh, June 27, 2016;
- *Grouping Games: Finding Clusters in Graphs, Digraphs and Hypergraphs*, M. Pellilo, July 4, 2016;

- *Sensor Scheduling in Variance Based Event Triggered Estimation with Packet Drops*, S. Dey, July 20, 2016.

All seminars were held at the Department of Information Engineering (DEI), University of Padova, Italy, unless otherwise specified.

I also attended the *SIGNET Meetings*, that is, the weekly seminars of my research group at the Department of Information Engineering, University of Padova, Italy.

Participation to international conferences and workshops

I attended two international conferences to present research contributions:

- IEEE International Conference on Communications (IEEE ICC'15), London, United Kingdom, June 8-12, 2015;
- IEEE International Conference on Communications (IEEE ICC'16), Kuala Lumpur, Malaysia, May 23-27, 2016.

I also attended the following three conferences as an auditor:

- Italian Networking Workshop (INW16), San Candido, Italy, January 13-15, 2016;
- Symposium on Medical Information and Communications Technology (SMICT2017), Yokohama, Japan, March 8, 2017;
- Wireless Technology Park (YRP2017), Tokyo, Japan, May 24-26, 2017.

Other learning activities

I visited the R&D division of the following companies:

- Nokia Bell Labs, Stuttgart (Germany), April 22, 2016;
- Hitachi, Yokohama (Japan), March 23, 2017;
- NTT DoCoMo, Yokosuka (Japan), June 20, 2017;
- Fujitsu, Kawasaki (Japan), July 13, 2017.

Teaching/tutoring activities

I served as tutor for the students of the following courses:

- “Mathematical Analysis,” November 2015 – February 2016, supervisor: Prof. Gandin;
- “Probability Theory,” March 2016 – July 2016, supervisor: Prof. Vangelista.

The activities consisted in holding weekly meetings with students and solving homework and exercises proposed to/by the students.

Mobility periods

I spent two periods of time abroad, for an aggregate of ten months.

- September 1 – December 31, 2016, Nokia Bell Labs, Stuttgart (Germany), under the supervision of Dr. Stephan Saur. The title of the joint research was “Comparison of Collision-Free and Contention-Based Radio Access Protocols for the Internet of Things.”
- January 16 – July 21, 2017, Yokohama National University (YNU), Yokohama (Japan), under the supervision of Prof. Ryuji Kohno. The title of the joint research was “Reliability and Dependability in the Internet of Things.”

Part 2 – Research Activity

My research activity dealt with the design of protocols for the Internet of Things (IoT). In particular, the work can be divided into two parts.

Part 1 “Standards and Technologies for the Internet of Things.” In this part, we focused on two enabling technologies for the IoT, exploiting long-range wireless links:

- the next-generation cellular network (5G) and
- Long-RangeTM (LoRa), which is one of the most prominent technologies in the class of Low-Power Wide Area Networks (LPWANs).

Both 5G systems and LPWANs are based on a star network topology, that is, every end device is connected to a single radio concentrator via a single hop. On the other hand, while 5G operates on licensed frequency bands, LPWANs utilize unlicensed spectrum to communicate.

As for the 5G, we first identified and discussed the issues of the current cellular network, i.e., the Long Term Evolution (LTE, 4G) standard, in supporting massive uplink (UL) traffic coming from IoT terminals [C9, C11]. Then, we surveyed the state of the art to understand how other researchers tackled the so-called *massive access* problem [J3]. Finally, in collaboration with the researchers of the Nokia Bell Labs located in Stuttgart (Germany), a contention-based radio access protocol for 5G systems which overcomes the issues of the 4G was proposed, characterized from the mathematical point of view, and compared against 4G [C4, C6, J1]. The proposed approach provides a much shorter delivery delay and a massive reduction in the downlink (DL) feedback.

Regarding LoRa, we first surveyed the principles of this technology and its competitors (Sigfox and Ingenu) [J2]. Then, we evaluated the performance of a crowded LoRa deployment through extensive simulation campaigns, showing that tens of thousand nodes can be served efficiently [C5]. Moreover, during the mobility period at YNU, we studied the negative impact that is induced by acknowledgement messages sent in downlink to a large-scale LoRa network [C2]. Finally, we envisioned some basic design principles of a Radio Resource Management (RRC) entity in a LoRa system [C1].

Part 2 “Fundamental Research on the Internet of Things.” In the second part, we contributed with innovative ideas to the research on the Internet of Things paradigm at large. In particular, we focused on the following two research fields:

- physical-layer security mechanisms for IoT networks and
- flow allocation strategies for Wireless Sensor Networks (WSNs).

Regarding the former field, we addressed the security issues of IoT networks by providing a novel authentication protocol for IoT terminals: it consists of a hypothesis test based on the estimations of the wireless channels between each end device and a group of trusted anchor nodes [B1, C8]. Moreover, using a similar approach, we proposed a location verification protocol for IoT terminals exploiting the channel estimates of some trusted anchor nodes [C2].

Regarding the latter research field, we investigated the trade-off between the cost of transmitting data (*transport cost*) and the cost of compressing them (*compression cost*) in order to optimize the allocation of flows of data on the wireless links of a WSN [C7]. We found that by enabling the compression of raw data at the source nodes, we can offload the wireless links that generate a bottleneck in the transport network.

Throughout the doctoral course, I served as a reviewer for international conferences (IEEE ICC'16, IEEE European Wireless 2016, IEEE ICC'17, IEEE European Wireless 2017, IEEE PIMRC'17) and journals (IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, IEEE Internet of Things Journal, IEEE Transactions on Mobile Computing, IEEE Communication Magazine, IEEE Transactions of Industrial Electronics, IEEE Communication Letters, Elsevier Computer Communications).

Part 3 – Publications

List of publications on international journals

- J1** M. Centenaro, L. Vangelista, S. Saur, A. Weber, and V. Braun, *Comparison between Contention-Free and Contention-Based Radio Access Protocols for the Internet of Things*, IEEE Trans. on Commun., preprint, May 2017. DOI: 10.1109/TCOMM.2017.2707074
- J2** M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, *Long-Range Communications in Unlicensed Bands: the Rising Stars in the IoT and Smart Cities Scenarios*, IEEE Wireless Communications, vol. 23, no. 5, pp. 60-67, Oct. 2016. DOI: 10.1109/MWC.2016.7721743
- J3** A. Biral, M. Centenaro, A. Zanella, L. Vangelista, and M. Zorzi, *The Challenges of M2M Massive Access in Wireless Cellular Networks*, Digital Communications and Networks, vol. 1, no. 1, pp. 1-19, Feb. 2015. DOI: 10.1016/j.dcan.2015.02.001

List of publications on conference proceedings

- C1** L. Vangelista, M. Centenaro, and D. Magrin, *Innovative Strategies for Efficient Radio Resource Management in LoRaWAN Networks*, submitted to IEEE WF-IoT 2018.
- C2** M. Centenaro, L. Vangelista, and R. Kohno, *On the Impact of Downlink Feedback on LoRa Performance*, to be presented at IEEE PIMRC, Montreal, Canada, Oct. 8-13, 2017.
- C3** G. Caparra, M. Centenaro, N. Laurenti, and S. Tomasin, *Optimization of Anchor Nodes' Usage for Location Verification Systems*, in Proc. ICL-GNSS, Nottingham, UK, Jun. 2017. DOI: not yet available.
- C4** S. Saur and M. Centenaro, *Radio Access Protocols with Multi-User Detection for URLLC in 5G*, in Proc. IEEE European Wireless, Dresden, Germany, May 2017. DOI: not yet available.

- C5 D. Magrin, M. Centenaro, and L. Vangelista, *Performance Evaluation of LoRa Networks in a Smart City Scenario*, in Proc. IEEE ICC, Paris, France, May 2017. DOI: 10.1109/ICC.2017.7996384
- C6 M. Centenaro and L. Vangelista, *Analysis of Small Packet Access Support in LTE*, in Proc. IEEE WTS, Chicago, USA, Apr. 2017. DOI: 10.1109/WTS.2017.7943524
- C7 M. Centenaro, M. Rossi, and M. Zorzi, *Joint Optimization of Lossy Compression and Transport in Wireless Sensor Networks*, in Proc. IEEE Globecom, Washington DC, USA, Dec. 2016. DOI: 10.1109/GLOCOMW.2016.7848945
- C8 G. Caparra, M. Centenaro, N. Laurenti, S. Tomasin, and L. Vangelista, *Energy-Based Anchor Node Selection for IoT Physical Layer Authentication*, in Proc. IEEE ICC, Kuala Lumpur, Malaysia, May 2016. DOI: 10.1109/ICC.2016.7511624
- C9 M. Polese, M. Centenaro, A. Zanella, and M. Zorzi, *M2M massive access in LTE: RACH performance evaluation in a Smart City scenario*, in Proc. IEEE ICC, Kuala Lumpur, Malaysia, May 2016. DOI: 10.1109/ICC.2016.7511430
- C10 M. Pesce, M. Centenaro, L. Badia, and M. Zorzi, *Impact of Correlated Primary Transmissions on the Design of a Cognitive Radio Inference Engine*, in Proc. IEEE ICC, Kuala Lumpur, Malaysia, May 2016. DOI: 10.1109/ICC.2016.7503867
- C11 M. Centenaro and L. Vangelista, *A Study on M2M Traffic and Its Impact on Cellular Networks*, in Proc. IEEE WF-IoT, Milan, Italy, Dec. 2015. DOI: 10.1109/WF-IoT.2015.7389044
- C12 M. Centenaro, G. Ministeri, and L. Vangelista, *A Comparison of Energy-Efficient HARQ Protocols for M2M Communication in the Finite Block-Length Regime*, in Proc. IEEE ICUWB, Montreal, Canada, Oct. 2015. DOI: 10.1109/ICUWB.2015.7324397
- C13 M. Centenaro and L. Vangelista, *HARQ in LTE uplink: a Simple and Effective Modification Suitable for Low Mobility Users*, in Proc. IEEE ICC, London, UK, Jun. 2015. DOI: 10.1109/ICC.2015.7248910
- C14 M. Centenaro, M. Pesce, D. Munaretto, A. Zanella, and M. Zorzi, *A Comparison Between Opportunistic and Fair Resource Allocation Scheduling for LTE*, in Proc. IEEE CAMAD, Athens, Greece, Dec. 2014. DOI: 10.1109/CAMAD.2014.7033242

List of other publications (books, book chapters, patents)

- B1 G. Caparra, M. Centenaro, N. Laurenti, S. Tomasin, and L. Vangelista, *Energy-Efficient Physical Layer Authentication in the Internet of Things*, in "Information Theoretic Security and Privacy of Information Systems," Cambridge University Press, Jun. 2017. DOI: 10.1017/9781316450840

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Student signature



 Supervisor signature