ERCIM "Alain Bensoussan" Fellowship Scientific Report

Fellow: Luca Mottola
Visited Location: Swedish Institute of Computer Science (SICS)
Duration of Visit: January 1st, 2009 – December 31st, 2009

Scientific Activity

Wireless Sensor Networks (WSNs) are distributed systems composed of embedded devices equipped with a processing unit, a wireless communication interface, as well as sensors and/or actuators. WSNs bridge the gap between digital and virtual worlds. Most often, the WSN devices are battery operated and can hardly perform any useful task individually. Rather, it is the collective collaboration of a high number of nodes that makes WSNs a viable solution to sense from—and act on—the real world. However, because of the characteristics of devices employed, their requirements and mode of operation inherently differ from traditional distributed computing.

During the fellowship, my research activity in WSNs has mainly concentrated on the design, implementation, and evaluation of WSN programming abstractions. Indeed, developing distributed applications for WSNs still requires abilities that domain-experts are typically not provided with. Therefore, high-level programming abstractions are needed to manage complexity and hide distribution. To achieve this goal, I applied an approach where programming constructs are co-designed with the underlying system-level, distributed mechanisms required to implement their semantics. As outlined next, during the fellowship I particularly addressed storage-centric scenarios, where the WSN is required to work autonomously and without access to external back-end infrastructures.

Meanwhile, I further broadened the scope of my WSN research, while continuing to work in the field of WSN programming. For instance, I started tackling issues in static verification of sensor network software and in distributed algorithms and theory, as well as looking into problems related to low-power communications and the design and optimization of WSN MAC protocols.

Academic Activity

Right after my arrival at SICS, the group organized a seminar where I introduced myself to the other lab and group members. During the talk, I illustrated my background and the research I carried out during my Ph.D. studies. Thereafter, I laid

out ideas and prospective plans for my stay at SICS, gathering precious feedback. I then started to work on the issues arising in programming WSNs in storage-centric scenarios; constantly updating the other group members on my progresses and gaining further insights form their comments. At the some time, I collaborated with other group members on existing or new projects. For instance, I worked on issues related to low-power neighbor discovery and interference handling in low-power MAC protocol with different members of the research team at SICS.

During the fellowship, I was invited to give a keynote speech at 2nd Wireless Sensing Demonstrator Showcase, London (UK) in July 2009. The talk, titled "Monitoring Heritage Buildings with Wireless Sensor Networks: The Torre Aquila Deployment", was very well received. I also participated to several technical program committees throughout the duration of the fellowship, the major ones being:

- The 6th IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS10).
- The 9th Int. Workshop on Real Time Networks (RTN10).
- The 3rd Wireless Sensing Demonstrator Showcase (WSDS10).
- The 1st International Workshop on Software Engineering for Sensor Network Applications (SESENA10 - co-located with ICSE10).
- The 3rd IEEE Int. Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC10).
- The 9th ACM/IEEE Int. Conference on Information Processing in Sensor Networks (IPSN10).
- The 7th European Conference on Wireless Sensor Networks (EWSN10).

Finally, throughout my stay I supervised (or co-supervised) three M.Sc. students carrying out their thesis work at SICS. Among them was Marco Zimmerling, whose thesis on dynamic adaptation of MAC protocol parameters won the Best M.Sc. Thesis Award at the 1st International School on Cyber-Physical and Sensor Networks (SensorNets) in Monastir (Tunisia), December 2009.

Research on Storage-centric Sensor Networks

Early deployments of WSNs consisted of embedded devices that immediately communicated sensed data to the user. Accordingly, the dominating design was characterized by a sense-and-send pattern, possibly with some local filtering. In this communication-centric setting, the storage capabilities of the devices play little role.

This strategy has proved to be not always successful, due to the difficulties in setting up energy-efficient, real-time collection networks. Moreover, as deployments have grown in complexity, the amount of data harvested from the environment has started to outweigh the capabilities of present radio devices. WSNs have also entered fields where real-time data collection is not feasible. For instance, this is the case when nodes are attached to roaming entities such as wild animals, or when deploying a base station is not possible.

A new breed of storage-centric sensing systems has emerged to tackle these issues. In this setting, storage operations tend to prevail over communication activity. This paradigm shift—favored by decreasing costs and increasing capacity of storage hardware—brings several advantages. It allows the system to perform batch data collection, providing significant energy savings. It also enables delay tolerant mobile applications and disconnected operations in static networks, by providing means to retain data until the first upload opportunity arises

During the fellowship, I developed SQUIRREL, a stream-oriented programming framework for storage-centric sensor networks. SQUIRREL simplifies developing such applications by decoupling data processing from storage, and by transparently handling the latter. SQUIRREL's was applied to three real-world applications, each corresponding to a different storage-centric scenario, demonstrating that SQUIRREL both relieves programmers from a significant burden and achieves efficient utilization of storage areas, enabling energy savings independently of the storage technology.

(Selected) Publications During the Fellowship

Luca Mottola. *Programming Storage-centric Sensor Networks with Squirrel.* In Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks - IP Track (IPSN/IP), Stockholm (Sweden), April 2010.

Abstract: We present SQUIRREL, a stream-oriented programming framework for storage-centric sensor networks. The storage-centric paradigm—where storage operations prevail over communication activity—applies to scenarios such as batch data collection, delay-tolerant mobile applications, and disconnected operations in static networks. SQUIRREL simplifies developing such applications by decoupling data processing from storage, and by transparently handling the latter. We achieve this through: i) a modular programming abstraction, and ii) a lightweight run-time layer that efficiently allocates data to different storage areas, based on size vs. energy tradeoffs. We demonstrate SQUIRREL's effectiveness based on three real-world applications, each representing a different storage-centric scenario. The results show that—while relieving programmers from a significant burden—SQUIRREL achieves efficient utilization of storage areas, enabling energy savings independently of the storage technology.

Carlo Alberto Boano, Thiemo Voigt, Nicolas Tsiftes, Luca Mottola, Kay Romer, and Marco Zuniga. *Making Sensornet MAC Protocols Robust Against Interference*. In Proceedings of the 7th European Conference on Wireless Sensor Networks (EWSN), Coimbra (Portugal), February 2010.

Abstract: Radio interference may lead to packet losses, thus negatively affecting the performance of sensornet applications. In this paper, we experimentally assess the impact of external interference on state-of-the-art sensornet MAC protocols. Our experiments illustrate that specific features of existing protocols, e.g., hand-shaking schemes preceding the actual data transmission, play a critical role in this setting. We

leverage these results by identifying mechanisms to improve the robustness of existing MAC protocols under interference. These mechanisms include the use of multiple hand-shaking attempts coupled with packet trains and suitable congestion backoff schemes to better tolerate interference. We embed these mechanisms within an existing X-MAC implementation and show that they considerably improve the packet delivery rate while keeping the power consumption at a moderate level.

Arshad Jhumka and Luca Mottola. *On Consistent Neighborhood Views in Wireless Sensor Networks.* In Proceedings of 28th IEEE International Symposium on Reliable Distributed Systems (SRDS), Niagara Falls (NY, US), September 2009. *Best Paper Candidate.*

Abstract: Wireless sensor networks (WSNs) are characterized by localized interactions. Indeed, several WSN algorithms and protocols work in a decentralized fashion by coordinating nodes within the wireless communication range, e.g., localization algorithms and MAC protocols. Nevertheless, most often these mechanisms do not address faults that may affect the way wireless neighborhoods are recognized by nodes, e.g., as in the case of data corruption. As the operation of these mechanisms is rooted in the use of topology information, these faults may be a significant detriment to correct and efficient system operation.
In this paper, we argue that the above issues are particular instances of a general problem of consistent neighborhood view. We present three increasingly weaker specifications of the problem. Next, we prove the impossibility of solving the two stronger specifications, and provide an algorithm to solve the weakest specification. In addition, we implement our algorithm in a commonly used WSN network stack, and assess its performance both in simulation and in a real-world testbed. The results show that, when possible, our mechanisms efficiently solve the problem of consistent neighborhood view, providing higher-level mechanisms with a re-usable building block to leverage off

Attended Seminars, Workshops, and Conferences

- EU Concertation Meeting, Brussels (Belgium), October 2009.
- The 28th IEEE International Symposium on Reliable Distributed Systems (SRDS), Niagara Falls (NY, USA), September 2009.
- The 8th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN/SPOTS), San Francisco (CA, USA), April 2009.
- The 6th European Wireless Sensor Network Conference (EWSN), Cork (Ireland), February 2009.
- The 2nd Wireless Sensing Demonstrator Showcase, London (UK), July 2009

Research Exchange Programme

First period: 1 week at ETH Zurich
Project team: Distributed Systems Group
Scientific contact: Dr. Kay Roemer
E-mail: Kay Roemer <roemer@inf.ethz.ch>

Kay Roemer works on distributed debugging of wireless sensor network, a fundamental topic complementary to my own research on programming abstractions. Networked embedded sensing systems are indeed typically exposed to a hostile and unpredictable environment, often leading to failures despite extensive pre-deployment validation in testbeds. Once deployed, these systems are then hard to debug due to limited access to the deployment site and due to constrained system resources. During my stay at ETH, I looked together with Kay Roemer and his students at the fundamental techniques to debug such systems, and discussed concrete debugging systems that they are working on, along with their possible integration with the programming systems I was developing.

At the beginning of the visit, I gave a 1 hour talk illustrating my past and present research, with particular attention to the real-world deployments I was involved in. About 30 people attended from different departments at ETH. In particular, this has provided useful inputs to the work of Kay Roemer's group, in that they could gain a better understanding of the issues at stake when deploying WSNs in the real world in non-trivial applications

Second period: 1 week at Fraunhofer IAIS
Project team: Networked Embedded Systems Group
Scientific contact: Prof. Pedro Jose Marron
E-mail: Pedro Jose Marron <pjmarron@uni-due.de>

Pedro Jose Marron is a leading figure in the field of cooperating objects, systems at the intersection between sensor networks, pervasive computing, and robotics. Cooperation is defined as the ability of individual entities or objects to use communication as well as dynamic and loose federation to jointly strive to reach a common goal, which will typically be a goal in sensing or control. At the same time, these objects have to take care not to overtax their available resources, which are, in general, very limited. Such scenario includes and extends my work on sensor networks and programming in particular. In this sense, the visit at Fraunhofer IAIS gave me the opportunity to broaden the perspective of my research work, taking into account issues and problems not purely germane to sensor networks but nevertheless of conceptual and practical importance.

After a 1 hour seminar where most of Prof. Marron's group attended (about 20 people), during the stay we scheduled a series of joint meetings with a few of Prof. Marron's students, typically at most 2 or 3 at the time. These were opportunities for me to gain deeper insights into the different projects going on in Prof. Marron's group, as well as for the students to get a glimpse at specific sensor network issues.