Constructing Reliable Architectures for Networked Embedded Systems

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Baseline

In recent years the design of computing systems of all scales and types has been strongly influenced by an ever growing importance of networked connectivity. Today, the majority of systems being designed and built are not any more standalone configurations of a single CPU plus memory/storage but rather ensembles of many such devices often distributed hierarchical and interconnected frequently supporting connectivity on a global scale, i.e. to the internet. While commodity computing systems such as servers and workstations characterized by high average performance requirements are more likely to leverage the advances of parallelization and better performing hardware (Moore's Law) embedded systems pose special design challenges that are further exacerbated in the networked context: Large-scale distribution often with connectivity provided over unreliable network links (wireless) has strong impacts on the predictability and reliability of a system. Resource scarcity, high application complexity and customization demands lead to unsuitable and under provisioned system architectures, a fact that is most likely to be only observed post design phase in real operation. Lastly a new focus on energy as a primary optimization goal on a system level mainly brought about by the myriad of battery powered portable devices is opening up significant opportunities for new paradigms and design methods.

In tackling the specific challenges of networked embedded systems design, especially in the context of reliability, we believe that it is detrimental to excel both in the understanding and developing the foundations as well as involvement in practice and applications. The latter focus on practical aspects necessitates the collaboration with suitable partners across interdisciplinary domains, on a longer timeframe and with a minimum critical mass.

In the following, we will concentrate on the field of wireless sensor networks which is now in a stage where serious applications of societal and economic importance are in reach such as industrial process monitoring and control, environment monitoring, logistics, healthcare applications, home automation, and traffic control. In many of these applications, measurements are precious and must not be lost, reliable data must arrive in real-time, sensors are relatively expensive, and deployment of a sensor network and repair/update are very labor-intensive and expensive. We argue that in order to significantly advance the application domains by using a wireless sensor network as a novel means of observation and interaction, it is inevitable that such a tool be created as a high quality system with known and predictable properties. We will provide a short overview about new models and methods that lead to predictable and efficient networked embedded systems such as formal testing and testing infrastructure, optimized use of harvested solar energy, data cleaning methods, network tomography and sensor calibration. Moreover, we will describe a new design approach that allows designing dependable end-to-end systems, from sensor data acquisition via conversion, local storage, communication to base-station, communication to host system, data-base storage, to final packet filtering and calibration. We will demonstrate their use in extensive, long-term installations of sensor networks in hostile environments for safety-critical applications such as mobile air quality measurements in cities and environmental sensing in permafrost regions.

Power and Energy

One of the major factors in designing highly autonomous and dependable networked systems is the availability of a continuous energy source as well as a low energy operation while still meeting reactivity constraints. For software development, testing is still the primary choice for investigating the correctness of a system. But visual inspection of power traces or reference measurement-based methods are not suitable for the large amount of tests required for analyzing the various properties of software on several hardware platforms or in different test environments. Therefore, it is highly desirable to non-intrusively detect implementation errors within the running system's hard- and software by exploiting power measurements. An example of such a methodology is the formal conformance test between a power trace of a wireless sensor network application running on actual hardware and a specification of the expected behavior of the system, see [WLT09]. Testbed architectures such as FlockLab can be used for observation, see [BLM09].

High autonomy requires the availability of a continuous energy source. In addition to approaches that minimize the power consumption subject to performance constraints, we also need to be concerned with optimizing the performance of an application while respecting the limited and time-varying amount of available power. Based on a prediction of the future available energy, one needs to adapt parameters and operation modes of the application in order to maximize the utility in a long-term perspective, see e.g. [MTB10]. If real-time responsiveness of a give application has to be guaranteed, task scheduling at the single nodes should account for the properties of the energy source, capacity of the energy storage as well as deadlines of the single tasks. In this case, scheduling algorithms need to jointly handle constraints from both energy and time domain, see [MBT07].

But in case of networked embedded system, such a node-centric analysis is not sufficient. Instead, communication as well as in-network processing is an important ingredient to achieve energy efficiency: Reducing the amount of data that has to be communicated, under the typical assumption that computation is by several orders of magnitude cheaper than communication. As a result, a network-wide analysis is necessary taking into account end-to-end timing constraints, see e.g. [SZT07].

WSN System Design

While modeling of systems and precise analysis methods allow to predict prospective system behavior are just choices for early design decisions, measurements are indispensable for the characterization of a system under real operating conditions. To this extent the FlockLab testbed architecture [BLM09], based on a set of co-located powerful observer and target platform, extends the traditional back-channel model of Wireless Sensor Network (WSN) testbeds (c.f. MoteLab, TWIST) by a fully synchronous distributed observation capability that is not limited by a bandwidth bottleneck at a single data collection sink. The device under test, typically a WSN mote is locally augmented by the observer platform which allows remote reprogramming, fine-grained logging, excitation, power control as well as power profiling, see Figure 1. The FlockLab observer is capable of accommodating up to four different hardware architectures for supporting different user requirements. The current testbed at ETH Zurich consists of 30 nodes distributed in- and outdoors around the campus buildings as well as connected to a climate chamber. With this setup realistic operating conditions both on the wireless domain but also concerning the physical influence of the environment can be combined with power full logical data capture.

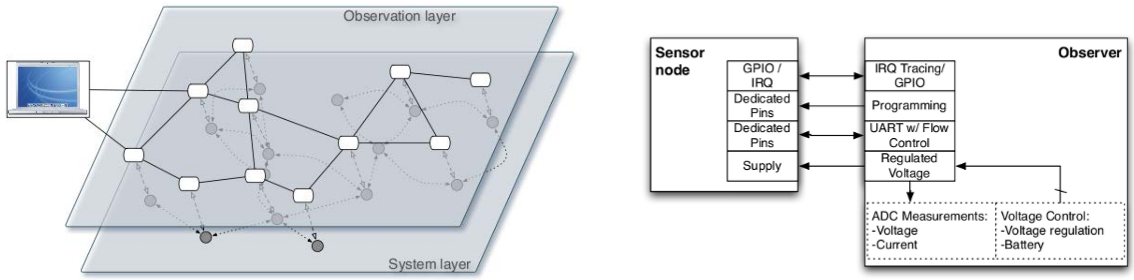

Figure 1: FlockLab system and software architecture.

To expose remote observability of both the environment and the system under real-world conditions, we argue that as a first step feature-rich nodes should be deployed. Such an over-provisioned test-deployment then allows observing, experiment, and learning on-site, see [BBF11]. Not only does this give the possibility to draw from actual deployment experience and clearly, and close to exhaustively, define the design possibilities within the application's requirement specification, but also permits profiling of system performance before the first application specific prototype is even built. Hence, continuous hardware refinement, as is necessary with the conventional approach, can be largely omitted.

To facilitate such an investigative approach, we use an over-provisioned "node", a tried and tested, highly flexible CoreStation, see Figure 1. This platform, together with a user configurable software framework, permits design space exploration of low-power network nodes, specialized high-rate sensors (GPS, Cameras, etc.), or base stations under real-world conditions.

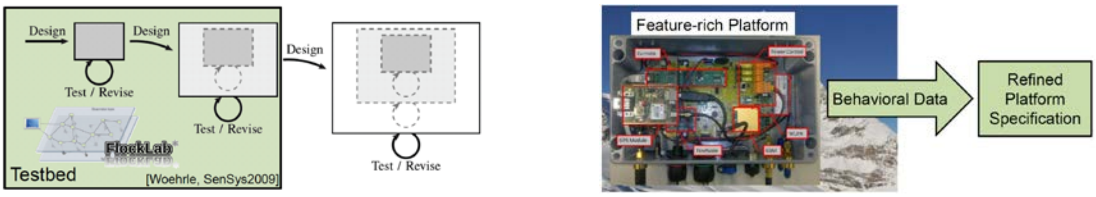

Figure 2: The traditional waterfall (left) uses continuous refinement whereas the design approach using a feature rich CoreStation to derive detailed behavioral requirements from in-situ experimentation for the development of optimized X-Sense wireless GPS sensors.

Predictable and efficient communication is best achieved using TDMA scheduling and synchronous approaches. To this extent we are performing research in synchronous system architectures and protocols. The PermaDAQ sensor node architecture [BGH09] tackles this by a separation of concerns using very coarse grained locally synchronized processes. In contrast, Glossy [FZT11] is a radical approach towards a globally synchronous system architecture at all layers. The underlying network synchronization mechanism is extremely efficient and fast and makes intelligent use of coding schemes and constructive interference which are specific properties of the underlying radio.

Unanticipated and non-obvious at first glance was the fact that over the years it was revealed that the primary data generated in such wireless networked embedded systems is not correct-by-design meaning that there were not only observations on gaps attributed to outages but also significant sequence ordering problems and data duplication, see [KTB11]. Before domain experts can analyze the data, extensive cleaning, conversion, and mapping operations need to take place. The goal of data cleaning is to generate a stream that contains duplicate-free data that are in the correct chronological order of data acquisition and contain information about the acquisition time, e.g. a time interval that provides safe bounds. Additionally, data that does not conform to system specifications is removed, see Figure 3.

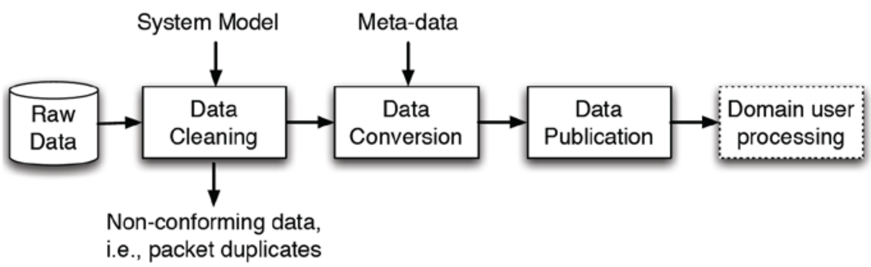

Figure 3: Collected raw data is firstly cleaned by involving a formal model of the data generation and transmission system.

Interdisciplinary Collaborations Application

In order to gain expertise in and a deeper understanding of real application scenarios we have been performing collaborative projects with partners from environmental sciences. Apart from cross-pollinating technology oriented research this has also enabled significant results in the environmental sciences involved which would not have been possible without the use of state-of-the-art wireless sensors.

The PermaSense consortium (http://www.permasense.ch) is a multi-project partnership of research groups from both engineering disciplines and science focusing on long-term environmental monitoring in environmental extremes performing groundbreaking basic research in the context of mountain permafrost, climate change and natural hazards, see [HTB08], [BBF11]. For the past four years we have been designing, deploying and operating wireless sensor networks in high alpine locations such as the Matterhorn/Zermatt and Jungfraujoch/Grindelwald in Switzerland for the purpose of investigating the stability properties of permafrost in steep rock walls as well as large scale mass movements (rock glaciers), see [HGB12], [WGG12]. The systems designed have to endure harsh weather and operate reliably and autonomously without a loss in quality or quantity of the data gathered.

Apart from refinements to the architecture to improve the overall performance this learning lead to a focus on a strand of research that would have not come about without the arduous, long-term operation of ultra-low-power WSNs high up in the glaciated mountains at 3500m above sea level.

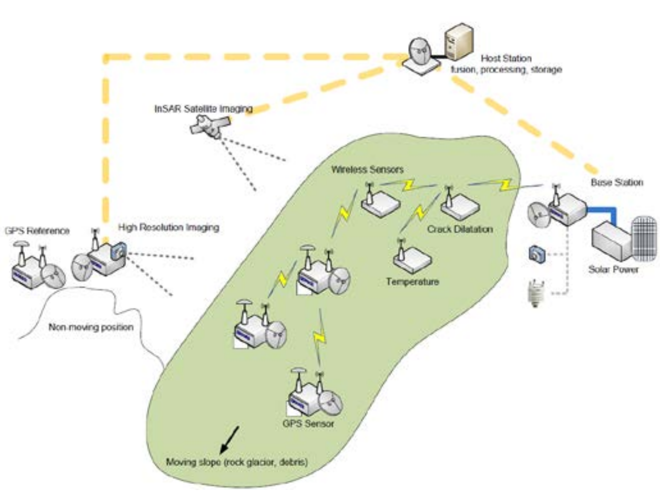

Figure 4: A multitude of sensor types as well as the fusion of information from different time and space scales are used for the detailed analysis of rock terrain movements

A more recent activity is the OpenSense project (http://www.opensense.ethz.ch): The objective here is to make use of mobile sensors mounted on fleets of vehicles to obtain a better coverage of environmental phenomena, such as air quality in cities. By leveraging a fleet of streetcars the spatial and temporal coverage of a city is extended albeit only using very few sensors themselves, see [SHN12]. The challenges here lie in dealing with mobile data and understanding the behavioral components of such data. Calibration must not only be performed during a service period but can be done by cross checking data when two or more mobile sensors meet, e.g. when a streetcar passes a reference air quality monitoring station, see [HST12].

Summary

We have been describing systematic design principles, applicable to networked embedded system development for diverse application scenarios that require highest possible data quality and yield, while maintaining system controllability and observability at lowest possible cost. Our experience stems from developing wireless sensor networks for environmental monitoring under extreme conditions (see http://www.permasense.ch, http://www.opensense.ethz.ch) as well as safety-critical sensor networks for building applications.

Acknowledgements

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Speaker
Lothar Thiele, ETH Zurich

Title
Designing Predictable and Efficient Networked Embedded Systems

Abstract
The area of wireless sensor networks had a huge impact on the research in various fields related to electrical engineering and computer science. Spatially distributed sensor nodes are used as a new kind of measurement instruments to collect physical or environmental data. Much of this work was driven by the early vision of SmartDust. One of the corner stones to achieve the required quality of service in terms of sensing density in time and space was the concept of 'reliability via over-provisioning'. The field of wireless sensor networks is now in a stage where serious applications of societal and economic importance are in reach such as industrial process monitoring and control, environment monitoring, logistics, healthcare applications, home automation, and traffic control. In many of these applications, all measurements are precious and must not be lost, reliable data must arrive in real-time, sensors are relatively expensive, and deployment of a sensor network and repair/update are very labor-intensive and expensive. We argue that in order to significantly advance the application domains by using a wireless sensor network as a novel means of observation and interaction, it is inevitable that such a tool be created as a quality scientific instrument with known and predictable properties. The talk will introduce new models and methods that lead to predictable and efficient networked embedded systems such as formal testing, optimized use of harvested solar energy, data cleaning methods, network tomography and sensor calibration. We will demonstrate their use in extensive, long-term installations of sensor networks in hostile environments for safety-critical applications (mobile air quality measurements in cities and environmental sensing in permafrost regions).

Bio
Lothar Thiele was born in Aachen, Germany on April 7, 1957. He received his Diplom-Ingenieur and Dr.-Ing. degrees in Electrical Engineering from the Technical University of Munich in 1981 and 1985 respectively. After completing his Habilitation thesis from the Institute of Network Theory and Circuit Design of the Technical University Munich, he joined the Information Systems Laboratory at Stanford University in 1987. In 1988, he took up the chair of microelectronics at the Faculty of Engineering, University of Saarland, Saarbrucken, Germany. He joined ETH Zurich, Switzerland, as a full Professor of Computer Engineering, in 1994. He is leading the Computer Engineering and Networks Laboratory of ETH Zurich.

His research interests include models, methods and software tools for the design of embedded systems, embedded software and bioinspired optimization techniques.

Lothar Thiele is associate editor of IEEE Transaction on Industrial Informatics, IEEE Transactions on Evolutionary Computation, Journal of Real-Time Systems, Journal of Signal Processing Systems, Journal of Systems Architecture, and INTEGRATION, the VLSI Journal. In 1986 he received the "Dissertation Award" of the Technical University of Munich, in 1987, the "Outstanding Young Author Award" of the IEEE Circuits and Systems Society, in 1988, the Browder J. Thompson Memorial Award of the IEEE, and in 2000-2001, the "IBM Faculty Partnership Award". In 2004, he joined the German Academy of Sciences Leopoldina. In 2005, he was the recipient of the Honorary Blaise Pascal Chair of University Leiden, The Netherlands. Since 2009 he is a member of the Foundation Board of Hasler Foundation, Switzerland. Since 2010, he is a member of the Academia Europaea. Lothar Thiele holds the position of Head of the Department Information Technology and Electrical Engineering.

Speaker
Jan Beutel, ETH Zurich

Title
A Process Chain for End-to-End Sensing in Disruptive Environments

Abstract
Sensor networks were conceived as a novel tool for distributed sensing, e.g. in environmental sciences. Initially it was thought that inherent imperfections in the data would be "oversampled", however this is only theory (so far). As a single sensing point in space and time is still expensive, many applications require accuracy in absolute terms and users are not flexible (yet) to deal with lossy data types this assumption has to be reconsidered. We argue that the high up-front investments of WSNs require a reliable interaction of all system components and layers and that for the user an exact knowledge of the origin nature of data along with the whole processing chain is key. We will introduce concepts and demonstrate initial solutions in the context of the PermaSense architecture used for high alpine environmental monitoring in the Swiss Alps.

Bio
Jan Beutel received his MSc and PhD in Electrical Engineering from the Swiss Federal Institute of Technology (ETH), Zurich in 2000 and 2005 respectively. He has been with u-blox AG, Zurich and spent time as a visiting researcher at the Berkeley Wireless Research Center with Jan Rabaey. He is currently working with Lothar Thiele heading a research group on networked embedded systems at the Computer Engineering and Networks Lab (TIK), ETH Zurich. Jan's research interests lie in the design, test and validation methodology for wireless networked embedded systems and their applications. He has been lead architect of the BTnode platform and designed the Deployment-Support Network and FlockLab, two popular WSN testbeds. The extensive background and expertise in ultra low-power wireless systems is applied in practice in a number of interdisciplinary collaborations with environmental sciences: PermaSense, a multi-project consortium focusing on long-term environmental monitoring in environmental extremes is performing groundbreaking basic research in the context of mountain permafrost, climate change and natural hazards. He is further involved in leadership in large research clusters such as the National Competence Center on Research in Mobile Information and Communication Systems (NCCR MICS) and nano-tera.ch. On an international level is expertise is frequently sought as a program committee and steering board member of the most prominent conferences such as ACM SenSys, IPSN and DATE. Jan is a member of IEEE and ACM as well as UIAGM certified mountain guide.