ESF/PESC Exploratory Workshop on Wireless Sensor Networks*

Zurich, April 1-2, 2004

— Scientific Report —

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1 Introduction

Recent technological advances allow the construction of so-called sensor nodes – small autonomous devices that combine sensing, computing, and wireless communication capabilities. Networks of these nodes are envisioned to allow monitoring of a wide variety of environmental phenomena with unprecedented quality and scale. Wireless Sensor Networks (WSN) are therefore expected to promote a variety of application domains that inherently depend on such unobtrusive real-world observations.

Making this vision a reality, however, requires substantial and coordinated research in a variety of disciplines, including computer science, microelectronics, communications, MEMS technology, and power engineering. The purpose of the ESF Exploratory Workshop on Wireless Sensor Networks was to bring together European researchers working on wireless sensor networks in order to help form a community and to initiate and promote coordinated research on this multidisciplinary topic within European academia and industry.

2 Executive Summary

The workshop was organized by Friedemann Mattern and Kay Römer and took place on April 1-2, 2004 at ETH Zurich, with 24 people from 11 countries attending the

*Many thanks to the scribes Christian Frank <chfrank@inf.ethz.ch> and Jan Beutel <beutel@tik.ee.ethz.ch> for their contributions to this document.

workshop. While most participants were academic researchers, there were also representatives from industry and from funding agencies.

In the opening session, Friedemann Mattern from ETH Zurich shortly presented the motivation for performing the workshop by summarizing the main expectations and driving technologies. Kay Römer continued with a presentation on the multidisciplinary nature of sensor networks, the need for coordinated research, and an overview of existing research activities across Europe. Louis Laurent, a representative from the European Science Foundation (ESF), then gave an overview on the activities of the ESF. Then everybody was asked to introduce himself briefly.

The remainder of the workshop consisted of 5 presentation sessions (lasting about 6 hours in total) and 3 discussion sessions (lasting about 4 hours in total). Each talk was alloted a time slot of 15 minutes, giving the lecturer an opportunity to present his background, his ongoing and future work, and his opinions in the area of wireless sensor networks without going into details. After one or two presentation sessions, a discussion session on the topics of the preceding presentation sessions was scheduled. For each of the discussion sessions, three participants were asked before the workshop to prepare some statements on the discussion topic.

The first presentation session focused on applications of wireless sensor networks. Werner Weber from Infineon Technologies presented an industrial view on wireless sensor networks and outlined a number of projects related to sensor networks at his lab. Rolf Riemenschneider then outlined activities related to cooperating objects and sensor networks in the 5th and 6th Framework Programme of the European Commission. Ian Marshall presented an ongoing project on the bathymetry of the ocean ground beneath a wind farm using sensor networks. Philippe Bonnet outlined a newly initiated project on monitoring the activity of pigs using sensor networks. Lionel Sacks presented an ongoing project about monitoring social interactions among seals using sensor networks.

The following discussion session on applications tried to identify issues related to the application potential of sensor networks in the European context. Alex Buchmann suggested to map techniques from the military application domain (that largely motivates research in the US) to civil applications. Werner Weber suggested to use existing communication networks such as mobile phone networks for sensor network applications. Ian Marshall emphasized that many wireless sensor networks applications require an additional background computing infrastructure that is connected to the sensor network.

The next presentation session focused on hardware, communication, and energy issues. Christian Enz presented an ongoing project to develop ultra-low power wireless radios for sensor networks. Michele Zorzi reported on current research related to the development of energy efficient MAC layer protocols. Jan Beutel presented a sensor network platform developed at ETH Zurich and talked about issues with the deployment of large-scale sensor networks. Juan Alonso presented a newly founded project on delay-tolerant solutions for sensor networks. Christian Prehofer's talk focused on the issue of re-configuring the node software in a running ad hoc network.

On the second day of the workshop, the first presentation session was devoted to system aspects and software infrastructures. Kurt Rothermel emphasized the need for flexible system software and presented potential approaches for its realization. Jörg

Kaiser presented a hardware platform and an event-based middleware for sensor networks. Kay Römer outlined his work on time synchronization and localization services for sensor networks and sketched ongoing work on software frameworks to support the development of sensor network applications. Stephane Donnay outlined the use of sensor networks for health monitoring and presented ongoing efforts on the construction of hardware and software for such applications.

The following discussion session focused on hardware and software platforms and testbeds, deepening the topics of the two preceding presentation sessions. Jan Beutel raised the question why so few research groups actually evaluate their research with real hardware and whether pure simulation is an appropriate way to evaluate sensor networks. Kurt Rothermel presented possible approaches for the construction of system software for sensor networks. Kay Römer discussed the issue which traditional middleware concepts can be applied to sensor networks.

The presentation session entitled "novel approaches" was opened by Adam Wolisz, who presented a possible service abstraction for sensor networks. Holger Karl discussed the concept of quality of service in the sensor network context. Thomas Fuhrmann's talk considered the possibility of applying results from peer-to-peer networks to sensor networks. Paul Havinga discussed the interaction across different layers in sensor network software.

The subsequent presentation session was devoted to data processing issues. Erdal Cayirci presented ongoing work on making data delivery in sensor networks reliable. Alex Buchmann discussed different abstractions for processing sensory data inside and outside of a sensor network. Petteri Alahuhta gave an overview on projects related to sensor networks in his institution.

The final discussion session on research challenges was initiated with a presentation by Holger Karl, Philippe Bonnet, and Juan Alonso. They suggested that the assumptions of current and future research should be better verified, that the sensor network design space should be made explicit and checked against the application space, and that researchers should focus on a few hardware platforms that cover the design space.

Besides the presentation sessions and discussion sessions, the workshop offered many opportunities to get to know and talk to each other personally and to establish contacts for possible future cooperations during four half-hour breaks, during two lunches in the Dozentenfoyer on top of ETH with a great view on the Alps, and during the workshop dinner in a fine restaurant in downtown Zurich.

3 Scientific Contents

Presentations and discussions at the workshop mainly covered the following five areas: *European coordination*, *applications*, *hardware platforms*, *software architectures and middleware*, and *communication aspects*. In the following sections we summarize the talks and discussions on these topics. Slides of the presentations can be found on the workshop home page at `www.vs.inf.ethz.ch/events/esf-wsn04`.

3.1 European Coordination

Friedemann Mattern: The motivation of the workshop - fostering a European community on sensor network research.

Recently, one could observe a number of activities that contribute to the formation of sensor networks as an independent research area. Among other things, dedicated workshops and conferences have been established and a new journal, the ACM Transactions on Sensor Networks, has been initiated. Interestingly, however, in the editorial board of this journal Europeans are almost completely non-existent. Also, of the 55 papers presented at three newly created workshops devoted to wireless sensor networks (WSNA 2002, IPSN 2003, SNPA 2003), only 4 had European (co)authors, whereas 48 papers were authored by US-based researchers.

Why is this the case? And what would be the consequences if Europe remains abstinent and absent from such an important area? Hence the purpose of this workshop: to identify the state of the art as well as the relevant European research groups, to help forming a European community on sensor network research, and to initiate and promote loosely coordinated research within European academia and industry.

Kay Römer: European research on sensor networks.

Sensor networks are a multidisciplinary area of research, involving areas such as computer science, microelectronics, communications, material sciences, MEMS technology, power engineering, and social implications. Hence, cooperation among the disciplines and coordinated research are essential for successful research in this domain. In this talk, Kay Römer gave a brief overview of existing local, national, and European research projects on sensor networks.

Louis Laurent: ESF presentation.

This talk presented the key characteristics of the European Science Foundation. The main aim of ESF is to contribute to the European science development by bringing together leading scientists and funding agencies as well as more strategic activities like forward looks. The ESF represents 76 research institutions from 29 countries and is oriented towards multidisciplinarity (organized around five standing committees). The emphasis of the talk has been put on the Physical and Engineering Committee and the instruments implemented to foster European networking activity (EURESCO conferences and exploratory workshops, research programs, and EUROCORES).

Rolf Riemenschneider: Sensor networks in the ambient intelligence environment - perspectives in the IST Framework Programme.

The 6th Framework Programme (FP6) of the European Commission sets out the priorities for the EU's research, technological development and demonstration (RTD) activities for the period 2002-2006, where IST thematic priority plays a vital role. The focus of Information Society Technologies (IST) in FP6 is the vision of 'Ambient Intelligence' - future generations of technologies in which computers and networks will be integrated into the everyday environment.

The focus in Embedded Systems will be on systems of cooperating objects which

are defined as platforms that can "glue" together diverse (physical) objects to enable seamless environments for computing, communication, and service delivery. Wireless sensor networks are considered to be an essential subset of these systems.

The talk summarized on-going research work in FP5 and FP6 in the area of cooperating objects and wireless sensor networks, respectively. Special attention was be placed on preparing the future work program 2005/2006, and encouraging the constituency to actively take part in that process involving a Web-based consultation process that will end in May 2004.

During discussions it was observed that European sensor network research is still in its infancy when compared to the US. This is evidenced by US domination of a number of workshops and conferences on the topic. In order to catch up with the US, the general impression was that one should not just follow the US agenda, but focus on the specific European needs and strengths. For example, European industries such as building management, mobile communications, and system constructions could drive sensor network research.

Some possible concrete actions were discussed, such as the development of an open source operating system for sensor networks, the harmonization of existing sensor network platforms, and the definition of a set of common services needed by sensor network applications.

Overall, the participants found the workshop a good opportunity to get to know each other and develop a first impression of the existing competence in sensor networks across Europe. It was suggested to establish regular informal meetings similar to this event, where early ideas can be presented and discussed. Such events should, in the future, also attract PhD students and potential users of sensor networks.

The general impression was that European research on sensor networks is still at its beginnings and further coordination actions are needed to form a European community on the topic.

3.2 Applications

Werner Weber: An industrial viewpoint on wireless sensor networks.

Sensor networks are seen as part of the current trend towards disappearing tiny electronic devices that may unobtrusively assist in everyday-life tasks. While the technology is fascinating, an industry perspective focusing on market success must follow several crucial criteria: one must concentrate on providing valuable services with significant benefits for the customer, which is not as easy as imagined. This involves an excellent man-machine interface which is deemed critical for success. In this context, especially if chip development is involved, one must always ensure that the accessible revenue volume is above a certain minimum. The presentation also emphasized that present reluctance to adopt new technology and fear of technology must be seriously considered to be successful on the market.

Three projects presently conducted at Infineon were discussed: ubiquitous sensor networks for home/office control applications; RFID tags (wireless network with pronounced hierarchy between central terminal and the peripheral devices) for

logistics applications; and Smart Textiles (a wired sensor network) for security and guiding functions.

Ian Marshall: Sensor networks for environmental applications.

This talk gave an overview of the Self-Organizing Collegiate Sensor Network (SECOAS) project. As part of this project, a sensor network is deployed around a wind farm off the coast of England in order to monitor the influence of the wind turbines on the ocean ground.

Philippe Bonnet: The Hogthrob project.

The Hogthrob project is a cooperation between the computer science department of University of Copenhagen, DTU, KVL, IO Technologies, and the Danish committee for pig production. Its goal is to develop a sensor network infrastructure for pig production. The project is funded by the Danish research agency from 2004 until 2007. The objectives, the rationale for the approach, and some first results were addressed in the talk.

Lionel Sacks: Sensor networks for social interaction discovery at land and sea.

The talk presented an approach to constructing distributed algorithms for sensor network applications. These algorithms are currently being developed for deployment in the SECOAS project (see talk of I. Marshall) to provide functionality for node clustering, policy management / control, location sensing, and data selection. Some of these approaches are being developed further for applications to measuring the social life of animals. The presentation gave an introduction to this problem space.

Juan Alonso: Delay tolerant solutions for wireless sensor networks.

Juan Alonso presented the project "DTN/SN: delay tolerant solutions for sensor networks", briefly describing the goals of the project and its industrial partners.

Then he explained a theoretical bound on the energy consumption of routing, presenting a formula that bounds the energy consumption of the best and worst route, in terms of the number of nodes one hop away from the base node(s).

Petteri Alahuhta: Mobile user and data processing in wireless sensor networks.

VTT is exploring a wide range of applications utilizing wireless sensors and networks thereof. Application domains currently under most intensive research are everyday living environments and health care. There are application demonstrators utilizing wireless sensors in context-awareness, user interaction, indoor localization, and sleep disorder monitoring system. Wireless sensing technology is mainly based on the SoapBox platform, developed at VTT starting in 2000.

VTT's approach is moving from single sensors towards networks of sensors used in various applications. A trend towards increasing use of mobile technology and increasing number mobile services in various application domains leads us to a situation where new solutions are needed to help the user of mobile applications to handle the amount of content and service supply. The use of context-information is

a key to handle the foreseen need. New methods are needed for producing required and reliable context-information - wireless sensor networks around us are one of the sources of required information.

During discussions it was noted that US-based research on wireless sensor networks is mainly driven by military applications. This application domain does not only include a wide variety of challenging problems (e.g., target tracking and localization, detection of toxic chemicals, rescue, homeland security), but has also defined the common view of a wireless sensor network as a large-scale, multi-hop ad hoc network of tiny resource and energy-constrained sensor nodes. In addition, the cost involved in using a sensor network for military applications is of less importance if the technology can provide a strategic advantage in warfare.

Since military research is both of less importance and acceptance in Europe, one should find a regime of wireless sensor network applications of particular importance for Europe which can drive European research on sensor networks. In this context it was suggested to map military applications to the civilian domain (e.g., using vital sign monitoring for elderly care, using material flow monitoring for logistics applications, using tracking for building security and disease control). However, this mapping is not trivial: sensor networks for these applications may have different properties (e.g., smaller scale, heterogeneous hardware , single-hop networks), and it is typically hard to convince potential users of these applications to invest money in research (at least when compared to the military funding).

There was quite a lengthy discussion about typical WSN structures and architectures that are adequate for envisaged applications in the civilian context. Representatives from industry suggested to focus on single-hop networks, potentially using existing infrastructures (e.g., the GSM network) and existing devices (e.g., cell phones augmented with sensors). Potential wide-scale civilian applications were envisioned for disaster relief and rescue operations: a WSN providing vital sign monitoring and positioning could provide critical data for rescue in an earthquake scenario, for example. It was also hinted that in some envisioned civilian applications sensor network applications rarely consist of a sensor network alone, but are integrated into larger computing infrastructures. In the case of privately owned networks, parts of these infrastructures are provided by a variety of microeconomic actors spanning a heterogeneous value chain (from WSN operation over subsequent data processing, to data consumers providing high level services).

It was also suggested to take a more systematic approach to explore the sensor network design space and corresponding applications by identifying the dimensions of the design space (e.g., node mobility, node heterogeneity, network topology, network size).

Other applications that were discussed during the workshop are:

- Detect submerged targets in a harbor / ocean environment
- Detect chemical or biological attacks
- Detect forest fires

- Smart farming and irrigation
- Space exploration
- Monitoring dangerous plants
- Tracking dangerous goods
- Monitoring social behavior of animals in farms and natural habitats
- Bathymetry of ocean ground
- Monitoring salinity of water
- Monitoring cracks in bridges
- Pacemakers for heart and brain
- Camera-equipped pills for health diagnostics
- Epilepsy monitoring and suppression

3.3 Hardware Platforms

Christian Enz: Ultra low-power radios for sensor networks - the WiseNET project.

WiseNET offers an ultra low-power platform for the implementation of wireless sensor networks. This low-power operation is achieved thanks to a careful co-design approach of a new medium access control (MAC) protocol called WiseMAC and a dedicated duty-cycled radio. WiseMAC is based on CSMA with an adaptive preamble sampling. It is particularly well suited to ad hoc and hybrid infrastructure networks. The WiseNET radio offers dual-band operation (434 MHz and 868 MHz) and runs from a single 1.5 V battery. It consumes only 2 mW in receive mode with a sensitivity smaller than -105 dBm at a BER of 1E-3 and for a 25 kb/s data rate. In addition to this low-power radio, the WiseNET system-on-chip (SoC) also includes all the functions required for data acquisition, processing, and storage of the information provided by the sensor. The WiseNET solution consumes about 100 times less power than comparable solutions available today.

Jan Beutel: Scaling it up - networking using the BTnode platform.

Deploying wireless ad hoc networking on real devices poses problems beyond the scope of common simulation environments. Apart from system design and implementation issues, really scaling it up to the vast amounts of heterogeneous nodes foreseen for wireless sensor networks by technology forecasters and researchers alike is by large an untouched domain. In this talk we describe our work on the BTnode platform from a networking perspective. Tools and mechanisms that have been used in the past to bring the tethered-up network from the developers desk out into the wide space of open deployment are detailed. We look into the future and at the challenges ahead for a world of a myriad of self-configuring, self-healing and infrastructure-less wireless sensor networks. Two key areas for future work are identified due to the lack of a

coordinated design approach for wireless sensor networks: models and methods for the design of WSN's and coordinated deployment of WSN devices and applications.

Stephane Donnay: Wireless body-area networks (WBAN) for health monitoring applications.

If we want to keep the rising cost of healthcare under control, new low-cost technologies have to be developed to better address disease prevention and detection, which at the same time can also dramatically improve the quality of life. This can be achieved with a wireless body area network (WBAN) consisting of a set of autonomous wireless sensors spread over the human body, e.g., integrated in clothing, or even implanted inside the human body with ultra low power requirements. These sensors can measure physical (e.g., ECG, blood pressure), chemical (e.g., pH, toxins) and biological (e.g., glucose, protein) properties of the body.

Ultra low-power radios are a crucial component of the sensor nodes in a wireless body area network (WBAN) for health applications. The ultra low-power radio allows the sensors to communicate with each other or with a master such as an advanced version of today's PDA which can temporarily store the data from the sensors, perform a first data analysis, provide immediate feedback to the user, or interface with standard telecommunication means and PCs to consult a physician, to offload data, or to make an emergency call. The presentation gave an overview on different technological and research challenges that need to be addressed for the development of these body area sensor networks.

In the associated discussion sessions it was noted that five different groups participating in the workshop are or were involved in the construction of sensor node hardware. The question was raised whether one should avoid duplicating work and instead focus on the development of a few widely applicable platforms that are made available to the European community. On the other hand it was noted that significant experience can be gained by the construction of such a platform and that prototyping hardware is an adequate element in early-stage research. Also, constructing a general platform and providing it in large numbers to interested researchers and users induces a much larger overhead than constructing a specialized sensor node for internal use.

Another observation was that very few research groups actually build running systems in order to evaluate their research, and that the barrier to cross from a simulated to a real system seems to be rather high. This was in part attributed to missing development and debugging tools. In this context it was questioned whether pure simulation is a good approach to research evaluation, since it is hard to capture the influence of the real world (e.g., sensor input, radio propagation, environmental sources of errors) in sensor network simulations. While simulation was deemed a necessary tool for addressing the variety of sensor network application scenarios, verification and validation are very necessary and often missing.

Due to the novelty of the area it was argued that it is quite a challenge both in research and also in teaching to develop appropriate models and methodologies to design WSN systems and applications in a concise and coordinated way. It was felt that future research in the area should concentrate on bringing together knowhow from the

relevant areas involved and to apply their specific knowledge to this new domain.

3.4 Software Architectures and Middleware

Christian Prehofer: Reconfiguration in ad hoc networks.

Christian Prehofer considered coordinated operations in ad hoc networks. A specific problem is to reconfigure synchronously a group of mobile nodes in ad hoc networks without central control. The reconfiguration can enhance or update software on all communication layers, which means that communication during reconfigurations may not be possible. Furthermore, Christian Prehofer considered the dynamic nature of ad hoc networks, where nodes can join or leave at any time. A novel, timeout-based algorithm for synchronous reconfigurations for a group of terminals was proposed for these requirements. The algorithm achieves some basic consistency properties, where connected groups have the same configuration afterwards (old or new). The correctness of the algorithm was discussed and variations depending on failure assumptions were presented. Several applications for reconfigurations in ad hoc networks were also discussed.

Kurt Rothermel: System aspects in sensor networks.

Research in system platforms is essential for the development of sensor networks. Today, it is not clear what kind of programming abstractions those platforms should provide to ease application development. In the literature we find proposals ranging from SQL-like database abstractions to very generic communication and event management mechanisms. Also the architecture of those systems is an open question. In particular, cross-layer issues and the severe resource limitations of sensor nodes need reconsideration of traditional architectures. Finally, the algorithms and protocols very much depend on the application, its QoS requirements and the parameters of the underlying system, such as node mobility, node density, available bandwidth, and so forth. Those dimensions span a design space which is only partially understood today.

In the talk, Kurt Rothermel started out with two sensor network applications and compared them with regard to their required abstractions and their QoS requirements. In particular, various design alternatives for the aggregation performed in these two applications were discussed. Based on this requirements for a system platform for sensor networks were derived and an "algorithmic tool box" for the configuration of tailored protocol stacks was sketched. Finally, a list of fundamental open questions was presented.

Jörg Kaiser: Towards an experimental infrastructure for smart wireless sensors.

The talk gave a survey over concepts and problems of a wireless sensor network currently built up by the CORE (COoperative Real-timE) group at the University of Ulm. It is assumed that a sensor network is composed from heterogeneous nodes with different sensor capabilities, computational performance, and power requirements. There may also be mobile nodes and actuators which communicate with the sensor network. The research focuses on:

1. Adequate communication abstractions for such networks. It is seen that in gen-

eral sensor networks form an open environment in which new sensors of different types may be integrated and in which they have to communicate with previously unknown nodes. The same is true when mobile nodes dynamically form part of a sensor network or exploit the available information. An event-based approach where messages are spontaneously disseminated in a publish/subscribe scheme is investigated . They are routed according to their contents rather than by addresses. Dissemination constraints are enforced by filtering mechanisms.

2. In an open sensor network one may wish to know which kind of sensors are available. Therefore, Jörg Kaiser works on schemes to describe the information which a sensor provides. The goal is to have self-describing components which allow the dynamic use of information. The description has to be represented in a very compact format to meet the storage and bandwidth constraints in sensor networks.

3. On the network level, the timely dissemination of events in a sensor network is investigated. Jörg Kaiser works on a MAC layer protocol for a low power wireless radio link which strives for predictability for event dissemination and explores a slot-based protocol which aims at collision avoidance and includes mechanisms to establish a priority order between messages.

4. As a hardware basis and a test environment for networks of smart sensors, Jörg Kaiser designed the TINY-board which is equipped with a Motorola single chip 68HC908AZ60 micro-controller and a radio link. A spectrum of sensors and actuators is available which can be plugged to the basic TINY-board. Jörg Kaiser implemented a publish/subscribe middleware and the MAC layer protocol on this board and is starting experimental evaluation.

Kay Römer: Software infrastructures for sensor networks.

This talk gave a brief overview on work on software infrastructures that support the development of sensor network applications. Approaches to two fundamental services in sensor networks were presented: time synchronization and sensor node localization. With the lighthouse location system, tiny sensor nodes known as "Smart Dust" can autonomously derive their location solely by observing laser light patterns emitted by a modified base station device. With timestamp synchronization, sensor node clocks need not be synchronized. Instead, timestamps contained in messages are transformed between the local time scales of sensor nodes on demand with little overhead. Moreover, a brief overview on current work on a framework for role-based self-organization of sensor networks, and on a framework for target classification was given.

Adam Wolisz: Towards a service definition for wireless sensor networks.

Adam Wolisz proposed a set of services and interface primitives to be offered to an application programmer of an ad-hoc wireless sensor network (AWSN). As the definition of sockets has made the use of communication services in the Internet independent of the underlying protocol stack, communication medium and even operating system, the proposed application interface, called the "sensor network services platform" (SNSP) identifies an abstraction that is offered to any sensor network application and supported by any sensor network platform. The SNSP builds on the query/command

paradigm already used in several sensor network implementations and further adds time synchronization, location, and naming services that support the communication and coordination among application components. A key position in the concept is assigned to an innovative Concept Repository Service. In addition, usage of the query/command paradigm to support management of the network was explained. This talk is based on a work conducted jointly with researchers from the Berkeley Wireless Research Center (BWRC). More details may be found in a white paper available from `bwrc.eecs.berkeley.edu/Research/Pico_Radio/Default.htm`

Thomas Fuhrmann: Applying peer-to-peer mechanisms to sensor networks: opportunities and threats.

Peer-to-peer systems establish overlay-networks, i.e., virtual networks on top of an existing communication infrastructure. Typical examples in the Internet are Gnutella, an unstructured file-sharing system, and Chord, a structured look-up system based on the idea of distributed hash tables. Besides these popular examples, many other implementations or proposals exist. Most of these solutions address problems in a wired network world. But since the key feature of peer-to-peer systems is the ability to create fully decentralized systems that do not require any central components, peer-to-peer mechanisms are an interesting opportunity for sensor networks.

Unlike in the wired world, here the quality of the matching between the topology of the overlay network and that of the underlying physical connectivity structure is of great importance. If not matched properly, the resulting excess traffic may pose a significant threat to the performance and life span of sensor nodes. The study of protocols that respect the specific needs of sensor networks has just begun. First results indicate that there might be a great potential for improvement.

Holger Karl: Quality of service in wireless sensor networks: mechanisms for a new concept?

While a lot of protocol design has happened for wireless sensor networks, some of the principal operational characteristics of this new type of network are still only poorly understood. One example for such a characteristic is the way how to define "quality" of the service that such a network renders, and how such a network can provide quality, what are the ways quality behaves over the lifetime of a network, and what fundamental bounds are.

The definition of quality of service of a WSN requires first a definition of service. While this is a lengthy discussion in its own right, here the simple provisioning of information and the taking of decisions is regarded as service. For such a service definition, the traditional quality of service attributes like "throughput" or "jitter" are evidently inappropriate. The talk suggested an integrated treatment of the accuracy of provided information, its precision (the probability with which a given accuracy is actually reached), the required energy, the resulting network lifetime, the delay, and the financial costs of a network deployment. Actually computing concrete relations between these attributes might prove to be too challenging a task, but characterizing principal behavioral characteristics - for example the existence of phase transitions - might be an achievable research goal with great practical consequences.

Alex Buchmann: Data aggregation and storage in sensor networks.

Sensor networks are eminently data centric. The entities handled by a (wireless) sensor network may be seen as data tuples or as events that are detected with data bound to them. Three major ways of performing aggregation in sensor networks have been reported in the literature: Firstly, diffusion algorithms assume that data is transmitted from one node in the sensor network to the next, thus percolating through the network to the destination. Along the way data may be aggregated, mostly with simple aggregation functions and assuming homogeneous data. Secondly, streaming queries are based mostly on SQL extensions for continuous querying. Here data is considered to be transient while the query is persistent. Streaming queries perform tuple aggregation with windowing relational operators. Thirdly, event graphs work on streams of events and compose simple events into composite events based on an event algebra. The event algebras from reactive middleware have been extended with temporal constraints for event correlation and transmission probabilities for sensor networks. Events are consumed according to event consumption modes that dictate whether events are consumed in chronological order, the most recent events, or in a windowing mode.

The key issues that must be dealt with when aggregating data/events in sensor networks are the location where aggregation is performed, how to deal with state and/or persistence, how to deal with time in distributed and unreliable environments, how to deal with asynchrony and unstable communication, and how to deal with redundancy and failed sensors.

These issues are not orthogonal. Wherever aggregation takes place, state must be maintained. The kind of aggregation will determine the size of the required storage and the required reliability and recoverability. In essence, different aggregation mechanisms require different resources and will, therefore, influence the routing strategy. Decisions must be made as to whether query processing is to be performed at sensor nodes or only at designated, resource rich nodes, placing simple filters at peripheral sensing nodes.

During the discussion session it was noted that software infrastructures and middleware were a key to the success to traditional distributed systems, since they substantially support the development of distributed applications. Similarly, the success of sensor networks may depend on the availability of appropriate distributed programming abstractions, software infrastructures, and middleware. Hence, this might be one important topic for future European research.

However, it was noted that traditional middleware approaches may not be appropriate for sensor networks. Limited resources of sensor nodes may preclude heavy-weight middleware and abstractions layers, the structure of the sensor network may be highly application-dependent (e.g., single-hop vs. multi-hop, heterogeneous vs. homogeneous nodes), many services are not independent of the application semantics (e.g., application-specific data processing combined with data routing), parameters like node location cannot be made fully transparent to the application.

Some potential mechanisms for system software were proposed, such as an extensible and modular minimal core. Based on the concrete application requirements and

platform characteristics, appropriate algorithms and protocols may be plugged into this minimal core. Some fundamental issues are the provision of appropriate programming abstractions, transparencies, QoS concepts, and adaptation mechanisms. The question was raised whether such fundamental services that are commonly required (and their interfaces) will be able to address a large portion of the application space or whether each WSN application will provide application specific implementations as it has been done in the past.

3.5 Communication Aspects

Michele Zorzi: On issues involving MAC and energy efficiency in sensor networks.

In this talk some issues related to the communications and networking layers in a sensor network were addressed. In particular, it was discussed how traditional communication theory approaches may lead to suboptimal designs of error control schemes. A new integrated MAC/routing scheme, designed to work in the presence of uncoordinated sleeping nodes was also proposed, which greatly reduces the energy consumption of the network.

Paul Havinga: Cross layer interaction in wireless sensor networks.

Recent research projects on WSN address several common challenges: energy efficiency, heterogeneity and diversity in hardware, protocols, and applications, the dynamics of the environment, competition for resources such as the network and available energy, and the required level of abstraction due to the heterogeneous sources of information.

The lessons learned in developing protocols for WSN that address these major challenges show that using the traditional layered approach has significant drawbacks in the resulting performance and efficiency. In his current work Paul Havinga addresses cross-layer interaction, in which he follows an information-centric approach, where the available information determines the protocols and services to use, based on a match between available resources, capabilities, and information.

Erdal Cayirci: End-to-end reliability and data querying in wireless sensor networks.

Wireless sensor networks are based on the collaborative effort of a large number of sensor nodes. The ultimate goal of a sensor network is the detection of specified events of interest in a sensor field. Since the detection range of sensor nodes often overlaps, the same event is usually reported by multiple sensor nodes. However, the sheer number of sensor nodes, the environmental characteristics of sensor fields and power limitation of the nodes may pose frequent unexpected loss of data packets. In some cases, all packets that report the same event may be lost. Therefore, an event may completely be lost although it is reported by multiple sensor nodes. To overcome this problem, new end-to-end event transfer schemes that fit the characteristics of sensor networks are needed.

Erdal Cayirci categorized end-to-end reliable event transfer schemes into two groups: Non-Acknowledgment (NoACK) Based Schemes and Acknowledgment (ACK) Based Schemes. In NoACK based schemes, two methods, namely event reporting

frequency and node density based schemes were discussed. For the second group, we present three new approaches, which are selective acknowledgment, enforced acknowledgment, and blanket acknowledgment. In these schemes, an acknowledgment mechanism is triggered only when an event is detected, so unnecessary acknowledgment traffic and thus energy expenditure are precluded.

During the discussions accompanying the talks, it was argued that the common view of a sensor network as a large-scale, multi-hop ad hoc network may not be appropriate for many real-world applications. One reason for this is the communication overhead for configuring the network into an operational state. Also, the use of existing infrastructures like the GSM network may perhaps be a viable alternative for many applications.

4 Results and Contributions

The workshop was a first initiative to bring together people across Europe working in the multidisciplinary area of wireless sensor networks. The workshop enabled the participants to get an overview of existing research activities in Europe and to establish contacts with other participants. But the workshop also made clear that further coordination actions are needed in order to form a strong European sensor network community that can keep up with the pace of research currently done in the US.

The participants appreciated the value of bringing European sensor-network researchers together and expressed interest in regular future meetings inspired by this event. The wish for similar events to include more industrial participants, potential users of sensor networks, and PhD students was expressed.

The workshop highlighted four important subtopics within wireless sensor networks: applications, hardware platforms, communication aspects, and software issues. A number of possible research directions with respect to these topics were identified:

- Define the sensor network design space by identifying its dimensions (e.g., heterogeneity, mobility, network topology, available resources/energy).
- Fill the design space with applications and identify regions in the design space that are worth further investigation.
- Develop hardware and software that covers the identified regions in the design space. Avoid overlaps and duplicate work, as it was observed that many groups build similar sensor node hardware.
- Create reusable components that cover the design space. In this context, establish service definitions and interfaces that allow interchangeability and transparency, inspired by traditional middleware.

Some possible approaches for identifying promising sensor network applications were also discussed:

- Map elements of military applications to the civilian context, e.g., using vital sign monitoring for triage in disaster situations, using material flow monitoring for logistics applications, using tracking for building security and disease control.

- It is important to make a business case for typical applications. Inspect the potential value chain for sensory data and identify possible markets for services dealing with sensor network data provision and analysis.
- Keep close contact to industrial sensor network users and aim research at industry needs. Exploit strengths of European industry, such as building automation.

5 Final Workshop Program

Thursday, April 1

10:00	**Coffee and Registration**
11:15	**Workshop Opening** Welcome, goals of the workshop, short introduction of participants. Friedemann Mattern: Workshop opening. Kay Römer: Wireless sensor network research in Europe. Louis Laurent: ESF presentation.
11:45	**Session "Applications"** Werner Weber: An industrial viewpoint on wireless sensor networks. Rolf Riemenschneider: Sensor networks in the ambient intelligence environment - perspectives in the IST Framework Programme. Ian Marshall: Sensor networks for environmental applications. Philippe Bonnet: The Hogthrob project. Lionel Sacks: Sensor networks for social interaction discovery at land and see.
13:00	**Lunch at the Dozentenfoyer**
14:30	**Discussion "Applications"** What could be driving applications for European research on sensor networks? Can we identify areas of particular relevance for Europe? How can European industry profit from sensor networks? Moderators: Alex Buchmann, Ian Marshall, Werner Weber.
16:00	**Break**
16:30	**Session "Hardware, Communication, Energy"** Christian Enz: Ultra-low power radios for sensor networks - the WiseNET project. Michele Zorzi: On issues involving MAC and energy efficiency in sensor networks. Jan Beutel: Scaling it up - networking using the BTnode platform. Juan Alonso: Delay tolerant solutions for wireless sensor networks. Christian Prehofer: Reconfiguration in ad hoc networks.
20:00	**Dinner at the restaurant "Zum Grünen Glas"**

Friday, April 2

8:30	**Session "System Aspects and Software Architectures"** Kurt Rothermel: System aspects in sensor networks. Jörg Kaiser: Towards an experimental infrastructure for smart wireless sensors. Kay Römer: Software infrastructures and middleware for sensor networks. Stephane Donnay: Wireless body-area networks (WBAN) for health monitoring applications.
9:45	**Break**
10:15	**Discussion "Hardware and Software Platforms and Testbeds"** What are requirements on hardware and software platforms and testbeds? Is there a potential for European sensor network platforms and testbeds? Moderators: Jan Beutel, Kay Römer, Kurt Rothermel.
11:15	**Break**
11:45	**Session "Novel Approaches"** Adam Wolisz: Towards a service definition for wireless sensor networks. Holger Karl: Quality of service in wireless sensor networks: mechanisms for a new concept? Thomas Fuhrmann: Applying peer-to-peer mechanisms to sensor networks: opportunities and threats. Paul Havinga: Cross layer interaction in wireless sensor networks.
13:00	**Lunch at the Dozentenfoyer**
14:30	**Session "Data Processing"** Erdal Cayirci: End-to-end reliability and data querying in wireless sensor networks. Alex Buchmann: Data aggregation and storage in sensor networks. Petteri Alahuhta: Mobile user and data processing in wireless sensor networks.
15:15	**Discussion "Research Challenges"** Discuss research in existing European research projects. What potential is there for future coordinated research in Europe? Identify interested parties. Moderators: Juan Alonso, Philippe Bonnet, Holger Karl.
16:30	**Concluding Remarks**

6 Final List of Participants

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7 Statistical Information

7.1 Country of Origin

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Italy: 1
Sweden: 1
Switzerland: 5
The Netherlands: 1
Turkey: 1
UK: 2

7.2 Age Structure

Young researchers: 8
Senior researchers: 16