Efficient and Light-weight Wireless Sensor Network Communications

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Abstract— **The efficiency and embedability of communications for wireless sensor networks is an extremely important topic, which will have a huge effect on the commercial success of the technology. The FP6 e-SENSE project aims at providing outstanding architectural and communication solutions especially for convergent sensor networks, i.e., sensor networks connected to the beyond 3G infrastructure. Use cases of the technology include lifestyle management, wireless healthcare, and asset management. The project is truly cross-layer, and provides optimised solutions from the physical layer up to distributed middleware and gateway solutions. Rather than introducing proprietary solutions, e-SENSE will provide reconfigurable protocol solutions and highly optimised improvements for IEEE 802.15.4 evolution standards. In this article we look at the goals of the project from the sensor network communication point of view.**

I. Introduction

The first IEEE 802.15.4 [1] compliant chips have hit the market during 2005, and system-on-a-chip (SoC) solutions in 2006. There are however many improvements in performance and power consumption to be gained. The e-SENSE project aims at radio SoC solutions with a tenth of the power consumption of current commercial chips. Both the 2.4 GHz 802.15.4 and the upcoming ultra wideband 802.15.4a [2] solutions are under optimisation. The optimisation of RF sensing, such as localisation information, is also an active goal of the project.

A new reconfigurable protocol stack concept is also being introduced by the project, called the e-Stack. Instead of using a strict OSI layering approach, the specialised applications of sensor networks allow for more optimised cross-layer solutions. In e-SENSE communication functionality is generalised into simpler protocol elements, which can be strung together into protocol stack instances. From the logical point of view it allows for many different cross-layer protocol stacks, each for a different use-case or role. From the implementation point of view the e-Stack allows for the efficient sharing of resources between protocol elements, and flexible compile- and run-time reconfiguration. The e-Stack can scale from the simplest SoC sensors up to B3G gateway solutions and it is illustrated in Figure 1.

Many different communication scenarios are being considered, including body sensor networks, object sensor networks and environment sensor networks. Along with project use-cases, a large range of requirements and performance metrics guide the research. Interesting research subjects include cross-layer routing/MAC solutions; rapid access improvements for 802.15.4; novel self-configuration and topology control solutions; inter-network interference and synchronisation issues; and efficient routing. The overall goal is to optimise the key metrics of any use-case scenario, while providing flexibility and context to the upper layers

The rest of the paper is organised as follows. Section II describes the e-SENSE project research on energy efficient air interfaces for wireless sensor networks (WSNs) including adaptation of existing air interfaces, complete physical layer (PHY) modelling, optimisation for ultra low power on architectural and integrated circuit (IC) level, and RF sensing. Subsequently, in Section III the related communication protocols between the link and application layer are considered. The topic also includes research areas such as self organisation and topology control, application dependent quality of service (QoS) issues, and mobility support and exploitation. Section IV of the paper describes the e-SENSE research topics related to cross-optimised designs of wireless sensor systems which will be first simulated and later demonstrated as a proof of concept platform in hardware. Finally, Section V concludes the paper.

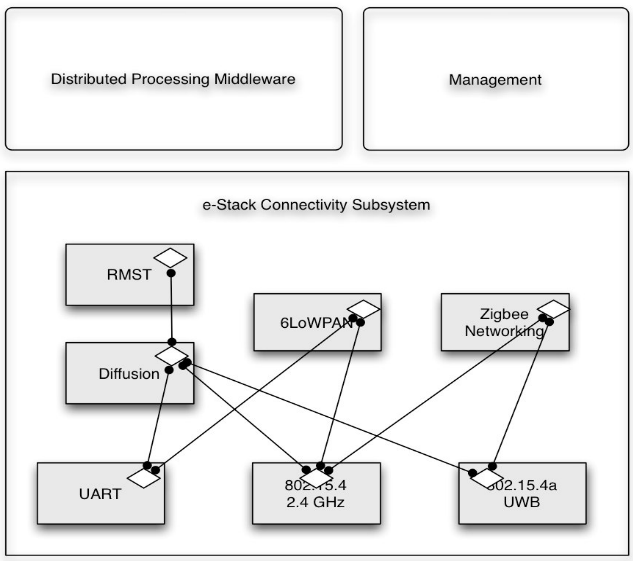

Figure 1: e-Stack protocol architecture illustrating the flexibility in protocol stack.

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II. ENERGY EFFICIENT AIR INTERFACES FOR WSNS

Low cost ultra low-power air interfaces are vital to the success of wireless sensor networks. However, attaining these goals requires an investigation into aggressively low-power IC design methodologies and architectures combined with full PHY system modelling in order to identify the crucial compromises between performances and power consumption. Since existing and upcoming IEEE standards, i.e. 802.15.4x [1],[2] are defined to also fulfil WSN applications, it is an adequate baseline for e-Sense to consider their specifications and implementations as starting points. Therefore, as far as the air interface is concerned, the IEEE 802.15.4 PHY layer will be used to benchmark energy efficient RF design and implementation on the one hand and the draft IEEE 802.15.4a UWB based PHY layer will be studied at architecture and model levels on the other hand. However, since many proprietary solutions which have been tailored to specific WSN applications exists, e-Sense partners will continuously monitor more globally the state-of-the-art evolution.

A. *Adaptation of existing interfaces*

The physical layer specification of the IEEE 802.15.4-2003 standard at 2.4 GHz, though giving precise definitions for modulation, provides space for different implementations and power consumption vs. performance trade-offs. As an example, the minimum requirements on the RF front end are quite relaxed and commercial products offer performance well above these requirements at the expense of tens of mW active power consumptions. A goal of e-Sense is in this respect twofold: find aggressive architectural and design compromises towards ten times lower power consumption in active transmit and receive modes, and exploit new RF component characteristics such as RF MEMs which make it possible to rethink RF architecture choices form the start.

The radically different technology of ultra wideband, characterised mainly by its very low transmit power and spectral density versus its high bandwidth (> 500 MHz) has also been proposed as an alternative PHY layer for the IEEE 802.15.4 MAC layer specification. The UWB has several potential advantages over narrowband approaches: a time resolution of about 2 ns inherently enabling precise ranging between nodes, less sensitivity to multipath fading, and opportunities for new and various receiver architectures. However, transmitted very broadband signals for low data rate transmission may look absurd from the power consumption point of view. But it turns out that, e.g. in [3]-[5], receivers can be low power with only some tens of mW of consumed power. Moreover, UWB transmitters are proven to be extremely low power [6],[7] and this feature is highly attractive in several short range applications like wireless body area networks (WBAN) as addressed in e-SENSE. Finally, the upcoming IEEE standard for low data rate UWB offers great scalability options in many respects such as bitrate, implementation options, etc.

Therefore, the goals for UWB in e-SENSE are to provide PHY layer abstraction models compatible with the IEEE 802.1.5.4a draft standard which are usable for cross-layer analyses, simulations and optimisations. These models will take into account the radio channel models, interference, waveforms, and bitrate options, but also power consumption for the transceiver building blocks and for different architectural approaches.

B. *Physical layer modelling*

Physical layer modelling, done mostly with Matlab and C/C++ based tools is used to characterise the theoretical PHY layer performance in terms of, e.g., packet error rate in different channel conditions. It is also used to characterise the transceiver performance upon design; implementation losses and sensitivity to in-band and out-of-band interferers are typical outputs of such modelling chains.

Link level simulations shall include precise models of analogue impairments. If possible, true models of the digital baseband while keeping reasonable simulation times to workout precise conclusions on expected performances of the PHY layer shall also be included.

System or network simulators generally can not afford embedding realistic link level simulators as simulation time scales are incompatible. Therefore, link level simulators should help in deriving accurate enough abstraction models either analytical or tabulated, that can be used in system simulators. E-SENSE targets to provide such models for the identified standards.

C. *Ultra Low Power Transceivers*

Conversely to the necessity of having reliable link level simulation results, the modelling is helpful in the design phase as well. Done in close cooperation between system/architecture and chip designers, the modelling is intensively used to compare and to select architectures taking into account design techniques suited for low power. The techniques include weak inversion in CMOS or new components very recently available to designers (e.g. RF MEMs), The target is therefore fine tuning of all requirements, avoidance of over-specification and therefore savings in power consumption. When relevant, novel digital compensation techniques may be proposed as well to relax some RF specifications. Finally, channel state information can be used to dynamically adapt the receiver power consumption vs. performance tradeoff. The e-SENSE will report on such innovative methodologies applied to the case of an ultra low power implementation of an IEEE 802.15.4 compliant transceiver.

D. *RF sensing for Context and Situation Awareness*

The RF sensing concept embraces metrics and pieces of information provided by the air interface separate from the transported payload itself. These parameters are classically received signal strength, time of arrival, angle of arrival, channel state information, etc. Depending on the PHY layer technology, the parameters may be available with practically no extra cost and provide meaningful information on the surrounding environment and the situation. Merged with the application sensor information, they may enrich the knowledge of the environment and the context even more for application purposes, which is one of the goals of e-SENSE. The merged information enables also for cross-layer optimisation of the wireless communication stack. In the scope of e-SENSE, RSSI algorithms, compact antenna arrays for UWB, and ranging performance for UWB are the principal technologies which will be investigated.

III. Efficient Protocol Element

Figure 2 illustrates an example of a body sensor network (BSN), which faces many challenges on the protocol levels. The following subsections highlight many of the challenges needed to be solved for a functional system like that of Figure 2.

A. *Application Dependent Quality of Service*

The e-Sense project is very aware of the need for standard wireless sensor network solutions convergent with B3G networks, but flexible enough to solve real application-specific requirements. In e-Sense, three specific use case scenarios are considered: wireless healthcare, personal lifestyle management, and asset tracking. Requirements for each use-case are considered in terms of, e.g., topology, network size, energy requirements, context requirements, traffic models, reliability and security. From these requirements, quality of service parameters can be defined for each use-case. The e-Stack protocol solution gives the flexibility to adapt to these, and other, specific applications either at compile-time or run-time.

B. *Self-organisation and Topology Control*

Based on the scenarios and architecture framework of e-SENSE, the sensor nodes need to self-organise into a communication infrastructure. Topology formation, management, and maintenance need to be addressed in an energy efficient manner. Of the flat and hierarchical topologies the latter is chosen because of the e-SENSE scenarios. An example of a hierarchical topology with routing can be found from [8]. The impact of different logical topologies and organisations on performance and energy efficiency will be assessed. This will be done first by commencing a survey of available techniques for self-organization in WSNs. The techniques are evaluated by mathematical analysis or simulations. The research goal will be a proposal for application dependant self-organization.

Topology control plays a key role in maximising the lifetime of the network by means of two possible approaches: power control and duty cycling. The former limits the emissions and therefore shapes the topology and mitigates interference. The latter offers techniques to distributed computation of the awake/asleep schedules of nodes lowering the energy consumption, but still enabling a communication infrastructure where a number of active nodes can carry information to the sink(s) with reasonable latencies at all times. Clustering also enables efficient communication and data aggregation inside the cluster. However, the clustering schemes also introduce extra overhead in cluster forming and maintenance. In the project the trade-offs in clustering schemes based on performance criteria will be analysed and the boundary to cluster the network based on network density and traffic patterns will be identified.

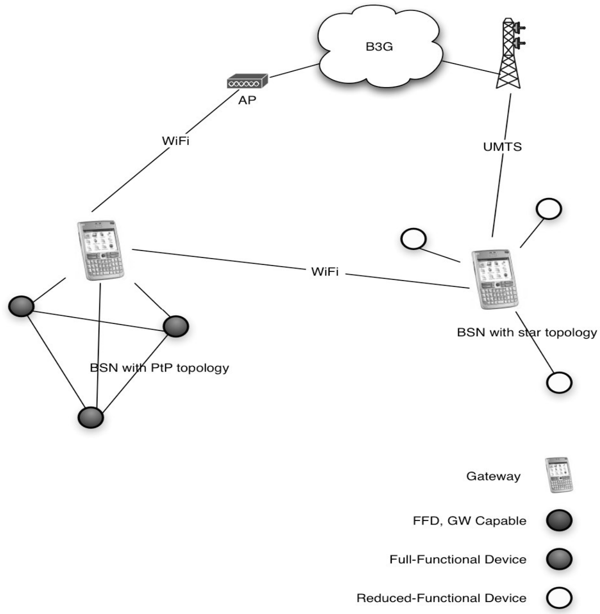

Figure 2: Example of a body sensor network (BSN).

C. *Sensor Protocols*

Sensor networks [9]-[11] are in many ways similar to the long studied mobile ad hoc networks (MANETs), but at the same time have some important differences. The similarities are to be found in the ad hoc nature of the topology, the shared communication medium and connectivity issues. Usually, sensor networks differ from MANETs as they involve little or low spatial mobility, they have much tighter computation and communication constraints and therefore, pose new challenges.

We note that existing solutions for sensor networks are often developed independently, limited to the optimisation of a subset of layers, and focus on a limited number of performance metrics at a time, such as network lifetime, power efficiency, delay, and so forth.

The design of a comprehensive set of protocols for wireless sensor networks is therefore one of the main objectives the current research in the field and of the e-SENSE project as well. These protocols have to span from the physical layer up to the application layer, and although they may be derived from the studied for MANETs, they have to be optimised for the peculiar needs of WSNs. The need for new protocols is therefore motivated by the lack of truly comprehensive, adaptable, self-starting, and scalable solutions which will jointly take into account the many constraints arising in WSNs. Also, these solutions should be capable of properly handling performance tradeoffs in terms of energy efficiency or delay vs. throughput and adapt the protocol behaviour accordingly.

As piconets, e.g. [1],[12] offer many feasible properties, like hierarchical topology, periodic synchronisation, implicit routing paths, and security they do have a serious deficiency for convergent networks; the inability to communicate with each other without topology changes. One of the goals for protocol research in e-SENSE is to provide a rapid access channel for piconets, in which sensor networks interacting for a brief duration can exchange data with low delay. The normal discovery, association, authentication, and resource allocation are omitted and contention access techniques are used instead. The method provides coexistence and short service communication with low delay, but discourages long-term channel abuse because all piconets can access the channel at any time.

D. *Mobility and Internetworking*

The application scenarios for wireless sensor networks are manifold. In a number of these scenarios mobility is an issue and should be accounted for in the network protocol design. As an example, sensors monitoring a moving mechanical part of complex machinery will experience mobility with respect to other sensors. As a further example, sensors used within a shopping mall to offer context-aware services must deal with the inherent mobility of the customers entering the place. In these types of scenarios, mobility may be a problem for the ongoing communication and ad hoc solutions need to be studied to reduce its negative effects.

On the other hand, in many sensor networks, considerably more units are available than necessary. This is done to increase energy efficiency and prolong the network lifetime by putting nodes to sleep (*duty cycling*) [13]. Augmenting sensor networks with motion can exploit this surplus to enhance sensing while improving the network's performance. For instance, when a major incident such as a fire or a chemical spill occurs, several sensors can cluster around the area affected by the incident. This ensures good coverage of the event and provides immediate redundancy in case of communication or node failure.

Another use of mobility comes about if the specific area of interest (within a larger area) is unknown during deployment [14]. For example, in case a network has to monitor the migration of a herd of animals, the herd's exact path within a given physical area will be unknown beforehand. In fact, as the herd moves, the sensor could converge on it to get the maximum amount of data. In addition, the sensors could move such that they also maintain complete coverage of their environment while reacting to its events.

Finally, nodes closer to the data gathering point (i.e. *sink*) suffer from higher energy consumption than nodes far away. This particular situation can be addressed letting the sink node move within the area, hence balancing the traffic load among all devices. As a conclusion, while node mobility in some cases may be seen as a problem, we may also think of exploiting a certain degree of mobility to improve performance. The study to be carried out in the e-SENSE project addresses both aspects, by giving particular emphasis to the latter (*mobility exploitation*).

IV. CROSS-LAYER OPTIMISATION FOR WIRELESS SENSOR SYSTEMS

A. *Cross-layer Analysis*

The classical layered protocol architecture is coming under close scrutiny from the research community. It is repeatedly argued that although layered architectures have served well for wired networks, they are no longer suitable for wireless sensor networks. It is now well recognized that, especially in wireless networks, cross-layer design has the potential of leading to better performance [9]. Generally speaking, cross-layer design refers to protocols that actively exploit the dependence between stack layers to obtain performance gains. There have been several proposals in this sense in the recent literature.

A layered architecture, like the seven-layer open stack interconnection (OSI) model, divides the overall networking task into layers and defines a hierarchy of services to be provided by the individual layers. The architecture forbids direct communication between nonadjacent layers and inter-layer communication is performed by means of procedure calls and responses. Cross-layer design, instead, implies a violation to this paradigm. In fact, a cross-layer approach for the design of a protocol may include the exploitation of metrics collected by other layers. A different option is to design two different layers jointly as a unique bigger layer. Finally, a layer may be designed by keeping in mind the processing being done at different layers.

In the following we report examples using the familiar TCP/IP stack of cross-layer design for different layers of the OSI stack [10].

1) *Physical*

Channel condition (e.g., bit error rate) status from the physical layer can be used by the link layer to adapt its error-control mechanism. Also the transmit power level can be adjusted at run-time by the MAC to enhance the performance.

2) *Data Link Layer*

The number of retransmissions at the link layer can serve as a measure of channel condition. A transport layer such as TCP may re-estimate its retransmission timers based on this data. Also, the link layer may adapt its error correction mechanism based on the quality of service (QoS) requirements of the application layer, that is, acceptable delay, packet losses and so forth.

3) *Network*

Mobile IP hand-off begin/end information can be used by TCP to manipulate its retransmission timer. The link layer's hand-off events can be exploited to reduce Mobile IP hand-off latency.

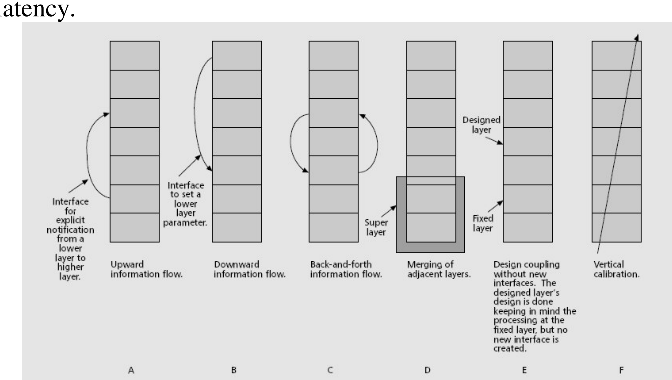

Figure 3: Different kinds of cross-layer design options. The boxes represent individual protocol layers in the traditional OSI model.

4) Transport

The packet loss rate at, e.g., TCP may help the application layer in adapting its send rate. Moreover, the error control mechanism of the link layer can be adapted according to TCP's retransmission timer information.

5) Application

An application may ask for stronger error correction at the link layer to enhance the communication quality. It is also possible to exploit channel condition information from the physical layer to adapt the send rate.

Cross-layer design is a crucial topic for the e-SENSE project as it enables further improvements than a single layer design. This is due to the cooperation between different layers that are no more isolated, but have to cooperate one with each other to achieve better performance for the communication task as a whole.

B. *Proof of Concept Platform*

In e-Sense, hardware proof-of-concept platforms will be designed to validate the part of the work done at air-interfaces level. The first one is the ultra low-power transceiver targeting an active power consumption being a tenth of the actual PHY layer implementations compatible with the IEEE 802.15.4 standard. The second one is a compact antenna array suited for UWB in the 6-10 GHz band with beam forming capabilities and related measured performances results being exploitable for cross layer optimisation.

V. Conclusions

The FP6 e-SENSE project aims at providing outstanding architectural and communication solutions especially for convergent sensor networks. In the e-SENSE project, use cases concerning lifestyle management, wireless healthcare, and asset management are considered. The diversity of use cases demand the development of a new reconfigurable protocol stack concept, called the e-Stack. Instead of using a strict OSI layering approach, the specialised applications of sensor networks allow for more optimised cross-layer solutions. The project is truly cross-layer, and provides optimised solutions from the physical layer up to distributed middleware and gateway solutions. Rather than introducing proprietary solutions, e-SENSE provides solutions and highly optimised improvements for IEEE 802.15.4 evolution standards.

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