SuperG: A Multi-Radio Architecture to interconnect multiple Wireless Sensor Networks

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***Abstract*—On the way to the “Internet of Things” the coexistence of highly adapted but yet deployed sensor networks and future wireless sensor networks using advanced radio technologies must be considered increasingly crucial. This is the reason why we do want to interconnect wireless sensor networks using diverse radio interfaces and communication protocols to form one homogeneous network from a logical point of view. Therefore, we developed a modular architecture for multi-layer multi-radio gateways. We also present our hardware prototype SuperG, which offers four sub** 1-GHz **as well as two** 2.4 GHz **based radio devices at a single node. To the best of our knowledge, this is the first paper describing a multi-radio gateway interconnecting more than two wireless sensor networks, where each of them uses different communication interfaces.**

I. INTRODUCTION

In recent years, both the number of Wireless Sensor Networks (WSNs) deployed and the diversity of Sensor Nodes (SNs) installed has increased. Therefore, the spectrum of radio devices used at such wireless platforms nowadays ranges from sub 1-GHz transceivers like RFM TR1000/TR1001 (e.g. at early platforms like EYES, ScatterWeb ESB, and MICA) and Chipcon CC1000/CC1100/CC1101 (e.g. at SNoW5, BTnode, ScatterNode, Mica2, and Mica2Dot), to 2.4 GHz IEEE 802.15.4/ZigBee compliant transceivers Chipcon CC2420/CC2520 (e.g. at MicaZ, TelosB, tmote sky, Sun SPOT, and Imote2) and System-on-Chip radio transceiver Nordic nRF24 (e.g. at EcoSpire). This very variety of radio interfaces as well as the offered communication protocols complicates the interconnection of miscellaneous WSNs.

However, the re-utilization of already installed sensor nodes is not only cost-efficient, but also inevitable in some cases, e.g. if nodes are firmly connected to the surroundings or even encased in concrete. Furthermore, coordination and interoperability between yet established and recently deployed WSNs using (potentially) incompatible communication interfaces becomes more and more important on the way to “Cooperating Objects” [1] and the “Internet of Things” [2]. The installation of one or more auxiliary gateways[1] is a simple, fast, and cost-efficient solution to establish communication links when incompatible communication interfaces are used within the heterogeneous network. Indeed, all messages are delayed when passing such a gateway. More precisely, protocol adaption and protocol conversion (cf. Sec. III-A2) are causing such a delay, which mainly depends on additional but specific calculation efforts as well as a potential waiting time for the next time of transmission.

In this paper we present our modular architecture for a multi-layer multi-radio gateway which supports the interconnection of an unlimited number of networks per se. This approach allows application dependent operation modes, like repeater, hub, and switch. In principle, our architecture is an adaption and extension of the IEEE 802.11 WLAN infrastructure [3]. To evaluate the suitability of this multi-radio gateway under real conditions, we developed the hardware prototype SuperG which offers four sub 1-GHz and two 2.4 GHz radio devices. First tests were successful and promising (see Sec. V), thus we are currently trying to interconnect several networks consisting of SNoW5 [4], and TelosB [5] sensor nodes respectively, assisted by our SuperG gateway node.

The remainder of this paper is organized as follows. In Section II, we give a brief overview of related work. Section III describes in detail our architecture for a multi-layer multi-radio gateway with a special focus on distribution and integration services. Section IV outlines potential operation modes of this multi-radio gateway node, whereas Section V presents our hardware prototype of such a gateway. A brief summary and an outlook to future work in Section VI closes this paper.

II. RELATED WORK

This section gives a short overview over current research concerning the interconnection of heterogeneous networks, and available gateway nodes in particular. General considerations about the interconnection challenges and strategies, especially when combining a WSN to the Internet, as well as the need for gateways at all, can be found in Karl et al. [6]. A good overview of nodes with more computational power is listed in [7]: these ”large sensor nodes” often offer more communication interfaces, e.g. an additional Ethernet connector. Of course, in some cases it is sufficient to just plug a specific sensor node to a more powerful device like an PC or PDA, e.g. via RS232 or USB interface. But our goal is the interconnection of multiple sensor networks, not just the Internet.

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[1] Within this paper, the term *(communication) gateway* means an instrument forming a homogeneous network out of a heterogeneous network in a logical point of view, whereat a heterogeneous network is a collection of two or more homogeneous networks.

Due to its modular design, the s-net Mobile Gateway [8] is very versatile, because it offers up to four Mini PCI Express slots. Amongst others, cards for s-net, WLAN, UMTS, and GSM network are yet available. This gateway architecture is pretty close to our vision of an interconnecting gateway for multiple WSNs, because it already allows the combination of up to four (different) networks at once.

One of the rare gateway nodes supporting both IEEE 802.15.4 and sub 1-GHz radio is the NanoRouter Ethernet 2.0 [9]. However, this gateway is just able to interconnect 6LoWPAN based enterprise sensor networks to IPv4/IPv6 Ethernet networks. Though, our intention is to stay independent of the used protocols as far as possible.

With respect to the installed radio devices, the sensor node of Ansari et al. [10] is most similar to our approach, because it also combines both IEEE 802.15.4 and proprietary sub 1-GHz radio units at one extended TelosB sensor node. This allows an interconnection of a burst radio interface realized by a CC2420 radio chip, and the low frequency radio chip CC1100. Indeed, the two different radio interfaces were used to find energy-efficient MAC operation, i.e. on the one hand a transmitter for data at high bandwidth, and on the other hand a sniffer for control messages at lower bandwidth. However, what we do want is the interconnection of quite different (wireless) communication interfaces. This also implies that our architecture has to offer application dependent operation modes, like repeater, hub, and switch.

III. OUR GATEWAY ARCHITECTURE

Our gateway architecture mainly was inspired by the IEEE 802.11 WLAN infrastructure [3]: There, a Distribution System (DS) provides logical support to map addresses to destinations and to integrate multiple subnetworks seamlessly. That means, for members of the subnetwork the access to the DS is offered by an Access Point (AP). Nevertheless, APs are sufficient, if all members of such a subnetwork use the very same protocol on both medium access as well as physical layer. Therefore, a so called *portal* (a specific AP) is required when integrating an IEEE 802.x LAN based network. Such a portal has to provide both distribution and integration services.

A. Our Multiple WSN Architecture

In the context of WSN, several sensor nodes in combination with a portal form a simple WSN. To interconnect various WSNs, an Extended Distribution System (EDS) must be installed. This EDS concatenates the portals of the corresponding WSNs with each other. According to Figure 1, a portal acts like a sensor node within the corresponding WSN, but offers access to the EDS. Due to our goal to simplify the integration of various protocols, the most significant software part relies on a portal: it should provide an interface for the required protocols without any changes concerning their implementation, if possible. Please note, the EDS Medium (EDSM) and the Wireless Medium (WM) must be clearly distinguished from a logical point of view: First, the EDSM should not be visible for the sensor nodes because the EDSM is not part of any WSN. Second, the EDSM should be exchangeable, i.e. the EDSM could be realized in various ways, e.g. at a single device (just like our SuperG does, cf. Sec. V), as a wired bus between specific portal nodes, or even wirelessly.

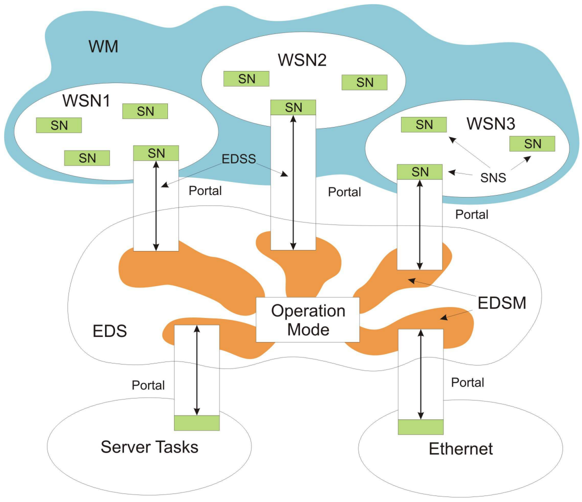

Fig. 1. Schematic of our multiple WSN architecture

This architecture classifies two subsets of the main services as follows: Each sensor node basically relies on the Sensor Node Service (SNS), which is defined by the communication protocol of the corresponding WSN. In contrast, the EDS implements the EDS Service (EDSS), which relies on both main services of the WSN Infrastructure: the Distribution Service and the Integration Service.

1) Distribution Service: Depending on the functionality of the entire architecture, the Distribution Service covers two essential tasks.

First, it has to achieve the message flow throughout the EDS. To support various architectures, the type of transmission is not made mandatory. For example, several sensor nodes can be interconnected via a wired bus system like Serial Peripheral Interface (SPI) to form an EDS. Obviously, in this case there is no additional transmission protocol within the EDS required. Indeed, timings and delays are going to become particularly critical, e.g. broadcast messages within such a wired EDS will not arrive at each destination at the very same time. An EDS could also be implemented for example at a single sensor node offering more than one radio unit (cf. also Sec. V). Here, the EDS complies to the controller's RAM in general. Thus, data packets have not to be propagated further within the EDSM, because the controller now serves all radio units. The delay of broadcast messages is not that critical anymore.

The second task is responsible for the operation mode, like hub, switch, and repeater. For example, if implemented as simple hub or repeater, data messages have to be transmitted to all other portals within the EDS. Whereas, to support switching or bridging some additional functionality is required, like providing and maintaining address tables as well as making a decision to switch.

2) Integration Service: So far, we have not yet discussed the hard problem of protocol translations. In fact, in some cases it is even impossible to translate one communication protocol into another to establish an interconnection between both networks. Basically, there are two methods for protocol translation: *protocol conversion* and *protocol adaption*.

Protocol conversion addresses the conversion of the complete functionality of protocols at a specific layer in terms of the provided services, interfaces, and the protocol's set of rules. Obviously, protocol conversion is not always applicable for all scenarios. Therefore S. S. Lam [11] and K. Okamura [12] developed a formal method to decide, whether a protocol conversion is possible, or not. They also advice some construction methods, to build a protocol converter when protocol conversion is possible at all.

In contrast, protocol adaption can be done in various ways. Addressed by von Bochmann et al. [13], service concatenation tries to install a global communication service which is built upon several basic communication services. This can be achieved either by service adaption or interface adaption. In both cases, protocols need not to be translated completely, instead the translation of a small subset of services is adequate to enable data transmission then.

B. Dealing with Dynamic

The multiple WSN architecture described so far is static, because we have not defined any service which connects newly entering sensor nodes to an existing WSN. This is sufficient for simple hub and repeater functionality. Therefore, if the functionality of a switch is desired and dynamic topologies shall be supported as well, additional services at both SNS as well as EDSS are required. That means, the protocol of the relevant WSN has to offer services for the entering and leaving of sensor nodes. With it, the EDS in turn has to offer services for (dis)connection of sensor nodes. When these services are invoked by those sensor nodes related to portals to introduce newly added nodes of the corresponding WSN to the EDS, the underlying protocol of this appropriate WSN must not be changed. These services allow the EDS to update e.g. its address translation table.

IV. OPERATION MODES

Due to the modular and variable design of the EDS architecture (cf. Sec. III), the following operation modes become feasible. As already mentioned before, these operation modes are defined within the EDS according to the relationship of its portals.

First of all, the functionality of a *repeater* can be implemented. That means, a pair of radio units is fixed permanently in such a way, that a packet received at one node of this pair will be transmitted immediately by the other node of that pair. Due to a shared SPI bus, a short delay has to be accepted.

Next, if any received packet will be propagated over the remaining radio transceivers without any deeper packet analysis, the functionality of a *hub* is implemented. Assumed, all radio units share the very same SPI bus, the broadcast of such a message probably will be delayed noticeably.

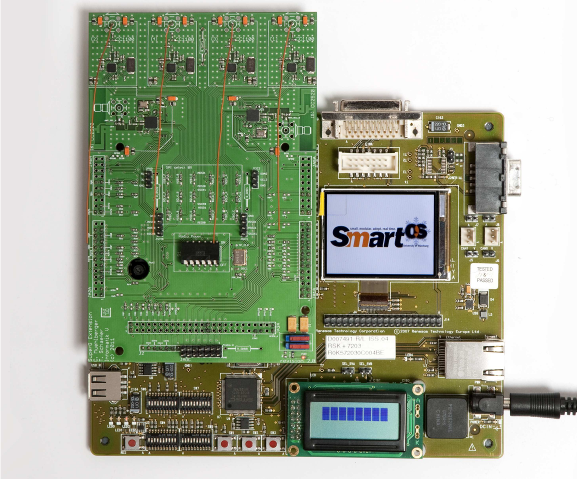

Fig. 2. SuperG expansion board stacked onto RSK+ SH7203

Also possible is the functionality of a *switch*. Here, the EDS has to analyze the MAC address of a received packet and to store it within a source address table. Entries in this table and the received MAC address determine, which radio device has to further transmit this packet. If there are packets addressed to unknown receivers, these packets are flooded to all remaining transceivers.

All in all, our gateway architecture not only allows protocol conversion depending on the used MAC protocols, but even offers some sort of media conversion when connecting networks of different frequency bands.

V. SUPERG PLATFORM

We developed the SuperG platform, which will be described within this section in detail, to first evaluate the suitability of our gateway architecture from Section III and finally to analyze the functionality of our hardware prototype when using one of the operation modes named above.

Using a high-performance microcontroller, the handling of multiple radio devices should become possible. Therefore, our gateway node SuperG is based upon the Renesas Starter Kit+ (RSK+) for SH7203 [14]. The SH7203 is a superscalar 32-bit RISC microcontroller, incorporating an SH2A-FPU core. The maximum operating frequency is $200\,\mathrm{MHz}$, peripheral functions such as a CAN controller, a serial communication interface, an USB host/server module, as well as an I2C bus interface are already integrated into the microcontroller (cf. [15]). In addition, the RSK+ evaluation board provides an Ethernet controller and connector. Besides, we use a migration of the real-time operating system SmartOS [16].

For wireless interaction, we developed a stackable expansion card consistent with the RSK+ evaluation board (see Figure 2). Here, we focused on sub 1-GHz radio as well as $2.4\,\mathrm{GHz}$ IEEE 802.15.4/ZigBee compliant radio systems, because both radio systems can be found at a broad variety of current sensor nodes (cf. Section I). In detail, we assembled four CC1100 radio units [17] and two CC2520 ZigBee compliant radio devices [18]. For each CC2520 radio device an inverted-F on-board antenna can be used alternatively. Each radio unit can be connected to the SH7203 microcontroller via both installed SPI buses. To provide the accurate timeline with a temporal resolution of $1\,\mu\mathrm{s}$ as requested by the operating system (cf. [19]), we attached an external $1\,\mathrm{MHz}$ quartz oscillator onto the expansion board.

A first implementation of the hub (and repeater) functionality upon our prototype gateway was successful and promising: Beside our SuperG prototype, we used several SNoW5 sensor nodes at the $915\,\mathrm{MHz}$ band for these tests. For medium access we used a proprietary CSMA protocol. To simulate incompatible communication interfaces even if the radio units are configured almost identically, we divided the set of SNoW5 sensor nodes into four disjoint subsets by using four different frequency channels. According to these subsets, each CC1100 radio unit of the SuperG node was now connected to just one of these subsets, i.e. it used the very same frequency channel. Because the relationship of the corresponding portals defines the operation mode of the gateway node, we just had to connect there two specific portals with each other (to get repeater functionality), and one specific portal to the remaining ones (to get hub functionality) respectively.

VI. CONCLUSION AND OUTLOOK

In this paper we introduced our approach of a multi-radio gateway platform. After a short overview of existing gateway nodes, we described our architecture in detail in Section III. In Section IV we listed possible operation modes of our gateway node, whereas we outlined our first hardware prototype in Section V.

Currently, we are setting up additional (cf. Sec. V) real-world testbeds consisting of SNoW5 [4] and TelosB [5] sensor nodes. With the help of these testbeds we hope to verify the feasibility of all operation modes listed in Section IV under real-world conditions. We also want to analyze and minimize the delay when a packet passes the EDS of the SuperG gateway. Additional server tasks, like information processing, data gathering, or data preparation, could be installed also at such a high-performance gateway node (cf. Figure 1). The interconnection of further networks like the Internet (cf. Figure 1 again) or support for other network services, like tunneling and remote management of data, are also part of our future research. Finally, we want to analyze and minimize the energy consumption of this gateway node and its radio chips in particular.

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