

Energy-Efficient Communication with Wake-Up Receiver Technologies and an Optimised Protocol Stack

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Abstract—In the domain of distributed embedded systems, available resources regarding computing power, energy, and memory are strongly limited. With focus on the energy resources, communication hardware and communication tasks represent critical consumers for most of the common application scenarios. Accordingly, optimised approaches for the communication have to be found, including routing, topology control, and scheduling. Wake-Up-Receiver (WuRx) represent a promising approach for minimising the energy consumption in wireless communication environments. To use the conceptual benefits of such technology, an adapted communication behaviour is required. Communication paradigm, communication protocols as well as the runtime behaviour must fit together.

In this paper, we introduce a WuRx-optimised routing and topology optimisation approach - WRTA. We discuss the hardware integration as well as the adaptation of the communication task scheduling on application layer. The design matching process of all these aspects allows significant improvements of the energy-efficiency in typical sensor network scenarios. For achieving these goals, WRTA represents a lightweight protocol for data-centric WSN environments. The approach combines complex route path calculations and topology optimisation mechanisms, considering a given asynchronous communication environment.

For proof of concept, we implement several heterogeneous test benches in both soft- and hardware. Hence, the presented simulation results as well as the respective real world measurements provide interesting results regarding the scalability and the efficiency. The analysis of the data shows minimum protocol overhead and outstanding characteristics regarding scalability and robustness. We clarify that application-specific adaptations & configurations within the overall system architecture are essential to ensure a reliable communication behaviour in energy self-sufficient WuRx environments.

Keywords— Wake-Up Receiver, WuRx, wireless, communication, low-power, Embedded Systems, Energy efficiency, Protocol Stack, Routing, Topology Optimisation

I. INTRODUCTION

In energy self-sufficient sensor networks, the management of several tasks for communication and measurements with strongly limited resources is one of the most challenging issues. In order to optimise the duty cycling behaviour and the respective energy consumption for the network standby mode, researchers all over the world develop low and ultra-low-power communication standards and energy-efficient hardware components [1][2]. With focus on energy-efficient communication systems, there are three major research fields, illustrated in

figure 1 (left). Here, energy-efficiency is mapped to a well-defined composition of *communication paradigm*, the respective *communication technologies*, and capable *communication protocols*, which provides adequate services and interfaces to the application tasks. The resulting intersection describes the subset of possible solutions, which fulfils all functional and non-functional requirements for the given application [3]. Figure 1 (right) illustrates this integration process.

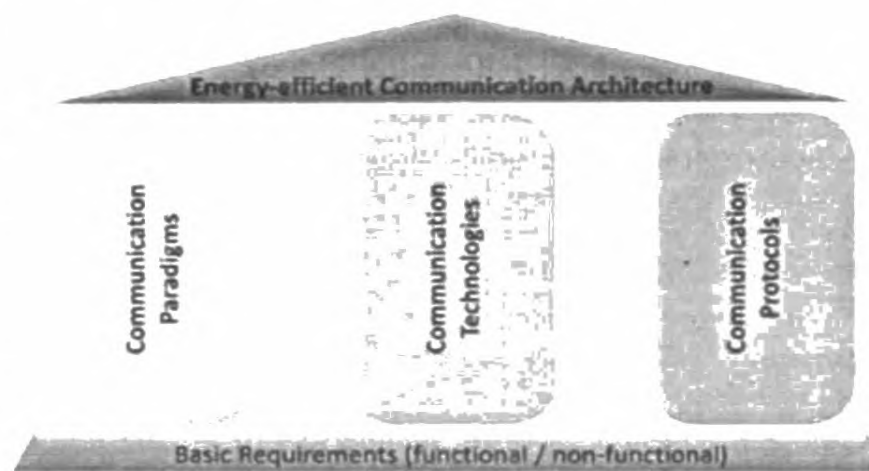


Fig. 1. Design of an energy-efficient system architecture with an application-specific integration process for the communication sub-systems.

In respect of long term measurement scenarios (e.g. *Smart Metering*) and applications with only a few specific communication events, related communication technologies still consume too much energy. Here, especially the waste of energy for the network standby and listening mode has to be reduced. At this point, the development of *Wake-up Receiver (WuRx)* technologies offers promising features for these application domains. Similar to wake-up power supplies, WuRx represent a secondary, dedicated network interface, which is modified to detect special wake-up signals from the network. Dependent on the specific application scenario, WuRx approaches provide enormous capabilities for energy-saving [4]. Due to this specific functionality, the adapted hardware design results in minimal energy consumption for the listening mode. In consequence, all the other communication hardware is switched off. The WuRx is able the wake-up these components on demand.

But not all applications are capable for an efficient usage of WuRx technologies. Environmental parameters, technological limitations and conceptual requirements have to be considered. Accordingly, adapted communication strategies and optimised

communication protocols are necessary to take full advantage of the WuRx benefits. Developers and engineers have to adjust the entire communication behaviour, including key protocols for *routing, topology control and media access*.

II. RELATED WORK

The major part of related research work and research projects in the domain of WuRx technologies focuses on improved hardware components and better communication characteristics. Researchers identify and optimise different key parameters within the wake-up receiver units. This includes the power consumption, the frequency band [5][6] and the receiver sensitivity [7]. Related WuRx units typically consume between 20 and 700 μW for the normal listening mode. In [8], the authors present a 2 GHz WuRx with 52 μW and -72 dBm sensitivity.

But the problem of traditional, active WuRx circuits still correlates with its system design and the required energy. In order to shrink the total energy consumption to a minimum, different research project focussing on passive, nano-mechanical system design. The *nanett* [9] research group develops a NEMS-based wake-up receiver approach (*nanoelectromechanical system*). The WuRx is based on a pure mechanical resonator, which triggers a specified frequency and generates the respective wake-up interrupt for the microcontroller and the main transceiver. The most important benefit of this approach is the operation without complex and energy-consuming electronic circuits. Accordingly, the goal is a power consumption of less than 10 μW in the listening mode. First developments provide basic wake-up features without selective coding. Further developments will allow unicast wake-up signals for specific network nodes or network subsets.

But anyway, the usage WuRx technologies changes the overall communication behaviour within the given network topology. In [10] and [11], the benefits and challenges of WuRx approaches are discussed critically. Especially, the differences between theory and practice regarding energy-efficiency are pointed out. The authors clarify the necessity of adapted communication protocols for routing and topology optimisation to handle the increased network latencies. Due to the asynchronous communication paradigm, several similar data requests of compressed measurement sets may result in critical transmission bottlenecks. The according packet loss has a significant impact on the energy-efficiency of the entire network. In consequence, developers have to consider these situations to implement capable counteractions, e.g. token-based transmission controls or further scheduling mechanisms.

In the context of a reliable, robust WuRx communication environment, routing represents one of the key challenges regarding to real-world applications. Most off the time, nodes are offline and not available for communication. Accordingly, the initialisation of transmission tasks consists of a time-consuming wake-up process and the additional handshake. Traditional routing protocols in the SANET / WSN domain, like OLSR (*Optimized Link State Routing*), DSDV (*Destination-Sequenced Distance-Vector*), AODV (*Ad-hoc On-Demand Distance Vector*) or DSR (*Dynamic Source*

Routing), have massive problems with the increased response times and the partial availability for communication of the WuRx nodes. Here, *Delay Tollerant Networks (DTN)* addresses this problem. Adapted routing approaches for DTN topologies, e.g. in [12] or [13], try to manage such kind of unstable communication paths. But related DTN routing algorithms do not consider the asynchronous, block transmission behaviour in WuRx topologies.

III. WRTA APPROACH

Due to the demand on specific communication protocols for WuRx-enabled sensor network environments, we developed *WRTA (Wake-Up-Receiver Optimised Routing and Topology Optimisation Approach)*. WRTA combines features for a lightweight routing with capabilities to optimise the given communication infrastructure on the lower MAC layer. The approach is designed for wireless sensor networks (WSN) or sensor actor networks (SANET) with dedicated data sinks. WRTA focuses on energy- and resource-efficiency. Hence, most of the time- and energy-consuming calculation tasks are reallocated from the network nodes to the sink. Here, resources for memory and computation are not critical. In order to use the benefits and to minimise the protocol overhead, several pre-conditions have to be fulfilled.

A. Operational modes on the application layer

The WRTA approach is based on several operational modes on the application layer, illustrated in figure 2.

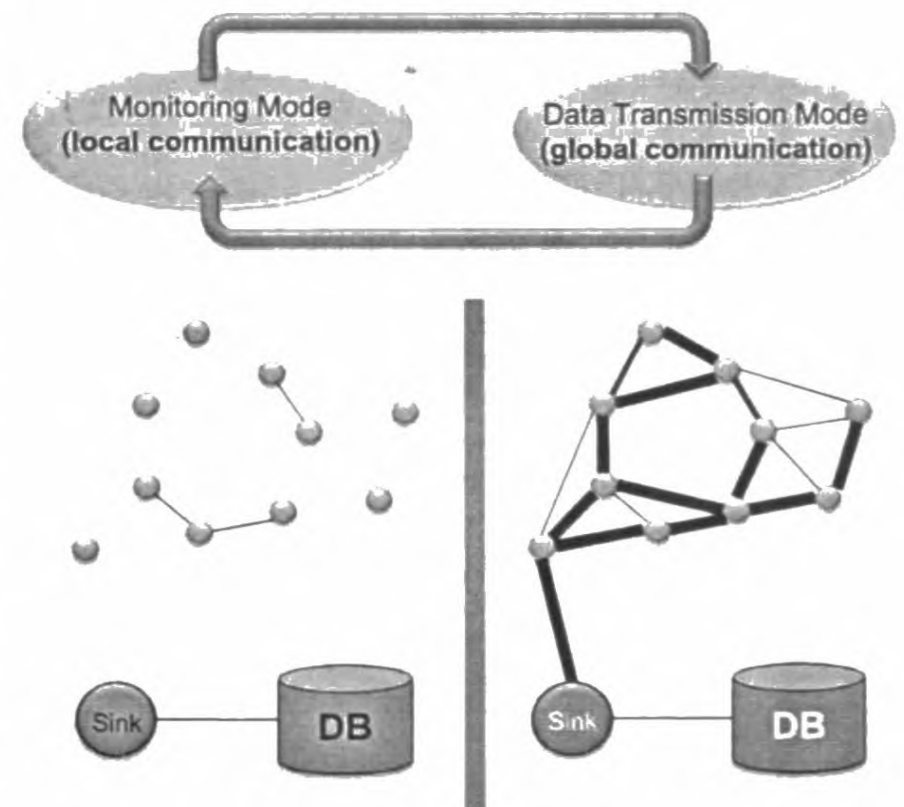


Fig. 2. Two dedicated operational modes: *Data monitoring* without communication (only local transmissions in case of emergency) and *Data transmission* with active network interfaces. The second mode is initialised by a specific wake-up signal from the sink.

These dedicated modes are necessary to minimise the power consumption of the nodes during the normal data measurements. During the first mode (*Monitoring Mode*), global communication is not required. It represents a local and

autonomous mode, where data sets are stored and aggregated in a local buffer. The communication hardware is switched off. Each node is sensing its environment with specific sensors components. WuRx-based communication requests are only allowed in case of emergency, e.g. low battery status or event of system failure. Here, the respective node is able to establish an ad hoc communication channel to its neighbourhood.

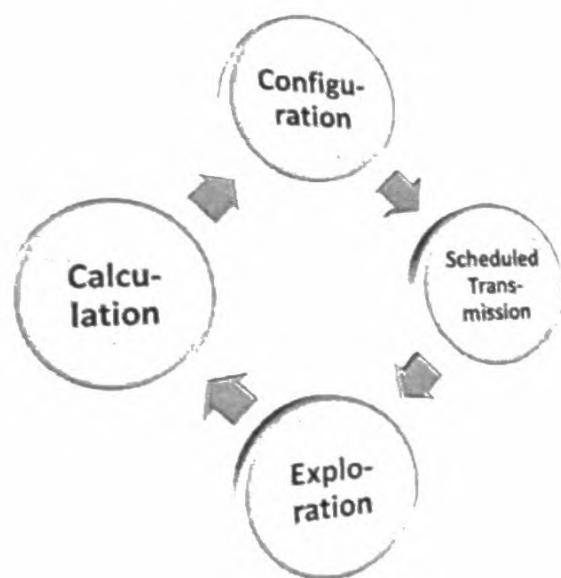


Fig. 3 WRTA operating stages

The second mode represents the data transmission mode. Here, locally stored data or specific information are transmitted. Usually, this mode is initialised by the data sink. A specific wake-up signal will be broadcasted into the network and the first stage of the WRTA approach will be started. All stages are shown in figure 3.

B. Stage I - Net Exploration & Information Gathering

Based on the wake-up signal, the *net exploration* is responsible for the transmission of node IDs and relevant neighbourhood relations to the sink. Each node generates a dedicated broadcast packet, which includes these basic information together with additional meta-data about the amount and priority of the locally buffered measurement. Accordingly, the data sink collects these status information from all available nodes. In a second stage, WRTA starts the *topology optimisation* and calculates the respective route path infrastructure.

C. Stage II - Topology Optimisation & Route Path Calculation

After a predefined timeout, WRTA analyses the set of collected data and starts to calculate a optimised communication tree. The root is represented by the data sink. The calculation routine is modified to use all possible first level links (one hop neighbourhood). A fitness function uses the meta-data from the nodes provide a balanced communication infrastructure. To ensure an energy-efficient operation, the metric tries to calculate short communication paths for nodes with a large amount of data. WRTA is also able to integrate several network and cross-layer parameter for the route path optimisation, e.g. battery status, bandwidth limitations or QoS parameters. The result represents an reduced, load-balanced and data-flow-optimised communication tree. Due to the complexity of such

optimisation tasks, several algorithms and calculation methods are still research in progress.

D. Stage III - Node Configuration

The next challenge deals with the configuration of the entire network topology and the respective data dissemination. In order to ensure a fast configuration process and minimal protocol overhead, the clustered dissemination approach is implemented. Thus, WRTA is able to inject *route configuration packets (RCP)* to specific network areas. For this purpose, the RCPs include special header elements for configuring the starting node. Accordingly, each RCP packet is transmitted to its defined starting point over the partial configured network topology. In consequence, parallel node configuration is possible. Especially in large-scaled network topologies, such capabilities are essential. Figure 4 illustrates the WRTA configuration process.

During the route configuration in each single nodes, WRTA also manages the number of active links on MAC layer. Accordingly, the given topology will be reduced to the generated routing graph as long as all communication path are active and stable. In consequence, the environmental characteristics of related WSN scenarios with WuRx capabilities allow a combination of routing features and topology optimisation. Thus, the number of command and controls packet can be reduced significantly, the protocol overhead decreases. WRTA shrinks the efforts and the energy-consumption for optimising a given network topology to a minimum.

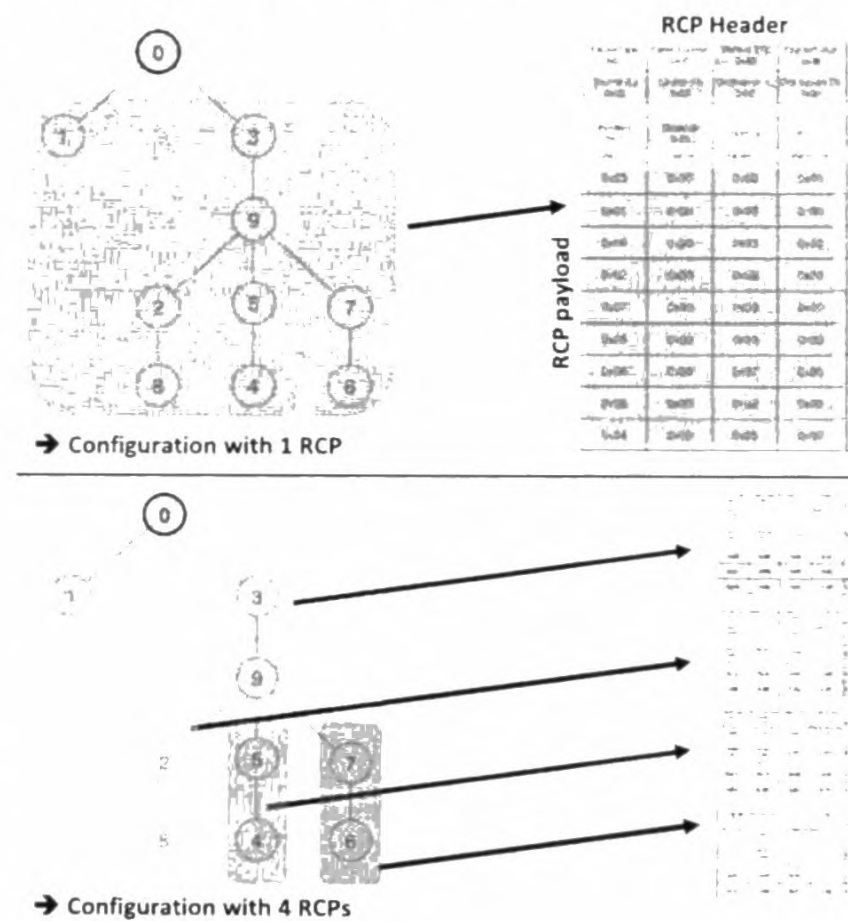


Fig. 4. WRTA route configuration process based on RCPs. The example shows an optimised communication infrastructure. The topology configuration was done with 1 RCP (top). Alternatively, a clustered configuration with 4 RCPs is shown on the bottom.

Broken links during the data transmission are detected by the data sink. In such cases, the routing problems are analysed

and solved by the sink. A route configuration update with alternative route paths will be transmitted to the respective topology subset.

E. Stage IV - Communication Task Scheduling

After the node configuration, the data sink is able to receive data sets from each node. Here, global data requests from the entire topology as well as selective requests from single nodes or subsets are possible. Based on the previous configuration stage and the RCPs, WRTA is able to schedule the data transmissions. Dependent on the application scenarios and the overall/average data amount within the topology, a level-order-based, QoS-based or data-volume-based scheduling of the transmission tasks is possible.

IV. TEST BENCH ENVIRONMENT

In order to analyse the WRTA capabilities, we design and implement two different test benches. Within the first test bench, we analyse the operational behaviour of WRTA regarding the scalability and timing aspects.

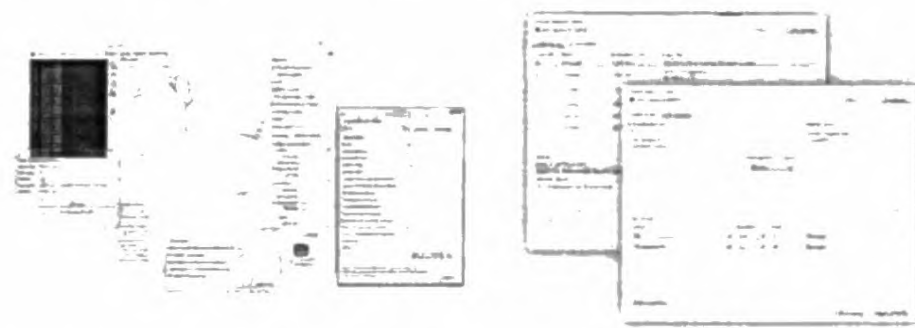


Fig. 5. Screenshots of the used tools. The *SimANet* simulation framework on the left side and the *GREASE* tool for the configuration of the hardware.

This analysis was done in two stages. In order to discuss the conceptual benefits of WRTA, we use a simulation framework for mobile Ad Hoc and sensor networks. The used simulator was *SimANet* (Simulation Framework for Ambient Networking) [14], illustrated in figure 5. It provides complex features for proof of concept and functional analyses on an abstract level. Based on the *SimANet* core, we created several sensor network topologies with WuRx capabilities and the respective data transmission schemes.

In order to evaluate the simulation results, we also implemented extended versions of the simulator scenarios in hardware. Here, different hardware platforms are merged into a heterogeneous real-world communication infrastructure. The first one represents the ultra-low-power sensor network evaluation platform of the *nanett* project (Nano System Integration Network of Excellence) [9]. This research project focuses on the implementation and evaluation of novel WuRx technologies as well as the analysis of critical system parameters for WuRx applications.

The second hardware platform is represented by *PLANet* (Platform for Ambient Networking) [15], a multi-purpose communication platform for heterogeneous ad hoc networks. *PLANet* can be described as a multi-interface, multi-standard platform, which is able to bridge different communication infrastructures dynamically. Due to the fact that the *PLANet*

design focuses on proof of concepts for novel communication approaches, a powerful ARM7 microcontroller is used. Accordingly, *PLANet* provides a lot of resources regarding computation power, memory and interfaces for realising a large variety of possible application scenarios. The platform uses a IEEE 802.15.4 compatible transceiver (XBee Pro) as main network interface.

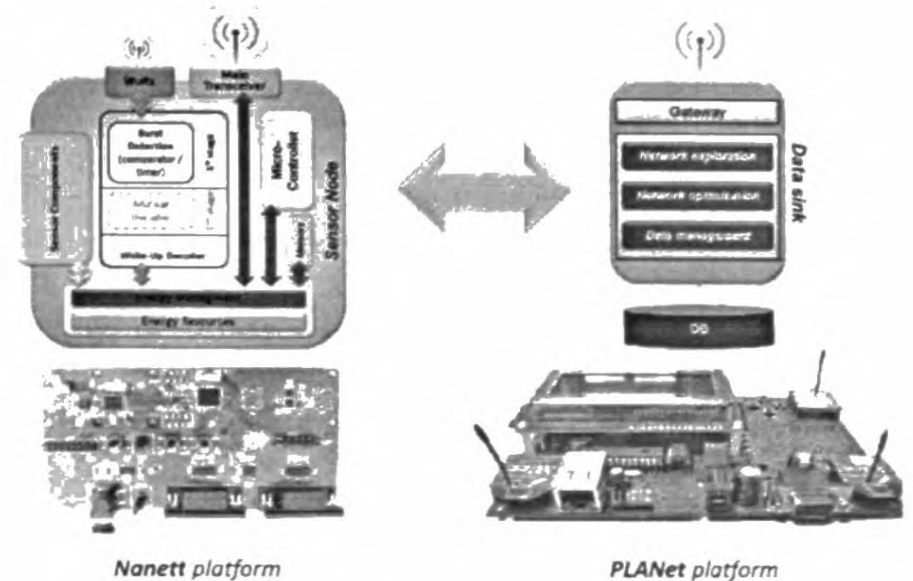


Fig. 6. Block diagrams and pictures of both sensor node and data sink hardware. The sensor nodes integrate the additional WuRx components, consisting of the receiver hardware and the decoder logic.

Both platforms provide WuRx-capabilities for an energy-efficient, asynchronous operation. Figure 6 illustrates both hardware platforms with the respective block diagrams. Each network node integrates several sensor components as well as an energy management unit. The nodes are measuring the environment and transmitting the data to the sink. There is no local communication intelligence inside the nodes. Based on WRTA, all complex tasks regarding topology optimisation or routing are processed within the data sink. Accordingly, the sink is also responsible for the entire data management, the network exploration, and the network optimisation.

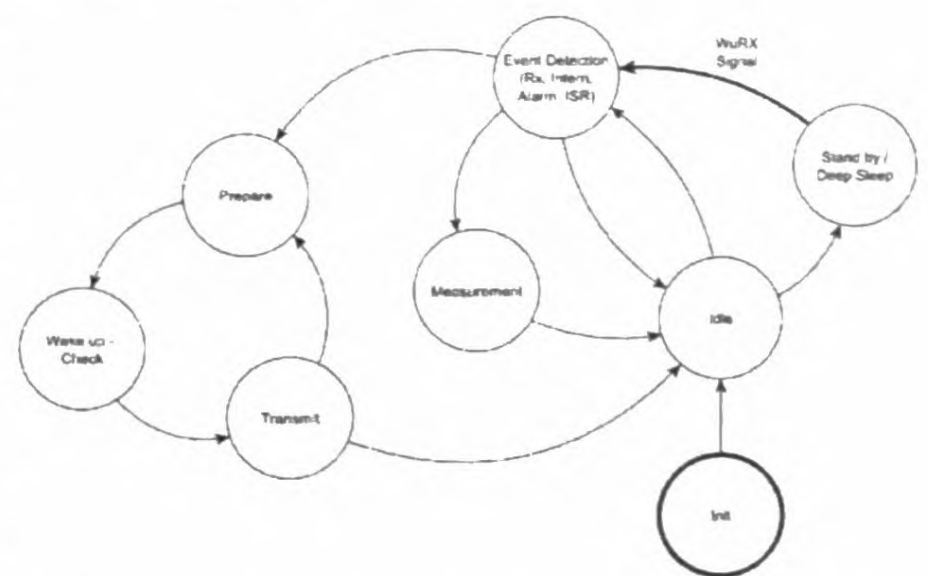


Fig. 7. Finite state machine for the hardware sensor nodes (both *PLANet* and *nanett* platform).

For a wireless configuration of the entire hardware test bench, additional tools are required. Here, we used the

GREASE (Generic Reconfigurable Evaluation and Aggregation of Sensor Data) configuration tool. The implemented behaviour of the sensor nodes during the runtime is shown in figure 7 as a finite state machine.

After the initialisation, the nodes switch into the local monitoring mode and measuring the environment. External events are analysed in the respective interrupt service routine. In case of a communication request (wake-up signal), the WuRx enables the main transceiver. Accordingly, incoming data queries are preprocessed and the relevant measurement sets transmitted. After completing the transmission tasks, the nodes automatically switch back into the energy-saving offline mode.

V. TEST BENCH I - WRTA FEASIBILITY ANALYSIS

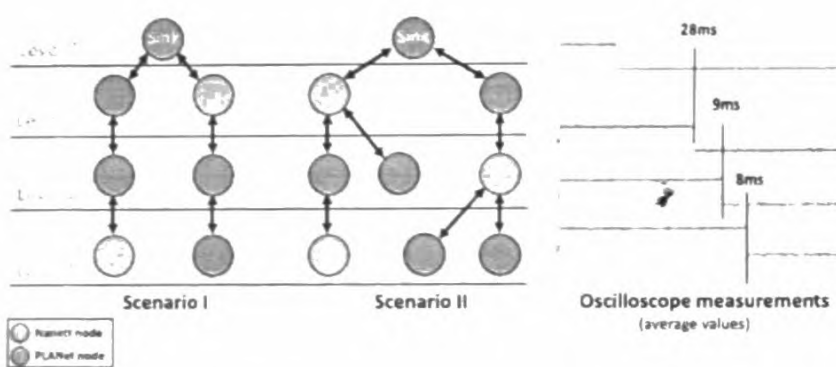


Fig. 8. Two implemented test topologies. Scenario I as simple chain topology. Scenario II describes a more complex structure. The oscilloscope measurements on the right hand side represents average values for the routing configuration time.

The results of the first test bench were measured on two different network topologies, illustrated in figure 8.

Here, the first topology was optimised by WRTA to a simple chain aggregation structure. The second scenario allows different optimisation alternatives. The shown tree topology is one possible version. With this topology, we want to provoke some communication bottlenecks, which are effected by simultaneous data transmissions from each node to the sink. During the transmission process, data sets from all nodes are concentrated within the level 1 nodes. Due to the limited network bandwidth of the 802.15.4 interfaces, an increased data volume may result in critical situations regarding packet loss ratio and latency.

The first diagram in figure 9 presents the measurements for the route configuration process, starting from the network exploration. We compare the simulation results on the left hand side and the real world measurements on the right hand side. The colours represent different configuration steps for each hop count (1, 2, and 3 hop neighbourhood). The optimised communication infrastructure allows constant latency values. The increased delay in the first level results from the process initialisation within the sink. All further nodes with reduced functionality are able to handle and forward data packet in less than 10ms. Both shown results in software and hardware are the calculated average values on 10 test cycles.

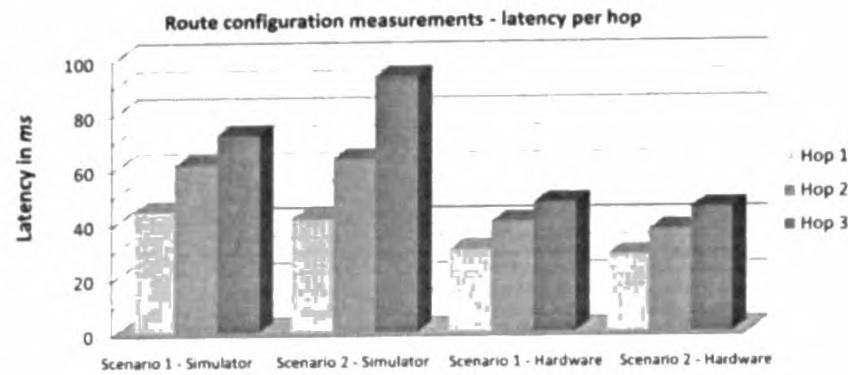


Fig. 9. Measurement of the WRTA route distribution and configuration process. Comparison between simulation and hardware implementation.

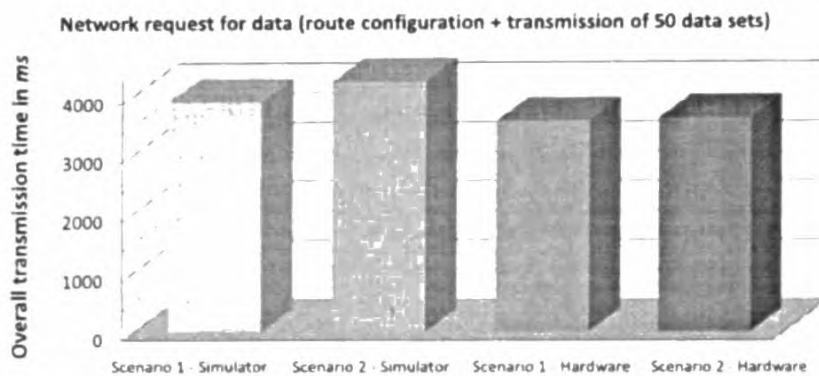


Fig. 10. Overall time measurements for a network-wide WRTA route configuration and data transmission.

The respective overall time measurements for route distribution, node configuration and data transmission are illustrated in figure 10. These values are measured after finalising the transmission process of 50 data sets in each node. Multiple data sets can be aggregated and compressed into one data packet. The packet payload is limited to maximum 8 single data sets. Accordingly, 7 data packets in each node are necessary. The measured transmission times for configuring eight nodes in three layers and the transmission of all the data via an IEEE 802.15.4 interface represent good results, especially in the domain of embedded, ultra-low-power WSN systems. The expected communication behaviour from the simulator is similar to the observed real-world characteristics.

Figure 11 as well as the following diagram in figure 12 present more detailed measurements within the hardware test bench. We analyse the transmission times and the packet loss ratios for different data queries. The tests starts with a specific request from the sink to the all nodes (selective queries are discussed later). Each node processes the data query and prepare the respective data sets for transmission. In our test cycles with queries of 1, 10, and 50 data sets, the respective payload consists of 1, 2, and 7 data packets for each node. The used protocol stack was configured to allow maximum 3 retransmits with hop-by-hop, MAC-based packet acknowledgements.

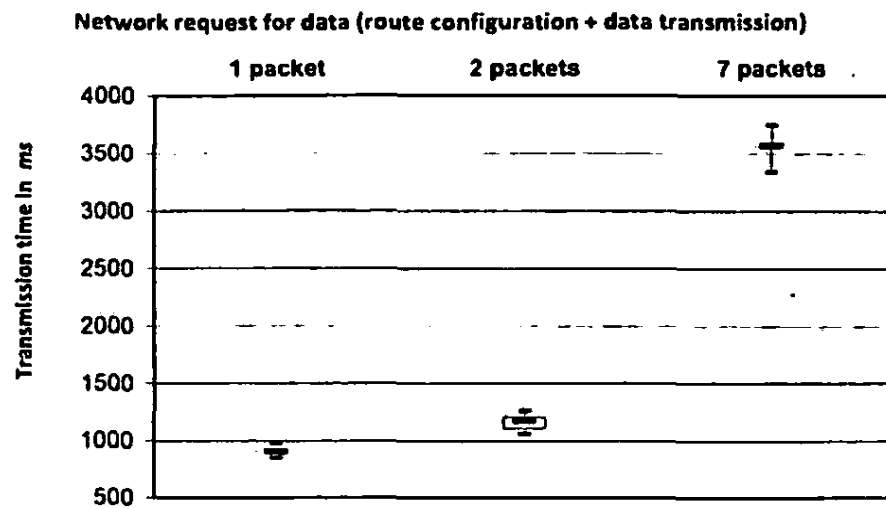


Fig. 11. Overall time for the network-wide route configuration and data transmission with different payload volume.

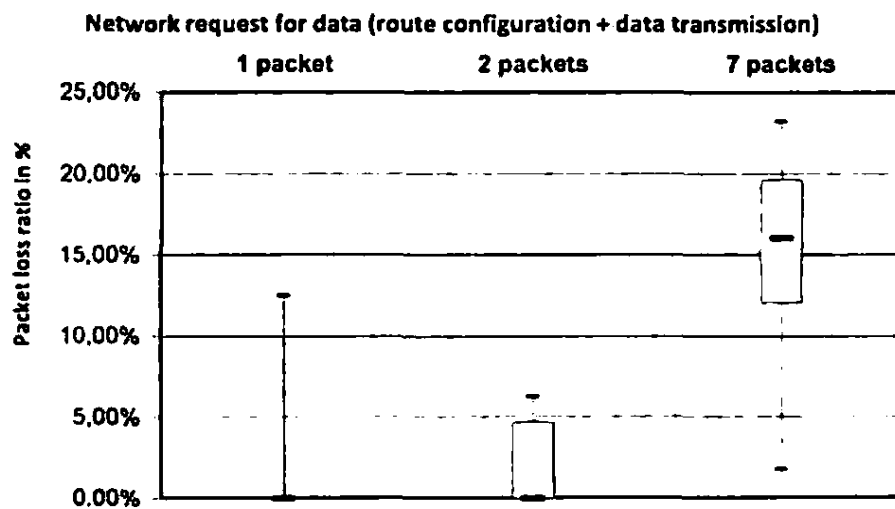


Fig. 12. Respective packet loss ratio with different payload volume.

As already mentioned, we try to provoke communication bottlenecks by increasing the data volume. In our IEEE 802.15.4-based WuRx test bench, the critical limit was reached at data queries with 50 data sets per node, respectively 7 data packets. Here, the drop-off with increased latency values, worse transmission times and significant higher packet loss ratio is clearly observable. Without additional approaches for scheduling or coordinating the simultaneous transmission, packet loss rates of more than 20% are observable. Such results have enormous impact on the energy-efficiency. Due to the increased uptime of the network interfaces for the communication tasks and the packet retransmission, important energy resources are wasted. In [11], these issues as well as capable solutions are discussed in more detail.

The hardware measurements in figure 13 illustrate the results for selective data queries in the network. The communication behaviour depends on the hop count and the data volume. The transmission is stable till reaching a limit of 7 packets per node. Here, significant deviations as well as increased time measurement are observable. All further deviations are minimal.

The overall communication behaviour in this first test bench is comprehensible and promising. The proposed real-world measurements fit to the simulation results. WRTA operates stable and generates minimum overhead. The cluster-based configuration scheme works well. We expect a very good scalability in larger network topologies.

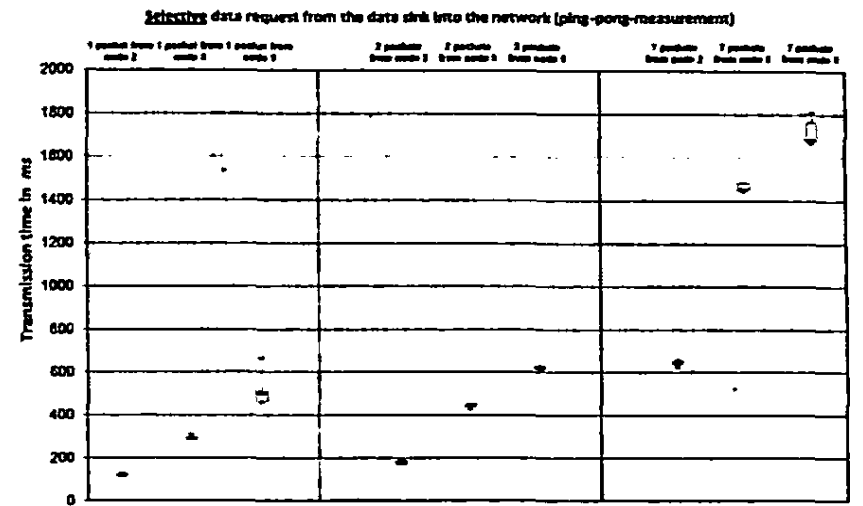


Fig. 13. Selective data request to single nodes in the topology.

VI. TEST BENCH II - IMPACT ON THE ENERGY EFFICIENCY

During the first test bench, we analyse the operational behaviour of WRTA regarding latency, robustness and resource consumption. In this second test bench, we now want to quantify the impact of WRTA and the respective WuRx-enabled communication architecture on the energy efficiency. The test environment consists of five nanett demonstrator boards. Each board represents a battery-driven, energy self-sufficient sensor node. The platform operates with an MSP430 microcontroller from TI. The communication interfaces include a IEEE 802.15.4 compatible transceiver unit (CC2420 with the CC2591 power amplifier) as well as an additional wake-up receiver module. For calculating the power consumption and the maximum system runtime, we used the μ RX1080 WuRx model from the Fraunhofer Institute for Integrated Circuits (IIS) [16]. The nanett demonstrator platforms provides a real time clock for triggering the measurement points. During the basic operation of the hardware, each system component consumes a specific amount of energy. Hence, table I summarises the power consumption of the hardware platform within different operational modes.

Mode	Description	mA
SLEEP	OSC = CPU = RX/TX = off	1.0
IDLE	OSC = CPU = on, RX/TX = off	5.1
MEASURE	IDLE + ADC + SPI/I2C + Sensors	5.7
RX	OSC = CPU = on, RX = on	28.1
TX	OSC = CPU = on, TX = on	131
WAKE-UP	OSC = CPU = on, TX = on, CW-Mode	147

Table I. Static power consumption of the nanett platform. OSC - Oscillator / Clock generator, CPU - Processing unit / μ Controller, RX/TX - Receive/Send communication interface, ADC - Analogue/Digital Converter, SPI/I2C - Communication bus subsystems, CW-Mode - Continuous wave mode (32kHz Wake-Up-Signal)

The proposed table I includes some power consumption values for sensors. These sensors are equipped on the nanett nodes as external peripheral devices. We used an impact sensor (piezo technology) as well as light sensitive sensor components.

Based on the measurements, we are able to discuss the impact of WRTA on the energy-efficiency in different communication tasks. Therefore, we separate the traditional test scenario in different operational modes and add the respective

values for the power consumption. We compare the power consumption with a traditional transmission scheme (no WuRx, on-demand route path calculation, no local data buffering techniques) with a WRTA-optimised transmission, which uses WuRx approaches as well as data aggregation and buffering mechanisms in an efficient way.

A. Application Stage I - Measurement

During this stage, a dataset of all internal and external sensors is measured each second. This also includes temperature and the actual battery voltage. The entire dataset is stored locally within the node-internal buffer memory. This process is clocked with the maximum frequency. Active communication interfaces are not necessary in this stage. In contrast, all internal bus systems (USART, I2C) as well as the ADC are enabled to process the sensor measurement tasks. A single measurement cycle needs approximately 40ms and the respective dataset allocates 16 Bytes of storage.

B. Application Stage II - Exploration and Configuration

In case of an WRTA-optimised communication, a network exploration task will be processed every 60 seconds. The discovery algorithm is initialised by the sink and generates a list of all currently available nodes within the network. This list contains additional information for calculating the routing table, e.g. node relations, link costs, or available communication resources. As already mentioned, the optimised route configurations are transmitted into the network. After configuring each sensor node, transmission of the data payload will be started.

C. Application Stage III - Data Transmission

The sink generates requests for each node to transmit measured sensor datasets. Based on the chosen IEEE 802.15.4 communication standards and the available transceiver modules, one data packet contains maximum 7 datasets. Before the transmission process starts, we have to ensure a full available multi-hop communication infrastructure between node and sink. Accordingly, we remain in the idle mode for predefined time slot (*worst case waiting*).

D. Application Stage IV - Sleep

This stage represents the default stage for an energy-efficient runtime behaviour. For optimising the power consumption of the communication scenario, we have to maximise the time within this stage without violating any functional requirement from the application. The network is pre-configured so that the sleep stage will be entered after one second without network activity. Accordingly, the radio receiver switches into the sleep mode (only in case of an available WuRx - the ready-to-receive capability must be ensured at any point in time). Furthermore, the CPU as well as all internal communication modules, e.g. USART, are stopped. No instructions will be executed (*LPM4*). The platform only responds on external interrupts, like wake-up signals (via WuRx), Real-Time-Clock (*RTC*) events, or signals from the attached sensor components.

E. Asynchronous Wake-up Events

If the system will be reactivated by a local event, specific routines allow situation-specific procedures. In case of a necessary transmission task, the surrounding network topology will be woken up by a respective wake-up signal (*CW-mode* of the radio transceiver). The wake-up process takes about 40-50ms.

Figure 14 illustrates an oscilloscope screenshot of such a WRTA-optimised communication task. The different operational stages are highlighted and separated with respective labels.

In consequence, our main goal for this test bench is to maximize the system runtime by using wake-up receiver capabilities and WRTA. In order to analyse this parameter, we monitor the detailed communication behaviour between two nodes. Based on the oscilloscope, we are able to trigger all transmission stages. With the measured time periods and the specification of the power consumption in each stage, the overall amount of energy will be calculated.

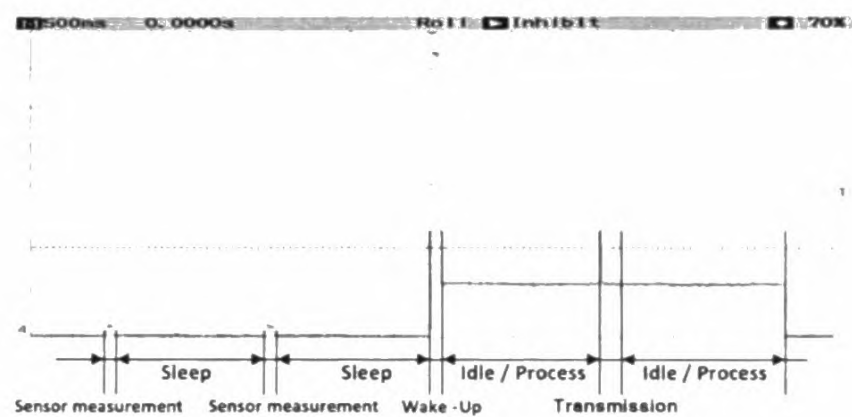


Fig. 14. typical Application: *Measurement (w/o Transceiver)* and *Data transmission* with network wake-up event.

Accordingly, the following figure 15 summarises possible system runtimes with conventional transmission schemes as well as with a WRTA & WuRx communication.

For calculating the values, we used an ideal 600mAh battery. As we can see, the system runtime with this energy storage strongly depends on the efficiency of the communication tasks. Without further optimisation, the system runtime stops at 22 hours of operation - less than a day. By integrating WRTA, we are able to use the WuRx technology in an efficient way. Additional buffering schemes allow store & forward strategies for the communication. Dependent on the buffering period, the maximum system runtime will be prolonged to up to 1316 hours - in comparison to traditional communication schemes more than factor 60 longer.

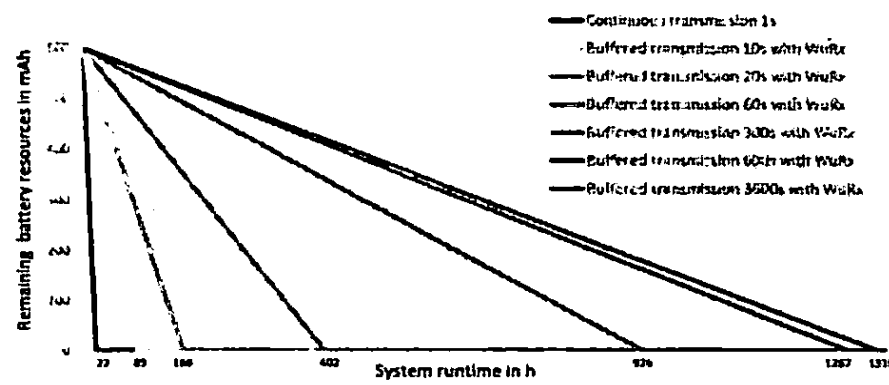


Fig. 15. Lifetime for a battery-driven system with different cycle times

VII. CONCLUSION

In this paper we demonstrate the capabilities of WRTA, a combined routing and topology optimisation approach for WuRx-enabled WSN environments. In order to use the conceptual benefits, we introduced two dedicated operational modes during the runtime. In combination with asynchronous communication paradigms and an efficient task scheduling, WRTA generates optimised communication infrastructures for an efficient data transmission in the network.

In [17], key parameters for a sufficient and efficient usage of WuRx capabilities were defined. In this paper, we integrate these parameters into a complex test bench and present the respective real-world measurements. As shown in the test results, WRTA provides good performance in both simulation and hardware implementation. But also critical limits for the communication were pointed out, which depend on the node topology and the communication standard. Regarding the energy efficiency, the combination of WuRx technologies and the WRTA approach allows a significant improvement of the communication behaviour. In the context of energy self-sufficient, long-term application scenarios, e.g. in the WSN domain, the system runtime can be prolonged significantly.

In conclusion, we clarify that WuRx-adapted communication protocols with a lightweight and simple design offer high potential for optimisations of the energy-efficiency, especially in the domain of embedded, resource-limited systems.

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