Energy-Efficient Communication in Distributed, Embedded Systems

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***Abstract*—Embedded systems are used in almost every domain of our daily life. Actual research and development activities focus on wireless connected and mobile system architectures. The resulting network topologies represent embedded, distributed systems, which are able to process complex tasks in a cooperative way. Here, most of the hardware platforms are energy self-sufficient with strongly limited resources. In consequence, the maximisation of the system runtime is essential to fulfil all application tasks as long as possible. Especially in long-term scenarios (e.g. WSN / SANET), the runtime depends on the efficiency of communication processes. Hence, the key challenge for researchers and engineers represents the application-specific integration of adapted communication concepts, radio technologies, and protocol stacks into an energy-efficient communication architecture.**

In this paper, we critically discuss energy efficiency in distributed, embedded systems with focus on the communication aspects. We introduce an easy to use estimation model for quantifying the energy efficiency on both local (system) and global (network) layer. The included cost functions consider the power consumption as well as timing aspects. In this context, we evaluate several optimisation strategies under real-world conditions within a heterogeneous network environment. We integrate an asynchronous communication paradigm, wake-up-receiver technologies, and data aggregation techniques in a stepwise process. Accordingly, the respective analysis compares the results and clarifies the importance of an application-specific system design. If the communication architecture and the configuration scheme fits to the environmental conditions, significant optimisations for the energy efficiency are observable.

***Index Terms*—Embedded Systems, Distributed Systems, Energy Efficiency, Estimation Model, Optimisation, Data Aggregation, Data Fusion, Wake-Up-Receiver**

I. INTRODUCTION

The number of embedded devices is rapidly rising. Especially mobile communication platforms and smart devices offer more and more interesting fields of application. The used hardware is small, cheap, and allows the integration of different sensor types. But at the same time, the limited resources of such embedded platforms results in a strong trade-off between computational capabilities and power consumption. Most of the devices are energy self-sufficient and accordingly, the dimensioning of the batteries is very important to provide a predefined system runtime. Optimisations regarding the energy efficiency are needed to prolong the runtime of the system.

In a next step, if we interconnect a multiple of independent (sub-)systems, a distributed, embedded system will be generated. Now, distributed resources are able to work together for a common purpose. In order to ensure the collaborative operation within this network, the availability of communication becomes a critical requirement. And also the energy-management becomes critical because the breakdown of one subsystem has effects to the entire distributed system. If we analyse the power consumption of related, embedded hardware platforms, the network communication consume a huge part of the available energy resources [1]. In consequence, our goal is to optimise the entire communication process regarding the energy efficiency. Here, side effects and correlations between different subsystems as well as environmental conditions have to be considered.

II. ENERGY EFFICIENCY ESTIMATION MODEL

If we want to optimise the energy efficiency ϕ, a clear definition is essential. Generally, the term ϕ is represented by the relation between the gain G and the cost C for a given process P:

$$\phi_P = \frac{G_P}{C_P} \;;\; G \in \mathbb{N} \;; C, \phi \in \mathbb{R} \;; C \geq 1 \;; 0 \leq \phi_P \leq 1$$

Accordingly, the energy efficiency will be optimised by increasing the gain (with constant costs) or otherwise by reducing the cost (with constant gain). We use the second metric. In consequence, the key challenge is to minimise the cost without violating functional requirements from the applications (represented by the gain). With a cost function c, different system parameters are mapped to an abstract cost value. The main cost parameters include the power consumption E as well as timing aspects D (communication delay). For this paper, we introduce two cost functions c_1 and c_2:

$$\begin{aligned} c_1 = \quad & c_1(E_{\text{total}}) & = 1 + \tfrac{E_{\text{total}}}{e_{min}} = 1 + \tfrac{E_{\text{Total}}}{1} \\ c_2 = \quad & c_2(E_{\text{total}}, D) & = 1 + E_{\text{total}} * D \end{aligned}$$

e_{min} represents the basic energy unit. For simulations, e_{min} is equal to 1 EU (abstract energy unit). For hardware evaluation, e_{min} is equal to 1 Joule.

A. Local Energy Efficiency

In order to quantify and compare the energy efficiency in complex real-world scenarios, an easy to use model is necessary. To handle this problem, we define two abstraction layers to describe the energy efficiency. On the *local* layer, we only consider the gain and costs for one subsystem and the respective hardware platform. Network communication processes are not included. The local gain G_{local} for a given subsystem s and a process P has two possible values:

$$G^P_{local_s} = \begin{cases} 1 \rightarrow \text{functional requirements satisfied} \\ 0 \rightarrow \text{anything else} \end{cases}$$

Hence, the local energy efficiency is calculated with:

$$\phi_{Local^P_s} \quad = \quad \frac{G^P_{Local_s}}{C^P_{Local_s}} \qquad C \in \mathbb{R}, K \geq 1$$

In order to compare two system implementations for the same application scenario, relative changes for the energy efficiency are observable. The difference $\Delta\phi_{Local^P_s}$ has a relation to cost difference. Due to the assumption, that energy self-sufficient systems are able to prolong their own system runtime by saving energy resources, $\Delta\phi_{Local^P_s}$ has a relation to differences in the system runtime ΔT_{up}.

$$\Delta\phi_{Local^P_s} \quad \sim \tfrac{1}{\Delta C^P_{Local_s}} \quad \sim \Delta T_{up_s}$$

Accordingly, we are able to optimise the local system energy efficiency by prolonging the system runtime without violating any functional requirements.

B. Global Energy Efficiency

In distributed systems, communication processes have to be considered for quantifying the overall energy efficiency. In the domain of energy self-sufficient, embedded systems, each communication task has a direct influence on the *global* gain G for the entire network. Furthermore, each communication process has huge impact on the abstract costs. So if we want to provide an easy to use energy efficiency model for distributed systems, we have to combine *local* data processing aspects with *global* communication aspects.

Therefore, we define two matrices $\mathcal{V}$ and $\mathcal{W}$ for the time period t.

$$\mathcal{V}_t \quad = \begin{pmatrix} 1 & \dots & v_{1,n} \\ \vdots & \ddots & \vdots \\ v_{n,1} & \dots & 1 \end{pmatrix} \mathcal{W}_t \quad = \begin{pmatrix} 1 & \dots & w_{1,n} \\ \vdots & \ddots & \vdots \\ w_{n,1} & \dots & 1 \end{pmatrix}$$

Each matrix element $v_{i,j}$ $(i, j \in \mathbb{N}; 1 \leq i, j \leq n)$ represents an available communication path between the subsystem i and the subsystem j for the time period t (necessary time for handling the process P). We define:

$$v_{i,j} = \begin{cases} 1 \rightarrow \exists \text{ utilisable path from } i \text{ to } j \text{ during } t \\ 0 \rightarrow \text{anything else} \end{cases}$$

The matrix elements $w_{i,j}$ $(i, j \in \mathbb{N}; 1 \leq i, j \leq n)$ represent the necessity for communication between subsystem i and subsystem j during a time period t (during a process P):

$$w_{i,j} = \begin{cases} 1 \rightarrow \text{comm. necessity between } i \text{ and } j \text{ during } t \\ 0 \rightarrow \text{anything else} \end{cases}$$

The elements $v_{i,i}$ and $w_{i,i}$ $(i \in \mathbb{N}; 1 \leq i \leq n)$ have a fixed value of 1 because the communication within the own subsystem is always available and necessary.

Based on these communication matrices, we now define the global gain G_{Global} for a subsystem s and a process P on the network layer with:

$$G_{Global^P_s} \quad = \quad \underbrace{G_{Local^P_s}}_{\text{Local tasks}} * \underbrace{\left\lfloor \frac{\sum\limits_{\forall i \in n} v^P_{s,i} * w^P_{s,i}}{\sum\limits_{\forall i \in n} w^P_{s,i}} \right\rfloor}_{\text{Communication tasks}}$$

Accordingly, if not all required communication paths for the process P are available, the term *communication tasks* changes from 1 to 0 and so the overall gain is also zero. Otherwise, if all communication paths are available and the local gain is fulfilled, the global gain is 1. In the special case, that no communication is required, the global gain is equal to the local gain.

Based on these equations, the global energy efficiency of a process P for a distributed system is quantifiable as follows:

$$\phi^P_{Global} \quad = \quad \frac{\sum\limits_{\forall s \in n} G^P_{Global_s}}{\sum\limits_{\forall s \in n} C^P_s}$$

This model is feasible for heterogeneous network topologies, which process common purposes with distributed resources. If all subsystems in a topology are necessary to process a given task, the sum of all global gains $(\sum G^P_{Global_s})$ will be replaced by a product $(\prod G^P_{Global_s})$.

III. RELATED WORK & CLASSIFICATION

During the last decade, energy-efficient system architectures and green IT became to one of the most important research fields [2]. Related research starts with the optimisation of large-scaled IT systems. Major projects did concentrate on central IT infrastructures, like data centres, network backbone entities and other server systems. But the situation has changed rapidly. Nowadays, embedded devices become even more in the foreground and represent huge potentials for energy-optimised technologies [3]. Due to the huge amount of hardware devices, even small improvements result in massive savings in material, costs and energy [4].

But if we focus on a given system architecture, improvements regarding the power consumption can be realised on different layer. Basic optimisation strategies deal with the development of improved hardware technologies for the main components, e.g. CPU / μController (low-power modes, System on Chip, scale of miniaturization) [5], peripheral equipment (optimised sensors and actuators), energy-efficient storage and network interfaces (radio standard, smart antenna, low-power transceiver) [6].

On top of these technologies, researchers identied different fields for an energy-efficient system operation. In this paper, we concentrate on the communication behaviour. Thus, we have to optimise the whole communication protocol stack in the abstraction layer called *network management*. It is responsible for establishing and maintaining communication features for the system. This includes optimised MAC protocols, which provide stable and energy-optimised links (EE-MAC [7], LEEM [8], LASA [9]), topology control mechanisms to handle large networks with high node density (LMST [10], EOSC [11]), and energy-optimised routing approaches, which calculate capable multi-hop communication paths (LEACH [12], EBCR [13], PAR [14]). In order to extend the available knowledge base for an energy-efficient communication, cross-layer strategies represent an important topic for research projects. Here, network and system status information are combined to provide optimised results [15]. Other research projects deals with time-synchronisation and localisation approaches to optimise the communication behaviour [16], [17].

A second abstraction layer on top of the network management, the *data management*, uses the communication features to handle the data exchange. By reducing the amount of network data, the power consumption for communication can be reduced and the energy efficiency increases [18]. This only applies for the assumption, that all functional requirements for the application tasks are fulfilled at any point in time of operation. Related research work in this field deals with data aggregation techniques to combine several data sets of one predefined type [19]. Data fusion approaches are more complex and merge different types of raw data to more abstract events or information sets [20]. But also the schedule of all communication tasks is managed within the data management. For long-term applications, energy-driven task scheduling offers very interesting concepts for an efficient-efficient communication architecture [21], [22].

IV. OPTIMISED COMMUNICATION ARCHITECTURE

Based on the introduced energy efficiency estimation model, we are now looking for application-specific strategies to optimise the communication behaviour in a given distributed, embedded systems. For creating an optimised communication architecture, three main areas (Figure 1) are categorised:

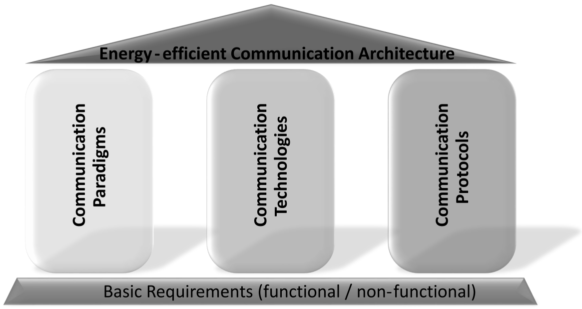

Fig. 1. Energy-efficient communication architecture design.

On top of the functional requirements, the combination of an adapted communication paradigm, capable technologies and application-specific protocols provides an energy-efficient communication architecture.

A. Communication Paradigm

Developers of distributed, embedded systems have to decide for a feasible communication concept. Conventional systems are using time-synchronised paradigms to schedule the communication processes in efficient way. Due to predefined time slots for the transmission of each node, the communication behaviour is predictable and overload situations regarding the network load can be avoided. On the other side, there is a huge energetic overhead for the time synchronisation protocols.

Asynchronous communication paradigms represents an interesting alternative. Here, no synchronisation mechanisms are needed and accordingly, the protocol overhead is minimal. Event-driven concepts are using a "communication on demand" strategy. In monitoring / detection systems or other long-term application scenarios, the network communication is only needed in few cases. Accordingly, periodical synchronisation tasks and network activities represent a huge waste of energy. But without a global transmission schedule, the network interfaces have to be in an active "ready-to-receive" mode all the time. In consequence, further mechanisms are needed to ensure a low-power listening mode for the different subsystems.

Energy-driven concepts represent another version of event-driven approaches. Here, the available energy resources are used for a prioritised schedule of transmission tasks. This paradigm is very interesting for hardware architectures with integrated energy harvesting components. So if the energy-level is critical, low prioritised communication task were cancelled or rescheduled.

B. Communication Technologies

In order to realise an energy-efficient communication architecture, optimised technologies are needed. Key research projects focus on the network interfaces. Here, smart antenna systems as well as innovative transceiver designs allow the energy-efficient data transmission [23].

Especially in correlation with asynchronous communication paradigms, additional low-power listening hardware is reasonable. Wake-Up-Receiver technologies (WuRx) represent one of the most promising ideas. These dedicated receiver modules are designed to detect a single predefined wake-up signal from the communication channel. The power consumption in the sensing mode is extremely low. In consequence, the system is now able to save energy of the transceiver hardware during the passive listening mode. And at the same time, the WuRx ensures a continuous ready-to-receive mode at any time. Figure 2 shows the schematic of a sensor system architecture with integrated WuRx component.

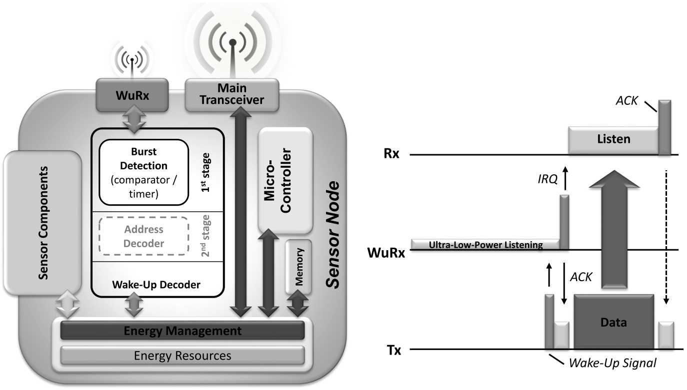

Fig. 2. WuRx integration - the platform is able to receive and decode special wake-up-signals. Accordingly, the main communication hardware will be switched on only on demand.

The conceptual advantages of wake-up-receivers regarding the energy efficiency are not suitable for all types of application [21], [22]. The technology fits to asynchronous application scenarios with sporadic communication events (event detection, monitoring tasks). In contrast, WuRx components are not capable for applications with frequent transmission tasks and time critical data. Here, conventional time-synchronised energy saving strategies offer more potential for optimisation.

C. Communication Protocols

Optimisations within the area of communication protocols consider the entire communication stack. All functional requirements from the application tasks are also mapped to this section. The key challenges regarding an energy-efficient communication can be structured by the respective abstraction layer:

Physical Layer:
Interference minimisation, stable band width, overhead-minimised signal coding, trade-off transmission power / transmission range

MAC Layer:
Overhearing, low level link management (topology control)

Network Layer:
Routing, load balancing, mobility management

Transport Layer:
Adapted flow control mechanisms, channel management & reallocation, prioritisation

Application Layer:
Data compression, task scheduling, result quality, event handling

D. Integration & Configuration

For developing or optimising a concrete system, all functional requirements have to be specified. After that, developers have to find feasible solutions regarding the communication paradigm, communication technologies and a capable protocol stack (see Figure 3).

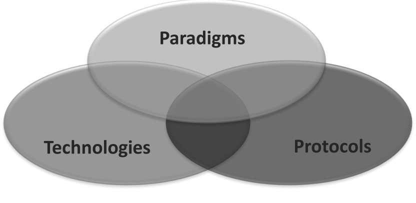

Fig. 3. Integration & configuration process for an energy-efficient communication architecture.

As shown, the mutual adjustment of the several areas is critical. If there is no intersecting set, the application scenario with all specified requirements is not implementable.

The configuration process and the chosen strategies for an energy-efficient system architecture are strongly application-specific.

V. TEST BED ENVIRONMENT

In order to evaluate the introduced energy efficiency estimation model, several optimisation strategies were analysed. The chosen test scenario for all measurements represents a distributed, embedded system in the domain of home automation and smart living (see Figure 4).

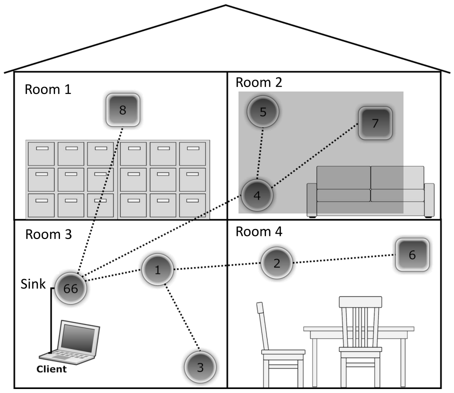

Fig. 4. Home automation - heterogeneous test scenario with the *PLANet* (circles) and *nanett* (rectangles) hardware.

Within the test bench, two different hardware platforms are used. The first one is *PLANet* [24], a evaluation board for WSN and MANET scenarios. The second one is the *nanett* platform [25], which was designed as an ultra-low-power system architecture. Both demonstrator boards are shown in Figure 5.

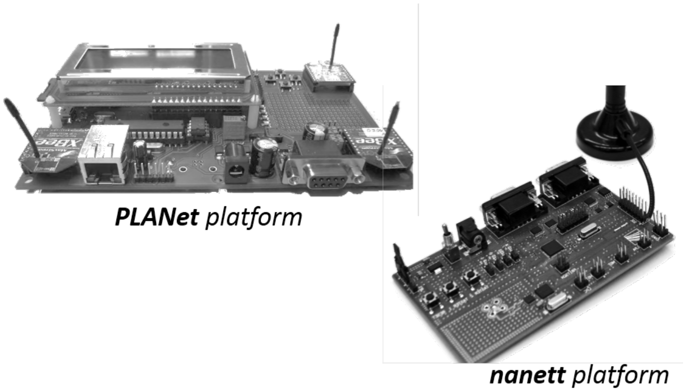

Fig. 5. Used hardware platforms *PLANet* and *nanett*.

The heterogeneous network topology operates energy self-sufficient and uses the IEEE 802.15.4 communication standard (PLANet with XBee radio modules, nanett with CC2420 transceiver with CC2591 amplifier). The measured power consumptions for both platforms in different operational modes are shown in table I.

Power consumption in *mW* (at 3.3 *V*)	**PLANet Board (ARM7 Controller)**	**XBee radio module (IEEE 802.15.4 / ZigBee)**	**nanett Board (MSP430 Controller)**	**TI radio module (CC2420 + CC2591) (IEEE 802.15.4 / ZigBee)**
Idle	$\leq$162	$\leq$115	$\leq$93	$\leq$74
Sleep	$\leq$0.16	$\leq$0,03	$\leq$3	$\leq$3
Receive (RX)	—	$\leq$165	—	$\leq$74
Send (TX)	—	$\leq$115	—	$\leq$413

TABLE I
POWER CONSUMPTION PLANET / NANETT EVALUATION BOARD, SEPARATED INTO BASIC HARDWARE AND NETWORK INTERFACE.

Accordingly, the required energy E_{basic} for transmitting 1 Bit payload (data rate 250kbps @ 802.15.4 / XBee specification) is calculated as follows:

$$E^{PLANet}_{basic_{Rx}} = 165mW * \frac{1bit}{250\frac{kbit}{s}} = 6,6 * 10^{-7}Ws = 0,66\mu J$$

$$E^{PLANet}_{basic_{Tx}} = 115mW * \frac{1bit}{250\frac{kbit}{s}} = 4,6 * 10^{-7}Ws = 0,46\mu J$$

$$E^{nanett}_{basic_{Rx}} = 74mW * \frac{1bit}{250\frac{kbit}{s}} = 3,0 * 10^{-7}Ws = 0,30\mu J$$

$$E^{nanett}_{basic_{Tx}} = 413mW * \frac{1bit}{250\frac{kbit}{s}} = 16,5 * 10^{-7}Ws = 1,65\mu J$$

These basic energy values are used for all further estimations with the introduced energy efficiency model. The calculations are simplified under static environmental conditions and with no accurate model on the PHY layer. But for comparing and discussing different optimisation approaches regarding their efficiency, these values are sufficient.

Both boards provide a dedicated interface for integrating a wake-up-receiver component. The used WuRx model is the μRX1080 from the Fraunhofer Institute for Integrated Circuits (IIS) [26]. The WuRx has a power consumption of 30μW in the listening mode with a sensitivity of 60dBm. The wake-up-delay is specified with 32ms at a maximum range of 30m. One wake-up-process consumes 320μJ of energy.

We use an adapted version of FreeRTOS as embedded operating system. All route paths from the nodes to the sink are precalculated with the WRTA routing approach [27]. Hence, we focus on the power consumption for the communication process.

VI. EVALUATION & ANALYSIS

In order to quantify and compare the energy efficiency, we measured a predefined communication task. Here, all temperatures of room number 2 (see figure 4) have to be measured and transmitted to the sink for calculating an average result. Each data set includes the *node-ID*, the *floor number*, the *room number*, and the *temperature value*. Each value is represented by 4 bytes and accordingly, one complete data set has 16 bytes (= 128 bits) of payload.

The reference measurement was done without any optimisation by sending a query from the sink into the topology. Accordingly, each data set was transmitted to the sink as one dedicated data packet.

In optimisation *stage 1*, we integrate a data aggregation mechanism, where each node collects the data from its neighbourhood and calculates the average value of all data sets. The result will be forwarded to the sink as one packet. In consequence, the data amount in the topology decreases significantly. On the other hand, due to the local data preprocessing, the average information delay increases.

In *stage 2*, we change the communication paradigm to an asynchronous, pure event-driven processing. There is no slotted data transmission and no synchronisation mechanism. In this stage, we only use the standard transceivers, which stay in ready-to-receive mode all the time.

Additionally in *stage 3*, we integrated the wake-up-receiver for providing a low-power listening mode for the nodes. The WuRx allows all unused nodes to switch into an energy saving standby mode. Based on the given application scenario, we are once more able to reduce the energy consumption for the transmission procedure.

With the proposed hardware platforms, the specified power consumptions and measured time values, we calculated the overall used amount of energy. All results are shown in the following figure 6.

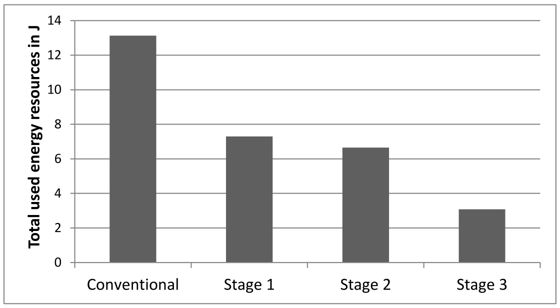

Fig. 6. Comparison power consumption (total).

The values clarify the optimisation potential of different communication strategies regarding the energy consumption. In stage 3, less than 25% of the reference measurement energy consumption was needed. The following figure 7 shows detailed energy measurements for the communication processes (without energy resources for the basic PLANet / nanett hardware platform).

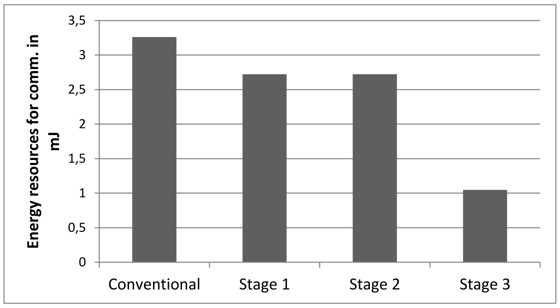

Fig. 7. Comparison power consumption (communication).

As we can see, the energy resources for communication represents the key indicator for the overall energy consumption in the distributed system. Stage 1 (data aggregation) and stage 3 (WuRx integration) allow massive power saving during the transmission process. Without adapted hardware components, stage 2 (asynchronous communication) provides no sufficient optimisation potential. Based on the introduced estimation model and the cost function c_1, the following results for the energy efficiency were calculated.

	Energy consumption E in J	**Efficiency ϕ**
Conventional	20,42	30,60 %
Stage 1	11,67	43,55 %
Stage 2	8,43	51,62 %
Stage 3	3,09	74,47 %

TABLE II
Energy Efficiency ϕ for the different optimisation stages.

If we analyse the energy efficiency results, the overall system power consumption was used. Starting with a value of 30.6% with a conventional wireless data transmission concept, we reached 74.5% energy efficiency with optimisation stage 3. The proposed results are measured in a good / best case scenario, where all environmental conditions and the application tasks fit to the optimisation strategies. Also the selected strategies complement each other. It has to be pointed out, that the application-specific selection and integration of energy-efficient approaches is essential for an optimised communication architecture.

A second analysis deals with different cost functions for quantifying the energy efficiency. Here we measured the communication overhead during the transmission of 10 data sets from each node to the sink. Each data set has 20 bytes. We used the same heterogeneous network topology as in figure 4. The conventional reference measurement was done without any optimisations. Each packet includes one single data set. A next measurement cycle uses tree data aggregation to combine the data sets from all child nodes to one average value. The last test case integrates additional data buffering / bundling techniques with a local buffer memory of 100 bytes. Thus, several data sets can be buffered locally till reaching a predefined filling level ($\eta = 0.25, 0.5, 0.75 \mathrel{\hat{=}} 25\%, 50\%, 75\%$). After exceeding these levels, the buffered data will be transmitted in one block. Here, the data payload is concatenated to larger packets. Within the IEEE 802.15.4 / ZigBee specification, the maximum payload size per packet is defined with 100 bytes. Accordingly, in these test cycles, data packets might be reorganised within the forwarding nodes. Diagram 8 illustrates the ratio between payload and overhead for the different transmission strategies.

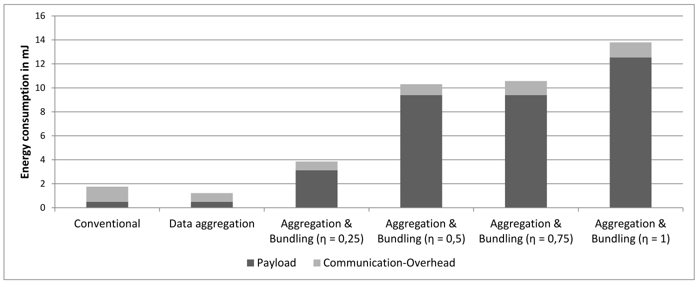

Fig. 8. Results - communication overhead.

The results pointed out that data aggregation and data bundling allows a much better usage of the communication interface. In consequence, the wasted energy for protocol overhead can be reduced. In case of sensor monitoring scenarios with small data sets, the impact on the energy consumption is significant.

With the introduced cost function c_1, only the energy consumption has influence on the efficiency of the overall distributed system. But what about timing aspects? Each of the used data preprocessing and transmission schemes has an impact on the communication latency. Especially, the buffering mechanisms results in a serious increasing delay. Hence, the following table summarises the calculated energy efficiency results with both introduced cost functions. Thereby, c_2 includes the respective transmission delay.

	Efficiency ϕ (c_1)	**Delay**	**Efficiency** ϕ (c_2)
Conventional	62,02 %	0,25 s	42,16 %
Data aggregation	70,18 %	0,25 s	51,23 %
Agg. & Buffering, $\eta = 0,25$	82,30 %	1,75 s	22,88 %
Agg. & Buffering., $\eta = 0,5$	79,21 %	3,25 s	11,57 %
Agg. & Buffering, $\eta = 0,75$	79,21 %	4,75 s	8,22 %

TABLE III

ENERGY EFFICIENCY ϕ BASED ON BOTH COST FUNCTIONS c_1 UND c_2.

As we can see, the interpretation of energy efficiency strongly depends on the field of application and the relevant parameters. For time-critical scenarios, data buffering techniques are not feasible for an efficient communication. Additionally, in large-scaled topologies an optimised dimensioning of the buffer size is difficult. Side effects from the used communication standard as well as mobility issues have to be considered.

On the other side, if timing aspects are non-critical, developers can choose other optimisation strategies to provide an adapted and energy-efficient communication architecture.

VII. CONCLUSION & OUTLOOK

In this paper, we analyse and discuss optimisation strategies for the energy efficiency of distributed, embedded systems. Therefore, we introduce an easy to use estimation model for the local system layer and for the global network layer. It is now possible to compare different communication concepts, technologies and protocols regarding the impact on the energy efficiency. We clarify the importance of an application-specific cost function for considering all relevant communication parameters. For evaluation of the model and several optimisation strategies, we implemented a heterogeneous network test bench with different hardware platforms. The results of each test scenario demonstrate the huge optimisation potential for energy-efficient communication in distributed, wireless systems. If we analyse these results, developers also have to understand, that a capable optimisation strategy demands deep knowledge about the environmental conditions and the functional requirements from the application. Based on this knowledge, specific approaches on different abstraction layer can be integrated and configured.

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