Resource Management for Advanced, Heterogeneous Sensor-Actor-Networks

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***Abstract*—Sensor-Actor-Networks (SANET) consist of several heterogeneous subsystems, which provide specific capabilities for measuring or manipulating its environment. During the runtime, the communication infrastructure as well as communication tasks and the available communication resources are changing dynamically. Furthermore, advanced application scenarios in this domain have strict requirements regarding to the minimal system uptime, QoS features or backup strategies. In this context, one of the most challenging objectives for researchers all over the world is the efficient integration and handling of heterogeneous, distributed SANET components to ensure a reliable and stable system operation. In respect of this issue, we present a novel cross-layer resource management approach for advanced SANET. We are now able to reallocate communication resources for each subsystem on-demand during the runtime. For this purpose, we developed a real-time radio standard integration concept and respective routing strategies with adaptive multi-standard, multi-interface metrics. A respective real-world demonstrator was designed and implemented. Based on this platform, we start a proof of concept evaluation and analyse the operational behaviour of a given SANET testbed configuration. The proposed measurements clarify the necessity as well as the feasibility of an intelligent, integrated resource management unit for advanced SANET architectures.**

***Keywords*-Energy Efficiency, Resource Management, Channel Reallocation, Dynamic Optimisation, Embedded Systems, Wireless Sensor Networks (WSN), Sensor-Actor-Networks (SANET)**

I. INTRODUCTION

Sensor-Actor-Networks (SANET) as well as Wireless Sensor Networks (WSN) represent distributed embedded systems which are able to sense its environment for specific events or behaviour. Based on wireless communication interfaces, the subsystems (*nodes*) are able to exchange information. Actuator nodes are additional entities of SANET, which allows the system to manipulate the environment based on a predefined set of rules. *Figure 1* illustrates a given SANET architecture, its different abstraction layers and the respective operational tasks on each layer.

To operate autonomously, each subsystem has limited energy resources. Here, the efficient management of these resources is essential. To maximise the system runtime, developers have to find a trade-off between working performance and power consumption of the hardware system architecture. In this respect, the trade-off starts with the used sensor components (accuracy, sample rate, size), resource limitations regarding to the μController (memory, number of I/O pins, speed) and ends with the wireless communication interfaces (data rate, transmission range, latency, interference liability). Besides these hardware aspects, the concrete application scenario implies further operational restrictions. In this context, scenario-specific communication protocols in the several abstraction layers are critical to optimise the system efficiency [1], [2].

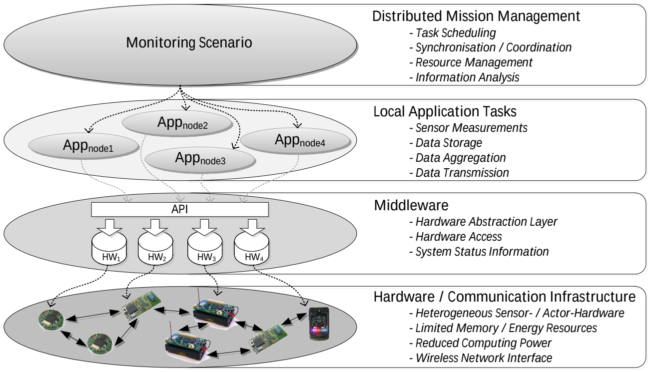

Figure 1. A given SANET architecture including four different abstraction layers. The first one includes the different hardware components. A middleware provides uniform access to the available subsystems for all applications. Single operational tasks are executed on capable nodes. A global mission management is responsible for calculating and coordinating all the tasks in order to fulfil the given mission objectives.

This paper proposes a resource management approach for coordinating the overall communication behaviour within SANET applications dynamically. It integrates different features for distributed, embedded system to ensure a reliable and robust communication infrastructure. It is structured as follows: After this introduction, section *II* provides an overview about related technologies in the domain of energy-efficient and robust SANET. This includes cooperative routing strategies, cross-layer approaches and further communication techniques. The proposed resource management concept and its basic components are introduced in section *III*. This section also provides respective examples and application scenarios. Section *IV* describes the chosen testbed configuration based of a capable hardware prototype platform. The results are discussed in section *V*. Finally, the paper concludes with a summary and an outlook for future work in this research area.

II. RELATED WORK

A primary objective of basic network optimisation techniques are stable and robust end-to-end communication *channels* through a given heterogeneous multi-hop topology. Channels represent the essential logical resource on top of the physical network interfaces. In order to balance the network load through these channels, a lot of research was done in the domain of multi-path routing [3], [4]. The idea is to split a data stream into multiple, potentially prioritised sub-streams and transmit these parts over different route path to the sink. Here, several problems have to be solved. On the one side, we have to find stable communication paths in dynamic, heterogeneous network infrastructure for a lossless date transmission. On the other hand, requirements for worst-case latencies and minimum transmission data rates have to be fulfilled. Most of the related multi-path concepts operate on a homogeneous network topology and uses unidimensional routing metrics. Regarding to our proposed work, these metrics have to extended for the multi-interface, multi-standard domain (e.g., *EBCR - Energy Balanced Cooperative Routing* [5], [6]).

Other routing approaches use multi-dimensional metrics for optimising the route paths. [7] and [8] describe concepts for gathering network information as well as additional system information from different abstraction layers. Such *cross-layer (X-layer)* approaches, like in [9], have a much better knowledge about the current network situation than traditional, uni-dimensional routing algorithms on the network layer.

In a further step, advanced research projects are looking for approaches to balance the network communication over multiple interfaces with different communication standards [1]. The main idea is to use the advantages of multiple radio standards. At the same time, we bypass the disadvantages of using one single technology, which result from their specific application fields. Accordingly, the developed radio standard integration concept provides a heterogeneous network infrastructure and an efficient real-time protocol conversion approach [10], [11].

Further technology integration approaches, like *Cognitive Radios (CR)* as well as *Software Defined Radios (SDR)* represent other concepts for optimising the communication in mobile application scenarios. CR is operating on the hardware-near layer to minimise radio interferences and to adapt the communication channel dynamically [12], [13]. SDR stands for a modular framework, which implements the whole protocol stack of a given communication standard in software. Accordingly, SDR provides an outstanding flexibility and allows a real-time conversion between different radio standard [14]. Unfortunately, due to the required hardware resources, SDR is not applicable for the embedded mobile domain like WSN or SANET [15]. Another promising research project represents *Ambient Networks* [16], [17], which are focusing on a platform-spanning communication infrastructure based on *Ambient Services* - an additional abstraction layer on top of the user application.

III. DYNAMIC RESOURCE MANANGEMENT

Regarding to our proposed concept and with focus on dynamic scenarios, one challenging problem deals with the varying communication resources and changing environmental conditions during the runtime. Dependent on the application scenario, different capacities for the data transmission are required. An advanced resource management for multiple physical interfaces has to consider several additional parameters, which includes the local system status and distributed network information.

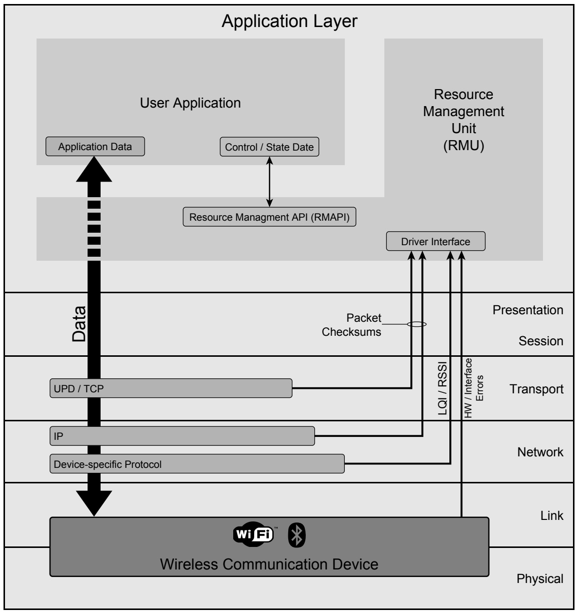

Figure 2. Resource Management Unit (RMU) and its integration into the protocol stack.

Figure 2 represents typical communication architecture and the integration of our proposed *Resource Management Unit (RMU)*. In contrast to related X-layer routing and communication approaches, the RMU uses standardised information, which are provided by the hardware components, the respective drivers or the embedded operating system. Specific modifications or adaptations in the hardware architecture or the protocol stack are not required.

In order to establish a logical communication channel from a source application to another remote application over a multi-hop network infrastructure, communication resources have to be allocated. Therefore, the usual way is to request a new communication socket from the operating system based on the respective transport protocol. In our proposed concept, instead of opening a communication socket directly, each application handles its requests over the RMU. The RMU operates as a software component in the application layer and provides a dedicated *Resource Management API (RMAPI)*. Based on a set of services, the RMU is able to monitor the network communication and to allocate communication channels for the user applications.

Furthermore, the RMU allows a proactive channel analysis for high prioritised data streams. For this purpose, two or more nodes exchange special *RMU tracker packets*. Even if it takes more energy and computing time, this technique is essential for data critical application scenarios, in which a simultaneous and continuous channel monitoring is not capable. In such critical cases, the RMU is responsible for backup channels and the respective reallocation.

The RMU is able to manage multiple interfaces and radio standards simultaneously. In order to use these advantages within the system architecture, a real-time on-demand switching technique is required. Therefore, an efficient radio module integration concept has to operate directly on top of the hardware devices as a kind of embedded middle-ware. For this purpose, the *EAN (Embedded Ambient Networking)* concept was developed and allows a dynamic conversion between different radio standards [1], [10], [11]. Currently, several international cooperation projects research for an embedded high-performance platform based on this EAN approach. In combination with the RMU, an adaptive and flexible communication architecture will be created.

A. Channel Modeling & Reallocation Schemes

As already mentioned the resource management metric includes local system information and distributed network information. In this context, rules and calculations are very similar to related cross-layer routing metrics. In contrast to multi-dimensional routing metrics on the network layer, the channel management operates parallel to user application on the ISO/OSI layer 7. Accordingly, the RMU coordinates all communication requests between user applications and network interface. For providing a optimised, scenario-specific reallocation scheme, a multi-dimensional set of parameters is required for estimating the current situation. These parameters are categorised as follows:

1) Latency:

- hop count (flat network hierarchy)
- number of protocol conversion (use less different interfaces as possible)

2) Data throughput:

- minimum or average data rate
- stream splitting / multi-path capabilities

3) Energy consumption:

- interface power consumption (standby, rx/tx)
- trade-off transmission range and route path length

4) Security:

- channel stability / robustness (based on channel monitoring techniques)
- channel prioritisation

5) Capacity utilization:

- interface load
- protocol overhead

B. Example Scenario I - Balancing & Optimisation

The decision making processes of the RMU represents a challenging problem. *Figure 3* illustrates a typical scenario. In order to optimise the network communication, $Node_{new}$ can be integrated in different ways. It is possible to split the data streams into two subchannels between $Node_{new}$ and $Node_2$ over the radio standards RS_1 and RS_2. In this case, both interfaces are used to balance the net load or to realise a multipath data prioritisation. Otherwise, one interface has to be preferred. Hereby, the remaining communication capacities in $Node_2$ (20% left) and $Node_3$ (50% left) have to be considered.

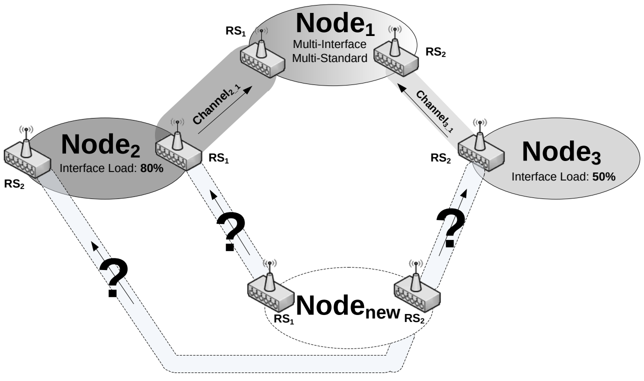

Figure 3. Channel allocation and reallocation scenario I. $Node_{new}$ has to be integrated into the existing node topology. Usually, each node has wireless network interfaces with different radio standards (RS_1 and RS_2). $Node_1$ and $Node_2$ integrate two interfaces. In $Node_3$, only one interface is available. The established channels between the nodes bind communication resources. The resource management has to decide about the channel balancing in a cooperative process.

C. Example Scenario II - Fault Response

Concerning the decision process, the RMU calculates the remaining interface capacities with theoretical parameters of the respective communication standard specifications. In real-world multi-hop application scenarios, environmental disturbances and unexpected effects also have an huge influence on the communication behaviour. Especially in dynamic scenarios, obstacles represent critical limitations for a stable, continuous data transmission. *Figure 4* visualises such a situation.

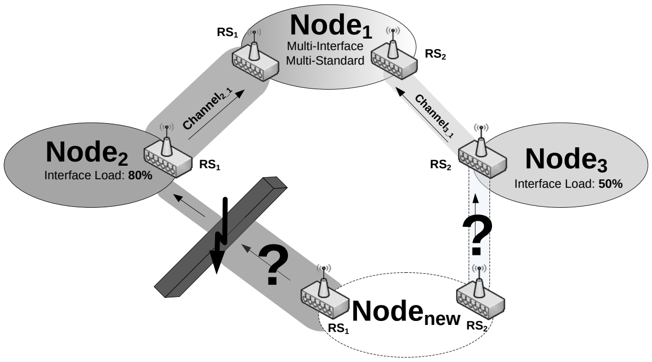

Figure 4. Channel allocation and reallocation scenario II. Typically, radio standard 1 (RS_1) provides more transmission capacities than RS_2 (backup channel). Due to obstacles, the usable channel capacity is not equal to the maximal capacities of the radio specification. The generated data stream in $Node_{new}$ requires situation-specific channel resources. In order to decide about the channel allocation, the RMU has to estimate the remaining capacities.

In consequence, the RMU monitors active channels for detecting bottlenecks in the communication. Accordingly, based on the given metric, critical data stream can be reallocated. Furthermore, such a proactive channel analysis allows a re-prioritisation of all active channels in order to optimise the network communication.

IV. TESTBED CONFIGURATION

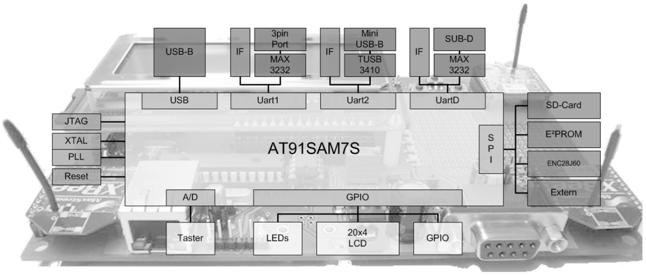

Figure 5. Prototype evaluation platform. The system architecture integrates different COTS wireless network interfaces into one integrated network node.

Based on the proposed concepts for a RMU, the radio standard integration and respective simulation results in [18], [11], we decided to design a prototype platform which implements the features in a multi-interface, multi-standard communication environment [10]. The platform interconnects up to four different network adapters with different communication standards. The wireless interfaces are connected via modular communication slots, which are compatible to COTS (*commercial off the shelf*) hardware components. *Figure 5* illustrates the system structure with the central ARM7 microcontroller. The platform is designed as an evaluation board on a proof of concept level. With respect to this application domain, the ARM7 provides a lot of computing performance for many possible test scenarios. Further developments will shrink the design to an ultra-low-power sensor board with a MSP430 microcontroller [19], [20]. Alternatively, an Artix-7 FPGA implementation is also possible.

This prototype platform allows us to test and analyse essential features of the proposed channel management concept, including the radio standard integration, the Ad Hoc communication standard switching as well as the dynamic resource reallocation. In this paper we present essential results regarding to the real-time protocol conversion and the respective channel reallocation capabilities.

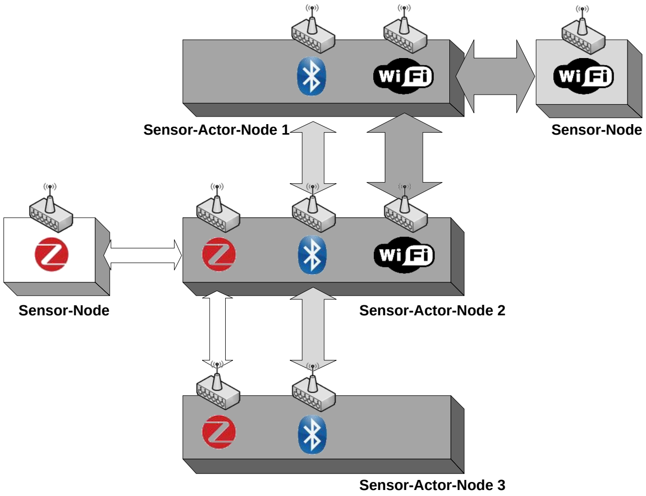

Figure 6. Demonstrator testbed environment. Each node provides several wireless network interfaces and capabilities for prioritised communication channels. The key challenge represents a cooperative management of different communication technologies.

Figure 6 shows the realised multi-hop network topology as a heterogeneous sensor-actor scenario. The given network infrastructure integrates three communication standards, based on IEEE 802.11, 802.15.1 and 802.15.4. During the test scenarios, each node generate sensor and control data with different priorities and different data volumes (acceleration, temperature, noise level, visual/audio data). Each communication standard is represented by a dedicated IP subnet. Accordingly, each node has the knowledge about technology-specific channel properties. Furthermore, additional information about the actual channel load and channel quality are available within the RMU. All the data streams have to be transmitted simultaneously. In consequence, the RMU allocates and reallocate various end-to-end channels. In case of a switching communication standard, the data payload will be converted dynamically in real-time. The conversion processes includes a header analysis, the packet reassignment and, if required, a re-segmentation of the payload.

V. RESULTS - PROTOCOL CONVERSION

The described testbed configuration represents an advanced multi-interface, multi-standard SANET. Based on this topology, we evaluate the channel reallocation capabilities, represented by the overall transmission times as well as the node internal protocol conversion times.

In a first scenario, we measure the latency for the protocol conversion during a bidirectional communication. As already mentioned, the conversion process is done on a hardware-near middle-ware between the ISO/OSI layer 2 and 3 (*EAN*). During the test cycles in *figure 7*, the data rate was increased step-by-step.

The illustrated diagrams visualise average values of 1000 continuous transmission cycles. As we can see, system architecture as well as the protocol conversion operate stable and efficient with delay times under 3ms. Anyway, each conversion process increases the communication overhead for a given channel. The overhead ratio is dependent on the data payload and the packet size. The key question is, how critical such a conversion process in relation to the overall multi-hop transmission is. If we take a closer look on our first scenario, the data forwarding latency increases minimally. *Figure 8* illustrates the results for a ZigBee to Bluetooth conversion with a normal packet size.

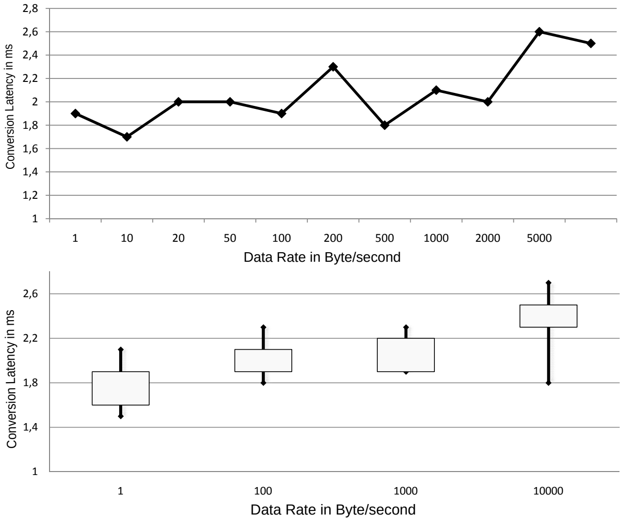

Figure 7. Top: Continuous protocol conversion measurements from Wifi (IEEE 802.11g) to ZigBee (IEEE 802.15.4). The transmission data rate starts with 1 Byte/second and ends with 10000 Bytes/second.
Bottom: Long term protocol conversion measurements from Bluetooth (IEEE 802.15.1) to Wifi (IEEE 802.11g) with different transmission data rates.

In contrast, the oscilloscope screenshot in *figure 9* represents a detailed waveform diagram of another conversion scenario from ZigBee to Wifi. This scenario uses very small data packets with minimal data payload. The environmental properties are similar to the first test scenario. The global addressing protocol is IP. As expected, the influence of the conversion process on the overall transmission delay is higher.

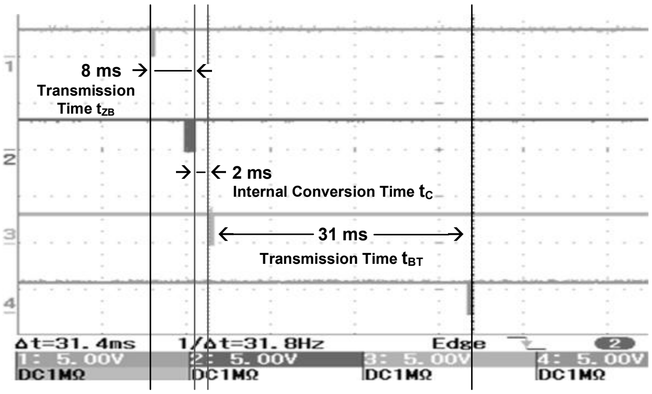

Figure 8. Bidirectional multi-hop communication measurement including a protocol conversion process from Bluetooth (t_{BT}) to ZigBee (t_{ZB}) and vice versa. The results were measured with an oscilloscope directly at the connectors without overhead from the operating system, especially by scheduling-based inaccuracies.

These results clarify the importance of an intelligent channel management, which is able to analyse the actual situation and considers both application-specific parameters and network behaviour.

Anyway, all test results provides a normal transmission behaviour without errors or disturbances. The dynamic channel reallocation between several multi-hop communication paths works stable. Hence, the proposed multi-interface channel management is feasible and very efficient for advanced application scenarios in the WSN and SANET domain.

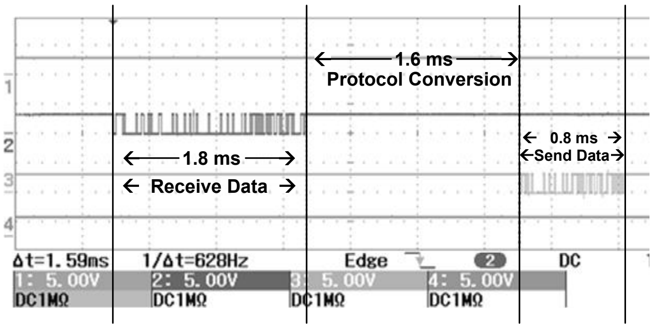

Figure 9. Detailed measurement of an Ad Hoc protocol conversion process from ZigBee (IEEE 802.15.4) to Wifi (IEEE 802.11g) standard on layer 3 (IP).

VI. CONCLUSION

In this paper, we propose a novel channel management concept for advanced WSN and SANET scenarios in heterogeneous communication environments. It focuses on dynamic channel switching techniques in order to realise an intelligent load balancing over the available wireless capacities. We clarify the importance of such concepts for critical application scenarios to ensure guaranteed resources. In combination with an innovative radio standard integration concept, we are able to optimise the communication behaviour significantly.

The presented test scenarios were done on a research prototype platform. The results demonstrate the feasibility of the proposed concepts. The realised network topology integrates several COTS sensor entities as well as multi-interface, multi-standard sensor-actor-nodes. All the measured timings for the protocol conversion need less the 3ms. Accordingly, the protocol overhead within a multi-hop communication increases minimal. At the same time, we create a reliable network infrastructure and improve the connectivity significantly.

Further research work combines the proposed resource management approach with *wake-up-receiver* technologies (*WuRx* [19], [20]) to evaluate innovative communication concepts for WSN/SANET applications. Another point of research deals with the integration of advanced transport protocols for WSN and SANET scenarios [21], [22].

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