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Resource Allocation and Resource Leveling in Heterogeneous SANET Environments

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***Abstract*: Actual research projects in the field of wireless communication systems focus on distributed, heterogeneous architectures for advanced Sensor-Actor-Networks (SANETs). Each subsystem provides specific capabilities for measuring or manipulating its environment. At the same time, a huge amount of sensor, status and control data has to be transmitted over different network interfaces and communication standards. During the runtime, the number and the quality of communication channels is changing dynamically. Especially in wireless multi-hop scenarios with several radio standards, the maintenance and the balancing of stable communication paths is critical.**

In this context, we present a cross-layer resource leveling approach in the domain of heterogeneous SANET environments. We are able to manage communication resources in an efficient and lightweight way. The introduced Resource Management Unit (RMU) ensures a cooperative communication and provides features for an on-demand channel reallocation. Hence, on lower layers we developed a real-time radio standard integration concept and use respective routing algorithms with adaptive multi-standard, multi-interface metrics.

For proof of concept, we designed and implemented an evaluation platform. Two different test scenarios focus on the dynamic channel reallocation capabilities as well as the real-time protocol conversion features between different communication technologies. The measured results of the test bed configurations clarify the necessity and the feasibility of a dynamic resource leveling concept in heterogeneous WSN/SANET environments.

Keywords: Multi-Interface, Multi-Standard, Multi-Channel, Resource Management, Heterogeneous Embedded Systems, Wireless Sensor Networks (WSN), Sensor-Actor-Networks (SANET), Energy Efficiency, Communication Optimization.

I. Introduction

Wireless Sensor Networks (WSN) and Sensor-Actor-Networks (SANET) represent distributed embedded systems which are able to sense its environment for specific events or behavior. Based on wireless communication interfaces, the subsystems (*nodes*) are able to exchange information. Actuator nodes are additional entities, which allow the system to manipulate the environment based on a predefined set of rules. To operate autonomously, each system has limited energy resources. Here, the efficient management of these resources is one of the most challenging research areas for mobile embedded systems.

To maximize 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 the hardware aspects, the concrete application scenario implies further operational restriction. In this context, a scenario-specific scheduling of all subtasks is critical to maximize the system efficiency [1].

Between hardware and the application layer, there are many possibilities for optimizations. The wireless communication interfaces and the respective resource management open a lot of interesting research topics. Topology optimization techniques reduce the complexity of network infrastructure. Novel routing algorithms are calculating efficient communication paths and adapted transport protocols ensure a complete information transmission with minimal protocol overhead.

Our proposed concept gathers system and network information from different layers to provide a topology-spanning management for communication resources. In order to introduce this resource leveling concept, this paper is structured as follows: After this introduction, section *II* provides an overview about optimized routing approaches, radio standards integration concepts and respective challenges. The proposed resource leveling concept is introduced in Section *III*, including the system architecture, channel modeling and reallocation schemes as well as different example scenarios. Accordingly, Section *IV* specifies the used test bed configuration and provides information of the respective evaluation platforms. Section *V* includes results of the first test scenario with focus on the dynamic channel reallocation and balancing capabilities. Test scenario two deals with the real-time protocol conversion features for heterogeneous SANETs. The respective results and a final data analysis is described and discussed in Section *VI*. Finally, the paper concludes with a summary and an outlook for future work in this research project.

II. Related Work

The result of all these techniques should be 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 [2], [3]. The idea is to split a data stream into multiple, potentially prioritized 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* [4], [5]).

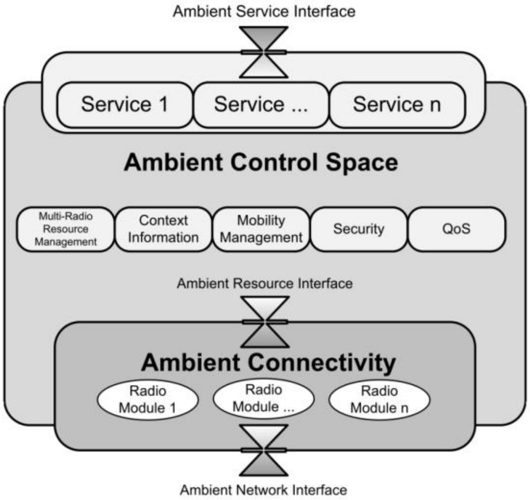

Figure 1. Radio Standard Integration: Ambient Network concept.

Other routing approaches use multi-dimensional metrics for optimizing the route paths. [6] and [7] describe concepts for gathering network information as well as additional system information from different abstraction layers. Such *cross-layer (X-layer)* approaches, like in [8], have a much better knowledge about the current network situation than traditional, unidimensional 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 [9]. 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 *Ambient Networks* [12], [13] create a platform-spanning communication infrastructure based a additional software-based abstraction layer with *Ambient Services*. Unfortunately, these services have to be managed on the application layer. The handling of available communication channels is coordinated by each user application. In consequence, each software has to be adapted for using the capabilities of Ambient Networking services. The concept is illustrated in *Figure 1*.

Cognitive Radios (CR) focuses on a low-level radio standard integration by allocating the available frequency spectrum dynamically. CR is operating on the hardware-near layer to minimize radio interferences and to adapt the communication channel dynamically [14], [15]. Bandwidth will be allocated on-demand and temporary. Based on the CR concept, a given communication technology is no longer associated to dedicated frequency bands (see *Figure 2*). Available resources are managed in cooperative way between the several devices [16], [17]. The problems here are governmental restrictions regarding the usage of protected frequency bands as well as compatibility issues and the adaptation of the device hardware.

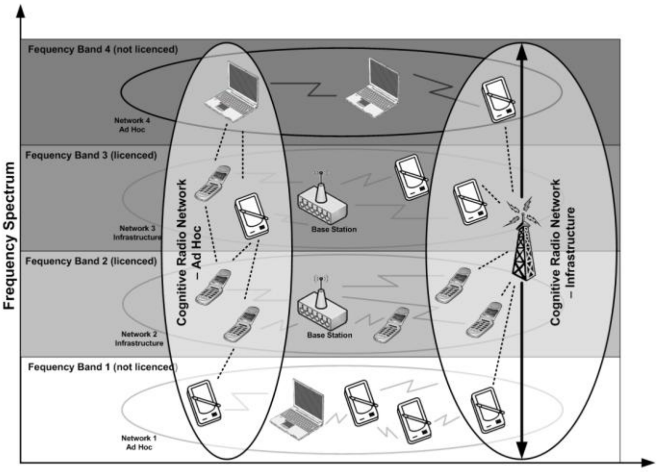

Figure 2. Radio Standard Integration: Cognitive Radio concept.

Software Defined Radios (SDR) represents another well-known concept for optimizing the communication in mobile application scenarios [18], [19]. 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 [20]. Unfortunately, due to the required hardware resources, SDR relies on high-performance DSPs (Digital Signal Processor) and general purpose CPUs. In contrast, SDR concepts are not applicable on resource-limited embedded systems with low-power microcontrollers [21]. Accordingly, SDR is not feasible to WSN / SANET application.

III. Dynamic Resource Leveling

Regarding to our proposed concept and with focus on dynamic scenarios, one challenging problem deals with 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. At the same time, we want to provide a concept, which is compatible to existing software applications and operating systems. Therefore, the management unit operates as a software component in the application layer and provides a dedicated API. Based on a set of services, the unit is able to monitor the network communication and to allocate communication channels for the user applications.

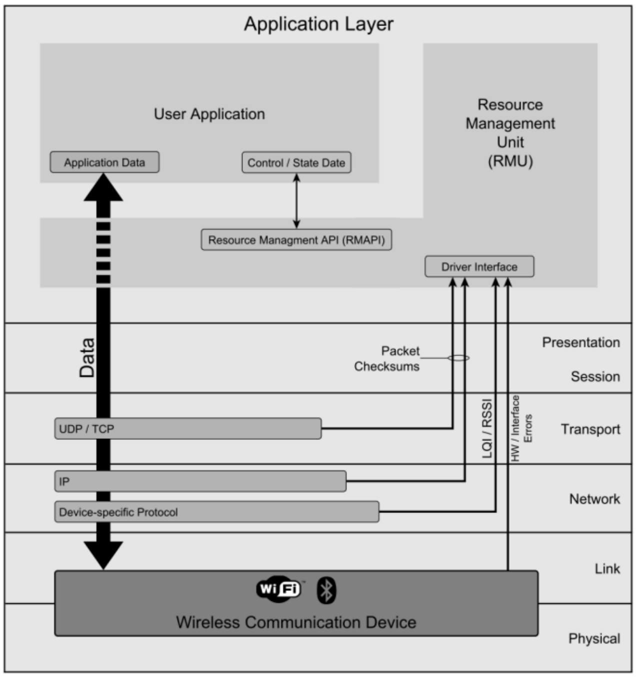

Figure 3. Resource Management Unit (RMU) and its integration into the protocol stack.

Figure 3 represents typical communication architecture and the integration of our proposed *Resource Management Unit (RMU)* [22], [23]. In contrast to related X-layer routing and communication approaches, the RMU uses standardized 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. The *Resource Management API (RMAPI)* provides a well-defined interface to the overall knowledge base of the RMU. Routing algorithms are able to retrieve status information of the system, e.g. the energy level or the actual channel quality at different wireless communication interfaces. On the other side, software applications are able to send specific constraints regarding bandwidth, priorities and timings to the RMU.

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 socket from the operating system, which means directly from the transport protocol interface. In our proposed concept, instead of opening the communication sockets directly, each application handles its requests over the RMU.

During the simultaneous communication with several channels, the RMU allows a proactive channel analysis for high prioritized 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 [9], [10], [11]. Currently, several international cooperation projects research for an embedded high-performance platform based on this EAN approach. In combination with the RMU, 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. For reallocating the communication channel or the communication technology, decision rules and calculation algorithm are very similar to cross-layer routing metrics. Accordingly, each decision within the RMU has direct influence to the routing mechanisms.

In contrast to multi-dimensional routing metrics on the network layer, the resource management concept operates parallel to user application on the ISO/OSI layer 7. Accordingly, the RMU coordinates all communication requests between user applications and network interface (see *figure 4*).

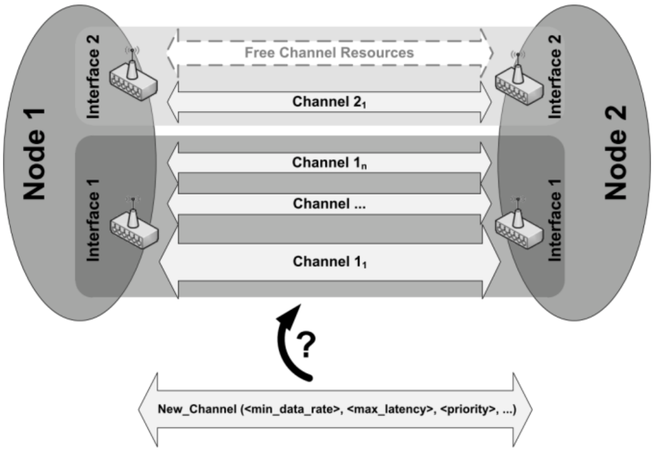

Figure 4. Dynamic resource allocation for efficient multi-channel communication

For providing an optimized, scenario-specific reallocation scheme, a multi-dimensional set of parameters is required for estimating the current situation. These parameters are categorized 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 prioritization

5) *Capacity utilization*
- interface load
- protocol overhead

B. *Example Scenario I - Balancing & Optimization*

The decision making processes of the RMU represents a challenging problem. *Figure 5* illustrates a typical scenario. In order to optimize 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 realize a multipath data prioritization. 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.

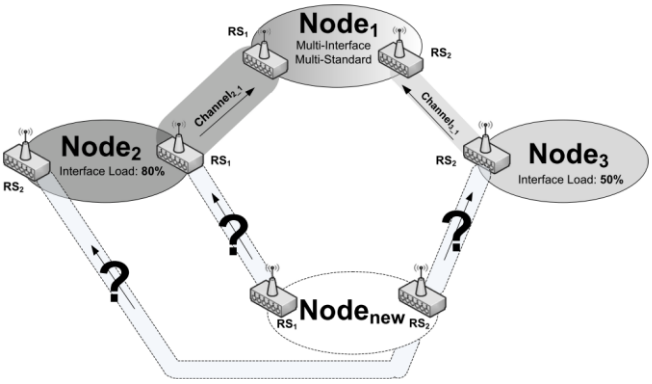

Figure 5. Channel allocation and reallocation scenario I. $Node_{new}$ has to be integrated into the existing node topology. Usually, each node has wireless network interfaces with different radio standards (RS_1 and RS_2). $Node_1$ and $Node_2$ integrate two interfaces. In $Node_3$, only one interface 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 behavior. Especially in dynamic scenarios, obstacles represent critical limitations for a stable, continuous data transmission. *Figure 6* visualizes such a situation.

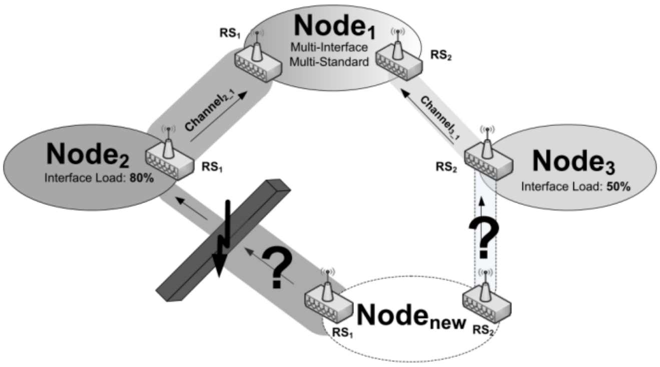

Figure 6. Channel allocation and reallocation scenario II. Typically, radio standard 1 (RS_1) provides more transmission capacities than RS_2 (backup channel). Due to obstacles, the usable channel capacity is not equal to the maximal capacities of the radio specification. The generated data stream in $Node_{new}$ 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-prioritization of all active channels in order to optimize the network communication.

IV. Test Bed Configuration

Based on the proposed concepts for a RMU, the radio standard integration and respective simulation results in [24], [25], [10], we decided to design a prototype platform which implements the features in a multi-interface, multi-standard communication environment [11]. 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 7* illustrates the system structure with the central ARM7 microcontroller. Additional sensor components are connected via dedicated communication busses, e.g. *I2C* (Inter-Integrated Circuit) or *SPI* (Serial Peripheral Interface).

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 [26], [27]. Alternatively, we actually develop an FPGA high-speed implementation, based on a low power *Xilinx Spartan-3E* FPGA. These kinds of platform offer an outstanding trade-off between performance and energy consumption.

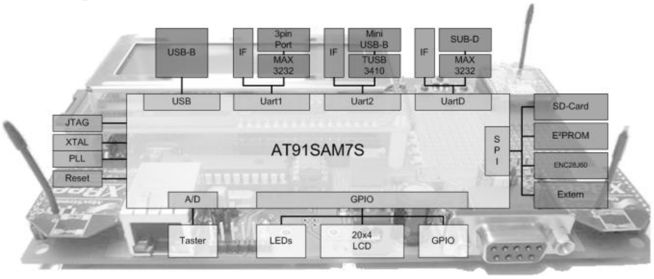

Figure 7. Prototype evaluation platform. The system architecture integrates different COTS wireless network interfaces into one integrated network node.

This prototype platform allows us to test and analyze 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 results regarding the channel reallocation capabilities for specific bottleneck situations (Section V) and the respective real-time protocol conversion features (Section VI).

V. Results – Proactive Resource Leveling

As already mentioned, the RMU allows a proactive analysis of communication channels. In order to fulfill the requirements of high prioritized data streams, critical communication paths have to be detected and to reallocate as soon as possible. Hence, we configured a test bench topology with five nodes, illustrated in *Figure 8*.

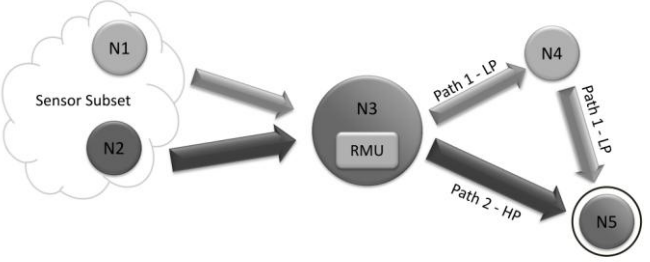

Figure 8. Network topology of test scenario I - Sensor data from the sensor nodes *N1* and *N2* with different priorities and volumes has to be transmitted to the data sink *N5*. There are 2 possible communication paths, one high prioritized, resource-intensive path directly from *N3* to *N5*. The other path via *N4* represents a low data rate, low power path for non-critical data. Both paths have a critical bottleneck, represented by node *N3*. Here, the RMU analyses the communication environment as well as application-specific constraints to avoid critical disturbance during the transmission.

Node *N3* represents the bottleneck for the communication between the sensor nodes (subset of node N1 and N2) and the data sink (node N5). Node N3 has to handle and forward data from different sources and with different priorities. During the test cycles, the sensor subset generates two dedicated data streams - one *low priority stream (LP)* and one *command & control stream* with *high priority (HP)*. Furthermore, there are two paths from the sensors to the data sink (node 5), the first one: *sensor nodes N1 + N2 → node N3 → node N4 → node N5*. The second connection (backup / high speed) *sensor nodes N1 + N2 → node N3 → node N5* has a dedicated interface with another communication technology. The characteristics of both communication interfaces are adapted to the low-power radio standard IEEE 802.15.4 / ZigBee and the mid-range standard IEEE 802.11b / WiFi.

The RMU within node N3 manages both interfaces based on the actual channel situation in the environment, to local network load and application-specific requirements. To fulfill the time-critical constraints of the HP data stream, these packets have to be transmitted directly to node N5. In case of normal operation, all LP sensor data is scheduled and processed through the low-power connection. In case of increasing net load, the decision engine of the RMU detects critical communication behavior and reallocates parts of the data stream to the second interface. In our test scenario, the primary reallocation indicator is the network interface queue. Here, 90% filling level represents the critical trigger value for the RMU. In addition, QoS aspects of each application task and the channel quality on the MAC layer are also analyzed by the RMU metric.

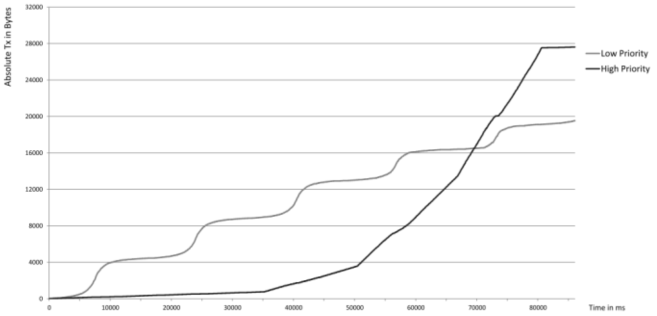

Figure 9. Absolute values for the transmitted data from the sensor subset to the data sink. The 2 lines represent both data streams (low and high priority).

Figure 9 visualizes the overall amount of the transmitted data. During the test scenario, the data rate was increased stepwise to provoke a stress level for the communication tasks.

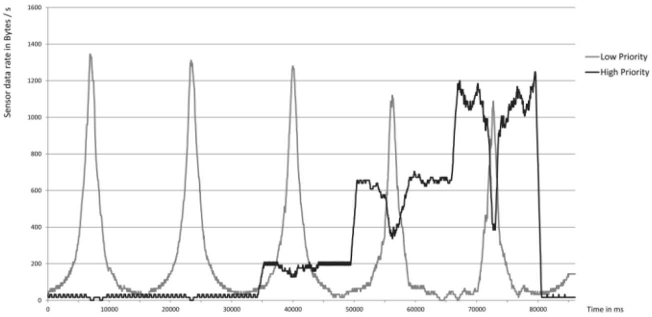

Figure 10. Visualization of the generated data load for both data streams. Based on these values and the environmental network behavior the RMU reallocates the communication resources dynamically.

The second diagram in *Figure 10* illustrated the respective data rate per second for both data streams. The sum of all data has to be processed by node N3 in an efficient way and with minimum delay. As we can see, both data streams provoke several communication peaks within N3. Without resource leveling capabilities, we generate worst case situations with an interface overload for the LP path. To avoid network disturbances, the RMU has to balance the netload. Based on the cross-layer knowledge base, the RMU optimizes the communication and bypasses the overload situation dynamically.

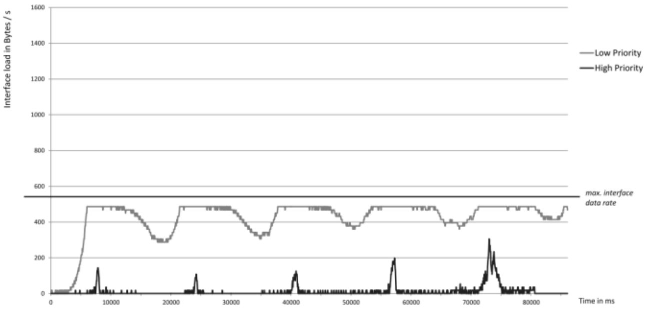

Figure 11. Visualization Measured interface load in the bottleneck node. The RMU uses additional capacities for the communication on demand. The maximum interface load of the low priority interface is marked with the horizontal line. The 90% trigger value for the RMU is clearly recognizable.

The results in *Figure 11* clarify the efficiency of the RMU resource leveling capabilities. By reaching 90% filling level of the LP interface, the RMU starts to reallocate the communication load.

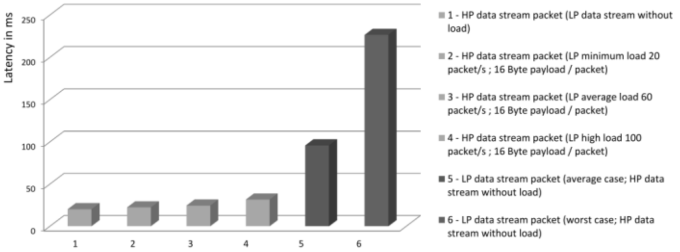

Figure 12. Measured end-to-end delays for both HP (*sensor nodes N1 + N2 → node N3 → node N5*) and LP (*sensor nodes N1 + N2 → node N3 → node N4 → node N5*) data streams. The different values represent different net load situations during the communication process.

In this context, *figure 12* shows respective latency measurements for both communication paths. As we can see, the end-to-end delay for the high priority data remains stable during different net load situations. In a worst case scenario, the LP stream shows significant increased latency values. Without resource management capabilities, the LP communication path would collapse immediately.

VI. Results - Real-Time Protocol Conversion

The second test scenario deals with the real-time protocol conversion features of the RMU concept.

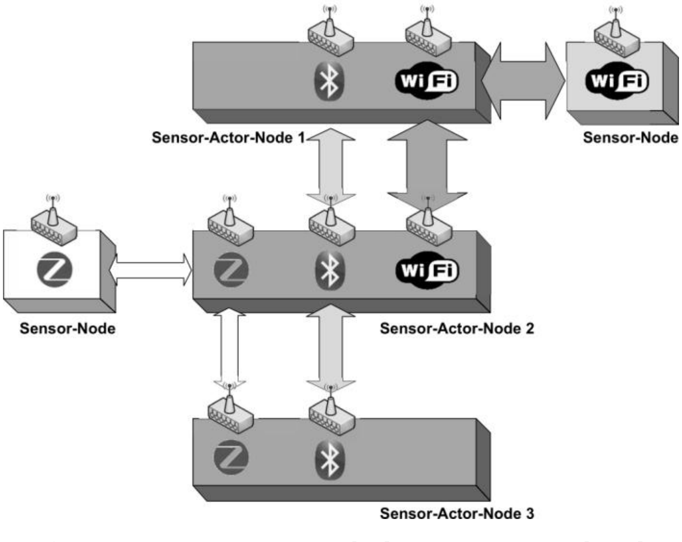

Figure 13. Demonstrator test bed environment. Each node provides several wireless network interfaces and capabilities for prioritized communication channels. The key challenge represents a cooperative management of different communication technologies.

Figure 13 shows the implemented multi-hop network topology as heterogeneous sensor-actor test bed. The given network infrastructure integrates three communication standards, based on IEEE 802.11, 802.15.1 and 802.15.4. During the test cycles, each node generates data with different priorities and different data volumes (acceleration, temperature, noise level, visual/audio data, command & control data). Each communication standard is represented by a dedicated IP subnet. Accordingly, each node has 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. For switching the communication technology, 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.

The described test bed configuration represents an advanced multi-interface, multi-standard SANET environment. Based on EAN concept, we evaluate the channel reallocation capabilities based on the protocol conversion latency as well as the overall end-to-end transmission delay. Here, we measured the latency for the protocol conversion during a bidirectional communication. As already mentioned, the conversion process is done on hardware-near middleware between the ISO/OSI layer 2 and 3 (*EAN*). During the test cycles in *figure 14*, the data rate was increased step-by-step.

The illustrated diagrams visualize average values of 1000 continuous transmission cycles. As we can see, system architecture as well as the protocol conversion operates stable and efficient with delay times under 3ms.

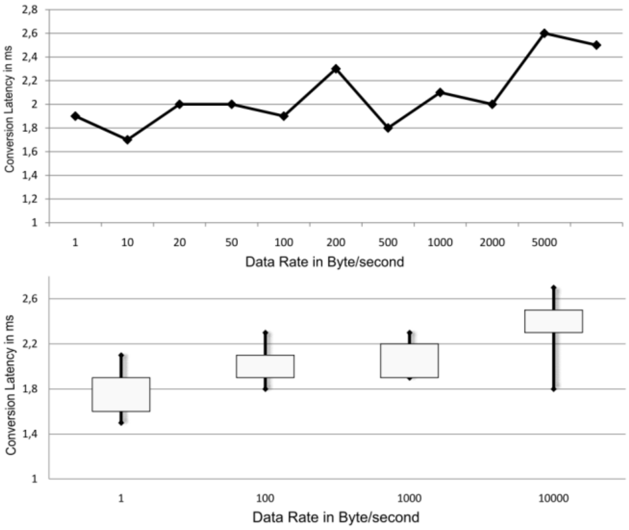

Figure 14. *Top*: Continuous protocol conversion measurements from WiFi (IEEE 802.11g) to ZigBee (IEEE 802.15.4). The transmission data rate starts with 1 Byte/second and ends with 10000 Bytes/second.

Bottom: Long term protocol conversion measurements from Bluetooth (IEEE 802.15.1) to WiFi (IEEE 802.11g) with different transmission data rates.

Anyway, each conversion process increases the communication overhead for a given channel. The overhead ratio depends on the data payload and the packet size.

The key question is, how critical is such a conversion process in relation to the overall multi-hop transmission?

If we take a closer look on our measurement scenario, the data forwarding latency increases minimally. *Figure 15* illustrates the results for a ZigBee to Bluetooth conversion with normal packet size.

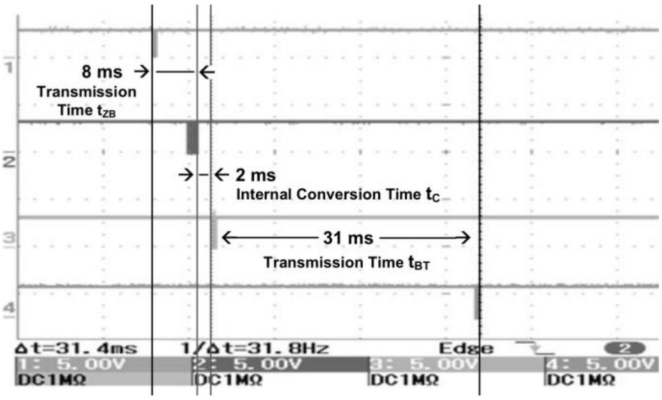

Figure 15. Bidirectional multi-hop communication measurement including a protocol conversion process from Bluetooth (t_{BT}) to ZigBee (t_{ZB}) and vice versa. The results were measured with an oscilloscope directly at the connectors without overhead from the operating system, especially by scheduling-based inaccuracies.

In contrast, the oscilloscope screenshot in *figure 16* 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. The results of both test scenarios clarify the importance of an intelligent resource management, which is able to analyze the actual situation and considers both application-specific parameters and network behavior.

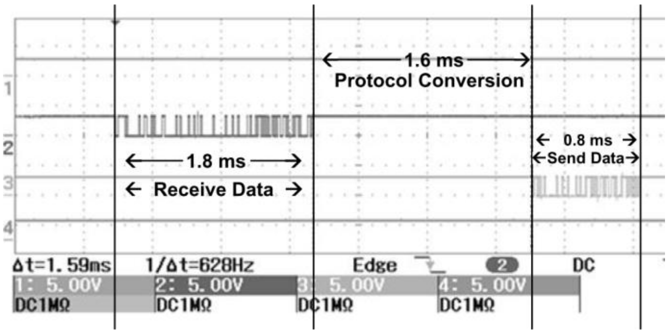

Figure 16. Detailed measurements of an ad hoc protocol conversion process from ZigBee (IEEE 802.15.4) to WiFi (IEEE 802.11g) on layer 3 (IP).

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

VII. Conclusion

In this paper, we propose a novel resource management and resource leveling concept for advanced WSN/SANET scenarios in heterogeneous communication environments. The concept focuses on dynamic channel switching techniques for realizing an intelligent load balancing of wireless communication capacities. In order to ensure guaranteed resources for critical applications with real-time constraints, we clarify the importance of such resource management approaches. In combination with an innovative radio standard integration concept, we are able to optimize the communication behavior significantly.

The presented test scenarios were done on a research prototype platform. The results demonstrate the feasibility of the proposed concepts. The realized 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 than 3ms. In consequence, these additional transmission delays are negligible. At the same time, we create a reliable network infrastructure and improve the connectivity in the topology significantly.

Further research work combines the proposed resource management approach with *wake-up-receiver* technologies (*WuRx* [27], [26]) 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 [28], [29].

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