Going All the Way – Detecting and Transmitting Events with Wireless Sensor Networks in Logistics

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***Abstract*—The logistics domain constitutes a promising application area for wireless sensor network technology. Wireless sensor nodes can be deployed for example in containers or trucks' load areas to monitor environmental parameters relevant to the condition of transported goods in real time. Exploiting their computation and communication capabilities, wireless sensor nodes can locally detect the occurrence of critical situations, so-called events, and send corresponding alarm messages to responsible decision makers via the network and corresponding gateway nodes in real time. Within this paper, we present a fully working solution and corresponding prototypical implementation of how such real-time monitoring and event detection can be realized in a context-dependent and user-specific way. As such a system requires transmitting alarm messages and sensor data from the wireless sensor network deployment to users' backend systems, we furthermore explore means to interconnect wireless sensor nodes and smartphones. In particular, we present findings from field tests concerning the link quality of such connections for different technological approaches for which we realized prototypical implementations.**

I. Introduction

Providing diverse sensing, computation, and wireless transmission capabilities, wireless sensor network (*WSN*) technology constitutes a very promising enabling technology to realize pervasive real-time monitoring solutions as asked for within the logistics domain. Wireless sensor nodes (*motes*) can for example be deployed in containers or trucks' load areas to monitor diverse environmental parameters relevant to the condition of transported goods and transmit alarm messages to responsible decision makers via according gateways in case a critical parameter value has been reached.

Within the logistics domain, the area of Supply Chain Event Management (*SCEM*) would in particular benefit from such an application of WSN technology. SCEM constitutes a management concept, which incorporates the management of logistics processes based on events and is supported by corresponding IT systems. The basic idea of SCEM is that process adaptation only takes place in case an event is detected, whereas an event is understood as an essential state change for certain addressees [2]. Thus, motes can be used to detect such events at the place of occurrence by locally assessing the gathered sensor data and comparing it for example to pre-defined goods-specific thresholds. In case a mote detects a threshold violation this would constitute an event in the sense of the event term used in the context of SCEM and the transmission of a corresponding alarm message would be initiated. Such a detection of events locally at their point of occurrence and in real time would allow to reduce the time between event occurrence and notification of a responsible decision maker, with the ability to initiate according countermeasures, to a minimum, which consequently reduces reaction times and can lead to a wider range of applicable countermeasures and process adaptations and thus to reduced damage caused by the occurred event.

To realize such an event detection system, several components are required, ranging from methods to detect events locally on motes over means to transmit such locally detected event information to users' backend systems up to the corresponding (visual) presentation of detected events to a user. In the work at hand, we present an architecture for such an event detection system and describe our realizations of the diverse components required in such a system. In particular, we additionally evaluate different means to provide a connection between motes and smartphones, employed as gateways for long-range data transmission in our architecture, in various field trials. Thus, the major contributions of our work are:

- An architecture for a system for real-time event detection and notification in logistics transport processes with WSN technology.
- A prototypical realization of the developed system.
- An evaluation of different approaches for mote and smartphone integration concerning link quality.

The remainder of this paper is structured as follows: Section II provides an introduction to the considered application scenario. In Section III, an overview over related work is given. Our system for real-time detection and transmission of events in logistics transport processes with WSN technology is outlined in Section IV. The implementation details for the developed prototype of our system are described in Section V. Section VI provides the setup and the corresponding results of the evaluation we conducted for our approach. We conclude with a summary of our findings and an outlook on future work in Section VII.

II. Application Scenario

As already indicated, the logistics domain constitutes a promising application area for WSN technology. In particular, WSN technology can be employed to realize real-time monitoring of transport processes (cf., e.g., [14]), for example

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to enhance process visibility and enable an early detection of critical situations during a transport. For this purpose, motes can be deployed for instance on different levels within a container, e.g., on container level, on the level of individual palettes, on the level of individual items, etc., and consequently be used to monitor diverse environmental parameters relevant to the transported goods' conditions. These parameters can for example comprise temperature values during temperature-sensitive transports, shake and tilt values in case shock-sensitive goods are transported, or gas concentrations during animal transports. Employing a corresponding gateway for long-range data transmissions to users' backend systems, like the use of a smartphone as we propose it in the work at hand, consequently allows to deliver status updates to users in real time. Such real-time transport monitoring would for example create substantial benefits during temperature-sensitive transport processes, as for instance temperature mismanagement and corresponding quality decay leads to product losses of up to 35% in food transportation [21].

Specifically, we envision SCEM as an area within the logistics domain, which would exceptionally benefit of such application of WSN technology in transport processes. As already indicated, SCEM represents a management concept, supported by a corresponding (software) system, which is based on controlling logistics processes on the basis of events (cf. [19]). In this context, events are understood as essential state changes for certain addressees [2]. An event occurrence constitutes the need for an appropriate reaction by taking an according (management) action, like initializing a process adaption. Exploiting their sensing, computation, and communication capabilities, motes deployed within a container can for example be used to detect such events by locally comparing sensor measurements to given critical thresholds and thus identify events in form of threshold violations in real time locally at the point of their origin and by using according gateways, responsible decision makers can be informed immediately of the event occurrence. This provides them with the opportunity for an early initialization of countermeasures to minimize the damage inflicted by the event on the whole process.

Consequently, our work is focused on supporting SCEM (systems) by enabling a local real-time event detection and corresponding notification of responsible decision makers in logistics transport processes on the basis of WSN technology. In particular, we focus on container transports, i.e. WSN deployments within a container like a swap trailer, a reefer container, a standard container for intermodal transportation, or even more generally a truck's load area. Thus, in the following we consider an application scenario as sketched in Fig. 1.

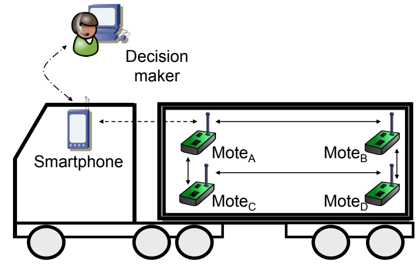


Fig. 1: Application scenario illustrated

III. Related Work

As outlined, real-time monitoring of logistics transport processes has been identified as a promising application area for WSN technology. Consequently, some initial realizations of real-time monitoring of logistics transport processes employing WSN technology have already been provided, both from researchers as well as from industry.

Applying WSN technology in logistics has been a major research focus of the Collaborative Research Center 637 "Autonomous Cooperating Logistic Processes" at the University of Bremen. In this context, research towards the realization of an "Intelligent Container" has been conducted [14]. Prototypical realizations of such an Intelligent Container have been developed making use of a WSN combined with RFID technology and a central processing and communication unit on the basis of an ARM-based embedded system placed within the container [10], [15], [1], [16]. In combination with the use of software agents, the researchers provided initial solutions for autonomously controlled transport processes in particular in the area of food and cold chain logistics [13]. In this context, they specifically focused on means for local, container-centric transport monitoring based on rules, which allows to realize automated transport planning and execution [12].

With the goal to realize reductions in insurance rates, Traulsen et al. investigate possibilities for real-time monitoring of container transports with WSN technology [27]. The authors provided a prototypical realization on the basis of motes developed in-house in combination with a mobile gateway as well developed in-house. Specifically, they made use of their so-called S3-nodes [8] as mote platform and used a customized mobile embedded Linux PC as gateway, which gathers the data from the motes, processes it, e.g., adding GPS or timestamp data, and provides a long-range data transmission channel to transmit the data to corresponding backend systems via UMTS/GSM.

DHL's solution "SmartSensor GSM" is an industry-driven development for realizing "near real-time visibility" in logistics transport processes [3]. The developed solution comprises a sensor module equipped with temperature, humidity, shock, and light sensors and an on-board GSM module for long-range data communication. Furthermore, the GSM module is used to determine the geographical location of the sensor module based on the corresponding cell ID from the employed mobile telephone system. This sensor unit is equipped with five AA batteries and for example stowed in the packaging of the transport good to be monitored. The module can be configured with individual sensing intervals ranging from 10 minutes to 24 hours and with data transmission intervals, for transmitting the gathered sensor data to a dedicated DHL website, ranging from 30 minutes to 24 hours. Additionally, threshold-based alarms are supported leading to data transmissions in case one or more monitored parameters exhibit a threshold violation. A similar solution is provided by FedEx with "SenseAware" [7].

Opposed to SmartSensor GSM and SenseAware, DB Schenker's solution DB SCHENKERsmartbox [22] is focused on container transports, in particular in the field of sea transport. DB Schenker employs a sensor unit with integrated communication technology for wireless long-range data transmission, which is attached to a container. This device allows real-time tracking based on GPS and with its sensors, it additionally allows the measurement of diverse environmental parameters like temperature, humidity, light, and vibration to enhance the visibility in an ocean freight transport process. The gathered data is provided to users via a dedicated website.

The described approaches usually employ dedicated hardware providing autarkic gateways to realize a connection between WSN and backend systems. This leads to additional costs for the overall WSN deployment, which is problematic in the cost-driven domain of logistics. Therefore, we focus on the interconnection of motes and smartphones to be able to use a smartphone available in the truck driver's cabin as gateway between WSN and backend systems. This allows to achieve cost savings by using hardware which is already available or can cheaply be purchased and additionally is used for multiple purposes within the truck during a transport process, like order processing or as navigation system. Furthermore, employing a smartphone as gateway between WSN and users' systems allows to directly inform the truck driver of the current status in the container, respectively the truck's load area, via a device which he is familiar with, so that even during transport stages in which no cellular phone network and thus no connection to a backend is available at least the truck driver is informed immediately of a critical situation and can react to it.

Moreover, the above described realizations do not explicitly focus on the benefits of employing event-driven systems and most often focus on the information needs of one stakeholder, which usually are incorporated locally on a mote by rather simple rules based on thresholds of the monitored parameters. Opposed to this, our approach explicitly accounts for the fact that usually different stakeholders with different information needs are involved in a logistics transport process by allowing to simultaneously take these different information needs into account with our event-based concept, making use of an event bus where different stakeholders can be subscribed simultaneously for different events expressing their information needs. In addition, our scoresheet-based approach allows a more fine-grained expression of individual information needs compared to the usually employed rather simple environmental parameter-driven threshold-based approaches by taking into account diverse context parameters for event detection.

IV. System Overview

In order to provide a system to locally detect events on motes and subsequently transmit corresponding alarm messages with the according event information to responsible decision makers in real time, several software and hardware components are needed (cf. Fig. 2). Specifically, a software solution for local event detection which can run on resource-constrained motes is required as well as means for long-range data transmissions to users' backend systems and corresponding means for distributing and displaying the incoming data to users. To provide decision makers responsible for the monitored transport processes with an easy access to the incoming sensor data and in order to easily visualize according event notifications to these decision makers, we suggest using a web-based user interface, which allows the decision makers to access the data via a standard web browser. Furthermore, a web-based user interface can provide decision makers with an intuitive means to individually adapt the parameters within the scoresheets for event detection employed in our system (cf. below).

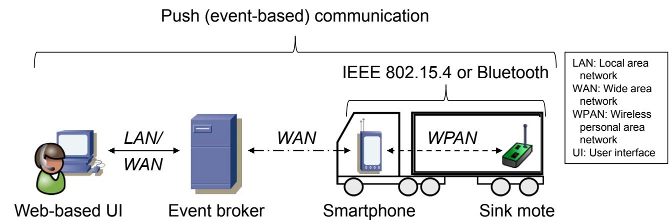


Fig. 2: System overview

The user interface is consequently connected to a web server and as the envisioned communication will be event-driven, we propose to follow the event-based push communication paradigm. Thus, the web server simultaneously hosts an event broker. This event broker allows the registration to different events and takes care of queuing and subsequently distributing incoming event data to the according registrars and vice versa allows to distribute the different scoresheets, which express users' individual information needs, to the deployed motes.

As already outlined, to realize the long-range data communication between WSN deployment and backend systems, we propose to employ a smartphone as gateway between WSN and the event broker. So, specifically the smartphone should be connected to the sink mote of the WSN deployment in the truck's load area. This can for example be realized either via IEEE 802.15.4-based communication or Bluetooth communication.

As means for the local detection of events on motes, we employ our approach from [29], [30], which is based on the application of so-called "scoresheets". These scoresheets allow users to individually define in a very fine-grained way diverse context parameters according to their information needs, which are afterwards used to locally assess sensor measurements on motes to detect events.

Thus, in summary within our system, a user would specify individually which parameters constitute an event making use of our scoresheets via a web-based GUI. The completed scoresheet would be transmitted via the event broker and the smartphone-based gateway to the in-container motes. In case a mote would detect an event according to the received scoresheet parameters, a corresponding alarm message would be transmitted through the WSN to the sink mote, which then would forward the alarm message to the smartphone-based gateway. From there, the alarm message would be pushed to the event broker, which would then distribute the message to the according user. Finally, the alarm message would be displayed to the user via the web-based GUI in his browser so that he could react immediately to the occurred event.

V. System Realization

As underlying mote platforms for our system, we chose the TelosB platform [18] and the SunSPOT platform [25], [24]. The TelosB platform as well as the SunSPOT platform constitute both established mote platforms within the WSN community and the TelosB has already been employed in prototypical realizations of smart environments in the logistics domain [17], [1].

As one basic foundation, our system requires a bi-directional communication channel between backend system and in-truck WSN deployment. In order to realize such a communication channel, we employ a smartphone, concretely a Samsung Galaxy S3 [20], as gateway between backend system and the WSN's sink mote for long-range data transmission of WSN data to users' backend systems. Specifically, we make use in our system of an extended version of our solution for inter-connecting smartphones and motes presented in [31]. In this context, we basically differentiate the usage of Bluetooth extension modules on motes as one possibility to connect a mote to a smartphone based on Bluetooth communication and the usage of extension modules capable of IEEE 802.15.4-based communication on smartphones to provide an IEEE 802.15.4-based communication link between a mote and a smartphone. Specifically for realizing the Bluetooth-based communication on the employed motes, we used two different Bluetooth extension modules, namely the SparkFun BlueSMiRF Gold-module [23] and the JY-MCU module purchased from DX [5]. Each module was attached via the UART pins both to a TelosB mote and a SunSPOT mote. In order to provide the Galaxy S3 with IEEE 802.15.4-based communication capabilities, we equipped the smartphone with an XStick 802.15.4 from Digi [4] via the smartphone's USB port with a USB On-The-Go cable. We employed the USB Host Mode offered by the Android operating system since version 3.1 and the Galaxy S3 to power the attached XStick. Concretely, the XStick acts as USB slave and gets the required power from the Galaxy S3 acting as USB host in this setting.

For the described hardware setups, we developed according smartphone apps, which realize the access to the smartphone's internal Bluetooth module or the smartphone's USB port, respectively. Thus, the apps are responsible for reading out data coming in from the sink mote via the smartphone's Bluetooth connection or via the employed XStick 802.15.4 attached to the smartphone's USB port. Vice versa, the apps are as well responsible to push data to be transmitted to a sink mote to the smartphone's internal Bluetooth interface or the USB port, respectively. For this purpose, both apps are basically used as wrappers to the corresponding interfaces of the smartphone and provide additional parser and logger functionalities to interpret the incoming data streams according to the underlying packet structures and write the parsed data to a local file on the smartphone. Furthermore, the apps can enrich the received sensor data with location information obtained from the smartphone's GPS unit and finally they take care of transmitting the received data to the backend system. Our app for realizing the Bluetooth-based communication setup, is based on the Bluetooth app provided by ElecFreaks [6] and makes use of its Bluetooth client capabilities. We have extended the app with the mentioned parsing and logging functionalities and added means for displaying the received data in hex format on the smartphone's screen. The app for realizing the IEEE 802.15.4-based communication setup, and thus realizing the access to the XStick 802.15.4 via the smartphone's USB port, is based on the D2XX driver and the corresponding demo app provided by Future Technology Devices International [9]. Again the used basic app has been extended with the mentioned parsing and logging functionalities. In order to capture the GPS data provided by the smartphone's internal GPS module to be able to add location data to the gathered sensor data, we employed the Big Planet Tracks app [28].

To realize a transparent communication between smartphone and motes even in the heterogeneous mote environment used in our prototypical setup with applying TelosB motes and SunSPOT motes, we modified the existing radio stack of the SunSPOT platform so that the SunSPOT is enabled to realize data transmissions similar to TelosB data transmissions. Therefore, we internally addressed the radio chip directly and could thus achieve a homogeneous addressing scheme and means for data transfer, which allowed our smartphone app to communicate with the corresponding sink mote in a mote platform-agnostic way.

Within our backend system, we make use of an event broker to realize the event-based data exchange. Specifically, we employ Apache ActiveMQ [26] for this purpose. Consequently, our smartphone app pushes messages originating from the WSN deployment to ActiveMQ, which afterwards distributes the messages to according registrars. Vice versa, the scoresheets specified by users for the local on-mote event detection are as well pushed from the user interface to ActiveMQ, which again afterwards distributes them to the according smartphone constituting the gateway for the WSN deployment to be addressed.

Concerning the user interface, we decided to realize a web-based GUI to achieve platform- and device-independence. Our web-based GUI is realized using Java and Javascript in combination with Google Web Toolkit (*GWT*) [11] and its corresponding tools. Thus, our web-based GUI can be consequently accessed by users with their browsers and offers them the possibility to specify individual scoresheet parameters for the local on-mote event detection. Furthermore, incoming event notifications are visualized in the web-based GUI as well. In this context, GWT provides us with a means for realizing the required website presentation as well as with the possibility to connect to the ActiveMQ in order to receive and transmit event messages, respectively scoresheet settings.

VI. Evaluation

In order to provide a reliable and accurate picture from the truck's load area, respectively a container, and accordingly being able to inform decision makers reliably and in real time about detected events, a stable link between WSN and smartphone, constituting the gateway to users' backend systems in our approach, is required. In [31], we already provided energy measurements for different approaches to basically connect motes and smartphones. Evaluating the energy consumption of Bluetooth-based and IEEE 802.15.4-based solutions there, we were able to show that Bluetooth-based solutions consume twice to six times as much energy than IEEE 802.15.4-based solutions. In consequence, we now did not conduct any energy measurements or otherwise energy-related experiments during our evaluation. We rather focused our evaluation in the work at hand on the assessment of link quality for different communication possibilities between motes and smartphones in order to assess the basic feasibility of interconnecting motes deployed in a truck's load area and smartphones positioned in a truck driver's cabin and the resulting link quality in such a scenario. More specifically, we measure packet loss rates and RSSI for different hardware settings and under different circumstances during field tests with a prototypical deployment within a truck-based transport.

A. Evaluation Setup

For our evaluation experiments, we made use of our Galaxy S3 attached to the front windshield of the truck (cf. Fig. 3). The Galaxy S3 acted as receiving gateway for data transmissions from the employed mote platforms, which constituted of the TelosB mote platform and the SunSPOT mote platform in combination with the different external Bluetooth modules as described in Sec. V. Using the two different mote platforms allowed us to assess the consequences of employing a rather lightweight platform, with the TelosB platform, compared to employing a rather heavyweight platform, with the SunSPOT platform, within our evaluation experiments. Concerning the Bluetooth extension modules, the usage of the JY-MCU module and the SparkFun module allowed us as well the comparison of effects originating from employing two contrasting modules. The JY-MCU module can be bought for less than 9USD and thus provides a rather cheap solution which comes at the cost of lower capabilities compared to the SparkFun module, which costs 50-60USD.

Within our test runs, we captured the incoming packets from the smartphone's internal Bluetooth interface, respectively from the USB port to which the XStick 802.15.4 had been attached, with our apps described above. During the tests, we specifically logged from the received packets the sequence numbers, to determine the packet loss rate, the timestamps and, within the setups employing the SunSPOT motes, additionally the x-axis and z-axis acceleration measurements provided by

Fig. 3: Measurement setup in driver's cabin

the SunSPOT's internal sensors. We stored all this information locally in a text file on the smartphone to be able to evaluate it later on.

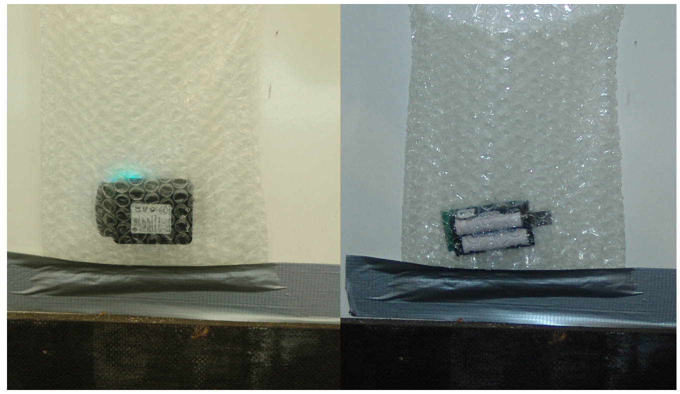
Additionally, within the test setups for evaluating the performance of the built-in IEEE 802.15.4-based radio modules of the employed motes, we in parallel made use of a SunSPOT as packet sniffer. Therefore, we attached a SunSPOT basestation to a laptop within the truck driver's cabin (cf. Fig. 3), which received the broadcasted packets from the mote deployed in the truck's load area and as well logged timestamps and sequence numbers, but additionally recorded RSSI values for the received data packets. This became necessary as the full API mode of the XStick 802.15.4 module is currently not supported on the employed Android platform and in the default transparent operating mode, we made use of instead, only the payload portion of the received data packets is made available to the Android smartphone via the module's serial interface. Thus, we were not able to access information on the signal quality of the data transmissions by means of the XStick 802.15.4 module on our Android smartphone and had to make use of the described SunSPOT-based packet sniffer solution.

The correspondingly employed measurement setup is depicted in Fig. 3.

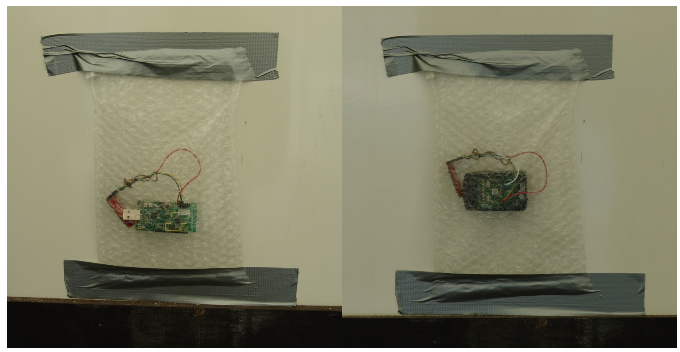
During our field tests, we conducted individual test runs, always attaching one of the above described mote setups within a plastic bag at the middle of the back wall of the truck's load area, approximately at the same height at which the receiving smartphone setup has been positioned at the front windshield in the truck driver's cabin (cf. Fig. 4). Within the experiments, the motes were configured to regularly initialize data transmissions employing broadcast communication transmitting five data packets per second in order to achieve enough data transmissions during a reasonable period of time. We conducted measurements for the TelosB platform and for the SunSPOT platform, both during different stages of the transport. Thus, we performed three different test runs for each mote setup measuring the packet loss during data transmission while the truck was standing still with its engine off, while the truck was standing still with its engine on and during a test drive, which was conducted along a route comprising route segments within a city environment, implying a maximum speed of 50 km/h and regular stop-and-go traffic, as well as route segments on highways beyond the city limits, implying a maximum speed of 90 km/h. This leads to 18 test cases as summarized in Tab. I.

TABLE I: Evaluation Test Cases

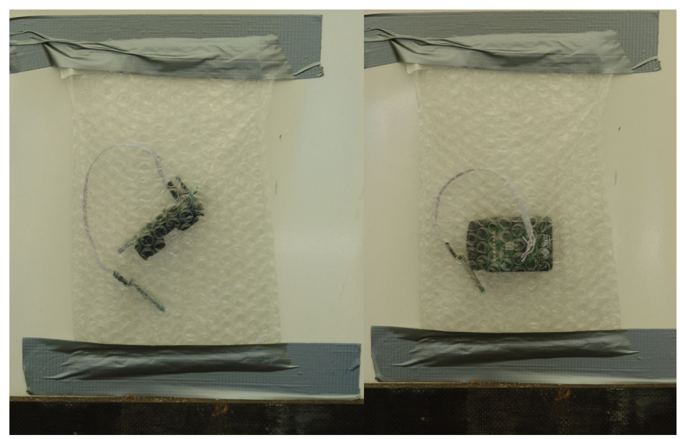
Mote	Radio Module	Truck Status	Abbreviation
TelosB	BlueSMiRF Gold	Standing, Motor Off	*TBBluSOff*
		Standing, Motor On	*TBBluSOn*
		Driving	*TBBluD*
	JY-MCU	Standing, Motor Off	*TBJYSOff*
		Standing, Motor On	*TBJYSOn*
		Driving	*TBJYD*
	Internal IEEE 802.15.4-based	Standing, Motor Off	*TB15.4SOff*
		Standing, Motor On	*TB15.4SOn*
		Driving	*TB15.4D*
SunSPOT	BlueSMiRF Gold	Standing, Motor Off	*SPBluSOff*
		Standing, Motor On	*SPBluSOn*
		Driving	SPBluD
	JY-MCU	Standing, Motor Off	*SPJYSOff*
		Standing, Motor On	*SPJYSOn*
		Driving	*SPJYD*
	Internal IEEE 802.15.4-based	Standing, Motor Off	*SP15.4SOff*
		Standing, Motor On	*SP15.4SOn*
		Driving	*SP15.4D*



(a) Mote deployment for IEEE 802.15.4-based communication evaluation



(b) Mote deployment for BlueSMiRF-based communication evaluation

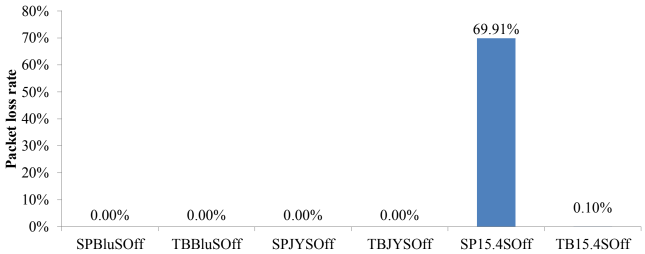


(c) Mote deployment for JY-MCU-based communication evaluation

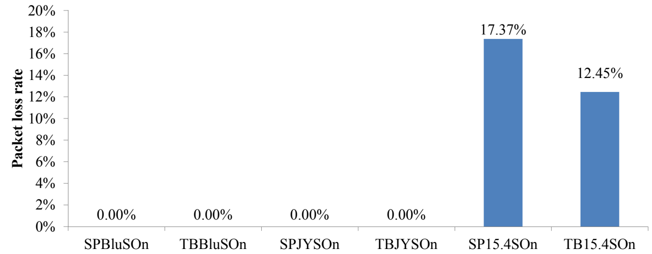
Fig. 4: In-truck mote deployments during test runs

B. Evaluation Results

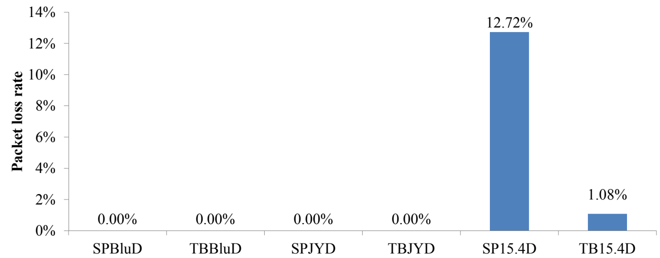
In our work in [31], we conducted initial evaluation experiments with regard to different means for connecting smartphones and motes, in particular comparing Bluetooth-based solutions to IEEE 802.15.4-based solutions as described above with a focus on energy consumption of the different solutions. We were able to show that the realized IEEE 802.15.4-based solutions were more energy-efficient than the Bluetooth solutions. Therefore, we focused our evaluation in the work at hand on the link quality provided by the realized Bluetooth-based and IEEE 802.15.4-based solutions. In this context, the obtained evaluation results showed that the Bluetooth-based solution outperforms the IEEE 802.15.4-based solution (cf. Fig. 5): All Bluetooth-based solutions, independent of the employed mote platform and the used Bluetooth extension module, did not exhibit any packet loss during all our evaluation runs. Opposed to this, all realized IEEE 802.15.4-based solutions exhibited packet loss during all conducted test cases. However, the TelosB-based solution performed quite well by exhibiting packet loss rates below 1.1% for the test cases TB15.4SOff and TB15.4D, with a nearly negligible packet loss rate of 0.1% for test case TB15.4SOff. Only for test case TB15.4SOn, the TelosB-based solution exhibited a packet loss even higher than 10%. The employed SunSPOT-based solution performed rather poor compared to the TelosB solution, exhibiting packet loss rates over 10% for all conducted test cases. During test case SP15.4SOff, we even encountered severe problems and sometimes experienced packet loss rates of nearly 100% with the normal test setup, only by putting the receiving XStick 802.15.4 with the smartphone close to the back of the driver's cabin, we were able to realize the lowest packet loss rate within this setting, which is still nearly 70%. Unfortunately, we were not able to find out the reasons for these outliers. This result is in particular surprising, because during this test case our employed SunSPOT-based sniffer received quite a significant amount of data packets and was able to record RSSI values quite similar to those measured during test case SP15.4D, as can be seen in Fig. 6, which depicts the RSSI values measured with our SunSPOT-based



(a) Results for test case “Standing still; Engine off”



(b) Results for test case “Standing still; Engine on”



(c) Results for test case “Driving”

Fig. 5: Packet loss rates in the different test runs

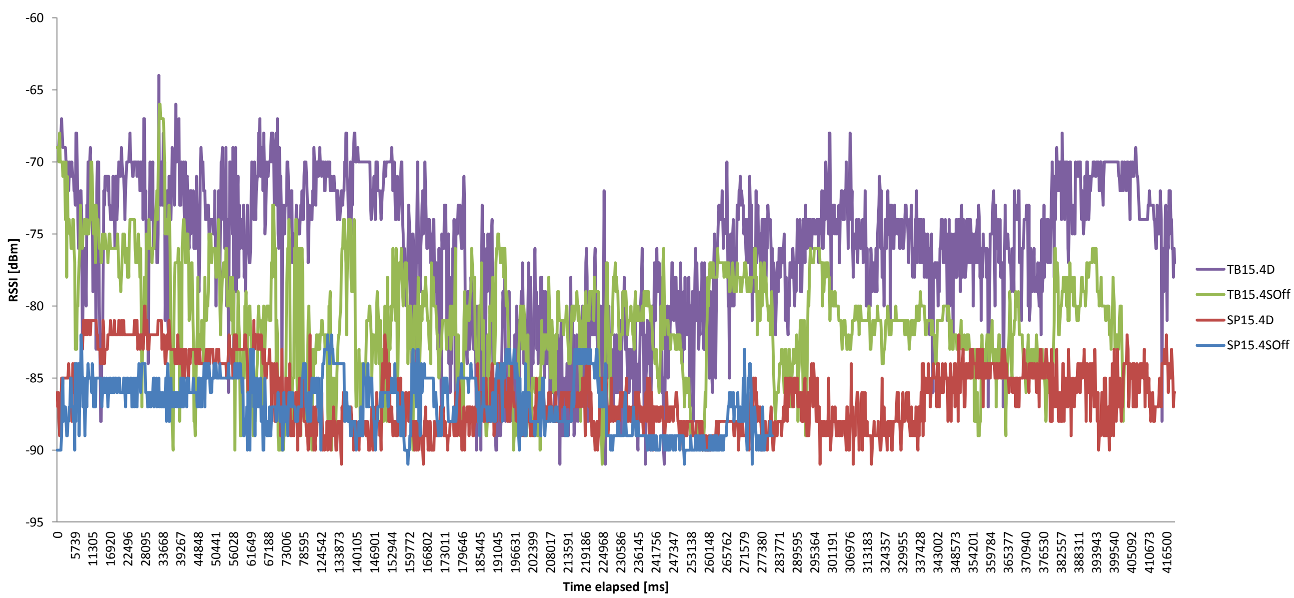


Fig. 6: Measured RSSI values during selected test runs

sniffer during the conducted test runs, which overall does not mirror the experienced packet loss rate of nearly 70% with the employed XStick 802.15.4-based solution.

Figure 6 shows as well, that the TelosB platform generally exhibited higher transmission power values compared to the transmission power values exhibited by the SunSPOT platform during all our test runs. In this regard, we could detect mean RSSI values for the TelosB platform of -80.83dBm during test setting TB15.4SOff and -75.9dBm during test setting TB15.4D. Opposed to this, the SunSPOT platform exhibited only RSSI values of -86.79dBm during test case SP15.4SOff and -86.23dBm during test case SP15.4D, respectively. Thus, we found a difference of mean RSSI value between TelosB platform and SunSPOT platform of 6.41dBm for the test cases in which the truck's engine was turned off and a corresponding difference of 10.33dBm for measurements conducted during driving with the truck. However, the SunSPOT platform's transmission power does not fluctuate as much as the TelosB platform's transmission power, which can be seen in 6, as well. In consequence, the mean deviation of the RSSI values for the SunSPOT platform we experienced during our test runs was only 1.7dBm, for test case SP15.4SOff, respectively 1.98dBm for test case SP15.4D, whereas the mean deviation of the TelosB platform's RSSI values were 3.03dBm for test case TB15.4SOff and 3.96dBm for test case TB15.4D. Nevertheless, the higher transmission power employed by the TelosB platform compared to the SunSPOT platform finally becomes obvious again when comparing the maximum and minimum RSSI values, we could measure during our experiments. In this context, we measured a minimum RSSI value of -91dBm for both platforms and both for the test cases of having the truck's engine turned off as well as for the test cases in which we were driving with the truck. However, the maximum RSSI values, we received for the SunSPOT platform were -82dBm for test case SP15.4SOff and -80dBm for test case SP15.4D, whereas the maximum RSSI values registered for the TelosB platform were -66dBm in test case TB15.4SOff and -64dBm in test case TB15.4D.

Thus, the RSSI measurements overall underline the better performance of the TelosB platform compared to the SunSPOT platform with regard to link quality, as it has already been expressed in the lower packet loss rates exhibited by the TelosB platform during our test runs.

Even against the background that we perceived flawless communication links exhibiting no packet loss for the Bluetooth-based solution within our evaluation, IEEE 802.15.4-based solutions for interconnecting smartphones and motes within the considered application scenario are promising as well. On the one hand, this is due to their superior energy efficiency, which can be twice to six times better as shown in [31], and on the other hand, this is due to the possibility to reach low packet loss rates as well, as two of the three test cases for the TelosB-based solution have shown. Even more, considering that our IEEE 802.15.4-based solutions refrain from acknowledging packet transmissions to keep the communication overhead low to achieve higher energy efficiency, opposed to the Bluetooth-based solution, which employs packet acknowledgments, the perceived evaluation results in particular for the TelosB platform are quite satisfying and even leave room for improvement.

VII. Conclusions and Outlook

Applying wireless sensor network technology provides a promising means to enable real-time monitoring of logistics transport processes. In particular, in-container wireless sensor networks can be used to immediately detect critical situations, so-called events, at their point of origin and correspondingly transmit alarm messages via gateways to users' backend systems in real time. Within the logistics domain, especially Supply Chain Event Management could significantly profit from such real-time event detection and notification, because this would shorten reaction times and increase reaction possibilities to such events and consequently allow for early process adaptations to minimize the consequences of an occurred event.

Thus, we developed a fully working system for real-time event detection and notification in logistics transport processes based on the application of wireless sensor network technology. Our system provides a web interface, which allows users to individually determine the criteria set employed by a wireless sensor node to locally identify events in a fine-grained way and correspondingly to visualize event information to users. For the communication between backend systems and wireless sensor nodes, we realized different means for an interconnection of wireless sensor nodes and smartphones and accordingly used a smartphone as gateway for long-range data transmission. Furthermore, we followed the event-based communication paradigm by employing event bus technology in the backend system to receive and distribute event information from the wireless sensor nodes to the appropriate receivers.

As a stable connection between wireless sensor nodes and smartphones constitutes one of the major foundations of our system, we evaluated our different prototypical realizations in real-world tests analyzing packet loss rates and RSSI values. We found out that with a Bluetooth-based solution a flawless communication channel, exhibiting no packet loss, can be achieved. However, our evaluation showed that even IEEE 802.15.4-based solutions can achieve satisfying packet loss rates of 1.1% and lower. Nevertheless, our evaluation showed as well that IEEE 802.15.4-based solutions are more error-prone than Bluetooth solutions, but exhibit a significantly higher energy efficiency as we could show in earlier evaluations.

Having provided the technical foundations for real-time event detection and notification in logistics transport processes with wireless sensor network technology, in future work we will consider the user view on our system and thus evaluate its usability. Furthermore, in the work at hand we focused on container transports with trucks, therefore we will analyze the possibility of transferring our solution to other logistics scenarios. Additionally, we will conduct more evaluation experiments to analyze the behavior of the solutions employing the internal IEEE 802.15.4-based communication modules in more detail and identify possibilities to enhance their performance.

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