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A Multi-Threshold Approach for Efficient and User-centric Event Transmission in Logistics Wireless Sensor Networks

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***Abstract*—Wireless sensor networks provide a promising means to enable real-time monitoring of transport processes in logistics. In a corresponding logistics wireless sensor network, energy-efficient operation is mandatory. Cost efficiency and customer satisfaction are additional requirements to be explicitly considered, particularly in the application domain of logistics. As data transmission constitutes the most expensive operation in terms of energy consumption and monetary costs, we propose in this paper a concept for local data filtering to reduce the number of data transmissions. Our concept utilizes multiple thresholds and explicitly incorporates customers' information demands to decide whether a data transmission shall take place or not. Thus, a local filtering is realized, which provides for energy- and cost-efficient operation of a logistics wireless sensor network and explicitly takes into account the customer's view while still offering the benefits of data fidelity and real-time event notification of a logistics wireless sensor network.**

I. INTRODUCTION

To meet the demand for pervasive real-time monitoring of transport processes in logistics, the application of wireless sensor network technology exhibits a huge potential. Wireless sensor nodes (*motes*), as the building blocks of wireless sensor networks (*WSNs*), provide the technology to monitor diverse environmental data relevant to the condition of transported goods, e.g., temperature, humidity, etc. Furthermore, motes possess a processing unit and a communication unit which allow processing and storage of sensed data as well as wireless data communication [1]. Thus, motes are able to detect events during a transport process and communicate corresponding event information to responsible decision makers in real time.

Motes typically use batteries as power sources. Therefore, energy is restricted in WSNs, which makes energy-efficient operation mandatory. As the major factor of energy consumption is data transmission, a substantial amount of research has been condcuted to realize energy-efficient data transmission schemes (e.g., discussed in [2] or [3]). However, data transmission is still more energy-consuming than data processing (cf. [4], [5]). As a consequence, we propose in this paper an approach, which realizes a local data filtering by comparing gathered sensor data against multiple thresholds to decide whether to transmit data or not. Thus, we reduce the number of data transmissions to a minimum. This minimal number of data transmission has to take into account not only energy efficiency aspects, but as well the information demand of the stakeholders involved in a transport process. Consequently, we explicitly incorporate measures to reflect this in the decision whether data is transmitted or not.

To be of any immediate use, the gathered event data of a logistics WSN has to be transmitted in real time to the users involved in the monitored transport process. For this purpose, typically long-range data transmission between the logistics WSN and the corresponding backend systems are required, which usually rely on communication technologies liable to fees, like satellite uplinks or cellular networks [6]. Thus, monetary costs are as well driven by data transmission, analogous to energy consumption. Therefore, by enabling local filtering on a mote to identify transmission relevant events leading to reduced data transmission, our approach contributes to cost efficiency, as another major requirement for logistics WSNs in addition to energy efficiency.

The remainder of this paper is structured as follows: Section II describes the application of WSNs in logistics processes in our envisioned application scenario and corresponding requirements. Section III describes our multi-threshold approach for local efficient and user-centric detection of events in logistics and their transmission with WSNs. The evaluation of this approach is presented in Section IV. Related work is covered in Section V. Section VI presents conclusions and future work.

II. WIRELESS SENSOR NETWORK APPLICATION IN LOGISTICS – POTENTIAL AND REQUIREMENTS

A. Integration of Wireless Sensor Nodes in Logistics Processes

Logistics comprises several functions. In the work at hand, we focus on the distribution of goods and thus on logistics transport processes. We particularly consider container transport, i.e., WSN usage within a container, which can be a standard container used for intermodal transportation by sea, rail, or road, a reefer container, a swap trailer, or in a generalized sense a truck's load area etc. In such a transport scenario, motes can be used to monitor various environmental parameters relevant for the condition of the transported goods, like temperature during the transport of temperature-sensitive

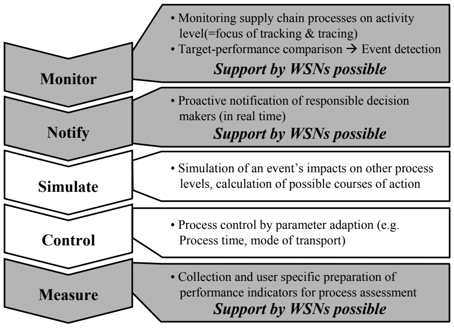

Fig. 1. SCEM functions and possible WSN support (based on [7])

goods, concentration of different gases during the transport of animals, or shake and tilt values during the transport of shock-sensitive goods, in real time. Subsequently, corresponding values can be transmitted wirelessly.

The specific deployment of motes within such a context can take place on several levels. For example, motes can be deployed on container level, on palette level, on package level, or even on individual item level. A mixed application incorporating motes deployed simultaneously on several levels is possible as well. Nevertheless, the approach presented in the work at hand is not restricted to a mote deployment on a specific level. Thus, it can be used independently from the chosen deployment level.

B. Event Concept in Logistics

Within the logistics domain, and particular in the context of transport processes, several methods and approaches utilize the concept of events. One such example is Supply Chain Event Management (*SCEM*). SCEM constitutes a management concept as well as a supporting (software) system [7]. It focuses on the detection of events, which constitute the basis for the management of the logistics process. In this context, events are understood as essential state changes for certain addressees [8]. On the basis of this rather abstract event definition, an event can be interpreted as a deviation between the current status and the regularly planned or scheduled status of an item or process, e.g., the violation of a threshold for an environmental parameter relevant for the condition of a transported good, like a temperature violation.

Thus, within SCEM, an event occurrence implies the need for a management action, realizing a management concept, which leans on the concept of management-by-exception. Such a management concept requires a corresponding (software) system support, which leads to the (software) system perspective of SCEM. In this sense, an SCEM system comprises the five functions *monitor*, *notify*, *simulate*, *control*, and *measure* [7], depicted in Fig. 1.

Within such an SCEM system, a logistics WSN can substantially support the monitor, the notify, and the measure function with its sensing, processing, and data transmission capabilities. The sensing units of motes can be used to monitor environmental parameters critical for the condition of transport goods, as described above. Based on these, target-performance comparisons can be conducted on the motes' processing units to detect events, e.g., threshold violations. With the motes' communication units corresponding event information can be transferred wirelessly through the WSN via an appropriate gateway to relevant stakeholders in the logistics process. Exploiting a mote's storage capacity, measured values and detected events can be stored for historical process assessments.

Having described the huge potential of WSNs in the context of SCEM, we consequently employ the understanding of the notion event as it is used within SCEM, and described above, for our work.

C. Requirements for the Use of Wireless Sensor Networks in Logistics Processes

To achieve the beneficial application of WSN technology within logistics processes as described in Sec. II-A and II-B, various requirements stemming from different domains have to be considered. Thus, we have identified four major requirement categories relevant to the deployment of WSN technology in logistics processes, which allow the differentiation of the various requirements based on their origin [9]:

- *Technological requirements* comprise properties and constraints originating from the employed WSN technology, e.g., energy constraints.
- *Economical and organizational requirements* comprise properties and constraints originating from the general economical and organizational context, e.g., the need for an integrated IT infrastructure or a sufficient cost-benefit ratio for the WSN deployment.
- *Regulatory requirements* comprise properties and constraints originating from laws or standards, e.g., available frequency bands for wireless data transmission within the WSN deployment.
- *Logistics market specific requirements* comprise properties and constraints originating from the specifics of the application domain of logistics, e.g., massive cost pressure or the urgent need to fulfill customer demands.

As several interdependencies between these requirement categories exist, they must not be viewed isolated from each other. In the work at hand, we focus on the technological requirement of energy efficiency and the economical and organizational, and logistics market specific requirements of cost efficiency and customer satisfaction. We exploit the interdependencies between these requirement categories with our approach of locally filtering data to reduce the amount of data transmissions to simultaneously enhance energy efficiency, cost efficiency, and customer satisfaction by just transmitting relevant data.

III. MULTI-THRESHOLD ALGORITHM FOR LOCAL EVENT DETECTION

Our multi-threshold-based approach for locally detecting events and deciding upon their transmission relevance builds upon two core components: the *event sensor component* and the *event monitor component*. The event sensor component is responsible for interpreting sensor samples and thus detecting transmission relevant events, ensuring an efficient and adaptable transmission of event information. The event

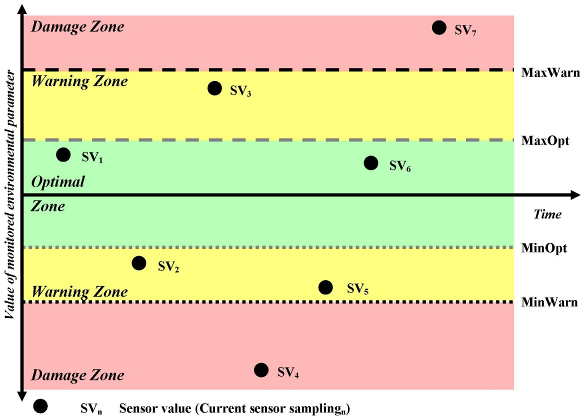

Fig. 2. Zone classification of monitored parameters

monitor component initiates the concrete data transmission and provides an energy-efficient transmission of regular status messages to indicate the proper functionality of a mote to corresponding users in a backend.

A. Event Sensor Component

The event sensor component basically interprets the actual sensor readings and decides whether a data transmission shall take place or not. The interpretation of the sensor data and the decision-making is based on a multi-threshold concept. Within this multi-threshold approach initially four basic thresholds are specified which partition the range of potential sensor readings in three zones (cf. Fig. 2): an *optimal zone*, which is delimited by a *MaxOpt*-threshold and a *MinOpt*-threshold and indicates that the current environment status of the transported goods is optimal, a *damage zone*, which is delimited by a *MaxWarn*-threshold and a *MinWarn*-threshold and indicates that the environment parameters are critical to the condition of the transported goods, and it is likely that the goods have been damaged, and a *warning zone*, which is in analogy to the damage zone delimited by the MaxWarn-threshold and the MinWarn-threshold and indicates that the current environment status is approaching values critical for the condition of the transported goods, but are at the moment still acceptable. This partition into three zones based on product-specific quality parameters provides only an initial coarse-grained means to decide upon the transmission relevance of the measured data. To cater for the technological requirement of energy efficiency in WSNs and the economical and organizational requirements as well as the logistics market specific requirements of cost efficiency and customer satisfaction, a more detailed analysis is required. Thus, in our approach, we take the division of sensor samples in these three zones only as a basis to differentiate between simple sensor samples and events (e.g., samples constituting a zone change by exceeding or falling below a threshold). Based on the detection of such an event, a more detailed analysis on the basis of an event sensor algorithm is conducted locally on a mote as depicted in Fig. 3. The sampled sensor value is firstly compared against the upper and lower bounds of the current zone to detect zone change events. This means the sensor sample is compared against MaxOpt and MinOpt, when the current zone status is optimal and MaxWarn and MinWarn, when the current zone status is “warning” or “damage”.

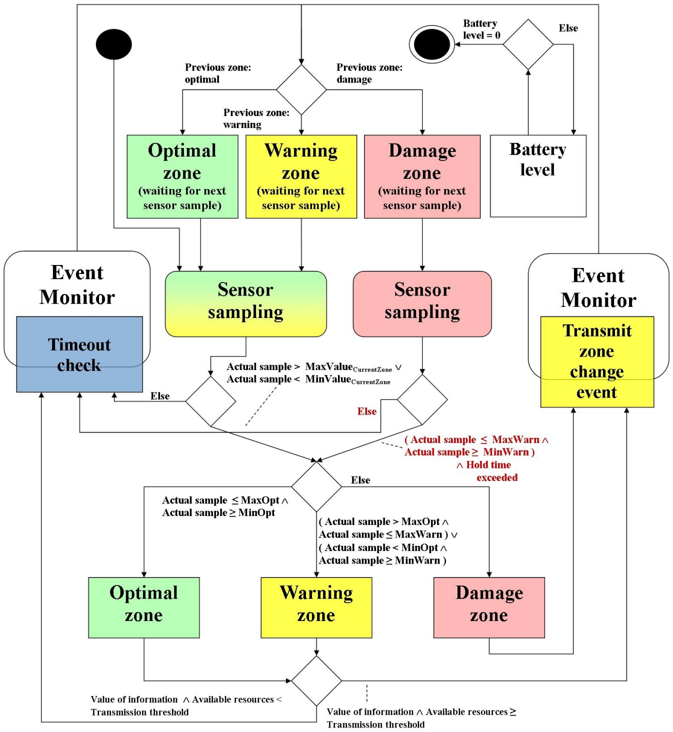

Fig. 3. Event sensor algorithm

In case no zone change event has taken place, no further analysis has to be conducted as no significant environmental change (no zone change event) occurred. Thus, no potentially transmission relevant event was detected and consequently no data has to be transmitted. In this case, the event monitor component is called in the next step to check whether a regular status message has to be sent (cf. Sec. III-B). Afterwards, the event sensor component returns to the current zone state waiting for the next sensor sample.

In case a potentially transmission relevant event in the form of a zone change event has been detected, two basic cases can be differentiated:

1) the zone changed into the damage zone,
2) the zone changed into the warning or optimal zone.

As the primary goal of a logistics WSN is to inform the stakeholders whether the transported goods are still intact or not, Case 1 (change into damage zone) constitutes a transmission relevant event, because with entrance in the damage zone and the corresponding exceeding of the MaxWarn-boundary, respectively falling below the MinWarn-boundary, the transported goods are expected to have suffered damage. Thus, the event monitor component is called to initiate a corresponding data transmission. A change into the warning or optimal zone (Case 2) has to be further analyzed. Firstly, oscillation in the form of fast changing sensor samples indicating fast zone changes into the optimal or warning zone out of the damage zone and back into the damage zone might occur. These have to be recognized to not generate unnecessary and irrelevant immediate data transmissions due to sensor samples entering the damage zone (Case 1) again and again after having left it for only a short time. To prevent such data transmissions, we use a hold time as additional threshold. Only when the sensor samples indicate a stable change out of the damage zone, i.e., the latest sensor samples have left the damage zone for a time equal or greater than the hold time threshold, the current zone status is changed to the warning or optimal zone state. If the change out of the damage zone is not stable, i.e., the latest sensor samples have left the damage zone only for a time less than the hold time, the actual zone state is not changed and remains "damage". Thus, no transmission relevant event (no zone change event) has been identified and no data has to be transmitted. Therefore in the next step, the event monitor component is called with a check timeout query to check whether a regular status message has to be sent (cf. Sec. III-B). Afterwards, the event sensor component returns to the current zone state ("damage") and waits for the next sensor sample. Secondly, the major problem is to decide whether a zone change into the optimal or warning zone (Case 2) should be transmitted. In principle, no critical status has been encountered. Nevertheless, a significant change has taken place, as either the relevant environmental parameters worsened, which led to the entrance into the warning zone, or they improved, which led to the drop out of the warning or the damage zone. This indicates a potentially transmission relevant event. To decide whether a data transmission shall be initialized in such a case, we use an approach which explicitly takes into account the mentioned technological, economical and organizational, and logistics market-specific requirements of energy efficiency, cost efficiency and customer satisfaction. Thus, the zone change event is further analyzed against the background of different context parameters relating to these requirements. In this analysis the current availability of energy resources on the mote is incorporated to enable energy-efficient transmission and a value of information is assigned to the detected zone change event. Just in those cases in which the event is worth transmitting in comparison to the available resources and the value of information, the event information shall be transmitted. Thus, only when the available resources and the value of information are equal or exceed a certain transmission threshold the detected zone change event is finally classified as transmission relevant event (1) and passed on to the event monitor component for transmission.

$$\begin{aligned} Transmission\ relevant\ event \Leftrightarrow \\ Value\ of\ information \wedge\ Available\ resources \geq \\ Transmission\ threshold \end{aligned} \tag{1}$$

Concerning the value of information, we use an aggregated value of several distinct parameters, which can be individually weighted and contribute to customer satisfaction and cost efficiency. We explicitly consider:

- the basic interest of a customer in getting information concerning the status of his transported goods,
- the number of messages sent,
- the extent to which the environment conditions have changed,
- the degree of cost pressure the logistics service provider is facing.

This ensures that in case of zone changes into the optimal or warning zone (Case 2) enough messages are sent to satisfy a customer's information demand and allow an early warning. At the same time, transmissions are reduced to a minimal number to prevent a user from an information overload with irrelevant information and enable cost- and energy-efficient operation.

If the detected zone change event is categorized as transmission relevant event (Equation (1) holds) the event monitor component is called to initiate a corresponding data transmission. Otherwise, the event monitor component is called to check whether a regular status message has to be sent (cf. Sec. III-B). Afterwards, the event sensor component returns to the current zone state and waits for the next sensor sample.

B. *Event Monitor Component*

The event monitor component is responsible to initiate data transmissions at the right time. Primarily, it ensures that specific control messages are transmitted on a regular basis to transmit the current status of a mote and indicate its correct operation to the user. Furthermore, it is called when a transmission relevant event has been detected by the event sensor component to initiate the corresponding data transmission for this event.

Based on given initial parameters (specifically cost pressure, information demand of the customer, sensor sampling interval, and residual energy resources) a timeout is calculated after which the event monitor component sends a regular status message to the user containing the current status of the mote, the current timeout (indicating to the user when the next status message is due), and the current environmental status. After having sent such a status message, the event monitor component resets the timeout timer and waits until it is called from the sensor monitor component, either in the form of a transmit zone change event or with a check timeout query.

In case it is called with a transmit zone change event, it reads out the current energy reserves. Based on this value in combination with the above mentioned parameters of cost pressure, information demand of the customer, and sensor sampling interval, a new timeout value is calculated. Correspondingly, the timeout is set to this new value. Afterwards, the data transmission is initiated sending the current sensor data and the current timeout value. Finally, the event monitor component resets the timeout timer again after having initiated the data transmission and waits until it is called again. In case the event monitor component is called with a check timeout query, it checks whether the actual timer value is equal to or exceeds the currently set timeout timer. In this case it proceeds analogously to the above described case with a zone change event by calculating a new timeout value based on the different parameters and afterwards initiating the corresponding data transmission. In case the current timer value is below the timeout threshold, the event monitor component returns into its waiting status, waiting to be called either by a zone change event or by a check timeout query.

To balance the trade-off between the need for energy-efficient operation and the need for regular status messages of the mote, an additional threshold for the remaining energy resources is introduced. When the remaining energy resources drop below this threshold, no more status messages are sent to achieve a prolonged lifetime of a mote. With a last status message sent to the user, he is informed that he should not expect any more regular status messages from this point on, as the remaining energy resources have reached a critical value.

IV. EVALUATION

To assess the energy efficiency of our multi-threshold-based approach, we compare it to the two currently prevalent reporting approaches for WSN deployments in a logistics context: Periodic reporting and single-threshold-based reporting. In the latter solution, sensor nodes use only two static thresholds (a strict upper and a strict lower bound), leading to two zones (corresponding with the optimal and damage zones in our approach), performing strict checks against these thresholds. Once a reading exceeds a given threshold, an event is generated and transmitted without further analysis. In the case of periodic reporting, status messages containing the latest sensor readings are transmitted at regular intervals.

A. Implementation & Parameter Selection

Based on the description in Sec. III-A, the parameters to calculate the information value of an event had to be further broken down and operationalized.

For the operationalization of the basic interest of a customer in getting information concerning the status of his transported goods, a decision parameter *informationNeed* is introduced. This decision parameter is set using a customer-specific static value between 0% and 100%, which can be interpreted as a weighting of this parameter from irrelevant (0%) to most relevant (100%). The specific value of this decision parameter can be derived from, e.g., the monetary value of the transported goods and their importance. For our simulation we chose a value of 75%.

For the operationalization of the degree of cost pressure a logistics service provider is facing, a decision parameter *costPressure* is used. This decision parameter is set with a logistics service provider-specific value between 0% and 100%, which can be interpreted analogously to the operationalization of the basic information interest of a customer. The specific value can be derived from the financial solvency and the pressure of competition the logistics service provider is facing, for example. In our simulation we used a cost pressure value of 50%.

The determination of the relevance of a state change in the form of the extent to which the environment conditions have changed is realized by evaluating the distance to the critical (damage) zone of the current sensor measurement (in percent) and the gradient between the current and the previous sensor measurement. This leads to two decision parameters *criticalBorderNear* and *criticalGradient*. In our simulation, the threshold for the *criticalBorderNear* parameter was set to 30% and the threshold for the *criticalGradient* parameter to 2°C.

The customer satisfaction and the cost pressure of the logistics service provider is reflected by exploiting the number of messages sent. Specifically to save transmission costs (in terms of money and energy) as well as to avoid an information overload on the customer's side, a threshold *maxMessagesPerInterval* is used, which defines an upper bound for the number of data transmissions in a given time interval. This threshold is derived from the cost pressure of the logistics service provider and the information demand of a customer. Thus, a decision variable *consumedMessageBudget* as quotient of the number of messages sent and the maxMessagesPerInterval threshold is employed to determine how much of the available data transmission budget is consumed. In our simulation we used a time interval of 600 seconds, a *maxMessagesPerInterval* parameter of eight messages and a threshold for the *consumedMessageBudget* of $\frac{7}{8}$, respectively 87,5%.

Based on these decision parameters and thresholds we operationalized (1) as follows:

$$\begin{aligned}
&Transmission\ relevant\ event \Leftrightarrow \\
&Value\ of\ information \wedge Available\ resources \geq \\
&Transmission\ threshold \Leftrightarrow Value\ of\ information \geq \\
&Transmission\ threshold_{ValInf} \wedge Available\ resources \\
&\geq Transmission\ threshold_{AvailRes} \Leftrightarrow \\
&(((criticalBorderNear \geq threshold_{criticalBorderNear} \\
&\vee\ criticalGradient \geq threshold_{criticalGradient}) \wedge \\
&consumedMessageBudget \leq \\
&threshold_{consumedMessageBudget}) \vee \\
&\frac{informationNeed + criticalBorderNear}{costPressure + consumedMessageBudget} \\
&\geq threshold_{InfCostRatio}) \wedge Available\ resources \geq \\
&Transmission\ threshold_{AvailRes}
\end{aligned} \tag{2}$$

In our simulation we used a $threshold_{InfCostRatio}$ of 100% and a $Transmission\ threshold_{AvailRes}$ of 10%.

Taking further into account that the event monitor component regularly sends status messages after the expiration of a timeout as described in Sec. III-B, unnecessary data transmissions due to a zone change event and a regular status transmission because of a timeout expiration shortly after the zone change event have to be prevented. Therefore, after having detected a potentially transmission relevant zone change event, we first check the time until the next regular status message. This is reflected in the decision variable *timeoutExpired*, which provides the quotient of the current timer value and the current timeout. If this decision variable exceeds a corresponding *thresholdtimeoutExpired*, the detected zone change event is transmitted immediately and the timeout timer reset. Thus, the planned transmission of the regular status message is substituted by the transmission of the detected zone change event, saving one redundant data transmission. In our simulation with a timeout interval of 600 seconds, we set the *thresholdtimeoutExpired* to 90%.

B. Simulation

In general, motes are mounted in fixed positions within a truck's load area or a container. Hence, topology changes are rare and usually occur due to nodes failing because their energy budget has been exhausted or they have been physically damaged. Thus, topology control mechanisms are generally applied before the actual data collection phase. Therefore, we did not consider topology control mechanisms in the conducted simulations. Furthermore, our approach aims at individual local mote-centric decision making and we do not focus on optimization approaches for data transmission through the network. In consequence, we assume that every message transmission of a mote shall get to the remote user backend. Therefore, our simulations were concentrated on the energy consumption on a single mote during the application of a periodic reporting approach, two single-threshold approaches, and our multi-threshold approach without taking into account possible gains by using in-network processing.

For the simulations, we chose the initial energy budget of a mote as 10,000 Joules, which is roughly the charge of two rechargeable AA cells. As energy consumption values for the different operation modes of a mote, we used the values given in Tab. I. These values are based on data sheets of existing motes in order to apply realistic values in the simulations.

TABLE I
ENERGY VALUES USED FOR SIMULATION

Sleeping	**Sensing**	**Sending**
2 mJ (per cycle of 10 s)	*1 µJ*	*135 mJ*
Processing (Periodic)	**Processing (Single-threshold)**	**Processing (Multi-threshold)**
1 mJ	*1 mJ*	*5 mJ*

In scenarios without zone change events (i.e., no threshold violations), the single-threshold-based reporting approach will not transmit any data, and our multi-threshold approach will neither have data to analyze, because a zone change is the basic requirement for data transmission in the context of the single-threshold-based reporting, or to conduct further data evaluation for the decision whether or not to send data in our multi-threshold approach. Thus, we based our simulations on a scenario with phases during which sensor samples violate given temperature thresholds. For the temperature readings in our simulations, we used a linear interpolation of temperature traces presented in [6] as depicted in Fig. 4. Regarding data collection, we assumed a sampling interval of 10 seconds, as it was proposed in [10].

We evaluated our multi-threshold approach in comparison to two single-threshold-based approaches with temperature values at 9°C and 15°C (the values, which delimit our warning zone) and temperature values at 5°C and 19°C (the values, which delimit our damage zone) and a periodic reporting approach with a transmission interval set to equal the sampling interval (i.e., 10 seconds). For our multi-threshold-based approach we used the values stated in Sec. IV-A. The results of our simulations are shown in Fig. 5 for the cumulative number of packet transmissions and Fig. 6 for the residual mote energy. Table II presents a summarized comparison of the cumulative number of packet transmissions and residual mote energy at the end of the simulated transport after 5 days for the four different approaches we simulated.

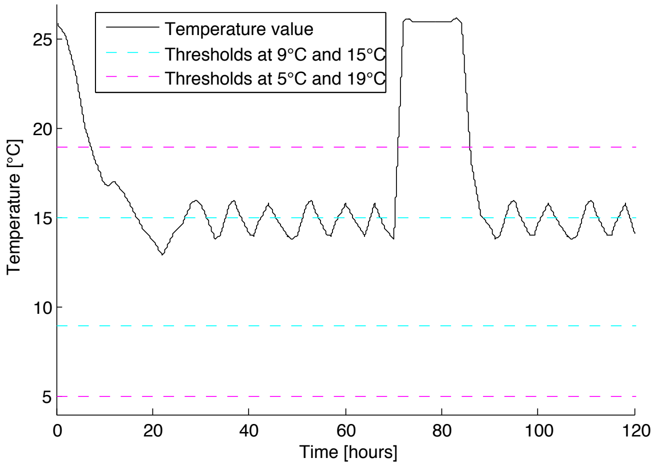

Fig. 4. Temperature and threshold values used for simulation

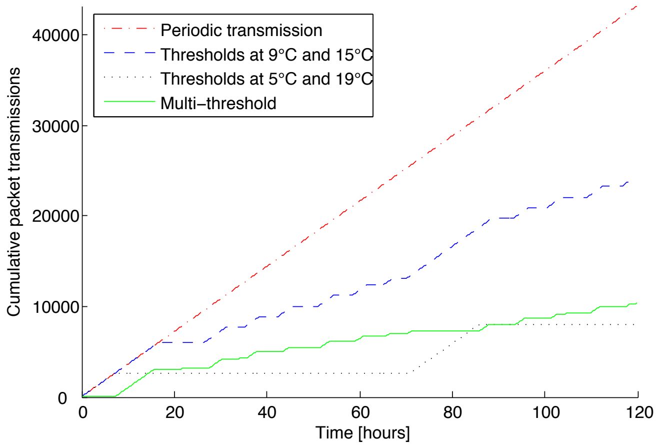

Fig. 5. Cumulative packet transmissions during a transport of 120 hours

TABLE II
CUMULATIVE PACKET TRANSMISSIONS AND RESIDUAL ENERGY AFTER A SIMULATED TRANSPORT OF 120 HOURS

	Cumulative packet transmissions	**Residual energy**
Periodic reporting	*43200*	*4038.36 J*
Single-threshold approach (thresholds at 9°C and 15°C)	*24171*	*6607.27 J*
Single-threshold approach (thresholds at 5°C and 19°C	*7994*	*8791.17 J*
Multi-threshold approach	*10345*	*8300.98 J*

As expected, the cumulative number of sent packets grows linearly for the periodic reporting approach with the sending interval of 10 seconds. Thus, as anticipated, the energy consumption for the periodic data transmission in the context of the periodic reporting approach is significantly higher leading to a faster decrease of residual energy and a corresponding

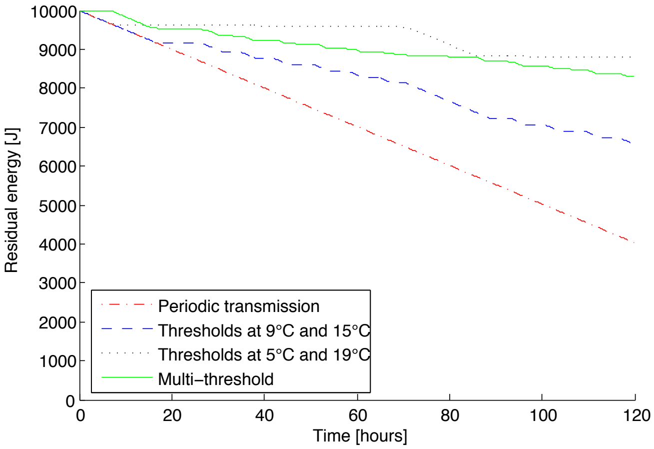

Fig. 6. Residual energy during a transport of 120 hours

shorter mote lifetime in comparison to the single-threshold and multi-threshold approaches.

In comparison to the single-threshold approach with thresholds set to 5°C and 19°C (the values, which delimit our damage zone), our multi-threshold approach performs slightly worse in terms of cumulative packet transmissions as well as in terms of residual energy. This is due to the fact that in the given scenario, our approach transmits the huge violations of the upper warning zone threshold as transmission relevant zone change event into the damage zone analog to the single-threshold approach considered here. Furthermore, it transmits additional zone change events to enable an early warning of the customer and satisfy the customer's information demand, like the zone change out of the damage zone or selected zone changes between the optimal and the warning zone, which are not transmitted by the considered single-threshold approach. Nevertheless, the difference between the two approaches is only small and in comparison to the single-threshold approach with the threshold values set to the upper and lower limits of the warning zone, our approach explicitly provides early warnings and a better satisfaction of users' information demands concerning their transported goods. The single-threshold approach with thresholds set to 9°C and 15°C allows for early warning messages, comparable to our multi-threshold approach, as the thresholds are set to the values, which delimit the optimal zone. Comparing this single-threshold approach and our multi-threshold approach the advantages of the multi-threshold approach become obvious. Significantly fewer packets are sent and significant less energy is consumed, which results in a higher residual energy at the end of the simulated transport and thus implies significant longer mote lifetime. A major reason for this provides the temperature oscillation around the upper limit of the optimal zone. The single-threshold approach considered here is fully exposed to this oscillation and sends every time a corresponding warning message. Our multi-threshold approach limits the data transmissions to relevant transmissions. Thus, only selected changes between optimal and warning zone with an adequate information value are transmitted. With the fewer packet transmissions of our multi-threshold approach not only a longer mote lifetime can be achieved, but as well a higher cost efficiency, because significantly fewer messages have to be transmitted to user backends, which saves long-range communication technologies liable to fees. Additionally, considering the user's point of view the data quality and thus the customer satisfaction is improved with our multi-threshold approach as it incorporates several parameters explicitly reflecting users' information demands to adapt the data transmission.

V. RELATED WORK

Several WSN routing methods have already made use of the idea to locally assess and filter data based on context parameters, e.g., SCAR [11], EM-GMR [12], and EMA [13].

Furthermore, the potential benefits of shifting decision-making processes to individual motes and especially the positive impact on battery lifetime due to reduced communication has already been emphasized by several works (cf. [5]). Thus, different approaches have been developed in this context, which we describe in the following.

Evers and Havinga present in [14] an approach for efficient and secure reprogramming of motes in a transport scenario. They consider possibilities for monitoring and autonomously verifying correct handling conditions during a transport process with WSNs, specifically detecting overtemperature conditions and sending corresponding alarm messages. However, the decision whether an alarm message is sent relies only on a threshold for the environmental parameter monitored and does not take into account other relevant context parameters. In an earlier work, Evers et al. considered a storage logistics scenario and mention in this context as well the idea of "transferring additional intelligence and responsibility to sensor nodes" [15]. Thereby, employing rules with a corresponding rule engine on a mote is mentioned for the decision whether an alarm message should be sent. Nevertheless, the authors focus primarily on issues related to localization.

Concerning business rule usage on motes within logistics WSNs, Marin-Perianu et al. provide a work on protocol issues and the efficient distribution and update of rules [16]. They emphasize as well the benefits of an enhanced local logic within a WSN to reduce communication overhead and energy consumption by transmitting data only when certain conditions are violated. Their approach is based on the idea that simple business logic is mapped to rules which are executed by a local rule engine on a mote, which decides whether an action like sending an alarm message to a user should be initiated. Nevertheless, the authors focus in their work strongly on how to efficiently distribute and update their rules and present a tree-based dissemination protocol for this purpose.

Another rule-based approach for logistics WSNs is described by Son et al. [10]. Similar to [16] the authors propose to locally decide on a mote whether a data transmission should take place. The rules the authors use are designed to check whether relevant parameters exceed a given interval or not. However, the authors do not explicitly describe any possibility to interconnect rules. Thus, dependencies between parameters for a full evaluation of the current context are not reflected.

Several of the described approaches already realize local filtering in the context of logistics WSNs, but on a relatively strict and rather technologically-oriented basis. Thus, they lack for example the explicit incorporation of economical and organizational requirements and several of the most important logistics market specific requirements, like the huge cost pressure or the need for sufficient customer satisfaction. In contrast, our approach provides the opportunity to weigh different relevant parameters against each other and explicitly incorporates more (qualitative) user-focused parameters, related to the specific needs of logistics. Thus, a more complex and sensitive decision logic can be integrated, which provides, e.g., for the explicit consideration of diverse dependencies and more user-centric decisions. In comparison to context-aware routing methods, we focus on the step before data is routed and decide directly at the originating mote if gathered data needs to be sent. This allows to beneficially use our approach in addition with the mentioned routing methods.

VI. CONCLUSIONS AND FUTURE WORK

In the work at hand, we have shown the application potential for wireless sensor networks in logistics transport processes, particular within the concept of events in logistics and the corresponding supply chain event management. Several requirements to be considered for beneficially applying wireless sensor networks in a logistics context have been identified. As two of the most important requirements are energy efficiency and cost efficiency and data transmission is the major influence factor for energy- and cost-efficient operation of a logistics wireless sensor network, we proposed to locally assess data on wireless sensor nodes concerning its transmission relevance to prevent unnecessary data transmissions. Such prevention of unnecessary data transmission additionally provides for an improved consideration of customers' information demands and thus leads to improved customer satisfaction, another requirement particularly important in the logistics domain.

We have presented our multi-threshold approach to realize a local assessment of data and decide on a wireless sensor node whether to transmit data or not. Within an evaluation by simulation, we compared our approach to a periodic reporting approach and two single-threshold-based approaches, representing two prevalent reporting methods in logistics wireless sensor networks. The simulation results have shown the advantages of the multi-threshold approach both in terms of data transmission and energy consumption. The reduced number of data transmissions additionally leads to the reduction of monetary costs. Consequently, our multi-threshold approach improves cost efficiency in logistics wireless sensor networks, too. Finally, not just energy efficiency and cost efficiency benefits are realized with the presented multi-threshold approach, but as well an improved customer satisfaction as the approach is user-centric by design due to the explicit incorporation of user needs in the realized data assessment.

Currently, our approach is focused on individual wireless sensor nodes. Therefore, in future work incorporating a more encompassing network view and the potential of a distributed and cooperative application of our multi-threshold approach and other in-network processing possibilities appears promising. Furthermore, possibilities and consequences of a more adaptive adjustment of various employed parameters, like the used timeout parameter, will be investigated.

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