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Communication techniques and challenges for wireless food quality monitoring

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Remote measurement of product core temperature is an important prerequisite to improve the cool chain of food products and reduce losses. This paper examines and shows possible solutions to technical challenges that still hinder practical applications of wireless sensor networks in the field of food transport supervision. The high signal attenuation by water-containing products limits the communication range to less than 0.5 m for the commonly used 2.4 GHz radio chips. By theoretical analysis of the dependency of signal attenuation on the operating frequency, we show that the signal attenuation can be largely reduced by the use of 433 MHz or 866 MHz devices, but forwarding of messages over multiple hops inside a sensor network is mostly unavoidable to guarantee full coverage of a packed container. Communication protocols have to provide compatibility with widely accepted standards for integration into the global Internet, which has been achieved by programming an implementation of the constrained application protocol for wireless sensor nodes and integrating into IPv6-based networks. The sensor's battery lifetime can be extended by optimizing communication protocols and by in-network pre-processing of the sensor data. The feasibility of remote freight supervision was demonstrated by our full-scale 'Intelligent Container' prototype.

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1. Introduction

According to Gustavsson *et al.* [1], roughly one-third of all food produced worldwide is never consumed. An important share of these losses is caused by improper handling and temperature mismanagement along the cold chain [2]. This share can be reduced if the information about the state of the transported product is provided without time delay after the appearance of a problem. The transport operator can initiate measurements to remedy obvious mistakes such as wrong temperature set points. Products that are still acceptable for consumption with a reduced shelf life that is insufficient for extended transport routes can be assigned to immediate sale in nearby locations [3].

Although several new telematics and wireless sensor systems have come on the market in recent years, there is still no satisfactory solution for the complete information chain. The required chain for remote monitoring starts with a set of sensors mounted directly on food products inside a truck or container and ends on a remote server and display at the desk of the transport operator. In this section, we first give an overview of relevant market-available and state-of-the-art systems for remote monitoring and then introduce the most severe technical challenges that we found during tests with our prototype solution for remote temperature and quality monitoring of food products, which still hinder the wide application of such technologies. Section 2 describes the technical background of our prototype solution, the so-called 'Intelligent Container'. The subsequent sections handle the four identified challenges one by one.

(a) Market-available sensor systems

The events of 11 September 2001 triggered various developments of container tracking systems. There are several systems on the market with a focus on homeland security aspects, such as unauthorized opening of the doors and deviations from the prescribed transport route, e.g. [4]. Standard telematics systems for transport monitoring provide only the GPS information and at best the readings of the cooling unit's supply and return air temperature. Only a few of these systems provide interfaces for wireless temperature and humidity sensors. The container security box [5] offers the option to install interior sensors at different positions in the container that send temperature and humidity measurements to the main unit installed on the roof of a container. An alternative system from Ceebron [6] consists of single-use smart-trace-tags that can be attached to temperature sensitive items. They send their data to a telematics unit, which forwards it together with the GPS position.

The Israel company BT9 provides a similar solution: Xsense wireless sensor tags are placed within pallets or packaging to monitor the actual temperature and relative humidity of the perishables. As long as the tags are in close proximity to a control unit, the data are transmitted in real time [7]. Traditional data logger companies, such as Sensitech, equip their devices with RF-interfaces [8]. A TempTale RF Gateway is installed at the warehouse entrance, and it can automatically download the temperature data from the loggers placed in the arriving goods.

The battery-assisted passive TMT-8500 class 3 RFID temperature-monitoring tag from Intelleflex Cooperation [9] provides a free-space reading range of 100 m. Temperature data can be read out by standard RFID readers in accordance with the EPCglobal class 1 generation 2 protocol. Already existing infrastructure for RFID-based tracking and tracing can be used, but it requires software extensions to integrate temperature data.

The development of sensor systems equipped with a passive RFID interface is still going on. Their reading range can be extended by ultrawide-band communication and low-power analogue–digital converters [10], but these technologies are still in a research state.

(b) Challenges in food monitoring

Deviations of fruit quality can be deduced from temperature data if remote monitoring is combined with biological modelling. Although such quality-oriented tracking and tracing systems [11] have a large potential to reduce food losses along the chain, their market share is rather marginal in comparison to the total amount of food transports. This is partly owing to the structure of food chains consisting of a high number of parties with different interests. The retailer, who benefits most from better and sustained quality, has only a loose relationship with the transport operator, who ultimately has to pay for additional technical equipment and sensor systems. Although an early detection of problems is for the benefit of all partners in the supply chain, the required trust to make faults visible by concise sensor supervision is missing in most chains. But besides these structural problems, there are still some technical challenges. We start our discussion with the question of sensor placement.

During our field tests, we found large differences between the temperatures of supply air, pallet surface and product core inside trucks and containers, as well as variations of the core temperatures of pallets at different positions inside the same container. Sensors on the products surface are easier to install and the radio signal interferes less with the product itself; surface temperature measurements can indicate cooling and packing problems, but in order to predict the effect of deviating cooling conditions on the product's quality, the core temperature has to be known. In this regard, do Nascimento Nunes *et al.* [12] suggested estimating the core temperature by a simple thermal model or an artificial neural network with the surface measurements as input. But if the initial core temperature is not known, or the packed food generates a varying amount of heat by itself, as many fruits such as bananas do, best accuracy can only be achieved by direct core measurement.

The need for core measurements leads to the first technical challenge: the high water content of typical food products that hinders the propagation of radio waves. The communication range can drop below 0.5 m [13]. A direct communication link between the sensors in the core and the telematics unit is mostly unavailable. Instead, a sensor-to-sensor communication with message forwarding is required. Passive RFID technologies cannot provide such a multi-hop communication because their principle of operation allows only direct communication between tag and reader. Sensors mounted on the product surface are partly affected by the same problem, depending on the product, packing and amount of free space between pallets and container walls. In §3, we show, based on a model for signal attenuation, that related problems can be reduced by lower operation frequencies.

The second challenge concerns protocols for communication inside the local sensor network and with the outside world. Systems available on the market mostly use proprietary protocols to monitor individual transports. But a complex 'networked' supply chain requires a high level of compatibility between sensors and telematics devices from different manufacturers. Although communication protocols for passive RFID have achieved a high level of standardization, they do not support multi-hop forwarding, which makes it necessary to search for a better solution for seamless integration of wireless sensors into a global network such as the protocol stack presented in §4.

The need to forward messages raises the third problem for battery-powered devices. In the worst case, the radio has to be permanently powered on to listen to the incoming messages. The required energy for this 'idle listening' can be largely reduced by mechanisms such as low-power-listening (LPL), but a detailed analysis of the relation between energy consumption and different protocol components in §5 shows that further optimization is necessary.

The fourth challenge is related to the limited bandwidth and volume costs for communication networks. Therefore, the sensor data should be processed directly on the sensor or the subsequent system level, as discussed in §6. Only data summaries and warning messages should be transmitted instead of the entire set of raw data. Biological models for assessing the effect of deviations from recommended transport conditions have to be translated in software code that is able to run on the hardware of a sensor node or a telematics unit.

2. The communication system of the intelligent container

The Intelligent Container was set up as a prototype solution to demonstrate the feasibility of remote quality monitoring and as a test bed for related communication problems. So far, the

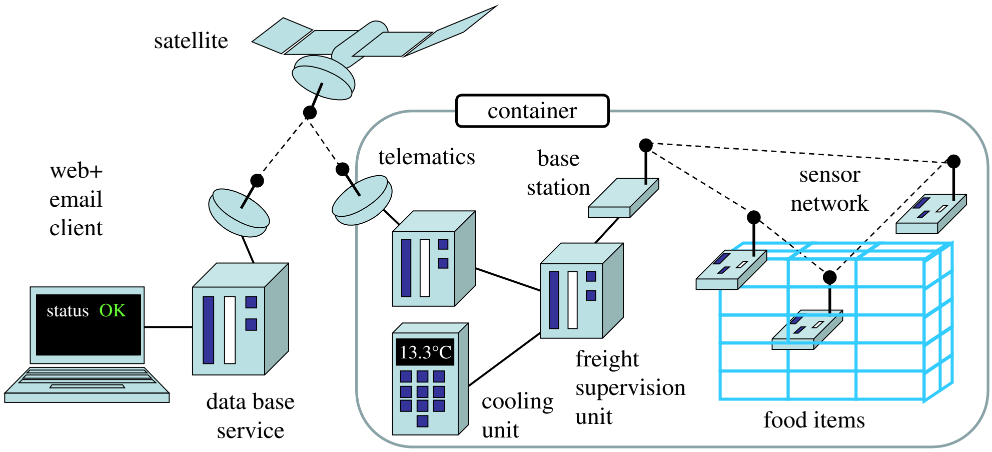

Figure 1. Schematic communication diagram. (Online version in colour.)

system has been tested on three trans-ocean transports of bananas [14]. The centrepiece of our prototype is made up of a 'freight supervision unit' (FSU) installed in a standard 40 foot reefer container. The FSU pre-processes the sensor data and calculates deviations in the remaining shelf life. Full temperature records are only transmitted upon request; otherwise, the FSU sends only warning messages on critical quality losses.

The wireless sensor network (WSN) installed in the Intelligent Container is able to forward messages over multiple hops to compensate for signal attenuation. The sensor nodes are based on the TelosB [15] platform operating at 2.4 GHz in accordance with the IEEE 802.15.4 standard. Our nodes are embedded in a water-protected housing and are equipped with an external SHT75 temperature and humidity sensor [16]. In order to transfer the sensor readings, the constrained application protocol (CoAP) [17] was installed on 20 sensor nodes during the field tests in 2012 and 2013. Details of the protocol are described in §4. The second set of 20 sensor nodes were deployed for testing of alternative communication protocols during the same transport, such as the BananaHop protocol [13]. The FSU is based on a fan-less, in-vehicle computer from Nexcom [18] and interlinks the different communication channels as a base station for the WSN (figure 1).

Furthermore, the FSU can directly access the controller of the cooling unit over a serial interface. The command set enables switching on/off the economy mode with reduced fan speed and either reading out or modifying the set points for temperature and the fresh air vent. In the future, the FSU is planned to automatically make decisions on the basis of predicted remaining shelf life and adjust the settings if necessary, e.g. switching the economy mode off if a risk of food quality is detected. Currently, the FSU only forwards user requests from the telematics to the cooling unit.

The telematics unit uses the Iridium satellite network to transmit quality, temperature and GPS data. Configuration commands are sent over the same network, e.g. for adjustment of set points or measurement intervals for the wireless sensors and thresholds for minimal remaining shelf life. The messages received from the telematics are stored in a database of a commercial service provider ashore. The end user can either query summaries of measured data and predicted quality or register for email notifications.

A similar solution was set up for land-based transports in trucks [19]. The major difference to the monitoring of overseas transports is the usage of the more cost efficient cellular GPRS network for data transmission. The telematics unit from Cargobull [20] is directly connected to a WSN provided by the Virtenio company [21]. Further wired sensors can be connected via a LIN-bus. The interface to the cooling unit provides additional features such as reading maintenance information and fuel level. Accumulated sensor data can be directly read out by a tablet PC over a wireless LAN interface.

3. Signal attenuation and operating frequencies

Most WSNs operate in the 2.4 GHz frequency range. This frequency range has the advantages of high bandwidth of 83 MHz, small antennas and availability of several radio chips based on the IEEE 802.15.4 standard. Whereas for outdoor and in-building applications, a transmission power of 1 mW is sufficient to achieve a transmission range between 10 and 100 m, signal propagation is largely hindered by water-containing food products. In our tests with packed banana containers, the maximum transmission range between two adjacent sensor nodes dropped down to 0.5 m. For this distance only one-third of all links provided reliable communication, another third had temporary dropouts and the last third failed completely [13].

Similar problems were observed by other authors in farming applications where either one or both communicating sensor nodes were buried in the soil. In test applications of such wireless underground sensor networks (WUSN), the maximum depth of one sensor in the soil, enabling reliable communication with a top soil sensor, was 9 cm [22] or 6 cm [23] at a frequency of 2.4 GHz. Vuran & Akyildiz [24] described a model to predict the signal attenuation for different frequencies, soil types and water-content values, which is based on a previous model by Dobson *et al*. [25].

As the problems that we found in wireless supervision of food transports seem to be very similar to problems in WUSN, we adapted the related model to our application. The model in [24] comprises three steps: (1) calculation of the complex dielectric constant of water $\varepsilon_{\mathrm{w}}' + j \cdot \varepsilon_{\mathrm{w}}''$ as a function of frequency f, (2) translation of ε_{w} to the dielectric constant of the water-containing medium, and (3) calculation of signal attenuation as a function of distance, frequency and dielectric loss factor.

The complex dielectric constant of water is calculated according to a Debye-type relaxation model (3.1)

$$\varepsilon_{\mathrm{w}}' + j \cdot \varepsilon_{\mathrm{w}}'' = \varepsilon_{\mathrm{w}\infty} + \frac{\varepsilon_{\mathrm{w}\infty} - \varepsilon_{\mathrm{w}0}}{1 + (2\pi \cdot f \cdot \tau_{\mathrm{w}})^2} + j \cdot \frac{2\pi \cdot f \cdot (\varepsilon_{\mathrm{w}\infty} - \varepsilon_{\mathrm{w}0})}{1 + (2\pi \cdot f \cdot \tau_{\mathrm{w}})^2}, \tag{3.1}$$

with the static dielectric constant of water $\varepsilon_{\mathrm{w}0} = 80.1$ at 20°C, its high-frequency limit $\varepsilon_{\mathrm{w}\infty} = 4.9$ and the relaxation time of water of $\tau_{\mathrm{w}} = 9.23 \times 10^{-12}$ s.

The model of Dobson *et al.* [25] calculates the complex dielectric constant of soil as a function of water-volume content V_{C}, $\varepsilon_{\mathrm{w}}(f)$ and soil composition with percentage of clay and sand. If water is absorbed to a surface, such as clay, its dielectric effect is reduced. In our simplified model, we calculate the dielectric constant of packed bananas $\varepsilon_{\mathrm{b}}(f)$ as a weighted mixture between those of air ($\varepsilon_{\mathrm{r}} = 1$) and water. The factor $a_{\mathrm{W}} < 1$ describes how far the influence of water is reduced owing to absorption. The conductivity of the medium σ contributes to additional losses, especially for low frequencies. As bananas contain very few free ions, this effect is rather small. Their conductivity measured for DC current was $\sigma_{\mathrm{B}} = 0.005\,\mathrm{S \cdot m}$.

$$\varepsilon_{\mathrm{B}}' + j \cdot \varepsilon_{\mathrm{B}}'' = a_{\mathrm{w}} \cdot V_{\mathrm{C}} \cdot (\varepsilon_{\mathrm{w}}' - 1) + 1 + j \cdot \left[a_{\mathrm{w}} \cdot V_{\mathrm{C}} \cdot \varepsilon_{\mathrm{w}}'' + \frac{\sigma_{\mathrm{B}}}{2\pi \cdot f \cdot \varepsilon_0} \right]. \tag{3.2}$$

According to the free-space path loss equation, the received signal power P_{R} depends on distance d and wavelength λ.

$$P_{\mathrm{R}} = \left(\frac{4 \cdot \pi \cdot d}{\lambda} \right)^2. \tag{3.3}$$

It has to be noted that equation (3.3) is only valid for ideal isotropic antennas. It should not be misinterpreted in a way that lower frequencies have a higher communication range *per se*. The advantage of lower frequencies is only achieved if the antenna size is increased in proportion to λ. For a fixed, maximum antenna size, the effect of a higher λ is compensated by a lower antenna gain.

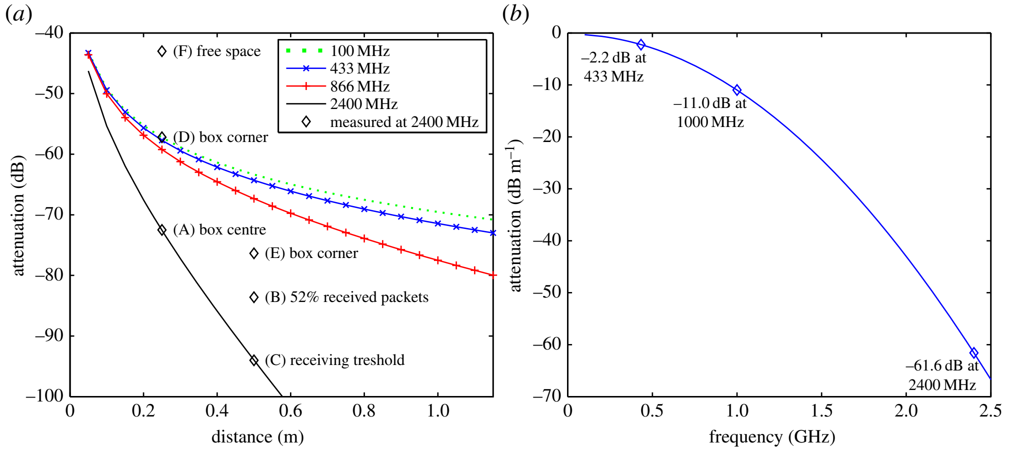

Figure 2. Model prediction for signal attenuation as a function of distance: (*a*) fitting to measured values, (*b*) attenuation per metre as a function of frequency. (Online version in colour.)

The advantage of lower frequencies in dielectric media is given by the following equation for the real part α of the propagation constant that describes the signal attenuation of a medium [26]

$$\alpha = 2\cdot\pi\cdot f\cdot\sqrt{\frac{\mu_0\varepsilon_0\varepsilon'_B}{2}\cdot\left[\sqrt{1+\left(\frac{\varepsilon''_B}{\varepsilon'_B}\right)^2}-1\right]}. \tag{3.4}$$

Even if the complex dielectric constant is almost independent of frequency as observed for frozen shrimp [27] and simulated meat emulsions [28], the signal attenuation increases with the frequency because equation (3.4) contains it as a proportional factor. The lower reading rates of RFID tags at 915 MHz compared to 433 MHz, observed by Laniel *et al.* [29] in a container with frozen bread, can be explained by this factor.

The electrical field strength E drops according to (3.5)

$$E = E_0\cdot e^{-\alpha\cdot d}. \tag{3.5}$$

Converting to a logarithmic scale and combining with the free-space path loss leads to equation (3.6) for the received power. The constant P_0 contains factors such as transmitter power and antenna gain, but for the moment we focus only on the effect of frequency on the signal attenuation and the transmission range.

$$P_{dB} = P_0 - 20\cdot\log_{10}(d) - 8.688\cdot\alpha\cdot d. \tag{3.6}$$

In our tests, each box with a volume of 50 l contained 18 kg of bananas with a water content of 0.81 kg^{-1}, resulting in a water-volume content $V_C = 0.288$ relative to the box. The remaining unknown parameters P_0 and a_W were estimated by received signal strength indicator (RSSI) values read out from the radio chip during field tests in 2009 and 2011. Figure 2*a* shows a simulation of the model for the signal attenuation as a function of distance at 2.4 GHz.

For a distance of 0.25 m, we measured an average attenuation of P_{dB} ($d = 0.25$ m; $f = 2.4$ GHz) = −72.5 dB for sensors placed in the centre of the banana boxes (Point A in figure 2). For a distance of 0.5 m, only 52% of the packets were received with an average RSSI of −83.6 dB (Point B). The average RSSI of all packets, including those too weak to be properly decoded by the radio, was set to the receiving threshold of the radio CC2420 chip of −94 dB (Point C) based on the assumption that nearly the same number of messages had a RSSI of above and below the receiving threshold for a packet rate close to 50%. A fitting of the model led to an attenuation by the medium of −61.6 dB m^{-1}. This is in accordance with our earlier analysis in [13] with an attenuation of $-52\,\mathrm{dB\,m^{-1}}$ for sensors placed in the corners of the banana boxes (Points D and E), where there was more free airspace. The model was extrapolated to other frequencies based on the estimated parameters $P_0 = -69.2$ dB and $a_W = 0.24$. Figure 2*b* shows the tremendous influence of the operating frequency on the water-related signal attenuation. The signal attenuation per metre is 50 dB lower at 1 GHz than at 2.4 GHz in our example scenario for the supervision of banana transportation.

(a) Additional influences on transmission range

Besides the selection of a lower operation frequency, improvements with regard to antenna gain, receiver sensitivity and transmission power can help increase the reading range. Because the transmission range is limited by national regulations, practical improvements can only be achieved by better design of printed or ceramic chip antennas and new radio chips with a higher sensitivity. However, the following two effects that reduce the reading range should also be considered.

In their model for underground sensors, Vuran & Akyildiz [24] included the effects of multi-path fading caused by reflection of the wave at the surface, diffraction and scattering at obstacles with a different dielectric constant. In our test case, the variation of signal delays on different paths in an air/banana mix can enhance the effect of multi-path fading.

Furthermore, the effects of non-optimal antenna orientation cannot be neglected if a networked sensor is required to communicate with neighbours in different directions. The detuning of the antenna has also to be considered if the antenna is in touch or in close proximity to a dielectric medium. Vidal *et al.* [30] observed, for example, a detuning by the maximum offset of 70 MHz for an antenna that was first optimized for 403 MHz and then implanted into the human body.

(b) Alternate operation frequencies and communication standards

The advantage that can be achieved by operating on frequencies below 1 GHz outweighs the effect of better antennas or a higher transmission power. The selection of an alternative operation frequency with regard to national regulation is the first choice to improve communication for sensors inside water-containing products. Whereas the 866 MHz range is only available in Europe for licence-free applications, the industrial, scientific and medical (ISM) radio band at 433 MHz offers a bandwidth of 1.74 MHz worldwide. The global availability of the 433 MHz ISM band (with a slight frequency change required in Japan) is an attractive solution for food logistics owing to its ubiquitous nature.

The IEEE and DASH7 Alliance [31] both have standards for the use of the 433 MHz band: IEEE 802.15.4f and DASH7 Mode 2 (DM2), respectively. DM2, however, is the predecessor of the new DASH7 Alliance Protocol Specification Draft 0.2 (An Advanced Communication System for Wide-Area Low-Power Wireless Applications and Active RFID) that is in effect in late 2013. This new specification is available for evaluators under the LGPL v. 2.1 licence. DM2 is an extension of the ISO/IEC 18000-7 : 2009 technical specification, which defines the air interface for RFID devices operating under 433 MHz to promote compatibility and inter-operability [32]. Our tests here concern only DM2 release version 12, which is available to the public under an open source licence.

The DM2 implementation supports multi-hop communication—currently a maximum of two hops are allowed. However, the DASH7 specification, including the most recent one, does not specify routing algorithms or any suggestive means or rules to implement them. Therefore, it is up to the user to write an implementation based on his application scenario.

DASH7 hardware is limited. Few companies offer full or semi-evaluation kits. WizziKit by WizziLab, France [33], is a full evaluation kit based on the CC430F5137 system on a chip (SoC) by Texas Instruments (TI). Another full evaluation kit by Agaidi Oy, Finland, which is no longer available for purchase, is also in circulation. Both these kits are tested to work with the open source software called OpenTag based on DM2. TI offers transceiver modules like CC1150EMK for 433 MHz, which has to be self-integrated onto a microcontroller of your choice along with custom software.

Currently, only outdoor tests to compare the range of 433 MHz and 2.4 GHz devices have been carried out. Tuset-Peiró *et al.* [34] found that 433 MHz was significantly better in free airspace by field tests and theoretical analysis. Our outdoor tests with 433 MHz wireless nodes were conducted with OpenTag running on the Agaidi evaluation kits, based on the CC430F5137 SoC. We used typical 10 cm whip antennas. The receiver base station was fixed and the transmitter node was gradually distanced from the transmitter at 20 m steps. The tests were repeated for three similar transmitter nodes mounted vertically on a staff at a height of 2.1 m above the ground and the received signal strength was measured. At RF output powers of −15, 0 and 10 dBm, the maximum communication range was approximately 120, 280 and 360 m, respectively. This is slightly less than what is indicated by Tuset-Peiró *et al.* [34] for 433 MHz nodes fixed at a height of 2.1 m above the ground. The main reason for that, as per our investigation, are the irregularities of the RF circuit tuning of the used wireless nodes. Two out of three nodes recorded far less range than the above figures under the same test conditions, which validates our suspicion on the wrong tuning of the RF circuit. In a test with a TelosB at the RF output power of 0 dBm, the recorded outdoor range was approximately 100 m.

The tests in free airspace as well as the model for signal attenuation by water-containing products indicate that the 433 MHz range is much more suited for supervision of food products than the commonly used 2.4 GHz range, although no direct experimental comparison for the conditions of banana transportation is yet available.

4. Communication protocols

In logistic applications such as the 'Intelligent Container' described earlier, local WSNs are used for gathering information such as temperature and humidity readings of the goods. The selection and implementation of reliable and efficient communication protocols to transfer the readings of multiple sensors over multiple hops to the FSU is of high importance.

In most existing solutions, vendors and manufactures use their own protocols to exchange information between connected devices. In general, these proprietary protocols do not allow for a seamless integration into existing, well-known protocols and nor do they make the system compatible, flexible and transparent to other solutions.

If we consider the data exchange on a company level, standardized protocols are of great advantage to inform partners about the location, temperature and current quality state of transport items. But if we consider the case that sensors of different ownership and manufacturers are mixed in a worldwide supply chain, standardized protocols become almost obligatory. Otherwise, the telematics unit of a container owned by haulage company A might not know how to interpret and forward the data received from a sensor owned by food trading company B. If items and sensors from different manufacturers are consolidated into a single truck, even the data forwarding inside the sensor network might become challenging.

This compatibility can be achieved by using a combination of different standards in different layers on each device. Currently, numerous standardized Internet protocol (IP)-based protocols exist and have been deployed in millions of devices in the World Wide Web. Protocols such as the hypertext transfer protocol (HTTP) or the file transfer protocol are outstanding examples of compatibility and flexibility and are commonly used to transfer data through the Internet. However, most protocols show high parsing and header complexities and, as a consequence, generate vast packet overhead. Additionally, to provide reliability of the exchanged message, most protocols rely on the underlying transmission control protocol (TCP), which adds additional overhead to the entire message exchange.

However, WSNs diverge in several aspects from the devices connected to the Internet. WSN nodes are usually battery powered, have limited memory and processing capabilities, and the underlying radio protocols for low-power applications, such as IEEE 802.15.4, allow only for

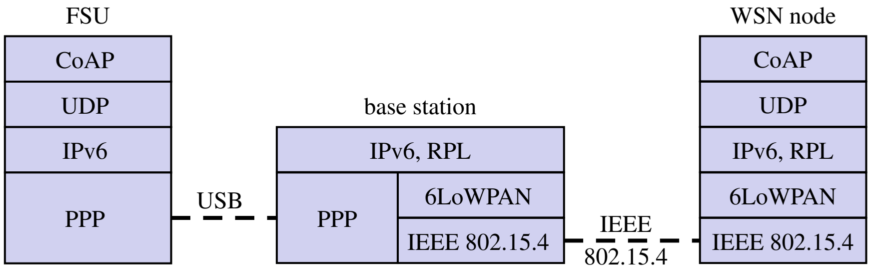

Figure 3. Overview of communication layers between WSN and FSU. (Online version in colour.)

the exchange of small data packets. Hence, the conventional IP-based application protocols are not suitable for typical WSN-based networks.

In order to comply with these requirements, the following sections detail the protocols that are used in the 'Intelligent Container' set-up. In this context, we use a combination of several standardized protocols in different layers on the devices. Besides the adaptation layer for providing IPv6 over low-power and low-rate networks (6LoWPAN), we also show a suitable routing protocol for multi-hop scenarios (RPL) and the CoAP that provides the missing link between the lower layers and accessibility over the Internet (figure 3).

(a) IPv6 over low-power wireless personal area networks

IPv6 over low-power wireless personal area networks (6LoWPAN) is a set of standards that has been defined by the internet engineering task force (IETF). By introducing an IP adaptation layer, it provides an efficient use of IPv6 over low-power and low-rate wireless networks for simple embedded devices [35]. By defining a very simple and compact header format, 6LoWPAN takes the nature of wireless networks into account and enables IPv6 functionality to constrained devices. Furthermore, additional specifications define further improvements for 6LoWPAN-like header compression [36] to reduce the header size and neighbour discovery [37] to detect neighbours if routing is not available.

The Berkeley IP implementation for low-power networks (blip) is an IPv6/6LoWPAN implementation for TinyOS, an operating system for wireless sensor nodes, which provides numerous techniques to integrate IP-based protocols in WSNs.

In order to test the inter-operability of the blip implementation with other available implementations, the authors took part in the first ETSI 6LoWPAN Plugtest in July 2013. The test event was organized and run by the European Telecommunications Standards Institute (ETSI) as a neutral body with the main scope of evaluating the inter-operability of the products to validate the understanding of the protocol specification and to identify the gaps and ambiguities within the specification. The overall test result showed high inter-operability of the 6LoWPAN core specification as well as the compliance with the header compression specification.

(b) IPv6 routing protocol for low-power and lossy networks

Routing protocols are used by routers (e.g. sensor nodes) to forward packets within and across networks. The main purpose is to find the best (preferably shortest and most reliable) path between source and destination. As routing is essential in any kind of network to transfer packets throughout the network, several standardized routing protocols exist. Most of the protocols are designed to comply with their intended applications. Where routing in fixed networks is often realized with static routes, wireless networks make use of dynamic routing. Owing to the nature of wireless networks, mobility and unstable links make static routing unreliable and inefficient. Furthermore, the dimensions of, for example, WSNs may reach from a few to several thousand nodes and make the routing even more challenging. Additionally, the limited memory and computational power of the resource-constrained nodes require additional consideration in terms of complexity, implementation size and message overhead.

Al-karaki & Kamal [38] and Sha *et al.* [39] give an overview of existing routing protocols in WSNs. However, as a response to the upcoming interest of connecting IPv6 enabled WSNs to the Internet, the IETF 'Routing Over Low power and Lossy networks' working group has proposed a routing protocol for targeting IPv6-based low-power and lossy networks. It defines the IPv6 Routing Protocol for Low-power and lossy networks, called RPL in short [40]. Its main goal is to provide efficient and reliable routing, even in large-scale networks. It is optimized for traffic from or to one or more roots. An RPL root acts as a sink or a base station and is usually connected to a backbone network, e.g. the Internet. RPL makes use of the distance-vectors to calculate the paths and provides three basic traffic flows: point-to-point (device to devices), point-to-multipoint (central control point to a subset of devices) and multipoint-to-point (subset of devices to a central control point).

Distance-vector routing protocols select their best routing paths by means of a metric (distance) and an interface (vector). In order to find the best routing path (the distance-vector), the RPL makes use of different objective functions. Objective functions are an extension to RPL and define how nodes calculate and select the routing paths [41,42]. In [43], the authors have shown a performance evaluation of RPL in WSNs.

In contradiction to link-state routing protocols, nodes using distance-vectors communicate only with their direct neighbours. Therefore, all nodes in the network create their routing table according to the routing information (updates) received from their neighbours. In case a node detects a change in the network topology, it sends out an update of its routing table to inform its neighbours. Resulting from this, all nodes are informed about topology changes within the network after a certain time. To provide consistency of routing information without flooding the network, especially during the start-up phase of the network, RPL makes use of the Trickle algorithm [44]. This algorithm allows RPL to reduce the forwarded packets to a minimum as long as consistency of routing information is detected by the nodes. Especially in dense networks with battery-powered nodes, this mechanism reduces the number of transmitted messages significantly and allows for lower power consumption of the nodes.

In [45], the authors have analysed the Trickle algorithm of the RPL routing protocol in WSNs by means of simulations and analytical models. From the obtained results, design decisions of the network size, the number of supported nodes and trade-offs for the Trickle parameters can be found.

(c) Constrained application protocol

The CoAP is a standardized, lightweight web transfer protocol that has been designed to meet the requirements of constrained networks and nodes. The main focus is to fulfil machine-to-machine requirements, such as low header and parsing complexity, asynchronous transactions and simple caching and proxying capabilities. Furthermore, it provides both multicast and reliable unicast support by using the user datagram protocol (UDP) as its transport layer. It strictly follows the 'Representational State Transfer' [46] architecture style: resources are identified by uniform resource identifier, accessible with the methods GET, PUT, POST and DELETE, and represented by their content types. By providing stateless mapping to HTTP by the use of proxies, the interaction with existing web applications is given.

In contrast to HTTP that uses TCP as its transport protocol, CoAP exchanges messages asynchronously over UDP. Even though UDP is a connectionless and, therefore, an unreliable transport protocol, CoAP provides reliability by making use of its own stop-and-wait retransmission scheme with an exponential back-off timer. The main advantage of using UDP instead of TCP is the small message overhead and the absence of additional messages (handshakes) to establish and terminate connections. Moreover, UDP provides broadcast and multicast connections to enable group communication. Basically, CoAP is oriented on the client/server model of HTTP and represents its interaction model in a similar manner. As the endpoints of both protocols usually act as both the server and the client simultaneously, the message exchange of CoAP uses equivalent approaches as HTTP. CoAP implements detection of duplicate messages by using randomly generated, unique transaction IDs as well as built-in discovery.

The CoAP base specification describes the basic functionalities of the protocol [47]. Additionally, several other IETF Internet drafts are available to extend CoAP with, for instance, blockwise transport [48], observing resources [49] or group communication [50].

Currently, there are numerous CoAP implementations available for several platforms [51]. The implementation used in this work is named CoapBlip [52] and operates on TinyOS, which is an operating system for WSNs. CoapBlip is based on the C library libcoap [53] and hence supports the latest version of CoAP (coap-18). Besides that, it includes support for blockwise transfer, observing resources and other additional Internet drafts. During the development phase of CoapBlip (which had been initiated by the 'Intelligent Container' project), the application has become a default application of the latest TinyOS release [52].

Besides many other implementations, the inter-operability of our CoapBlip application has been tested in two CoAP-specific Plugtests, also organized by ETSI in March 2012 and November 2012 (first and second ETSI CoAP Plugtest). The test specification of the second Plugtest consists of 23 mandatory and 41 optional test cases. With a total run of approximately 1750 tests in 60 pairing sessions (different clients with different servers), the overall result showed a success rate of approximately 98% [54].

In some scenarios, Internet connectivity is disabled or only temporarily available on constrained endpoints, e.g. telematics devices. This might either be the case when Internet connectivity is switched off owing to power saving reasons or when cellular coverage does not allow for Internet connectivity. In such situations, short message service (SMS) can be used instead as a transfer protocol. In [55], SMS has already been defined as a transport protocol for small data transmissions. Besides that, existing implementations use SMS to trigger (wake-up) devices and to initiate or enable Internet communication. However, trigger messages are costly and usually do not carry any useful information. Additionally, current M2M applications that use SMS as its transport protocol, e.g. telematics devices, use diverse proprietary and closed binary protocols with limited public documentation.

As SMS service offers small packet sizes and high delays, it is therefore compliant with properties of low-power and lossy networks, i.e. WSNs. As the design of CoAP considers these limitations, the CoAP protocol is also applicable to be used with SMS services. In [56], the authors proposed an IETF draft to use SMS as an alternative transport for CoAP. This proposal defines an adaptation of CoAP to the SMS transport and specifies how this transport mechanism can be applied to IP-enabled devices. As a result, the Open Mobile Alliance has identified SMS as an alternative transport for CoAP messages in its lightweight M2M technical specification.

5. Energy consumption

Reducing the energy consumption is another crucial task in designing a network protocol beside the compatibility to open standards. In earlier studies [57], we showed that the majority of current consumption is owing to the radio chip. The CC2420 radio chip of the TelosB sensor nodes [15] requires almost the same current for receive (21.8 mA) and transmit modes (19.5 mA at 0 dB). The current consumption of the other hardware components is significantly lower. The MSP430 microcontroller draws 2.6 mA in active mode, as well as the SHT75 [16] temperature and humidity sensor that also requires 2.6 mA.

Battery lifetime of more than 1 year can be achieved if the radio operates only in transmit mode and wakes up only in long intervals to send the current measurements to a base station or a router that is permanently powered, e.g. [58]. But these systems have only limited capabilities to send configuration commands to the sensor nodes or to request a re-transmission if the first one fails. If messages should be forwarded within the network, the radio has to be periodically set to receive mode.

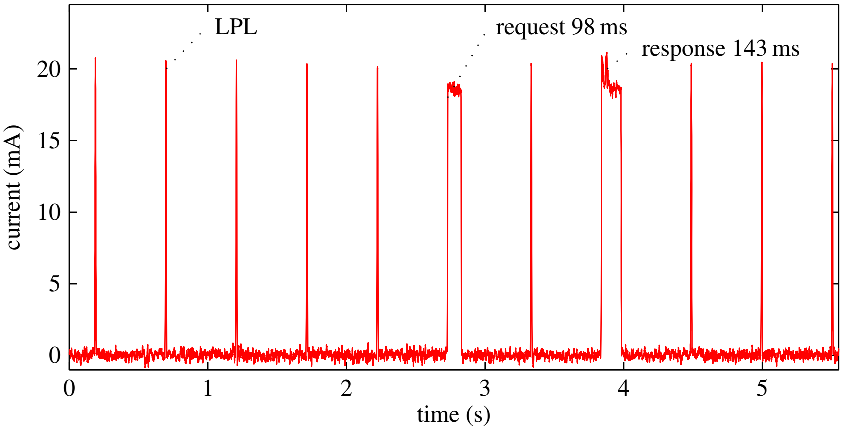

Figure 4. Measured total current consumption of a sensor node for LPL and forwarding of a request/response pair by the CoAP protocol. (Online version in colour.)

The share of time, during which the radio chip has to be powered on to sniff for new transmissions, can be reduced by the LPL approach [43]. The radio is turned on in fixed intervals (e.g. 512 ms) for a short period (e.g. 6 ms) to check whether another node tries to send a packet. The sender has to start its transmission with a burst sequence to wake-up the listening node. The burst sequence is aborted as soon as receiver's acknowledgement is received by the sender.

The total energy consumption of a network protocol depends on the implementation of data transmission and RPL routing. We analysed the energy consumption of the earlier described CoAP protocol as an example case study for querying 20 sensors inside a container every 10 min. The current consumption was measured as a function of time by the voltage drop over a 5 Ω resistor with an oscilloscope. The testbed set-up consisted of four nodes forming a typical line-scenario. The first node acted as a base station and was connected to a PC where the requests were initiated. The second node was an intermediate node and the remaining two nodes acted as sink nodes. The distances were so chosen such that no direct connection between the base station and the two sink nodes was possible. Therefore, the topology of this set-up was a multi-hop network where the intermediate node had to cope mainly with two tasks: process incoming request dedicated to itself and forward packets from the base station to the sink nodes and vice versa. Figure 4 shows the periodic turning on/off of the radio for short periods by the LPL mechanism. If the sensor forwards either a request to the target sensor node or a response back to the base station, the radio stays on to send the burst sequence until an acknowledgement is received and to transmit the data.

In average, the radio was active for 1.06 s to forward an incoming request and its corresponding response. The number of requests that have to be forwarded depends on the node's position in the network. In a bottleneck scenario, one sensor might have to forward queries to all remaining 19 sensors of the network. As the bottleneck scenario can be avoided by smart placement of the sensors, we limited the number of forwarded neighbours to 12 per sensor.

The sensor nodes have to update their routing tables periodically and exchange them with their neighbours. Furthermore, the standby current of the microcontroller of 11 µA has to be taken into account. The contributions of the above-described factors to the total current consumption are compared in table 1.

In total, the radio is active 4.56% of the time or 65.6 min per day. The TelosB node is powered by a pair of AA batteries. If two-thirds of the nominal battery capacity of 2950 mAh can be used until the battery voltage drops under a critical threshold of 1.2 V, the sensor nodes can run the CoAP protocol for about three months in the given example scenario. During our field test at Dole in 2013, the battery voltage dropped from 1.5 to 1.425 V after three weeks. A further laboratory test

Table 1. Contributors to current consumption for implementation of a multi-hop protocol.

contributor	required resources	relation (%)	minutes per day
LPL	6 ms every 512 ms	1.17	16.9
12 sensor requests and responses every 600 s	12 × 1.06 s every 600 s	2.11	30.4
routing without LPL	154 messages in 50 min with average length of 236.6 ms	1.21	17.5
standby current	11 μA related to 20 mA	0.06	0.8
total		4.56	65.6

with a single sensor and data rate equivalent to the bottleneck case with 20 requests per 10 min resulted in a battery life of about three months until the voltage dropped below the critical limit.

More than half of the energy is required to maintain the network functionality by LPL and routing messages. Although this case study is specific to our test scenario, our example calculation showed how several components of the network protocol contribute to the energy consumption.

The transmission of the raw data requires only few milliseconds; most of the active radio time for sending a data packet is made up of the burst sequence to wake-up the receiver. Further optimization is possible by an intelligent burst control mechanism that delays the start of the burst sequence if the sender already knows or estimates the wake-up interval of the receiving node. A similar mechanism is implemented in the Contiki protocol [59]. But measurements of energy consumption provided by the Virtenio company show that the Contiki protocol requires more energy for LPL. Their Preon32 sensor node [21] requires an active radio time of 3.02% at a current consumption of 37 mA, consisting of 2.88% for LPL, 0.09% for data transmission according to our test scenario, 0.05% for routing and 0.13% related to standby-current, resulting in an energy consumption only slightly higher than that with TinyOS on the TelosB hardware. Optimizations are possible for both protocols either on the LPL or burst sequence mechanisms, as well as by means of data pre-processing, as shown in §6.

6. Local and flexible pre-processing of sensor data

The supervision of spatial temperature deviations inside a truck or container can produce large datasets. But the share of information that is of interest for the transport operator in the end can be expressed with few bytes: the number and location of pallets with a low shelf life or out-of-range temperature conditions. In order to save costs for external communication and energy consumption of the internal WSN, it is most useful to process the data directly on the sensor or the subsequent system level. Even very simple algorithms lead to tremendous data compression:

(1) In an approach suggested by Usman *et al*. [60], a model-driven data acquisition technique called derivative-based prediction is used to represent measured data as approximated models. An update of the model is only transmitted if the measured data start to deviate from the previous model. In its simplest form, the processor checks after each measurement if the speed of temperature change per time unit has changed. In our first test, the implementation of this technique has already revealed a suppression of data transmission of up to 90%.

(2) Simple shelf life models evaluate the effect of temperature deviations according to the Arrhenius Law for reaction kinetics or by a simple exponential relation to temperature [2].

An analysis of required CPU time and memory [61] showed that the hardware of typical wireless sensor nodes, such as the TelosB with 8 MHz clock speed and 48 kB of RAM, is fully sufficient to host such algorithms. The first commercial data loggers with wireless interface and embedded shelf life model are available by CliniSense/Lifetrack [62] and Ambient Systems [58].

More powerful processors enable the implementation of complex algorithms. The Preon32 sensor node from Virtenio [21] provides an ARM processor with a clock rate of 72 MHz and 256 kB flash memory. During recent years, we tested the following approaches for enhanced pre-processing:

(3) More accurate shelf life models calculate the bacteria growth rate as a function of temperature. The Gompertz model requires, for example, the calculation of three exponential and two logarithmic functions per measurement interval to update the shelf life [63].
(4) A thermal model can be applied for verifying the balance between the heat removal by cooling and the heat generated by respirations of fruits. For example, the model for temperature changes inside banana boxes presented in this issue [14] requires the identification of two model parameters.
(5) Spatial interpolation can predict temperatures for positions that are not equipped with a sensor. The sensor measurements are multiplied with a weighting factor according to the Kriging method [64]. The calculation of the weighting factors needs the inversion of a matrix with a size equivalent to the number of sensors.

Dannies *et al*. [63] showed that even such complex operations can be carried out in sensor nodes equipped with an ARM processor. The most CPU time-consuming task was the inversion of a 20×20 matrix for calculation of the Kriging weights, which required 2066 ms on the Preon32 sensor node. But even if the matrix has to be recalculated after each frame of 10 min, the share of active time of the CPU is only 0.34%.

A further crucial challenge for the implementation of sensor data processing is the required flexibility of the software. A supervision system for perishable goods cannot be considered as a static software system. Sensors, trucks and containers are used for different food products and operators. Different perishable goods need different types of shelf life models. A thermal model has to be adapted to different types of packing.

In order to provide this flexibility on the FSU, or even sensor nodes, a software framework has to host different algorithms, which are only installed on demand. On the FSU, we implemented the open source gateway initiative (OSGi) framework [65] that is capable of installing, updating and remotely administering JAVA software bundles. OSGi also enables dependencies between bundles. For example, an updated bundle can publish a service that calculates the shelf life for a certain product. Another installed bundle queries this service and decides when and to whom a warning message is sent.

Dynamic installation of new software components on the sensor node level can be provided by the Java micro edition framework [66] that requires fewer resources. In a test set-up, we demonstrated how a new type of shelf life model can be transferred over a mobile network, first to the FSU and from there to a sensor node [63].

7. Summary

Wireless sensors, suitable for remote monitoring of freight core temperature in containers, are currently not available off-the-shelf. In this article, we examined four challenges that hinder the wide applications of sensor networks in logistics. Single solutions are available that solve part of these challenges, but there is no single system that solves all. Technical problems are solved in principle, but are not integrated into a full solution yet.

The largest obstacle in our field tests was the high signal attenuation at 2.4 GHz. By theoretical considerations, we could show that the attenuation drops below $11\,\mathrm{dB\,m^{-1}}$, if the frequency is reduced to values less than 1 GHz. There are already systems on the market that operate at these less humidity-sensitive frequencies such as at Ceebron 433 MHz [6], Sensitech at 866 MHz [8] and Intelleflex at 915 MHz [9].

The problem of signal attenuation is often underestimated. The effect can be reduced by restricting the sensor placement only to surface positions and thus enabling a direct link between sensor tag and reader as a precondition for the application of passive RFID systems. But in several food applications, the necessity to compensate high signal attenuation by message forwarding cannot be avoided, especially for products with high water content, dense packing or with the requirement of covering the entire area inside a 40 foot container.

If the sensors should be applied in a worldwide transport network with multiple companies involved, the communication protocol has to be compatible with other widely accepted standards. This can be the EPCglobal standard for RFID tags—as used by Intelleflex—or standard IPv6 Internet protocols, as described in §4.

The DASH7 standard at 433 MHz is the most promising candidate for future food supervision systems because it is possible to implement protocols for message forwarding and the lower operation frequency will enable communication even for sensors placed between water-containing food products. Although DASH7 does not provide routing mechanisms itself, multi-hop capabilities can be provided by implementing protocols such as RPL, 6LoWPAN and CoAP on top of the DASH7 specification, which is an important task for future research.

Extending the battery lifetime for multi-hop protocols is still challenging. With our current solution, we achieve a lifetime of about three months for a measurement interval of 10 min. Most energy is wasted by bursts that are sent to wake up the receiver. If the sender keeps track of the wake-up period of the neighbouring nodes, a large share of the energy can be saved by implementing an intelligent burst mode.

More energy can be saved by the reduction in the communication volume. In particular, the models for shelf life calculation require only a negligible amount of energy for running on a sensor node; periodic transmission of measurement data is then replaced by occasional updates of the model parameters.

Considering the magnitude of worldwide food exports of more than 800 billion dollars [67] and food losses at times exceeding 30% [1], there is a large market for sensor solutions to improve food quality. Therefore, it is a matter of time until the above-described approaches are commercialized and sensor systems for remote supervision of food transports are available, which will integrate attributes such as multi-hopping, compatibility to open standards, data pre-processing and operation at frequencies less sensitive towards water-containing products.

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Data accessibility. Source code for the implementation of CoAP is integrated into the main branch of the TinyOS source code repository at GitHub Inc. 2013. Main development repository for TinyOS: https://github.com/tinyos/tinyos-main.

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