Testing network protocols and signal attenuation in packed food transports

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Abstract: Two sensor network protocols for the monitoring of packed food products were tested in different sea containers. The packet rate and the signal strength of all sensor-to-sensor links were recorded in the flash memory of the sensor nodes. The performance of the two protocols was compared and protocol improvements were tested by simulation based on this data. The high signal attenuation by water-containing products was identified as the major problem. One of the two tested protocols was newly developed with a focus on low energy consumption. A simplified link estimator, which required only a minimum number of control messages, detects the correct routing in most cases.

Keywords: signal attenuation; monitoring of food transports; multi-hop protocols; wireless sensor networks.

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1 Introduction

Due to global trade, most food products already have a journey of several thousand kilometres behind them before they arrive in the local supermarket. In order to keep high quality standards, a continuous monitoring of environmental and transport parameters is of increasing importance. For certain products the share that is lost during the transport process by quality decay can reach up to 35% (Scheer, 2006). Most of these losses are caused by temperature mismanagement. The effect of local temperature deviations inside a truck or container on the product's shelf life cannot be neglected. Typical temperature deviations can reach up to 12 Kelvin inside a truck (Moureh and Flick, 2004) and 6 Kelvin inside a packed sea container (Tanner and Amos, 2003).

The monitoring of spatial temperature deviations is a typical application field for wireless sensor networks (WSNs). But for the food sector, there are so far only few studies and applications, most of them covering the farming (e.g. Lopez Riquelme et al., 2009) but not the transport chain.

The water content of most food products hinders the communications of sensors that are packed inside pallets with food products. The high signal attenuation is a serious problem for the application of WSN inside a packed truck or container. This might be the main reason why there are only few application reports as Richardson and Walker (2006), who describe an Australian project to monitor trucks by Smart-Trace sensors. The transports of strawberries from Spain to Germany are monitored by Smart Point active tags from Ambient Systems (2009). But detailed studies about signal propagation inside food and resulting network problems are hard to find, except for Ruiz-Garcia et al. (2008).

1.1 Project overview

The aim of our project is to develop a sensor system that provides online access to the spatial distribution of transport parameters like temperature and humidity during transport. A WSN collects the environmental data inside the truck or container. The base station of the WSN is connected to a gateway that handles the external communication. Data is forwarded over wireless LAN, GPRS or UMTS networks, or in the case of sea transportation, by a satellite link. The sensor data can be pre-processed by the gateway or by the sensors in order to reduce the communication volume. A mathematical model locally evaluates the effects of temperature deviations onto the product's shelf life (Jedermann et al., 2008).

The first field test of the full system took place in September 2009. Two containers, fully loaded with bananas, were equipped with a gateway and 20 sensors each. Temperature and humidity data were forwarded to a web server during the two weeks of transport from Costa Rica to Hamburg.

The well-known SensorScope protocol (Barrenetxea et al., 2008) was installed on the sensors nodes in one container. A new developed protocol with a simple but more energy-efficient routing was applied in the other container. Because the new multi-hop protocol was initially developed for the monitoring of bananas, it was given the name BananaHop protocol.

The second goal of our project was to collect sample data for signal propagation in packed food products. This data will be used for the further testing and development of WSN protocols. A matrix with the time-dependent Received Signal Strength Indicator (RSSI) for all possible links was recorded during the test.

1.2 Design considerations for sensor network protocols

The most critical point in selecting and designing a WSN protocol is its energy consumption. As a matter of fact, the most costly factor is receiving messages, not their transmission. This is illustrated by the following example calculation for a TelosB sensor node at a battery voltage of 2.4 Volts. The radio uses 20 mA for 15 ms in order to transmit one message, resulting in an energy consumption of 720 μJ per message. The current draw for receiving is almost the same, but because the exact point of time of the transmission is unknown, the time window has to be extended. For a receiving window of 100 ms the energy consumption increases to 4800 μJ. The required energy for mathematical operations can be almost neglected, compared to latter values. The above-mentioned shelf life model requires the calculation of two exponential functions and two divisions per step. An optimised integer implementation requires only 1 ms of processing time (Jedermann et al., 2008). At a clock rate of 4 MHz the MSP430 processor of the TelosB consumes 1.3 mA, leading to an energy consumption of only 3 μJ per step. An energy-efficient protocol should reduce the number of control messages and the time window for receiving as much as possible.

Traditional protocols, such as the SensorScope (Barrenetxea et al., 2008) and S-MAC (Demirkol et al., 2006), for example, are organised in frames in order to reduce the radio-up-time. All sensors use the same fraction of the frame to transmit messages. Newly developed protocols like X-MAC and Low-Power-Listening (LPL) (Boano et al., 2010), shift the radio power control to the scale of milliseconds. The radio regularly wakes up for short periods to sniff for preamble messages. The transmitter has to send a repeated sequence of preambles in order to hit the active period of the receiver. The advantage of the latter approach is that messages can be transferred without delay. But, it is assumed that turning the radio on and off takes very little time and the additional power consumed is small.

Furthermore, typical sensor network protocols differ by the mechanisms, which they apply to avoid collisions, to estimate the quality of links, and to find a reliable route to the data sink. Collisions are avoided by either Time Division Multiple Access (TDMA) or Carrier Sense Multiple Access (CSMA) mechanism. Whereas TDMA assigns an individual time slot to each sensor, all sensors use the same time slot in CSMA, but they await a random delay after the beginning of the assigned time slot, and then probes whether the channel is clear. If so, the data is sent immediately; otherwise, the procedure is repeated.

The link quality is usually estimated by sending probe packets to the neighbours, to-and-fro, and counting the lost packets. There is a vast number of routing mechanisms;

however, the Collection Tree Protocol (Fonseca et al., 2006) provides a simple solution for the case that only one or few data sinks or tree roots exist. Each sensor estimates its distance to the tree root as the number of expected transmissions (ETX). Data messages are then forwarded in the direction of sensors with a lower ETX value.

Our application for cool-chain monitoring is marked by the following boundary conditions: (a) the temperature should be measured in fixed intervals by all sensors at the same points of time, (b) latency of one frame length is uncritical because the speed of temperature changes is slow, (c) the amount of user-data is rather low; 6 bytes are sufficient to contain temperature, humidity, and battery voltage measurements, (d) the size of the network is limited by the metal walls of the container. The maximum size is not expected to exceed 50 sensor nodes.

Because of (a) and (b) above, a frame-oriented protocol was applied. The initial idea was to transmit RSSI and link information over the network instead of storing them in the flash memory. The SensorScope protocol was selected because it was the only one supporting neighbourhood topology reports and packet trace-route reports. Furthermore, the SensorScope protocol was already tested by its authors in various deployments.

Nevertheless, the application of the SensorScope protocol on a new hardware platform caused some stability issues and took far more time than expected. Furthermore, the amount of control messages is rather high compared to the required 6 bytes of sensor data. For these reasons we started to develop a new protocol in parallel. This new protocol applies the idea of the Collection Tree Protocol in a modified form. Collisions are avoided by a combined TDMA and CSMA approach. The link quality estimation is based on a new method that is introduced in Section 3.4.

1.3 Outline

The next section describes the experimental set-up including the sensor hardware and external communication. Section 3 presents an evaluation of the recorded data for temperature and signal strength. Section 4 describes the new developed protocol. The performance of the two applied protocols is compared in Section 5. Possible modifications of the sensor hardware and protocol improvements are also discussed. A summary is given in Section 6.

2 Experimental set-up

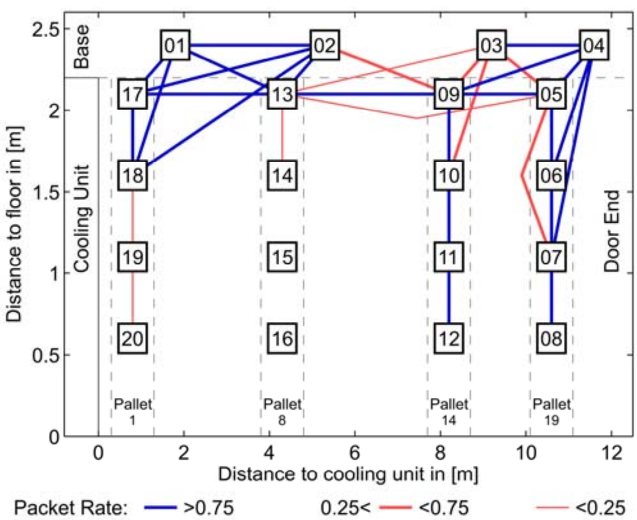
The TelosB motes from Crossbow (2005) were used as the sensor platform. The Chipcon CC2420 radio was set to the maximum transmitting power of 1 mW. The sensor node hardware was protected by a waterproofed housing. A pressure balance element prevents the humidity to penetrate into the housing due to temperature changes. The on-board humidity sensor SHT11 was replaced by an external SHT75 sensor that provides a higher accuracy of ± 1/3 Kelvin for the considered temperature range and ± 3.5% relative humidity. The complete hardware is shown in Figure 1, with the external sensor on the left and the pressure balance element on the right side. The sensor nodes were powered by two AA-Size batteries with a capacity of 2950 mAh.

Figure 1 TelosB sensor mote with housing, external sensor, and pressure balance element (see online version for colours)

The BananaHop and the SensorScope protocol were implemented with TinyOS as the operating system. A software module to record the RSSI values of the received control messages was added to both protocols.

Twenty pallets of bananas were loaded to each container with an inner length of 11.5 m, 2.3 m width, and 2.25 m height. The container was almost completely filled with the bananas. Only above and below the pallets was an air space of 0.1 m in height. In front of the door was an additional airspace of 0.3 m in width. The sensor nodes numbers 1–4 were placed on top of the pallets. Four pallets were equipped with four sensor nodes each. The sensors were placed in different tiers with a vertical distance of 0.5 m in between. The sensor positions are given in Figure 2. This diagram also gives a firsthand overview of the links detected in the container with the SensorScope protocol. Sensor 15 and 16 could not establish a link to the remainder of the network due to the high signal attenuation by the loaded bananas. Further, a TelosB mote was programmed as the base station and mounted on the grid of the cooling unit for return air.

Figure 2 Sensor positions and detected links in container 2 (see online version for colours)



The access to external networks was handled by a communication gateway. The base station sent the collected sensor data to the gateway over a USB port. The gateway stored the sensor and link information in its database. From there the compressed measurement reports were sent over a wireless LAN access point to the vessel's satellite communication system, which in turn sent it to an email account. A web server ashore regularly checks the email account and retrieves the data, inserts it in its database, and creates several dynamic web pages, RSS feeds and graphics.

Two preliminary tests were carried out in a banana ripening room in Hamburg. The software module to record RSSI data was tested on 12 sensor nodes for four days during the first ripening room experiment. For the second ripening room experiment 18 sensors were programmed with the BananaHop software and tested for three days. After the successful completion of the ripening room experiments, the sea container test was prepared.

3 Evaluation of recorded data

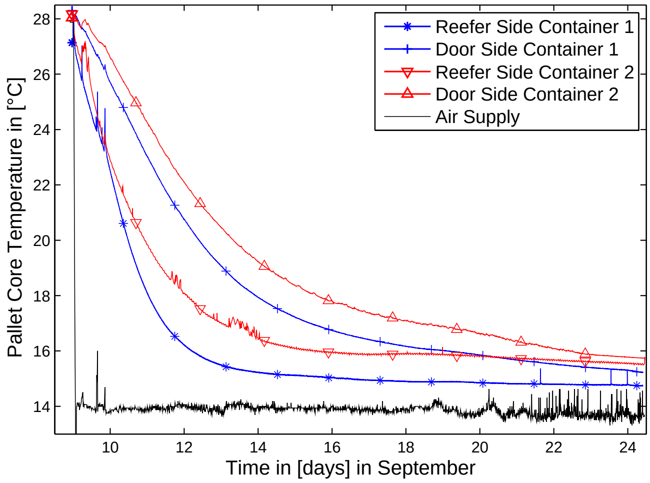
The sensor and the radio link data were logged in the flash of each sensor during the test. Because of memory limitations, only every fourth frame was recorded. In order to evaluate the radio links to the neighbour sensors, one type of control message was selected, which was sent once per frame by every sensor. The RSSI values of all received neighbour messages were written to the flash. The packet rates for the neighbour links can be calculated by counting the existing RSSI entries.

The SensorScope protocol buffers the messages to be sent, which might delay the transmission by several frames, if the channel is overloaded. This leads to a problem: the selected control message was not sent in 5–10% of the frames, but two control messages were sent in the next frame instead. Because only one entry per neighbour is written in the flash per frame, the calculated packet rates of the neighbours for the SensorScope protocol are a bit too low. Even for good links only 90–98% were achieved instead of 98–100% as for the BananaHop protocol.

3.1 Sensor records

Temperature, air humidity and battery voltage were logged in the flash as well. The analysis of the temperature data revealed the spatial deviations as well as the deviations between the two containers. Figure 3 shows the core temperature of pallets at given positions. Although the final temperatures after two weeks of cooling during the transport are rather similar, there is a huge difference in the time behaviour of the curves. Pallets at the door end of the containers needed more than double the time to cool down as those at the side of the refrigeration unit. Furthermore, the cooling in container two took about 30% longer than in container one. The ripening process of bananas is not completely stopped by the cooling. The conversion from starch to sugar generates some additional thermal energy that cannot completely be removed by the air stream. At the end of the transportation the core temperatures were still between 1 Kelvin and 2 Kelvin warmer than the air supply. But, the ripening process can switch to an uncontrolled form for some boxes, especially if they were loaded in a poor quality state. The process generates more heat than the cooling unit can remove. The ethylene gas is generated, which boosts the ripening process in other pallets. Local temperature peaks are an indicator of such an unwanted ripening process. But, this case was not observed during our experiments. For the future, an ethylene gas sensor is planned to take direct measurements of the current speed of the ripening process.

Figure 3 Pallet temperatures over time (see online version for colours)



The average air humidity rose from 90% to a maximum of 98% during the transportation. A spatial dependency could not be detected. One analogue input of the TelosB was used to measure the battery voltage, which dropped from initially 3 Volt to 2.77 Volt for the BananaHop protocol and 2.64 Volt for the SensorScope protocol. The lower voltage drop indicates that the BananaHop protocol is more energy efficient.

3.2 RSSI and packet rate

The signal attenuation by the bananas was estimated based on the vertical links within the same pallet. For the vertical links the whole signal has to travel through the bananas, as long as there is no airspace beside the pallet. The two data sets from the sea containers and the data from two preliminary experiments in a ripening room were evaluated. Table 1 shows the average packet rate for links between sensor nodes sorted by the distance in the ripening rooms and the containers. After the promising test in the ripening rooms, the minimum sensor distance for the sea container test was set to 0.5 m. Therefore, unfortunately, there are no measurements available for distances of 0.25 m and 0.75 m for the sea containers. The related table entries are marked as 'n/a'.

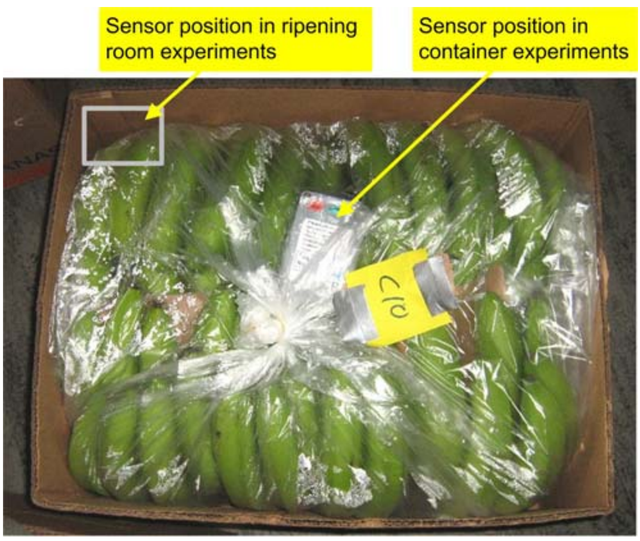
Table 1 Packet rate as a function of sensor node distance

Distance	*0.25 m*	*0.50 m*	*0.75 m*	*1.00 m*
Ripening Room 1	1.00	1.00	0.52	n/a
Ripening Room 2	1.00	0.99	0.99	0.58
Container 1	n/a	0.52	n/a	0.00
Container 2	n/a	0.53	n/a	0.01

For a distance of 0.5 m no problems were detected in the two tests in the ripening room. All expected radio links were present and the average rate was above 0.99. But in the container experiments, the average packet rate dropped to 0.53 for the same distance. In both containers two sensors out of 20 did not establish any neighbour link at all. The much lower performance of the radio links was caused by the following two factors:

- The air humidity was 10% higher in the container experiments and achieved almost 100%. Due to the cooling down, part of the humidity condensed to fog or water drops, both of which might have hindered the signal propagation more than the water in its gaseous phase. But for the ripening room experiments, condensation was prevented by higher ventilation and constant temperature.
- The sensors should ideally measure the banana pulp and not the air temperature. To be as close to the fruits as possible the sensors were placed between the fruits in the centre of the box for the container experiments. But due to restrictions by our partner company, we had to select another position for the ripening room tests. The sensors were placed in one corner of the box. Although this position should be avoided because of temperature inaccuracy, it seems that the corner position reduces the signal attenuation. The free air spaces in the corners of the stacked boxes form a channel that makes signal propagation easier. Figure 4 shows the different sensor positions.

Figure 4 Sensor position inside banana box for ripening room and container experiments (see online version for colours)



The measured poor link quality is in accordance with an experiment carried out by Ruiz-Garcia et al. (2010). Four Micaz sensor nodes with a Chipcon CC2420 radio were distributed inside a truck loaded with lettuce. Only one sensor node achieved a packet rate over 90%. Two nodes could not establish any link.

Table 2 gives the average RSSI value for the ripening room experiments. But, the available data for a distance of 1 m were insufficient for a proper calculation for the container experiments. For a distance of 0.5 m the average RSSI values were –83.2 dBm and –84.0 dBm respectively for the two containers.

Table 2 RSSI as a function of sensor node distance

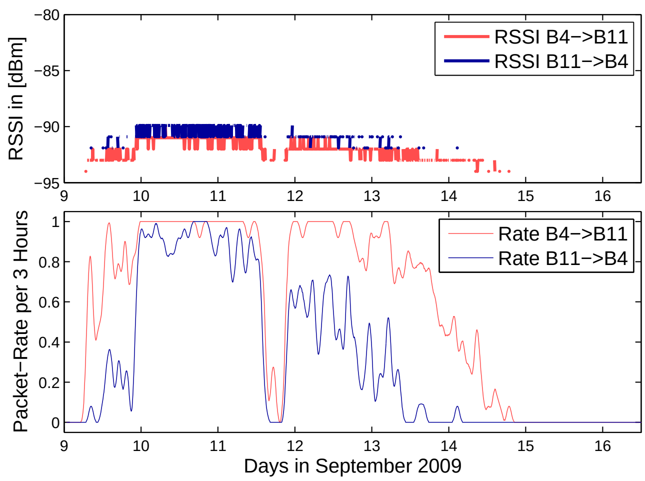
Distance	*0.25 m*	*0.50 m*	*0.75 m*	*1.00 m*
Ripening Room 1	–57.7 dBm	–77.9 dBm	–87.7 dBm	n/a
Ripening Room 2	–56.7 dBm	–74.8 dBm	–70.6 dBm	–87.7 dBm

A simple attenuation model was estimated based on the measurements in the ripening room for a distance of 0.25 m and 0.5 m. The left term in the equation (1) gives the free-space path loss, which is proportional to the inverse squared distance d (measured in metre). The right part of the equation assumes that the attenuation by the material is linear to the distance with a factor *A*. The attenuation *A* was estimated to be –52 dB per metre (*offset* = –11 dBm).

$$rssi = -10 \cdot \log(d^2) + A \cdot d + offset \quad (1)$$

Figure 5 shows the RSSI and packet rate over time for one example link. The changes of the RSSI value over time were rather slow. The packet rate for a certain point of time was calculated by weighting the existing links within a time-window of three hours in length, equivalent to 23 flash entries, with a Hamming type window function.

Figure 5 RSSI and packet rate over time for one link (see online version for colours)



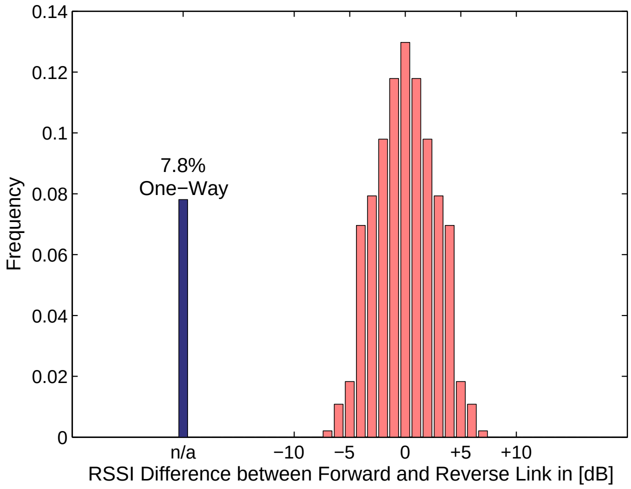
After 2.5 days the packet rate showed a sharp drop for seven hours, but then recovered for the next two days. For the remaining eight days of transportation the link between

sensor 4 and 11 diminished almost entirely. Half of all the links showed similar drops outs. The packet rate fell to zero for an interval with a length between eight hours and several days. A quarter of the links failed completely or in more than 90% of all the frames. The remaining quarter of the links provided almost stable data transfer over the full experiment duration.

3.3 Symmetry of RSSI

Figure 5 shows only a small difference between the RSSI values for the forward and the reverse link. It seems that the RSSI behaves rather symmetrically in settings of packed food containers with high signal attenuation by water-containing goods. This symmetry hypothesis was tested by plotting a histogram for the RSSI difference per frame between the forward and the reverse direction for all existing links. Figure 6 shows the histogram for the first container test. The other experiments show similar results: The RSSI difference was less or equal to 5 dB for at least 85% of all existing links. Srinivasan and Levis (2006) also concluded that the RSSI is almost symmetrical for the Chipcon CC2240 radio, whereas poor hardware calibration of older radio chips like the CC1000 and TR1000 led to asymmetrical RSSI measurements.

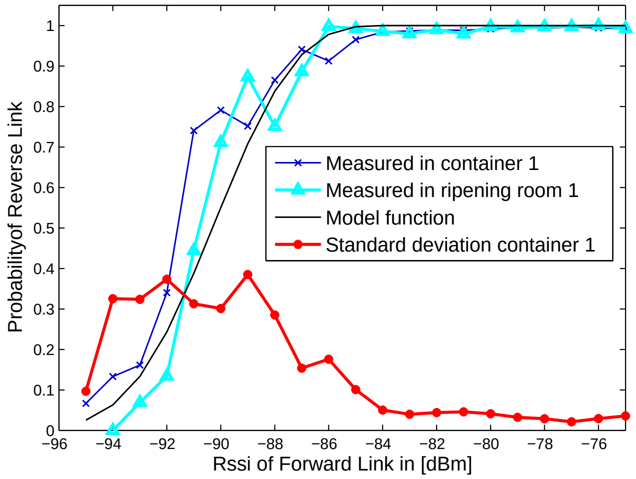
Figure 6 Histogram for RSSI difference between forward and reverse link in container 1 (see online version for colours)



3.4 Inverse packet rate

The share of one-way links was between 4.7% and 9.3% in the four experiments, implying that one message from a certain neighbour was received but a single attempt to send back data over the reverse links failed. Almost all of these one-way links are found for RSSI values below –85 dBm. The probability of a successful transmission over the reverse link is called the *inverse-packet-rate*, and it is plotted in Figure 7 as a function of the RSSI value of the forward link. The packet rate of the inverse link was calculated by using a hamming-type window with a length of ± 1 hour or ± 15 samples relative to the current frame. The experiments with the BananaHop protocol in the ripening room and in the container showed slightly different curves. The flash records of the SensorScope protocol had too many distortions by delayed control messages for analyses of the inverse-packet-rate.

Figure 7 Measured inverse-packet-rate and model (see online version for colours)



The measured inverse-packet-rate for the first ripening room test was approximated by a model, which is used by the BananaHop protocol. Above an RSSI value of –85 dBm almost all links work in both directions. Between –95 dBm and –85 dBm the rate is estimated by the equation (2):

$$rate = 10^{0.0012\cdot(rssi+84)^3} \tag{2}$$

Below –95 dBm the rate is set to zero. The model depends on the sensitivity of the radio chip. The given parameters of the model are only valid for the used CC2420 Chipcon radio. The error of the prediction by the inverse-packet-rate was estimated by calculating the standard deviation of the packet-rate for groups of inverse links with the same forward RSSI.

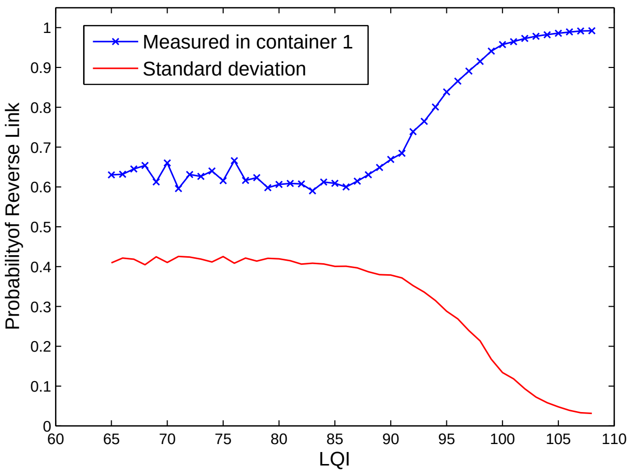
For links with an RSSI above –85 dBm the prediction is very reliable with a standard deviation below 0.05. But for links below –88 dBm the standard deviation grows to a value between 0.3 and 0.4.

Srinivasan and Levis (2006) related the packet-rate with RSSI in a similar study. In contrast to this study, they considered the packet-rate of the forward link instead of the reverse link. But the latter one is preferable as it directly gives the information that is required for routing.

The Chipcon CC2420 radio chip provides a second option for estimation of the packet rate. The Link-Quality-Indicator (LQI) is calculated based on the chip-error-rate of the received packets. The inverse-packet-rate was plotted in Figure 8 as function of the received LQI value. The graph shows that for a wide range of LQI-values the predicted packet rate is 0.6, but with a constant high standard deviation of above 0.4. Furthermore, it is not possible to detect links with an inverse rate below 0.6 on the basis of the LQI value of a single packet.

Srinivasan and Levis (2006) found that the average LQI can only be used as a link estimator if an average over several received packets is taken. They recommended to span the average over at least 120 packets. The LQI of a single packet gives only poor link estimation because the LQI value has a very high fluctuation over time. In contrast to this, the RSSI values change only slowly over time.

Figure 8 Inverse-packet-rate as function of LQI value (see online version for colours)



4 Simplified energy-efficient protocol

The following section describes the newly developed BananaHop protocol. The routing in mobile sensor networks typically creates huge protocol overhead. The air-channel is loaded with much more control messages than with the raw sensor data. Most of the time, during which the radio is powered on for receiving, it overhears only messages that are addressed to other sensors and not itself. The BananaHop protocol was developed in order to reduce the amount of control messages and to make better use of all received data messages.

The BananaHop protocol is organised in frames of 120 seconds. The first five seconds of a frame are reserved to forward beacons. Twenty seconds are reserved to forward data messages. But, there is no need to keep the radio awake for the full duration of these two active protocol phases. The radio is only powered on for a fraction of time, depending on the amount of forwarded messages. Afterwards, the radios of all sensors are completely powered down for the remainder of the frame.

The *beacon phase* starts with the initial beacon from the base station, which is forwarded only once by every network node. The beacon includes a time-stamp for synchronisation and a counter that is incremented after each hop or forwarding. This counter is used to set the hop-level for each sensor node. The hop-level gives the distance to the base station – or more precisely – the minimum number of hops that are necessary to transmit the data back to the base station over a reliable route. The maximum hop-level H_{Max} is currently set to 6. Details of the beacon phase are described later in this section.

The *data phase* combines elements from TDMA and CSMA. Each sensor is assigned a time slot according to its hop-level. But, in contrast to classical TDMA, several sensors are enabled to send during the same time slot. Collisions are avoided by a CSMA approach.

Sensors nodes with the highest hop-level H_{Max} transmit their data during the first time slot. Sensors nodes in the next hop-level H_{Max}–1 are set to receive-mode during the same time slot and to transmit-mode for the subsequent time slot. This is continued for the following hop-levels until all sensor data are forwarded to the base station. An acknowledgement policy prevents sending of redundant sensor data. Communication is rather broadcast between the hop-levels than between the individual sensors as in the SensorScope protocol.

This routing mechanism for the sensor data does not require any routing tables; it requires only the assigned hop-level. Data transmissions do not necessarily use the inverse route of the received beacon, but they use the same number of hops.

4.1 *Simplified link estimation*

During data transmission one node acts as the sender or the *data source*, the other as the receiver or the *data sink*. In order to select a reliable route, the source node needs to know how well its data is received by possible sink nodes.

Typically, the link estimation is not done by the source node itself, but on the sink side. The SensorScope protocol uses a dedicated neighbourhood message for link estimation. The sink node counts the received neighbourhood messages from the source. Missing packets are detected by leaps in the sequence number. This approach entails a higher radio-up-time because the sink node has to sniff for the maximum protocol interval for messages from the prospective source nodes.

The BananaHop estimates the link quality on the side of the source by the inverse packet introduced in Section 3.4. This simplified approach largely reduces the amount of control messages and radio-up-time by using only the RSSI value of received beacons for link estimation. RSSI measurement is a built-in feature of most 802.15.4 compliant radio chips. The Chipcon CC2420 radio provides a register from which the RSSI value can be directly read out.

The standard deviation of the inverse packet rate rises above 0.3 for RSSI values below –88 dBm as shown in Figure 7. This leads to a higher inaccuracy of the simplified approach compared to the estimation on the sink side. But in general, only a raw estimation is required for routing. The source node mainly requires a means to compare different possible links rather than the absolute value of the packet rate. The feasibility of this approach was proven in our field tests.

Designing a WSN protocol means keeping the balance between the data rate and the energy consumption. A few lost packets due to inadequate routing or erroneous link estimation can be tolerated, if the radio-up-time is reduced. An analysis of the achieved data rates is carried out in Section 5.

4.2 *Beacon phase*

An appropriate hop-level is assigned to each sensor, and the link quality information is updated during the beacon phase. Ten time slots of 0.5 seconds are reserved to forward the beacon from the base station to the sensors with the highest hop-level. After sending the beacon the radio is powered down. Each forwarded beacon contains its current hop-level, a time stamp for synchronisation, and the product of the inverse-packet-rates (*rate-product*) of the involved links as a measure of the probability that the sensor can send the data back to the base station over this route. The evaluation of link quality is largely simplified if the logarithm of the rate-product is taken as measure instead. In equation (2), only the value inside the exponent has to be calculated. The product of inverse packet rates is reduced to the sum of the exponents.

After receiving a beacon, the sensor node compares the signal strength of this last link with a threshold of RSSI ≥ –85 dBm in order to discern between 'good' and 'weak' links. If a good beacon is received, the beacon is directly forwarded in the next time slot with an updated rate-product and incremented hop-level. If several good beacons are received, the one with the best rate-product is forwarded.

If the RSSI of the beacon is weak, the forwarding is delayed for an additional time slot. During this time slot the sensor node could receive a beacon with a higher hop-level, but also with a better rate-product. If no better beacon is received the weak beacon is forwarded after two time slots.

4.3 Data phase

The messages with the sensor data are forwarded to the base station during the data phase. The data messages contain the sensor data, the ID (Identification number) of the sensor which made the measurement and the ID of the last node which forwarded the message. The nodes have a buffer to hold one received data message for each sensor as well as its own measurement data. In the current software version the number of sensors in the network is limited to 31.

Each sensor node is activated as a transmitter or a source node during a certain time slot according to its hop-level. The communication between the source nodes with hop-level H and the sink nodes with hop-level H-1 is described by the following procedure.

After a random initial back-off time of T_{B1} = 1 ms … 1600 ms, each source node transmits its first message from its buffer and waits for an acknowledgement implying that the data of a sensor has arrived at the next hop level.

In the ideal case, every sensor measurement is forwarded only once between two hop-levels. The source node listens to the communication of other nodes in order to avoid sending redundant data messages. If a sensor is already acknowledged by another sink node, it is deleted from the buffer of the source node.

After a further delay the sender-node transmits the next unsent data message from its buffer. The length of the back-off time depends on the received acknowledgement.

- If the sensor-node receives an acknowledgement for its own transmission, the next data is sent without delay. This enables to establish an uninterrupted communication between one source and one sink node until the entire buffer is sent.
- If an acknowledgement for another source node is overheard, the sensor waits T_{BO} = 100 ms … 500 ms in order to avoid collisions with the continued communication of two other nodes.
- If no acknowledgement is received the communication is retried after a delay of T_{BN} = 300 ms … 700 ms.

If all messages in the buffer are sent, the radio is powered down. Multiple sink nodes can receive the data and store them in their local buffer. In order to avoid collisions the acknowledgement is delayed by T_{BA} = 1 ms … 50 ms.

This procedure is repeated for each hop-level. The radio of each sensor is powered up for two consecutive time slots, for receiving during the first and for sending during the second slot, except for sensor nodes in the highest hop-level that only send. The length of the time-slots for communication between two hop-levels is between 2 and 5 seconds. The longest time-slots are assigned to the sensors nodes close to the base station because they have to forward the highest number of messages.

4.4 Optimisation of back-off times and slot lengths

Because the date for the field tests was already set, the range of the back-off times T_B between messages had to be adjusted by a rule of thumb omitting careful optimisation. The required duration of each slot depends on these back-off times as well as on the number of sensor notes. The slot lengths were set with some safety margin to a value that provides sufficient time for all sensors to transfer their buffered data.

A reduction of the back-off times reduces the required slot lengths, but it also increases the number of messages that are postponed by the CSMA mechanism. If messages are postponed multiple times, this finally leads to a congestion of the radio channel. A measurement with a spectral analyser showed that the transfer of one data message occupies the radio channel for 1.2 ms. But, prior to that, the channel has to be free for 2 ms, equal to the minimal time distance between two messages found during the experiment.

These two values were fed into a MATLAB-based simulation in order to estimate how far the back-off times can be reduced without creating a high risk for channel congestions. The simulation considered the case that 30 sensors in the same hop-level try to transmit one data message each. The number of messages that were postponed three times or more were considered indicative of a congestions risk. For the current setting of the back-off times this is the case for 0.2% of all data messages. If the back-off times are multiplied with a factor of 0.5, the share of three times postponed messages increases to 2.9% which is still acceptable. But, for a factor of 0.25 the share increases to 39.4%. So, it seems to be advisable to reduce the back-off times by a factor of 0.5. The maximum required slot length to safely transfer all 30 messages is thereby reduced from 5.1 to 2.8 seconds.

4.5 Independent routing per frame

This routing mechanism of the BananaHop protocol works stateless: it is independent from the previous frame and no routing tables have to be stored. The hop-level, determined for each frame, is the only required information. Although taking link quality information from previous frames into account could improve routing, stateless approach was retained for following reasons.

First of all, the software stability is improved. Complex software tends to hang-up if a state-variable is set to an erroneous value and the software cannot recover. In fact, severe problems were encountered with the implementation of the SensorScope protocol in our target hardware. Although the problem was resolved, an automated watchdog reset had to be programmed for the SensorScope protocol in order to run it for several days or weeks. But, because the BananaHop protocol is almost stateless, erroneous values of state variables do not affect the subsequent frames. All variables are set to zero at the beginning of each frame.

Furthermore, the start-up time of the network is shorter. Because it is not necessary to build up a routing table, the network immediately starts transmitting the sensor data in the first frame after powering up. Although in our experiments the links changed only slowly over time, the network could adjust fast to the changes of link quality. If sensors are moved or new sensors added, the network adapts to it within one frame.

5 Comparison of protocol performance

The SensorScope protocol works with a duty cycle of a fixed length; for all sensors the radio is turned on exactly for 15 seconds per frame. The situation for the BananaHop protocol is a bit more complicated. The radio is turned on and off two times per frame with varying interval lengths depending on the hop-level and the number of forwarded data messages. In order to analyse the energy consumption of the BananaHop protocol, the sensors were programmed to sum up the total radio-up-time per frame and to store the resulting value in their flash memory. The evaluation of the flash records showed that the BananaHop protocol required an average radio-up-time of 7.5 seconds with a maximum of 8.4 seconds for sensor number 2 that was always in hop-level one. For higher hop-levels the radio-up-time was between 6.4 and 6.9 seconds. The length of the active radio periods were verified by measuring the current consumption over time with an oscilloscope.

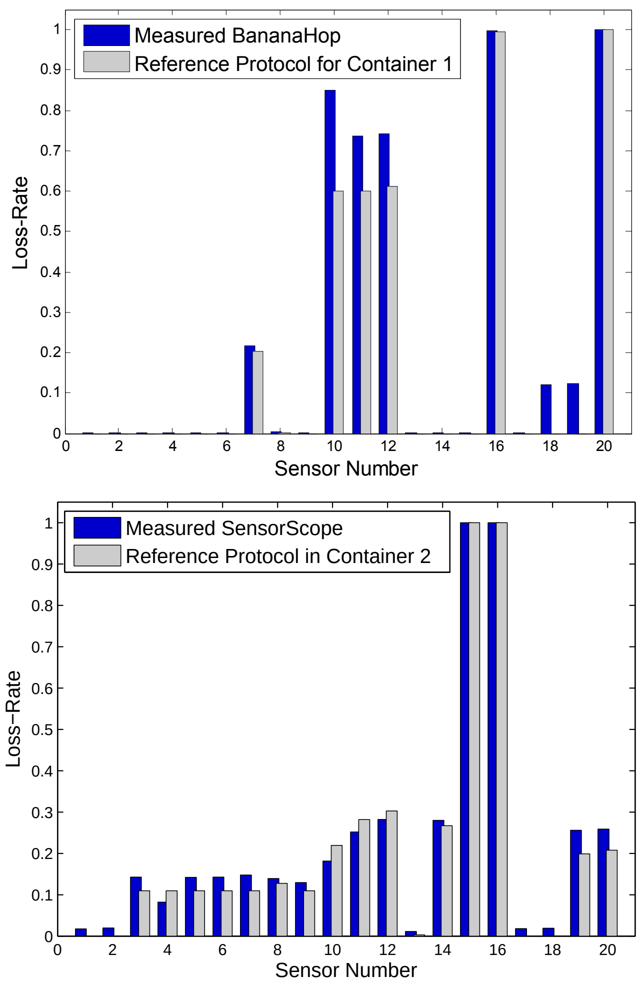
During every fourth frame few seconds of additional radio-up-time were required in order to sniff for beacons from neighbours in higher hop-levels and to record their RSSI values in the flash. But, because this information is not required for the routing, it was not considered. If no beacon is received, the sensor node should be set to power down mode for the remainder of the frame. Because this feature had not been implemented in time for the container tests, frames without the received beacons were also excluded from the evaluation of the radio-up-times.

In Section 1.2 it was shown that the energy consumption mainly depends on the length of intervals during which the radio is active. The BananaHop protocol transmits a complete set of sensor data each frame with an average radio-up-time of 7.5 seconds, whereas the SensorScope sends sensor data only every second frame. In total, a radio-up-time of 30 seconds is required by the SensorScope protocol to send one set of sensor data. From this follows that the BananaHop protocol requires in average only one quarter of the energy to transmit sensor data compared to the SensorScope protocol. But, it has to be questioned whether the simplified routing leads to unnecessary packet losses.

5.1 *Rate of packet losses*

All received data messages were recorded on a solid-state-disc by the two gateways. The number of messages that were received from each sensor node were counted and the share of missing messages was calculated as *loss-rate* per sensor. During the first test of the BananaHop protocol in the ripening room only one sensor node had a loss-rate of 0.05. But the subsequent tests in packed sea containers showed serious losses for both protocols indicated by the dark bars in Figure 9. For both protocols two sensors were completely lost. Three further sensors in the container with the BananaHop protocol had high loss-rates between 0.73 and 0.84. The poor quality of sensor-to-sensor links seems to be the main reason for the packet losses. Several links were physically missing as shown in Section 3.2 for several hours or even for the complete duration of the experiment.

Figure 9 Measured loss-rate (dark) and losses of reference protocol (grey) for the experiments with the BananaHop (top) and the SensorScope protocol (bottom) (see online version for colours)



5.2 Reference rate

However, it is not possible to compare the performance of the two networks protocols only on the basis of the measured loss-rates because the number and the position of usable links were different for the two containers. In order to discern which share of the loss-rate is caused by inadequate routing, the measured loss-rates were compared with a hypothetical reference protocol that performs the routing under almost optimal conditions:

- The reference protocol finds from a bird's eye view perspective any existing route between the base station and a sensor node.
- If a sensor-to-sensor link fails along the route to the base station, the communication is retried a maximum of five times.

Only the following restriction was introduced: A sensor can only send its data to the base station if it has received a beacon from the base station in the same frame. The simulation was written in MATLAB. In the first step the experimental data were used to generate a matrix of all usable sensor-to-sensor links for each frame. In the second step a network simulation was carried out based on this matrix.

The simulation results are indicated by the grey bars in Figure 9. But, because RSSI measurements were recorded only every fourth frame, the simulation results have diverted a little from the real situation. Furthermore, because of the problem of delayed transmission, which was described at the beginning of Section 3, the calculated packet-rates and thereby the reference rate are slightly too low for the SensorScope protocol. In total the SensorScope protocol almost met the performance of the reference protocol, although there are deviations in the loss-rate for single sensors in the range of $\pm$ 0.05.

For 13 out of 18 sensor nodes the BananaHop protocol provided the correct routing. But for the remaining five sensor nodes, the loss-rate was between 0.12 and 0.25 higher than the minimum given by the reference protocol. In situations where the BananaHop protocol falls back behind the reference protocol, the hop-level of the sensor nodes with a high loss-rate is estimated to low due to inaccuracies of the inverse-packet-rate estimation. It has to be questioned whether it is possible to improve the performance of the BananaHop protocol without increasing the number of control and data messages, thereby losing its advantage of very low energy consumption.

5.3 Improvements to the BananaHop protocol

The idea of autonomous cooperation, which has already been successfully applied to routing problems in transport logistics (Hülsmann and Windt, 2007), can also be applied to the routing inside the sensor network for the temperature supervision. Small objects, such as the sensor nodes, would be able to make local decisions. The sum of the local decisions leads to an improved performance of the overall system.

The suggested autonomous sensor nodes observe their own performance. Every node counts at the end of each frame the number of unsent data messages in its buffer for which no acknowledgement was received. If a routing problem is detected by a high number of unsent messages, the node starts to modify the protocol parameter and keeps the set which delivered best routing results. For example, the threshold for 'good' links of –85 dBm can be slightly increased; or the hop-level can be directly increased by a constant offset as a last resort. The learning process spans over several frames; therefore, this approach requires abandoning the initial feature of independent routing per frame.

The general feasibility of this approach has been tested in a further simulation. In this first test, the parameter modifications have been set manually. The improved version of the BananaHop protocol with parameter adaptation achieves, except for two sensors, almost the same loss-rate as the reference protocol.

5.4 Improvements on the hardware side

But even if the network protocol finds the best possible routing, the rate of sensor data losses is still too high to be accepted by the commercial transport operators. The evaluation of the packet-rates on the basis of the flash records in Section 3.2 showed that the signal attenuation by dielectric losses is very high inside a container that is packed with food products with high water content. One solution would be reducing the distance between the sensor nodes. But because the number of required sensor nodes is increased, this solution has to be rejected for cost reasons. The signal attenuation can only be compensated by the modifications to the radio hardware.

The first option is to reduce the radio carrier frequency. The dielectric losses are proportional to the imaginary part of the relative electric permittivity ε_R. The electric permittivity can be calculated according to the Cole-Cole diagram (Cole and Cole, 1941) as a function of frequency. Table 3 gives the values for water at the room temperature (ε_∞ = 6, ε_0 = 80, f_{Reso} = 16 GHz) for typical carrier frequencies of WSNs.

Table 3 Relative electric permittivity ε_R for water

Carrier frequency	ε_R
433 MHz	79.95–2.00j
866 MHz	79.78–4.00j
2.4 GHz	78.37–10.86j

The real part of ε_R is almost constant at 79. But the imaginary part is nearly linear to the frequency inside the considered range. The signal attenuation should be less crucial for the alternate frequencies of 433 MHz or 866 MHz compared to the TelosB CC2420 radio chip that operates at 2.4 GHz. But lower carrier frequencies have the disadvantage that they only provide a reduced bandwidth, which results in longer radio-up-times.

The other option is to use a radio chip with higher transmission power. The Meshnetics ZigBit Amp OEM Modules (Meshnetics, 2008) provides a radio output power of 100 mW, which is 20 dBm higher than that of the TelosB nodes.

The ZigBit Amp module needs three times more energy to operate the radio in transmission mode than the TelosB sensor node (50 mA at 3 Volt compared to 20 mA at 2.4 Volt), but a transmission is finished within 20 ms, whereas the radio has to be activated for several seconds for receiving. The total energy consumption was calculated for an example frame with 6.5 seconds of receiving and one second of transmitting. Under this condition the energy consumption of the Meshnetics module was only 53% higher than that of the TelosB sensor nodes.

6 Summary and outlook

The radio link quality and the performance of two WSN protocols were tested by recording the relevant data in the flash memory of all sensor nodes.

The high-signal attenuation of water-containing products turned out to be the major problem for monitoring packed food transports. About 20% of the sensor data were lost because there was no physical route possible between the sensor node and the base station. In order to handle this problem it is necessary to switch the sensor node hardware, either to a platform with a higher transmission power or to one with a carrier frequency that is less sensitive against the dielectric losses of water.

Additional sensor data were lost because the protocols were not able to detect the correct routing. For the BananaHop protocol this was the case for 4% of the sensor data, whereas the SensorScope protocol performed better with only 1% additional losses, but it required more than three times higher radio-up-time.

The introduced method to predict the link quality by the inverse-packet-rate turned out to be an energy-efficient link estimator, even though the prediction has some deviations for links with RSSI values close to the receiving threshold.

But, beside the signal attenuations there are several challenges that have to be met before the system can be sold on a commercial basis. The electronics has to be protected against high humidity, condensed water, and mechanical stress during transhipments. The cooperation between the different system components, such as sensor network, gateway, satellite link, and web server, has to be improved to avoid failures and data losses. Furthermore, an automated localisation of the sensors inside the container would be very useful, because it cannot be guaranteed that the workers in the packing station report the sensor positions properly.

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