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UHF-RFID IN THE FOOD CHAIN -
FROM IDENTIFICATION TO SMART LABELS

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1. Introduction: Food is different from other RFID applications

RFID has been successfully applied to track the transport of various goods. However, food products constitute a special case. Most foods consist of a high percentage of water, which damps the electromagnetic field of the RFID reader. Furthermore, transport chain supervision of perishables consists of more than solely identifying or discerning where each pallet has been unloaded. Temperature is the most influential factor in product quality. For reliable quality tracing, it is necessary to monitor the full temperature history of each item. To make the best use of RFID tracking, the system must outperform current identification systems. The reader should also be able to write data on the label, such as the product's temperature history or a quality index that is updated according to current transport conditions.

After introducing current RFID protocols, this article will examine in which ways UHF-RFID can meet demands for the quality tracing of food products and suggest solutions for handling the communication bottleneck that has been discovered by analyses of RFID data rates. These solutions include the use of active wireless communication as well as on-chip preprocessing of the temperature data by an intelligent RFID tag.

1.1. The need for spatial temperature supervision

The temperature profile of different transport systems was recorded by RFID data loggers. In addition to the RFID interface, these devices contain temperature sensors, batteries, and memory to record up to 700 temperature values [Tur06]. Currently, only 13.56 MHz HF-RFID is supported. The devices had to be read out manually because of their low reading range. The deviations over the length of a sea container varied from 5°C for deep-frozen goods from Germany to Nigeria to 2°C for a shipment of grapes from Chile to Europe. The highest differences inside a delivery truck with three different temperature zones were found in the deep freezer compartment. Differences of more than 9 °C were still present even after 6 hours of cooling [Jed07a]. This might have resulted from poor air ventilation below the ventilation unit (Green box in **Figure 1**). In the case of delivery trucks, there is no easy way to predict the temperature inside a single box. Multiple sensors attached to the walls of the container or inside the freight are necessary.

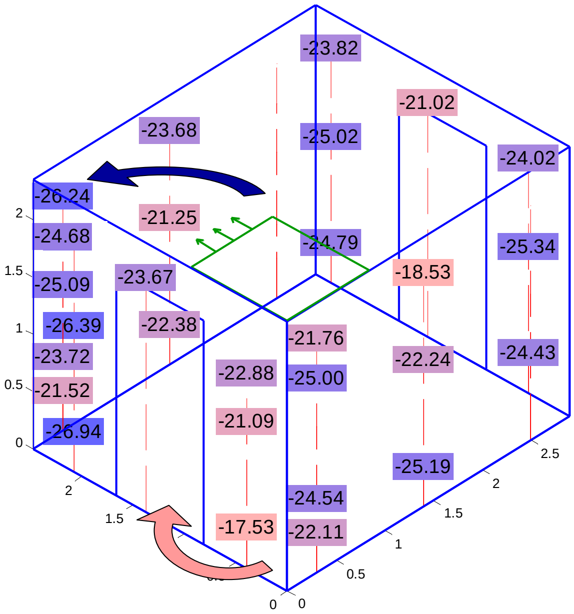

Fig. 1. Average temperatures inside the deep freezer compartment of a delivery truck after 6 hours cooling. (set point 29°C, arrows indicate direction of air flow, dimensions in meters)

1.2. Available technologies

RFID tags are available for three different frequencies: low (LF, 125 kHz), high (HF, 13.56 MHz), and ultra-high (UHF, 860 to 930 MHz). The selected tag type must meet the following requirements in order to be implemented in quality tracking applications: First, a high data rate is required to transmit temperature charts and additional quality information. Second, if a door reader scans items automatically upon arrival at the warehouse, the reading range has to cover several meters. Finally, all operators that make up the transport chain must accept the selected technology.

The EPC class 1 generation 2 protocol, also called GEN-2, [EPC05] currently offers the highest data and identification rates by using UHF. The reading range is about 3 meters with a line-of-sight view. Major suppliers such as Metro and Wal-Mart have already adopted the EPC UHF standard for tracking pallets. For these reasons we focused our research on this technology.

The GEN-2 tags from NXP offer 28 or 64 bytes of additional memory [NXP06]. New battery-assisted tags with higher memory capacities have been recently made available by PowerID [[New08]. An RFID temperature logger for the UHF range is currently produced only by the Italian company CAEN [CAE08], although this device does not yet support the GEN-2 protocol. New devices by other manufacturers are expected to become available by the end of 2008, and a new protocol for battery-assisted tags should be standardized by summer 2008.

2. Reduction of identification and write rates caused by moisture

The main disadvantage of UHF is its higher sensitivity to obstacles between reader and tag, especially metals and liquids. Tags that are packed between boxes inside a pallet can cause unreliable access or even prohibit access altogether. Clarke [Cla06] and Wehking [Weh06] have examined the influence of material type on the percentage rate of successfully identified tags on boxes inside a pallet, although their reports only consider identification. Additional experiments [Jed07b], [Ste08] were carried out to assess the feasibility of writing data onto tags mounted on the surface of or inside water-containing goods. The quality of both the signal and energy transmission between reader and tag can be evaluated by using different scales. The rate of successful identifications or write operations can be measured at a fixed reader power. Additionally, the reader power can be increased until a rate of almost 100% is reached.

2.1. Test setting

The identification and write rates for the Feig 2000 [Fei08] and the Sirit Infinity 510 [Sir08] UHF-RFID readers were measured with the following test setting: A stack of 6 boxes with 12 bottles of 1 liter mineral water was placed 1 meter from the reader antenna. 8 NXP Ryparian GEN-2 tags with a size of 75 by 75 mm were placed on the front side of the boxes, 4 tags behind the necks of the first row of bottles, 3 behind the second and 4 behind the third row (**Fig. 2**).

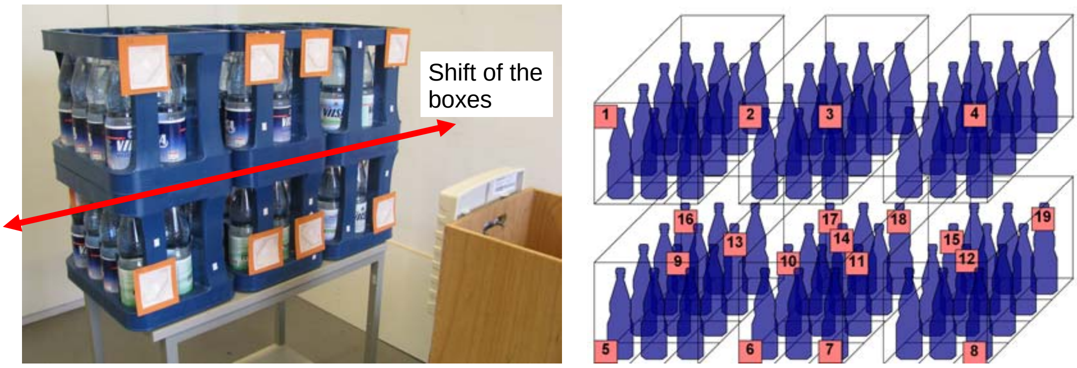

Fig. 2. Test setting and position of tags

The control software was programmed to first identify all tags and then write a random number to the 28 bytes of user memory. The reader output power was varied from 100 mW to 1000 mW. The boxes were horizontally shifted by distances of -15 cm, 0 cm, and +15 cm in order to simulate a movement of the goods. If at least one identification or write operation was successful from one of the three positions, the tag was counted. The experiment was repeated 5 times for each power level. The Sirit antenna with a gain of 6 dBm was used for both readers. The maximum effective radio power (ERP) was 1072 mW, which is half of the maximum value of 2 watts that is allowed by European regulation EN302208 [Fin06, page 188]. Unfortunately, the remote power adjustment of the Sirit reader did not permit a higher output power.

2.2. Results

The Odin report [Odi07] compares the performance of 7 readers from different manufacturers. The receiver sensitivity of the Sirit was listed as 10 dBi higher than those of the Feig reader, but in our experiments the effect of this difference was found to be much smaller than expected. **Figure 3** shows the measured identification rate as a function of power level. Both readers could read all tags on the

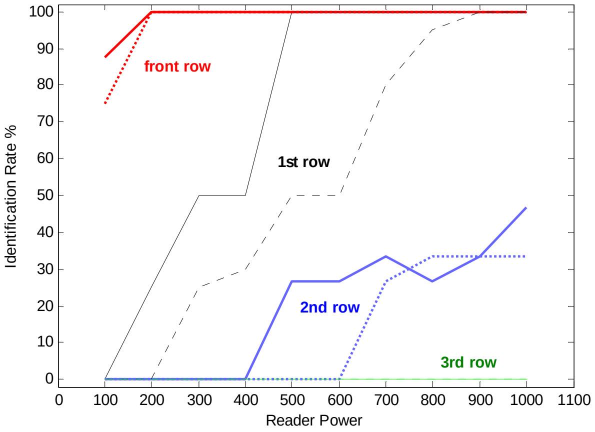

Fig. 3. Identification success rate for the Sirit (solid line) and Feig (dotted) reader as function of reader power. Best of 3 horizontal positions in a distance of 1 meter.

front of the boxes with 200 mW reader output power. With higher reader power it was also possible to identify all tags in the first row. Only some of the tags in the second row and none in the third row could be read.

Table 1 summarizes the results for identification and write operations. Reliable data writing was only possible for tags on the surface. For both readers, 400 mW were required to achieve a 100% identification success rate. A rate of no more than 50% was achieved in the first row.

The Feig reader was expected to have a better write rate due to its improved control software. If the first write attempt failed, the process was repeated with two blocks of half the size. However, even with the improved software, the Feig managed to achieved only the same write rates as the Sirit.

Tags in the third row could be neither identified nor written. This was partly caused by a shielding effect of the tags on the front row. If the surface tags were removed, the identification rate increased to 30% at 300 mW, the write rate to 30% at 1000 mW.

Reader	**Feig**	**Feig**	**Sirit**	**Sirit**
Position/Access	ID	Write	ID	Write
Surface (8 tags)	200 mW	400 mW	200 mW	400 mW
1st row (4 tags)	900 mW	50% @ 1W	500 mW	50% @ 1W
2nd row (3 tags)	35% @ 1W	0%	50% @ 1W	0%
3rd row (4 tags)	0%	0%	0%	0%

Table 1: Minimum Power for 100% Identification/write rate or maximum rate at 1000 mW

Tests with empty bottles showed that the shielding effect largely depends on the type of tag [Ste08]. This effect was not observed for tags with another antenna layout (Rako 2 by 4 inch), but the input sensitivity of those tags was too low to detect them behind three rows of filled bottles.

2.3. Recommendations

Although tags could be identified behind the necks of the bottles in the first row, reliable writing was not possible in this position. Therefore, placing tags inside moisture-containing goods should be avoided. Both identification and writing were possible with the surface tags. Only 20% of the legally-allowed power was necessary. The success rate of 100% relates to 5 repetitions with 4 or 8 tags. For a detailed analyses further experiments are required.

3. Data transfer rate

The application of RFID to the supervision of food transports is limited not only by the reading range, but also by the data transfer rate. All data must be transferred within the amount of time that a pallet needs to pass a reader gate during unloading.

Currently, only temperature loggers with HF interface are available. These labels require five seconds to send 700 recorded temperature values over the RFID interface. Future UHF devices are expected to transfer data at much higher rates. The following section analyzes the effective transfer rate for reading large data blocks that can be achieved by the GEN-2 protocol and its implementation in different readers. The aim of this section is to decide on the basis of effective data rate whether it will be possible to read multiple temperature tags per pallet without delaying transshipment processes.

3.1. Test setting

The GEN-2 protocol permits different bit rates for commands from the reader and responses from the tag. The symbol rate for responses was adjusted for both readers to T_{Sym} = 12.5 µS. The reader modulates its commands by pulse-interval encoding. The lengths of bits that are sent by the reader depend on their values. The length of the 0-bit is called Tari, which was also set to 12.5 µS. The length of the 1-bit depends on the reader type. For the Feig, the 1-bit is 1.5 Tari long and the average bit length is T_{Bit} = 15.63 µS. For the Sirit, the 1-bit is twice as long as the 0-bit, resulting in an average length of T^{*}_{Bit} = 18.75 µS.

The amplitude modulation of the carrier signal was recorded with a Tektronix RSA 3308A Real-Time Spectrum Analyzer for identification, read, and write sequences. Most reader commands have a unique bit length in the GEN-2 protocol; they were discerned by their resulting modulation length.

3.2. Identification

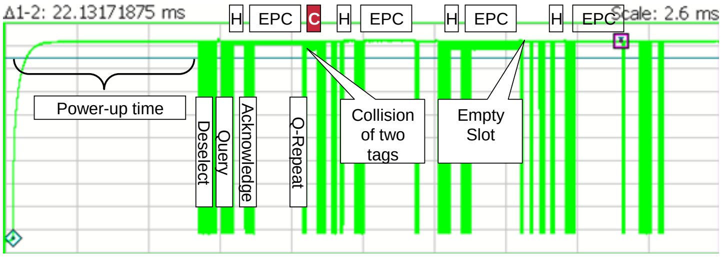

Fig. 4. Recorded protocol for identification of 4 tags with the Feig reader. The reader commands are marked by the vertical boxes. The tag answers with a 16-bit handle (H) and the 128-bit EPC.

The GEN-2 protocol defines a mechanism for avoiding collisions during the identification of multiple tags. When the identification sequence is initiated, several tags might respond simultaneously. This collision makes the responses unreadable. In order to avoid these collisions, each tag responds to the reader request after a random delay. In the first step only a 16-bit handle is transferred. In the second step the reader uses the handle to request the full 128-bit electronic product code (EPC).

Figure 4 shows the typical sequence of commands for the identification of four tags. A deselect command is sent to all tags in the first step. Thereafter, the reader opens a number of slots, introduced by a query command. When the reader detects a valid handle, an acknowledgement message is sent to the tag. The tag then responds with its EPC. The figure also shows one occasion in which the handles of two tags overlap. Five of the other slots are empty, without tag responses. The relation of 4 valid EPCs to 10 slots in total is in line with the theoretical efficiency of the Slotted Aloha protocol of 37% [Fin06, page 222].

A period with constant field strength preceded the command sequence. This power-up time is necessary to supply the tag with energy, to test whether the frequency is occupied by others and for the internal processing of the reader. The Feig divides the power-up in two blocks, but the total time is 27 ms for both readers.

3.3. Reading user memory

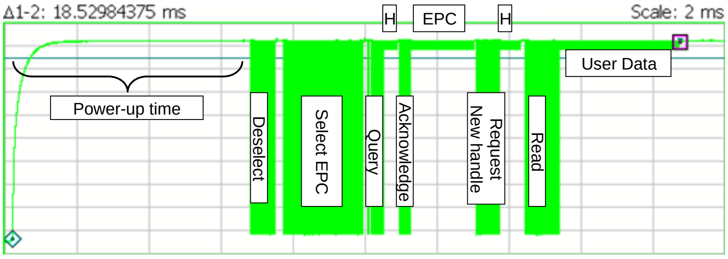

Fig. 5. Recorded protocol for reading the 28 byte user memory with the Feig reader.

The user memory of the tag is organized in words of 16 bits. The two RFID readers differ in their protocol implementation for the reading of the user memory. The Feig reader uses the sequence shown in **Figure 5**. In the first step, the tag is selected by its EPC. The following query retrieves a first handle from the tag. To send the read command, a second handle is required. The tag responds to the read command with the 14 words of user memory.

The Sirit reader offers two options to read the user memory. The direct command is less efficient; it reads the EPC a second time and then requests the access password, although the password was not set in our experiments. However, the Sirit also allows the combination of the identification with the reading of user memory. Because the handle from the identification could be used to directly address the tag for reading, it is not necessary to select or read the EPC a second time. The combined sequence requires only half the time compared the time needed for separate identification and read sequences (**Table 2**).

3.4. Writing user memory

The duration of the write process depends mainly on the chip type of the RFID tag. The tested tags with an NXP chip need 7.5 ms per word on average for their internal programming. Together with the command sequence, about 11 ms are required per word. The addressing of the tag is similar to the read sequence. The total time for writing multiple words is longer for the Sirit because of the duplicate EPC. Furthermore, the Sirit reads back the written values for verification. The required time for writing 4 words is listed in Table 2.

Reader	**Sirit**			**Feig**		
Operation	Power-up	Modulation	Total	Power-up	Modulation	Total
Identification 4 tags	27.0 ms	16.4 ms	43.4 ms	21 + 6 ms	14.7 ms	41.7 ms
Read 14 words	2.5 ms	19.3 ms	21.8 ms	21 + 6 ms	12.5 ms	39.5 ms
Combined ID + R	25.6 ms	10.7 ms	36.3 ms			
Write 4 words	12.6 ms	63.5 ms	76.1 ms	21 + 6 ms	49.3 ms	76.3 ms

Table 2. Measured duration of identification, read, and write operations

3.5. Extrapolation for large data blocks

To read out 700 temperature values from the Turbo Tag data loggers, 1 Kbyte of data or 8192 bits must be transmitted. The time required by the GEN-2 protocol to transmit this amount of data can be calculated according to the known command sequence and the bit length of each command. The value of the power-up time was slightly increased in order to compensate for short breaks between single commands. Equation 1 gives the total time needed to transmit N_R blocks of N_B bits:

$$T_{Read} = T_{up} + (283 + 61 \cdot N_R) \cdot T_{Bit} + (194 + N_R \cdot (N_B + 39)) \cdot T_{Sym} \qquad (1)$$

With a corrected power-up time of T_{up} = 28.4 ms, N_R = 32 and N_B = 256, this leads to a total time of 176 ms to read one temperature tag with the Feig reader. About 50 ms must be added for identification, which indicates that only 6 tags with full temperature history can be read during one second.

However, this calculation is based on optimistic preconditions. If data needs to be re-transmitted because of a communication failure, the total read time will be prolonged. Further delays are caused by the communication between the reader and user application, by interferences with other tags in the neighborhood, or by a required frequency change of the reader. The number of temperature tags that could be read per second might be half of the calculated value. Due to the limited data rate it will not be possible to read out the full temperature history of each item or box during unloading. Sections 5 and 6 will present two solutions to circumvent this communication bottleneck.

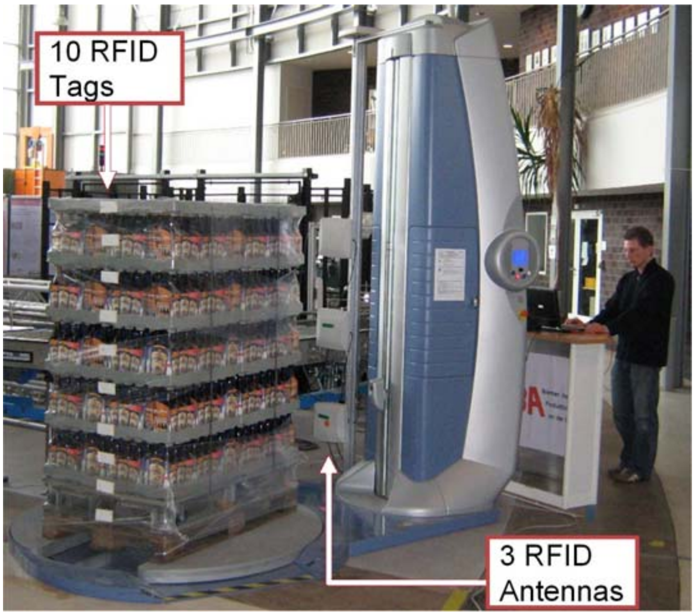

Fig. 6. Test setting with 10 tags on a rotating palette and 3

4. Test with moving objects

The previous tests were carried out with isolated commands in a static environment. In a real transport scenario, the reader must access moving tags with changing signal strengths. The control software must handle commands for multiple tags without causing delays. The access to multiple tags that were attached to a moving pallet was tested in an additional experiment.

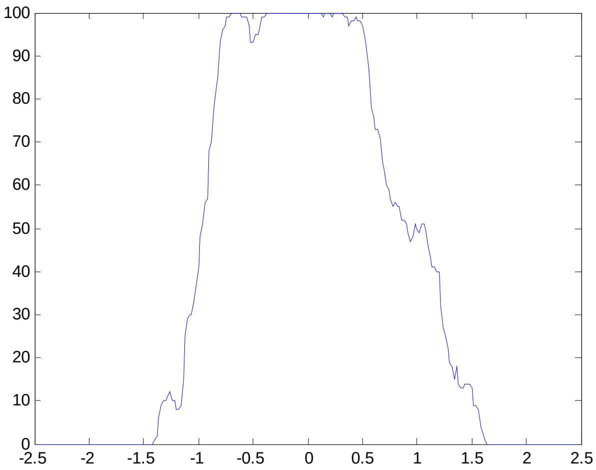

Fig. 7. Time window for identification of a rotating pallet (10 rpm). The value on the y-axis gives the percentage of tags that could be identified during an interval of ±75 ms to the time on the x-axis. Average over 10 turns

10 RFID tags (Rako 2 by 4 inch) were placed in a vertical row onto the surface of a pallet of beer bottles. The pallet was placed on a foil wrapper machine. The machine was programmed to rotate 10 times per minute (rpm), equivalent to an angular velocity of 0.6 m/s for the tags. The shortest distance between the tags and the 3 reader antennas was 75 cm (**Figure 6**).

In the first test, the number of tags that could be identified per time unit was counted. **Figure 7** shows the identification rate as a function of time. The time is given in relation to the zero position, where the tags directly face the antennas. A few blackouts were caused by interference with other readers. The related turns were excluded from the evaluation. All 10 tags could be identified at least 29 times during each of the other turns. For a period of 1.35 seconds more than 90% of the tags were visible.

A second experiment was carried out in order to test how many tags could be written during one turn. The control software attempted to write 14 data words into the user memory after each identification event. At 10 rpm, less than 50% of the tags could be written. This was mainly caused by the slow writing process. Each tag requires 197 ms on average for the internal programming of the 14 words. At a slower rotation speed of 4 rpm, 82% of the 10 tags could be written.

5. On-chip shelf life modeling

In most cases it is not necessary to transfer the whole temperature history. The interest of the transporter lies in the effect of temperature deviations on the product quality or the remaining shelf life. The calculation of a shelf life prediction model directly on the RFID tag largely reduces the communication volume.

Most models are based on the Arrhenius equation for reaction kinetics, such as the approach that was presented in the last workshop [Jed06]. The sensitivity of a product to chilling injuries can be modeled with a second Arrhenius equation. After each measurement, the model calculates the loss of quality per day of transport as function of temperature. The resulting value is multiplied with the measurement interval and subtracted from the current quality value. Other approaches calculate the loss per day by the interpolation of a reference table. Roberts [Rob03] suggested a one-dimensional table over the input parameter ‘temperature’. Emond [Jed08] suggested another approach that directly uses recorded reference curves for the decay of a quality attribute over time at different constant temperatures. The model uses the current quality state as a second input parameter in addition to the temperature. The speed of decay is interpolated over a two-dimensional table.

The critical question is whether it is feasible to calculate the presented models on a small-size microcontroller. For implementation in a low-cost RFID temperature tag, various restrictions must be observed: The available memory, computation power, and energy are very limited. The models were scaled to 16-bit integer arithmetic for practical tests on a microcontroller. The required memory and calculation time for each model step were measured on the MSP430 chip from Texas Instruments. **Table 3** shows the measured values and the calculated energy consumption.

Model type	Arrhenius	1-dimensional interpolation	2-dimensional interpolation
Program memory	868 bytes	408 bytes	1098 bytes
RAM memory	58 bytes	122 bytes	428 bytes
CPU-time	1.02 ms	0,14 ms	1.2 ms
Energy	6 µJ	0,8 µJ	7 µJ

Table 3. Required resources for different quality models per model step

If an Arrhenius model is updated every 15 minutes, it consumes

0.017 J of energy per month. This is even lower than the stand-by current of the MSP430 which is 5.7J per month. The zinc oxide battery that is used in the TurboTag data loggers with a capacity of 80 J could power such a shelf life tag for more than half a year. The shelf life tag is a promising approach to circumvent the communication bottleneck, although UHF tags with temperature recording and preprocessing facilities are not yet available.

6. Active Communication

The use of active communication is an alternative way to transmit large volumes of data. Active tags or wireless sensors nodes are equipped with batteries to power the transmission of the signal. The output signal has a power of about 1 mW, whereas the reflected power of passive tags is in the µW range. The higher power allows for a communication range of up to 100 m in free air space. It is even possible to communicate with devices that are packed inside the goods. The access is not limited to the time-span of a gate passage. A base station inside the container can almost always read the sensors. However, communication is the task that consumes the most power; the data volume is limited by the battery capacity.

The advantages of active devices have to be weighed against its price, which can be 5 to 10 times higher than for semi-passive RFID tags. An economical solution should make use of both technologies. A combined solution of active and passive devices is being tested by the “Intelligent Container” project (www.intelligentcontainer.com). Field tests with road and sea transport systems are planned for 2008 and 2009 in cooperation with 3 partner companies. A limited number of wireless sensors are mounted on the walls of the container or inside the freight itself. An embedded controller collects the data from the sensors and sends a warning message via external communication if a quality risk is detected [Jed06]. Only one passive RFID tag is required per freight item. The original idea incorporated writing back the calculated shelf life onto the item-level tags when the freight is unloaded. However, the slow write rate of passive tags may require a solution in which the shelf life information is transferred to the next warehouse or container by active communication.

The link quality between the sensors inside a packed container was tested in preparation for the supervision of banana transports from Costa Rica to Europe. 24 Sensors were packed inside 3 pallets of bananas. **Figure 8** shows the positions of the sensors inside the container and the signal levels that were received at the base station. The signal attenuation due to the fruits was rather high. Only one third of the sensors could establish a direct link to the base station. The sensors with connections to the base station were almost all in the top layer. The signal propagation takes place mainly inside air space of 10 cm height above the pallets. The poor link quality hinders the networking of sensor nodes, but does not prohibit its use. In a multi-hop protocol, the messages are forwarded over several short hops from one sensor to another.

The link quality depends greatly on the manner in which the container is packed. Ruiz-Garcia tested wireless sensors at the same frequency range of 2.4 GHz in a warehouse [Rui08]. He reports only a few communication disturbances within a row of 13 pallets. The good signal quality was likely caused by the free air space of 1 meter beside each pallet.

The access to tags or sensors with temperature information proved to be a crucial issue for the development of an automated quality monitoring system. Both the networking of active sensors and the integration of temperature recorders in UHF tags necessitate further research. The preprocessing of the temperature data directly on the tag or sensor is a promising approach to circumvent communication obstacles.

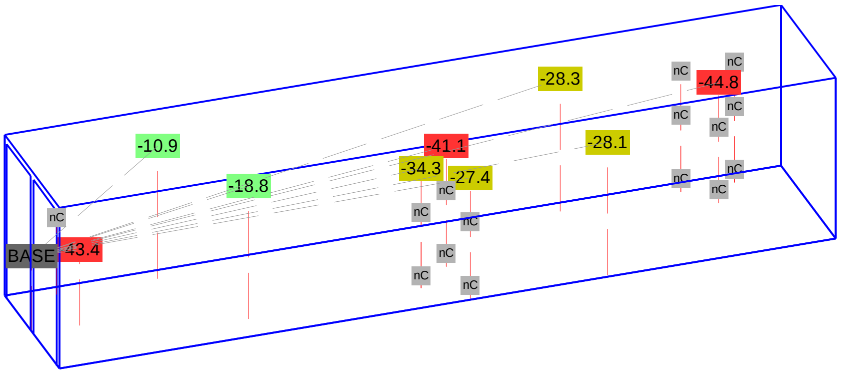

Fig. 8. Received Signal Strength Indicator (RSSI) at the base station and position of nodes with no connection (nC).

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