Design of a Printed Organic RFID Circuit with an Integrated Sensor for Smart Labels

Predrag Jakimovski, Till Riedel, Ali Hadda and Michael Beigl

Pervasive Computing Systems, TecO

Karlsruhe Institute of Technologie (KIT), Germany

Email: {firstname}.{lastname}@teco.edu

Abstract—For item-level tagging in supply chains and logistics the massive deployment of current RFID tags is still too costly despite a drastic decline in price. Therefore, efforts are made in developing organic and printed electronics to enable the vision of item-level tagging. This novel technology promises to overcome the current cost constraints and become ubiquitous. However, the constraints of organic and printed electronics allow merely the design of simple circuitry, which means that neither processor nor larger integrated circuits can be printed. In addition, the lack of high-performance in organic electronics does not even allow the application of traditional communication protocols. The high communication load between reader and tags based on traditional communication schemes is not practical e. g. for regular compliance checks of pallets with up to 1000 items.

In this paper, we propose a solution for a smart label system based on the constraints of the organic and printed electronics. The communication scheme uses simultaneous transmission of sensory data. We further present an analog circuitry for an tag specially tailored for the deployment of smart labels in a scenario such as the maintenance of perishables in a cool chain. The approach exploits the possibilities of printing irreversible sensor indicators and randomized structures when using organic electronics. Further on, we show first experimental results performed in our smart label test bed, and illustrate its business relevance towards managing massive amounts of tags in a short time frame.

I. INTRODUCTION

Organic and printed electronics will bring the vision of item-level tagging of all things, products and goods closer to its realization by reduced and higher integration in production processes [1]. In order to track goods the ultimate goal will be to realize smart labels based on polymer electronics, which will be capable of monitoring sensory data such as temperature, humidity or light exposure. Organic smart label technology promises ultra-low-cost massive deployment of such wireless sensors in industry, food, pharmaceutics, healthcare and consumer markets.

Currently, there is no commercial product available for printing or processing the information from organic and printed smart labels. This is due to the early stage of the technology. Further on, no standards have been set yet. However, a high potential for this technology is widely acknowledged. Industry analyst IDTechEx [2] forecasts the market potential for printed electronics will be over USD \$35 billion by 2018.

The need for organic and printed smart labels exists e.g. in cost sensitive retail: super markets have in average a shrinkage of 2.77% per year [3]. This is a significant amount as the average profit margin for super markets is only 1.10%. The percentage of perishable goods amounts 30%, which causes more than 56% of the entire shrinkage [4] by arising spoilage. The principal reasons for spoilage are expired products or interrupted cool chains within supply chains from the manufacturer to the retail stores.

Massive deployment of current radio-frequency identification (RFID) technology in supply chain or retail scenarios for item-level tagging is too costly. Currently, it is used in few application areas such as monitoring pharmaceutical products or other high quality products such as luxury goods. High implementation and running costs prevent further use in other domains. Furthermore, the high communication load between reader and tags is time-consuming, which makes item-level tagging using traditional communication protocols for many inventory-style applications impractical. Even though the EPC Gen2 protocol enables batch readings of RFID tags, the complete communication process requires too much time for ad-hoc checks of pallets with up to 1000 items (assuming a decent response rate). Capacity limits of state of the art RFID communication protocols are described in [5].

In this paper we propose an alternative approach for organic and printed smart label device that can be deployed for item-level tagging in domains such as monitoring of perishable products on shelves in a retail store. The circuitry of the smart label device is designed and created based on the current state of organic and printed electronics. Its conceptual design relies on simultaneous transmission of sensed data. The communication scheme itself is discussed in section IV. In section II related works regarding strategies for improving supply chain management is given. In addition, the related work concerning communications is outlined, which has provided the basis for this paper. In section III requirements and issues about current organic and printed electronics are discussed and, the architecture of our research platform is described. Because organic and printed smart labels are currently not available in the needed quantity and quality the test bed is created using silicon-based replacements, which are described in section V. It is assumed that the behavior of silicon-based circuits will be not fully comparable with future organic and printed circuits. However, the use of simple modulation scheme and low hardware complexity, in particular no processor, shall enable the realization of smart labels in polymer electronics in the future.

II. Related Work

Dada and Thiesse investigated the potential of RFID technology and sensor-based issuing policies on product quality in supply chain handling with perishables in [6]. To improve the quality of the items in supply chain management different simulation models and policies have been performed and compared. Their results show policies which rely on automatically collected expiry dates and quality measurements bear the potential to improve the quality of items in the stores. The cost and benifit of Smart Item technology (barcode, RFID, sensor networks) in logistic processes and supply chain management is further discussed in [7].

In [8] a study in a retail area is described. The monitoring of perishable products is performed by checking the sell-by dates. Besides the high potential for improving inventory workflows the analysis of RFID item-level tagging technology by reveals weaknesses in scalability. To increase scalability of batch RFID readings Multi-SDJS is proposed that is also used in this paper.

The novel approach called Synchronous Distributed Jam Signaling (SDJS) was originally introduced in [9]. The idea for this paper has been inspired by Krohns work (see also [10], [11]). It enables highly mobile and ad hoc wireless networks to estimate the number of present devices in real time. SDJS is a modulation scheme with superimposing and synchronous jam signals combined with a statistical evaluation. Another application based on SDJS is described in [11], where an efficient method for node localization in wireless sensor networks is presented.

III. Requirements and issues

The development of organic and printed electronics in industry and research is motivated by the prospect of ultra-low cost production and massive deployment in domains where common silicon-based technology due to high costs failed. Industrial standard printers, which print ordinary newspapers in large quantities, can be used to produce organic and printed electronics. Traditional electronic components based on silicon show a high performance, but their manufacturing requires dust-free facilities and is difficult to integrate with common packaging and labeling processes. This leads to relatively high cost compared to the product itself. On the other hand, polymer electronics are made by printing several layers with different materials forming the electronic components in this way. The printing process reduces material and tooling costs and integrates better with current printing technology. Thus, the production of the organic and printed circuits can be faster, cheaper and simpler. On the other hand, printed electronics cannot compete with in terms of performance and size. The need for organic and printed electronics is especially high in scenarios such as logistics and supply chains where condition monitoring of goods could be achieved using extremely cheap sensors. Here, one can think about perishable products in a cool chain, where an early detection of an interruption leads to avoid spoiled pallets. Sensor data obtained from the polymer tags can be used to improve supply chain management, thus saving resources, fuel and arising trash which in turn increases the profit. Thus, future organic and printed smart label technology has the potential of being sustainable and to contribute to develop green technology.

Current state of the art in organic and printed smart labels are simple polymer tags consisting of at maximum 4-bit ROM containing neither sensors nor battery. Based on data in [12] it is planned to build a 96-bit ROM by 2014. An application will be storing identification numbers on products by using the Electronic Product Code (EPC)[13] communication protocol. The type of memory Write Once Read Many (WORM) will be tackled in the near future. To enable more applications in terms of organic and printed smart labels researchers are developing polymer sensors for temperature, light, pressure or strain. Especially temperature sensors are important e. g. in supply chains. Currently, one binary polymer temperature sensor exist tilting at $60°C$ [14]. It is still in development to decrease the temperature-threshold drastically. The goal is having an temperature sensor that tilts below $8°C$. This would enable the deployment of organic and printed smart labels containing the temperature sensor in cool chains, in order to monitor perishables. However, the current stage of research allows only few applications. Here, we are suggesting e. g. the massive deployment of organic and printed smart labels in supply chains dealing with transporting lithium-ion batteries. Monitoring and controlling the pallets full of lithium-ion batteries by using organic and printed smart labels avoids unnecessary risks like fire hazards.

Future applications, such as monitoring perishable products in supply chains applying printed polymer tags are economically interesting. Here, the information system must have the ability of examining a pallet, processing and forwarding the data into a business system. It is assumed that a regular pallet contains approximately 1000 items [15]. When a pallet arrives it has to be checked for completeness and compliance to the terms of delivery. In case of cool chains, compliance checks are whether perishable goods were exposed to too high temperatures during transport. If a pallet shows compliance violation, it can be rejected or examined more thoroughly by checking every item. Another example for compliance, similar to the previous one is checking shelves with more than 1000 items in a retail shop. Here, compliance checks have to be carried out periodically.

Product monitoring and maintaining the cool chain by item-level tagging in cost sensitive retail scenarios cannot be implemented using regular transponder technology such as EPC Gen2 [13]. Massively deployed transponders generate a high communication load, so that the EPC Gen2 communication protocol is not able to reliably read out several hundreds up to thousands of transponders in a short time frame. Today's optimal protocol solutions proving the capacity limits are well documented [5]. This technology is still uneconomical to employ for the massive deployment, despite decline prices for silicon based RFID technology. Therefore, this situation calls for radically new ideas.
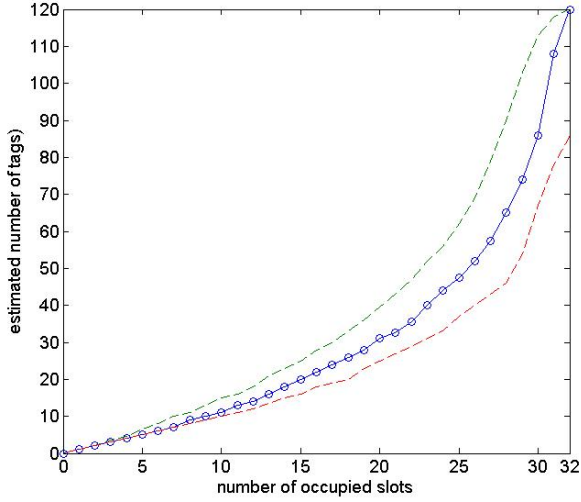
Fig. 1.   SDJS simulation using $s = 32$, $k \in [0, 120]$, $\alpha = 0.9$

IV. SDJS: Synchronous Distributed Jam Signaling

The challenges for item-level tagging by using polymer electronics are first to develop a smart label device based on constraints of the analog circuitry and second, to provide an efficient communication scheme between tags and reader device towards sensory information transmission. In the light of the performance limits even traditional RFID technology shows in terms of reading out thousands of tags in a short time frame, the realization of an organic and printed smart label system seems to be more infeasible. However, if the identity of each tag is abandoned and a concurrent transmission of sensed data is assumed, new possibilities towards circuit design and communications are opened. In this paper a concept for a communication scheme is implemented and an analog circuit design for tags presented. Additionally, the requirement of the above mentioned application scenario, i. e. being able to count damaged items on a pallet, has been included into the considerations. In order to enable the counting of e.g. the perished goods on a pallet one probabilistic approach is used, called Synchronous Distributed Jam Signaling (SDJS)[9]. Originally, SDJS is applied to estimate the number of activated sensor nodes in a wireless sensor networks for optimizing medium access. SDJS uses a slotted ALOHA scheme to estimate the number of activated senders based on the collision probability.

For our purpose, we are applying the mathematical framework of SDJS to estimate the number of damaged items. In the following a short review about the mathematical framework of the SDJS approach is given.

For better understanding, imagine, we have already installed a reader-system that can read out a whole pallet. In addition, the items were equipped with polymer smart labels that are activated by an irreversible 1-bit temperature sensor. The reading out process is as follows:

As in the case of classical RFID tagging a reader transmitted signal is used to activate those labels whose temperature sensor

has been tilted. In the next step the activated tags showing the damaged items back-scatter a so-called jam signal [1]. Such a jam signal is positioned in an evenly distributed randomly chosen time slot within a fixed number of time slots. On the other side, a receiver senses the air for a jam signal and registers it by occurrence into its reception vector. The sum of ones over the reception vector is used to estimate the actual number of transmitters belonging to those damaged items.

The estimation is required because when several transmitters send out their jam signal at the same time slot, collisions happen. The higher the number of transmitters exceeding the fixed number of time slots, the higher the collision rates. Just to increase the number of time slots significantly diminishes the performance of the approach to make the estimation in a short time frame. However, in our case as we will see later, the number of time slots is defined by the current organic electronics.

To describe the mathematical model of the estimator some variables are predefined here:

k: the actual number of transmitters
$\tilde{k}$: the estimated number of transmitters
A_k: stochastic variable for the number of received jam signals
a: number of jam signals received in one trial
s: number of time slots corresponding to reception vector length

At first we need to model the probability receiving a jam signals when k transmitter are actually sending out their signal. Using basic combinatorics we get for placing k elements into s slots s^k possibilities overall. In the case, where k jam signals occupy exactly a time slots we get $\binom{s}{a}$ combinations. The number of combinations to form groups of the size a is calculated by $\sum_{i=0}^{a} (-1)^i \binom{a}{i} (a-i)^k$. Hence, the probability we are searching for is modelled by

$$P(A_k = a|k) = \frac{\binom{s}{a} \sum_{i=0}^{a} (-1)^i \binom{a}{i} (a-i)^k}{s^k}$$

Here, the number of received ones is limited by the number of time slots s or by the number of transmitters k sending out a jam signal. Errors, such as getting more ones than are actually transmitted, are not modelled.

Now the resulting probability is used to build the estimator. This is done by using the maximum likelihood method:

$$\tilde{k} = argmax_k \ P(a|k) \tag{1}$$

The implementation of the likelihood estimator has been performed by using look-up tables containing for a certain a the estimation of transmitters $\tilde{k}$ with regard to the maximum likelihood.

A. Estimation accuracy using SDJS

The accuracy of the estimation of how many labels have indeed sent out a jam signal indicating the perished goods depends on the fixed parameters of the approach SDJS. In figure 1 the outcome of a simulation in relation to the

---

[1] In our experiments we used a sine signal of 130 kHz for jam signaling.

mathematical model is shown. A pallet with 120 items has been considered, and a fixed time frame of $s = 32$ slots was chosen. To get an estimation with an accuracy of 90%, curves for the assurance level of $\alpha = 0.9$ has been calculated, which surrounds the pointwise estimation. For example, if in a trial $k = 20$ time slots of overall $s = 32$ has been occupied, then the actual number of labels sent out a jam signal is located by considering a likelihood of 90% within 25 and 40. The pointwise estimation resulted into 31 labels.

B. Analog circuit design with SDJS

As previously described, we introduced the mathematical framework of SDJS as probabilistic approach able to estimate the number of transmitters by counting the received jam signals. Hence, we propose for future organic and printed smart labels a circuit design associated with SDJS, see figure 2, that can be fabricated through an industrial standard printer faster and cheaper. The proposed circuit has been designed with respect to current requirements, i. e. 4-bit Read-only-Memory (ROM), 1-bit irreversible temperature sensor consisting of low-tech electronic components such as resistor, capacitor or transistor. In section III are more information about current organic electronics. The operating principle of the designed circuit is as follows: by using an external trigger signal, all tags will be synchronized and transmit a jam signal if their temperature sensor is tilted. The point of time transmitting a jam signal occurs for every tag individually. As in the case of the SDJS approach a fixed number of time slots are predetermined through a multiplexer on the circuit. To determine in which point of time transmitting a jam signal, we propose to hardwire the temperature sensor to the multiplexer randomly. Here, the random process is even distributed as it is provided in the SDJS approach. The random hardwiring has to be implemented into the printing process directly. The proposed circuit with all its details is shown in figure 2.

For a better understanding, how the SDJS algorithm is working by the designed circuit, imagine there is a 1-bit irreversible temperature sensor value $\{0, 1\}$ being placed into an otherwise zero initialized 4-bit ROM randomly. Now, when the circuit is induced by an external trigger signal a procedure is started to read out the 4 cells of the ROM. The length of time for reading out a cell corresponds to the time length of one slot being used in the SDJS approach. When the temperature sensor bit e. g. has been placed at the third position of the ROM and it is tilted at this point of time, a jam signal is transmitted through the sender unit on the circuit. Reading out of all cells incrementally corresponds to the SDJS scheme. The reason for choosing 4 time slots comes from the limits of current organic electronic RFID tags having only at maximum a 4-bit ROM.

V. EXPERIMENTS

So far, we described the idea of one possible future organic and printed circuit using the SDJS algorithm, designed the circuit into SPICE [16] and simulated its functionality. To demonstrate the ability of the proposed approach we created
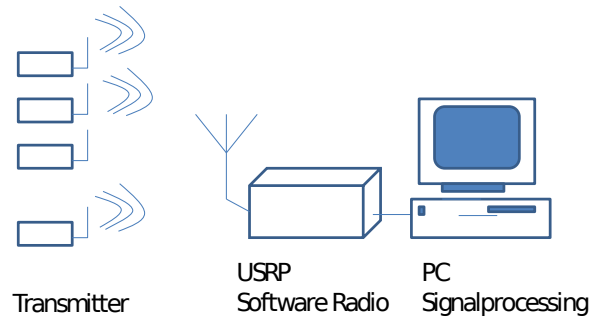

Fig. 3. Architecture of our research platform consisting of N transducer and a PC connected receiver for signal processing
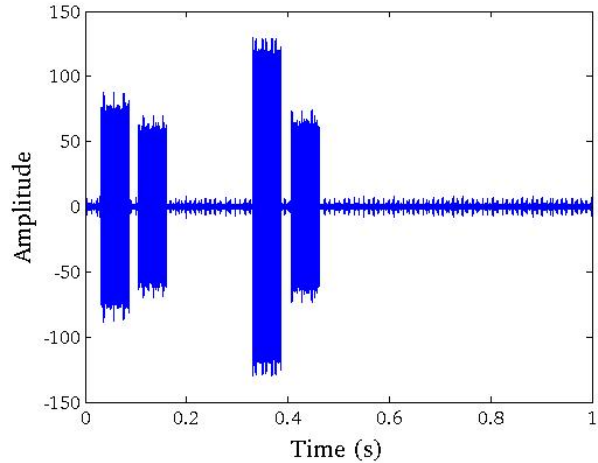

Fig. 4. Signal recorded using USRP shows jam signals of four transducers at time slots 0, 1, 4 and 5.

transducers on standard PCB-technology using of-theshelf components and therewith performed experiments.

The research platform of our experimental setup consists of 5 transducers and one receiver connected with one conventional PC, which performs the signal processing and visualization. The architecture of our platform is shown in figure 3. For signal processing, we are using Software Defined Radio (SDR), whereby the receiver comes from the Ettus Research [17], and is working in the low frequency domain as to reflect constraints of organic electronics.

To prove our approach, we set the time slot for transmitting a jam signal for every transducer individually. The considered time length is 1 second, divided into 80ms time slots. Each transducer sends out its jam signal within the provided time slot. The distance between transducers and receiver has been fixed to 50 cm. The carrier of the jam signal is set to 130 kHz. All experiments have been performed in an ordinary office, where common noise is prevailing. Example results of the tests are shown in figure 4 and 5.

The appearance of the jam signals are well distinguished by the captured signal, so that the number of transducers which are sending can be estimated easily. Further tests such as enlarging the distance between transducers and receiver
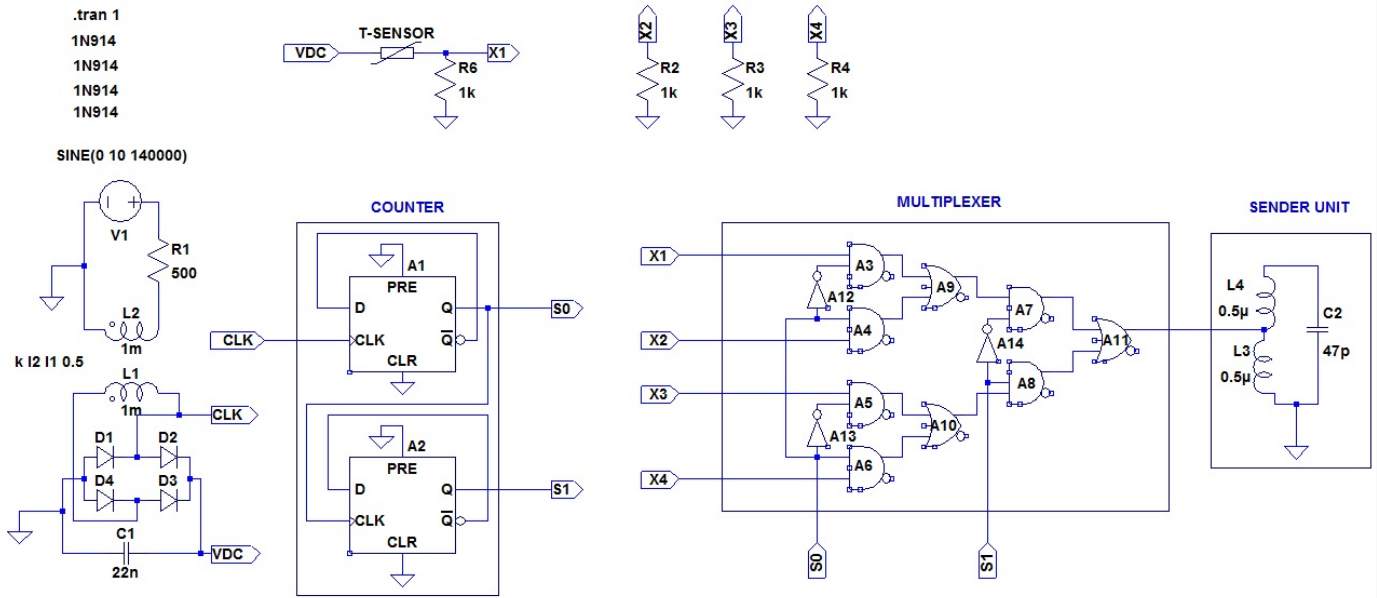
Fig. 2. First circuit for integrated sensor based SDJS designed and simulated using LTspice. The created circuit is made under consideration of organic printed electronics, e. g. a minimal number of simple electronic components have been used.
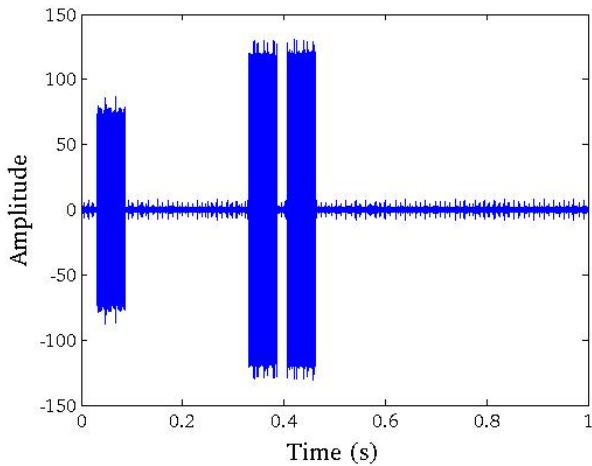

Fig. 5. Recorded jam signals of four transducers, two sending simulateously in timeslot 5.

yield worse signal-to-noise ratio. Here, some efforts have to be undertaken to improve the current state of the signal-to-noise ratio. However, our results show in principle, that it is possible to realize an organic and printed smart label system which can investigate a pallet in a short time frame.

VI. CONCLUSION AND DISCUSSION

In this paper we presented a solution for organic and printed smart labels which can be used for item-level tagging in domains such as supply chain management. The analog circuitry of the proposed smart label device is specially designed for polymer electronics and incorporates a simple communication scheme for data transmission. Based on simultaneous transmission and SDJS mechanism the number of activated smart labels can be approximately counted. In relation to maintenance and regular compliance checks of perishables on pallets in a cool chain, the amount of perished products on a pallet can be estimated. By detecting perished products or damaged goods a pallet can be investigated thoroughly or even rejected, which is in supply chain management business relevant. To investigate our approach, we created a smart label test bed based on silicon-based replacements. The experiments show under real environmental conditions the robustness of the approach, and that it is in principal possible to realize smart label systems based on polymer electronics.

For the realization of our approach through the upcoming organic printing technology randomness in hard-wiring during the printing process is required, that goes beyond a simple write-once ROM. By using printing technology this custom hard-wiring on item level will be much cheaper than with traditional electronics that require later manipulation in an extra step. The number of slots (and thus the ROM-size) can further be optimized by the number of items on a pallet when printing the packaging. This, however, will limit the scheme to pallets with same size items.

Our work relies on the assumption that remote batch reading of organic RFID tags will be possible. There are many unsolved problems in organic based RF communication that are not subject to this paper. Our experiments using substitute transponders only present a first proof-of-concept. The used ON-OFF keying scheme was used to minimize the requirements on the signal quality. Without complete proof we further assume that the synchronization of the signals

can be heavily relaxed by extending the estimation model if deterministic timing of the backscatter will remain an issue. In [18] we further present an alternative CDMA-based scheme for robust value encoding of analog type organic sensors.

Although considerable progress in the area of organic RFID is made, it seems likely that the first fully printed tags will use a combination of organic and non-organic materials. Although cost will be the driving factor here, our work does not rely on a fully organic tag. It can actually also be applied to silicon-based transponders to optimize reading and lower implementation costs. One goal of the paper is to highlight the advantages of an alternative to batch reading in general. The second important improvement of organic tags over classical circuit, which our work builds upon, is the close integration of cheap electronically interfaced indicators and sensors with packaging technology ([19]). Together with our industry partners we hope to see first prototypes using novel types of communication and sensor integration, enabling novel applications being build in the near future.

ACKNOWLEDGMENT

REFERENCES

[1] M. Beigl, T. Riedel, and C. Decker, "Smart objects-auswirkungen massengedruckter einfachelektronik auf die it-infrastrukturen (smart objects-effects of mass-printed electronics on it infrastructures)," *it-Information Technology*, vol. 50, no. 3/2008, p. 175184, 2008.

[2] IDTechEx, "http://www.idtechex.com/."

[3] National Supermarket Research Group, "National Supermarket Shrink Survey," 2005. [Online]. Available: http://www.securestoreadvantage.com/pdfs/ Supermarket_Survey_Executive_Summary.pdf

[4] Paul Beswick, Mathew Isotta, Stefan Winter, "A Retailer's Recipe for Fresher Food and Far Less Shrink," in *Oliver Wyman Journal Issue 24*, 2008.

[5] H. Vogt, "Efficient Object Identification with Passive RFID Tags," in *Pervasive 2002*. Zürich, LNCS: Springer-Verlag, 2002, pp. 98–113.

[6] Ali Dada, Frédéric Thiesse, "Sensor Applications in the Supply Chain: The Example of Quality-Based Issuing of Perishables," in *The Internet of Things*, Zürich, 2008.

[7] Christian Decker, Martin Berchtold, Leonardo Weiss F. Chaves, Michael Beigl, Daniel Rohr, Till Riedel, Monty Buster, Thomas Herzog, Daniel Herzog, "Cost-Benefit Model for Smart Items in the Supply Chain." The Internet of Things, 2008.

[8] Albert Krohn, Tobias Zimmer, Michael Beigl, Christian Decker, "Collaborative Sensing in a Retail Store Using Synchronous Distributed Jam Signalling," in *International Conference on Pervasive Computing*. Munich, Germany: Springer Verlag, 2005, pp. 237–245.

[9] Albert Krohn, Michael Beigl, Sabin Wendhack, "SDJS: Efficient Statistics for Wireless Networks," in *Proceedings of the 12th IEEE International Conference on Network Protocols*, Berlin, Germany, 2004.

[10] A. Krohn, "Überlagerte Funksignale in drahtlosen Sensornetzwerke," Ph.D. dissertation, Karl-Friedrich-Gauss-Fakultät für Mathematik und Informatik der Technischen Universität Carolo-Wilhelmina zu Braunschweig, TU Braunschweig, 2007.

[11] Albert Krohn, Mike Hazas, Michael Beigl, "Removing Systematic Error in Node Localisation Using Scalable Data Fusion."

[12] O. E. Association, "OE-A Roadmap for Organic and Printed Electronics," *White Paper*, 2008.

[13] "EPC Tag Data Standards, Version 1.3", in *EPCglobal Inc, Standard*, 2006.

[14] PolyIC, http://www.polyic.com.

[15] http://mstonline.de/mikrosystemtechnik/mst-smart-label/Clustermeetingrfid/locostix gesamt, "Locostix."

[16] SPICE, "http://bwrc.eecs.berkeley.edu/classes/icbook/spice/."

[17] Ettus Research, "http://www.ettus.com/products."

[18] P. Jakimovski, F. Becker, S. Sigg, H. R. Schmidtke, and M. Beigl, "Collective communication for dense sensing environments," in *2011 7th International Conference on Intelligent Environments (IE)*. IEEE, Jul 2011, pp. 157–164.

[19] S. Pankalla, R. Ganesan, M. Glesner, J. Krumm, and K. Ludwig, "Ein smart label zum auslesen und bertragen von temperaturwerten basierend auf organischer elektronik," *MikroSystemTechnik*, 2011.