Fully Functional Passive RFID Tag with Integrated Sensor for Item Level Tagging Based on Collective Communications and Organic Printed Electronics

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Abstract—**The development of Organic Electronics (OE) is promoted by the promise of being ultra-low cost technology in the future. One key application scenario is item level tagging, e.g., smart packaging, where items are equipped with organic printed tags using Radio Frequency IDentification (RFID) technology. However, current OE allows the printing of simple tags with ultra-low hardware complexity, but the printing of RFID chips with large numbers of transistors that implement RFID anti-collision protocols are far away from realization. In this paper, we present one sensor-based and fully functional passive RFID tag implementing collective communications a proprietary transmission protocol. Based on OE constraints, we describe the printable passive smart label down to the logic gate layer. Further on, we present an external clock synchronization strategy required by the passive reader system. Additionally, we provide a feasibility assessment towards printing the smart label, and conclude with simulating the proposed reader system.**

Keywords–smart label; RFID; polymer electronics; organic printed circuits; wireless communication.

I. Introduction

One key point in promoting polymer electronics is the promise of cost efficiency in relation to printing electronic devices in mass production. Another, the incorporated properties being light, thin and flexible are enabling novel applications in the area of pervasive systems and ubiquitous computing. The area of intelligent packaging is one key application for utilizing Organic Electronics (OE), for instance, the development of organic printed smart labels using Radio Frequency IDentification (RFID) technology [1]. OE tags can contain and provide useful information, such as the item identification and sensor readings. This data is created continuously while items travel through the supply chain, i.e., from the manufacturing plant to the final consumer, and enable participants and other stakeholders to improve their business processes: quality control, certification, logistics optimization or fraud detection are but a few examples. Such dealing results in cost savings for the producer, suppliers, as well as vendors and, increases product safety for consumers. The approach we describe in this paper can be applied in those business processes. It can, for example, be used to determine product quality in bulk reading scenarios, such as the goods inbound processing in a supermarket. For each item the quality is determined by the sensor-based smart label attached to the item. In operation, the sensor readings are acquired in a single query and interpreted by our algorithm that is specific to product type, e.g., to a quality rating on a scale from 1 to 7. The quality scale, however, is identical for all product types, i.e., a rating of 1 corresponds to a perished item for both milk packages and tomatoes. Otherwise, no compliance violation is detected, and the goods can be sold. Based on collective and simultaneous querying a single reader device can thus determine the quality ratings of multiple items belonging to different types.

Our paper is structured as follows. In Section II, we provide an overview about printed RFID technologies, and bring the state-of-the-art in relation to our smart RFID label approach. In Section III, we implement the smart label based on our earlier developed collective transmission protocol [2]. The specially developed communications for bulk reading of minimalistic tags is outlined in Subsection III-A and, its implementation into passive RFID circuitry is given in Subsection III-B. Thereafter, we describe an external clock synchronization strategy implemented within the proposed tag circuitry. The paper concludes with a validation of the proposed approach by utilizing simulations and a feasibility assessment towards printing the smart label device with current print technology.

II. Printable smart labels

RFID technology is in comparison to barcode in terms of memory capacity, readability, speed, being re-programmable, robustness and scalability vastly superior, but the high fabrication costs for Si-based RFID chips impede their wide deployment in item-level-based applications. However, the emergence of organic and printed electronics arises the opportunity to create affordable all-printed RFID tags, which can compete with the well established barcode system. Apart from the advantages of OE being thin, light-weighted, flexible and presumably ultra-low cost in the near future, the realization of this technology into printable smart labels is rather challenging, because the printing process itself is still an issue of current research. Further on, the created conductive inks indicate low electro-mobility which result into slow-switched transistors, i.e., yielding $627\,\mathrm{Hz}$ at $10\,\mathrm{V}$ electricity supply [3]. In addition, the printing of circuits on substrates, such as paper and plastic foils, consumes large areas, so that yet complex integrated circuits, such as a microchip can not be printed.

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However, an all-printed 1-bit RFID tag based on carbon nano-tubes and gravure printing process has been reported from the Sunchon University [4] in 2010. More recently, the research group presented an improved version of 16-bit RFID tag at the IDTechEx RFID Europe event [5]. The RFID circuit is printed entirely on a polyester film, whereby nano-silver is used to print the antenna, because of the better interconnectivity. The all-printed rectifier of the tag provides a $10\,\mathrm{V}$ Direct Current (DC) from the $13.56\,\mathrm{MHz}$ reader signal. The all-printed ring oscillator can generate a clock signal of $102.8\,\mathrm{Hz}$, which enables the transmission of a 96-bit transponder IDentification number (ID) in a second. In collaboration with the company Paru their goal is to achieve printing 96-bit RFID tags conform to the ISO 14443 (International Organization for Standardization).

The company ThinFilm Electronics and its partner companies PARC developing addressable memory, and Polyera developing printed displays, presented recently a smart sensor label, which can be printed at high volumes on roll-to-roll printing process. Their smart label system consists of a writable memory, sensing capability and a printed display which indicates visually the information when, for instance, the temperature of the product has exceeded the maximum threshold. This system is based on line-of-sight reading, and thus less applicable for mass-reading scenarios, such as monitoring of pallets in a cool chain, where items are highly dense stacked and invisible for inspection. However, it offers an additional support in supply chains, such as picking out of the damaged and expired products in a super market. In this way, options for improving supply chain management are extended.

The first fully functional printed RFID tag based on silicon ink has been announced by the company Kovio. The internal circuit logic of the tag consists of about 1000 printed transistors, and has the capability to radio its stored data from a 128-bit printed Read-Only-Memory (ROM) to an interrogator. The transmission is based on High Frequency (HF) ($13.56\,\mathrm{MHz}$) and synchronous tag-talks-first protocol. The entire RFID circuit is printed by inkjet on a thin metal foil substrate. The application area focuses on Near Field Communication (NFC), such as the NFC Barcode [6]. An implementation of long range communication is not available. The printing process uses inorganic silicon-based technology that can reduce the cost advantage the polymer electronics is offering.

The research group Holst Center and their partners in the EU FP7 project ORICLA created a fully functional RFID tag based on polymer electronics and thin-film technology. The RFID prototype is made on plastic foil with organic thin-film semiconductors and realizes reader-talks-first communication. In contrast, the above presented approaches toward printed RFID tags are based on tag-talks-first principle: as soon as the RFID tag gets powered from the RF field of the RFID reader, it transmits its data to the reader. Here, the problem occurs, when many tags try to contact the reader at the same time, which requires an effective anti-collision mechanism. However, current generation of printed thin-film RFID tags are in fact enabled with a basic slotted ALOHA protocol, but the implementation of the anti-collision scheme is limited to about maximum 4 tags, and come at the cost of a slow reading.

Driven by lowering the costs for fabricating RFID tags, further techniques are promoted to realize item level tagging, such as printable and chipless RFID technology. In contrast to printed RFID tags including an Integrated Circuit (IC) chip, printed chipless RFID tags are characterized mainly by encoding the product ID by using Time Domain Reflectometry-based (TDR) and Frequency Domain Signature-based (FDS) techniques, respectively. While TDR-RFID tags are based on microwave circulators and capacitors to generate RF wave transmission-lines in order to transmit the binary ID code, the FDS-RFID tags consist of resonators with different resonant frequencies which encode, i.e., the binary data. The coding capacity of TDR-based tags is currently limited by up to 8 bits, whereby FDS-based tags can contain theoretically unlimited capacity depending on frequency band and tag size. For example, Islam and Karmakar describe in their work [7] a 16-bit chipless RFID tag printed on a $1.65 \times 1.65\,\mathrm{cm}^2$ substrate area, which operates in the $6 - 13\,\mathrm{GHz}$ frequency band. The first type of fully printed chipless RFID tags suffer from limited encoding capacity, whereas the second type requires large-scale size and wide frequency bands, which can be scarcely deployed for applications operating in the Industrial, Scientific and Medical (ISM) radio bands. An overview about recent advances in printable chipless RFID technology is given in [8] and [9].

To reflect the related work the aim of all described approaches is focusing on implementing the EPCglobal Tag Data Standard (TDS) into printable RFID tags, which have the same capabilities as the conventional Si-based RFID technology is already providing. For instance, bi-directional communication between reader and tags, anti-collision protocol for avoiding interference, and large data storage capacity on tag. The implementation of these features into a polymer tag, that can be even printed on roll-to-roll process at high volumes, is currently rather challenging. The lack of printing integrated circuits with large numbers of transistors into small area and, the lack of mass production accuracy and reliability, is suspending the realization of fully functional organic and all-printed RFID tags into the far-distant future.

III. Collective Communications for Printed Smart Labels

In our earlier work, we developed with respect to future organic and printed smart labels robust and highly scalable communications based on collective transmission mechanism called *collective communications* [2][10]. In the following, we implement with regards to OE constraints the targeted smart label device into a fully functional polymer-based circuitry, and provide a feasibility assessment towards printing the smart RFID label in mass production.

A. Collective Communications

In general, collective communications is designed how to obtain information from a set of simultaneously sending nodes, in our application scenario the tags attached to goods on a shelf. We request from the set of items which proportion of tags measured *(proportion query)*, respective, contain which values *(binary query)*. In principle, this could be done by querying tags individually using any of the well-established protocols. However, implementing these protocols is not feasible in our scenario, since the senders need to be simple due to polymer electronics deficiency, and we consider large number

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of senders. In particular, our transmission algorithm is laid out to be on the one hand simple, so that the smart label device can be implemented in polymer electronics, and on the other hand to acquire maximal performance regarding information transfer, scalability and robustness. We achieve these objectives by employing the following fundamental principles:

1) All queried tags transmit their stored data simultaneously and start transmission at the same time
2) A randomly drawn bit sequence encodes a physical entity, such as an identification, sensor value, temperature range, etc.

By applying the rules, the signals sent from tags superimpose on the RF channel. However, the transmission mechanism enables to analyze the superimposed signal statistically at the receiver side, so that the transfered information, for instance, which proportion of senders sent which value, can be extracted. Basically, our communication mechanism is based on bit sequences c of fixed length, that are shared between a sender S and a receiver R. A bit sequence v is sent from S as $s = c \oplus v$, where $\oplus$ is the bitwise *exclusive or*. The receiver extracts v from s by computing $v = s \oplus c$. The double application of $\oplus c$ cancels out c and v is regained. Simultaneous connections between a number of senders S_i and corresponding receivers R_i can then be achieved: simultaneous transmission yields the superimposed signal as the sum $s = s_1 + s_2 + \ldots + s_n$ of signals s_i sent, since the amplitudes of synchronized signals of the same frequency are approximately added to each other when the bit sequences s_i are sent. The resulting signal s is *similar* to each of the original signals s_i, where similarity can be based on various distance metrics on bit sequences $v, w \in \{0,1\}^n$, e.g., on the Hamming distance:

$$d_H(v,w) = \sum_{i=1}^{n} |v_i - w_i|. \qquad (1)$$

The similarity is then defined by choosing a threshold T_n suitable for the length of the vectors n. Two bit sequences $v, w \in \{0,1\}^n$ are called *similar* if they differ only in a small number T_n of bits:

$$v \sim w \overset{def}{\Leftrightarrow} d_H(v,w) \leq T_n. \qquad (2)$$

A number of pairs of senders and receivers can thus communicate via codes c_i. If the codes c_i are chosen so as to be orthogonal ($d_H(v,w) = 0$), or at least sufficiently different ($d_H(v,w) \ll n$) from each other, this entails that we can obtain v_i from s by applying $v'_i = s \oplus c_i$. The result v'_i is similar to v_i, so that v_i can then be regenerated from v'_i, using error correcting codes. Codes c_i can be generated so as to be orthogonal, however, sufficiently long random bit sequences, are also suitable: statistical theory suggests that the probability to obtain two random bit sequences of low similarity is higher, the longer the sequences are. In order to ensure that different values transmitted can be retrieved from the superimposed signal, we directly encode the numerical values by using a single random bit vector z_0 shared by all tags and the receiver. We obtain sufficiently different codes z_i for numerical values i by circularly shifting z_0 by the amount of i bit, since shifting is a distancing operation. In this way, a single bit vector $z_0 \in \{0,1\}^n$ can be used to encode n values, and thus save memory capacity on the smart label device.

The received signal $s = s_1 + s_2 + \ldots + s_n$ is then simply a sum of encoded numbers z_i, directly encoding the multi-set of measured values. The algorithm for the reader system is outlined in Figure 1.

1) Tags come initialized with a register t set to default value 0, and transmit code z set to z_0.
2) Each tag measures continually its environment:
3) if the measured value is $m > t$, then
    a) it sets $t := m$.
    b) it shifts the code z accordingly: $z := z_t$.
4) Reader sends `start` signal to tags.
5) Tags send their respective z.
6) Reader receives overlaid signal s:
    a) **Binary Query:**
        i) Set $S := \emptyset$.
        ii) For each possible value z_i: if $z_i \sim s$ then $S := S \cup \{z_i\}$.
    b) **Proportion Query:** For each value $z \in S$: use Least Squares Estimation to compute proportion of contribution of z:
        i) Generate linear equation system for the found values $z_i \in S$.
        ii) Estimate parameters a_i so that error is minimal.
        iii) $M := \{(a_i, z_i) | s = \sum_{z_i \in S} a_i * z_i\}$.
    c) **Output:** return M.

Figure 1. The Collective Communications algorithm.

B. Circuit design

Based on our communication protocol described above in Subsection III-A, the implementation of the smart label device relies merely on features, such as fetching the sensor value, reading and sending out the corresponding bit sequence. Hence, the necessary building blocks of the circuit device are derived as follows: a sensor unit that consists of one Analog-Digital-Converter (ADC) and the sensor itself, a Read-Only-Memory (ROM) building block of fixed length that contains a randomly drawn binary sequence, and a circuit logic block that is enabled to generate the corresponding bit sequence to the sensed value, i.e., by employing the hardwired bit sequence stored in the ROM and carrying out an internal function operation on it. Further on, the smart label device contains a clock generator and counter to drive the transponder circuit. Exemplary, the block diagram in Figure 3 illustrates the interacting between all participating blocks of an 64-bit polymer tag, that implement, i.e., the clock generator realized by one ring oscillator, a 6-bit counter realized by 6 D-flip-flops, a ROM with 64-bit capacity, and a 3-bit ADC. Since the target is to create a reader system for passive polymer tags, the smart label circuitry includes in addition a DC rectifier concerning power supply, and a modulator transistor to convey the binary information to the reader device by deploying inductive coupling. Figure 4 shows in essence the schematic of the all-printable and passive polymer tag with its analog

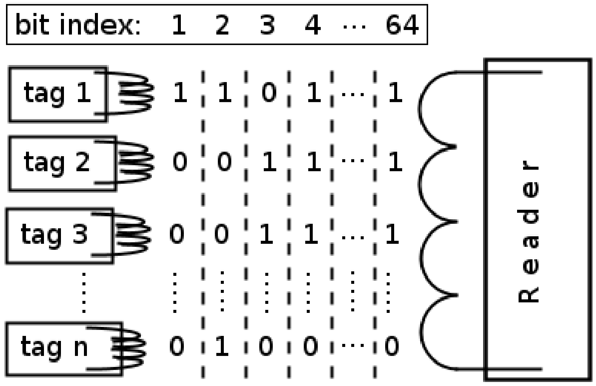

Figure 2. A passive tag reader system illustrates concurrent transmission of bit streams sent by several 64-bit smart labels.

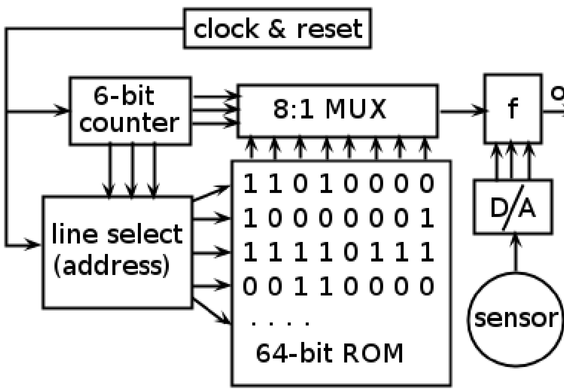

Figure 3. The circuitry implements the principle of collective communications.

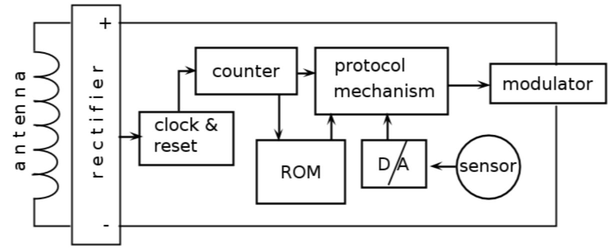

Figure 4. The circuit block diagram shows the holistic printable passive tag.

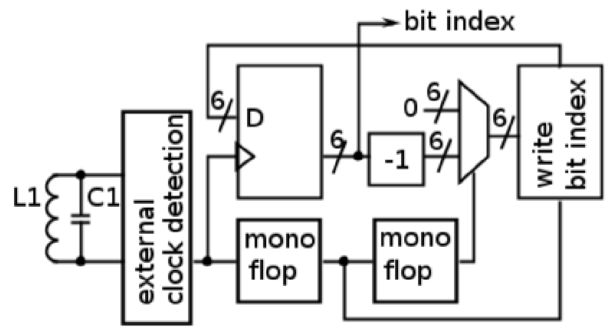

Figure 5. The schematic shows partially the circuit logic in connection with the tag rectifier for interpreting signaling coming from reader device.

and digital electronic components. The principle for collective communications is integrated in the protocol mechanism building block, where a bit sequence is generated according to the sensed value. The binary sequence is controlling the gate of the modulation transistor. When the modulator transistor is switched on, the transponder circuit draws power from the electromagnetic RF field of the reader. In the reverse, when the modulation transistor is switched off, the transponder circuit draws still power from the RF field, but considerably less than it is consuming in the on-state. In this way, the binary information is transfered by means of load modulation to the reader, i.e., by varying the power consumption.

C. Collective clock synchronization

With respect to bulk reading of smart labels in a dense area, i.e., when a set of tags are queried simultaneously, the response of the interrogated tags need to be collectively clock synchronized, but not phase synchronized as the collective transmission protocol is providing. On that issue, we developed for the reader system a collective synchronization method implemented into the transponder circuit. The circuit functionality is placed in the *clock & reset* building block (cf. Figure 4). Since conventional strategies, such as external reader-tag-synchronization applied in traditional RFID reader systems can not be employed straightforward in polymer electronics due to its hardware performance weakness, such as slow-switched printed transistors, appropriate solutions for reader-tag-communication needed to be elaborated. With respect to polymer electronics constraints, we developed collective synchronization procedures based on switching on/off the electromagnetic RF field of the reader device coil that empowers the polymer tags. By interrupting the wireless power supply all responsive tags can be instructed to either start with data transmission or, to send the next bit of their binary information. The transmission of data is based on inductive coupling. Figure 2 illustrates concurrent transmission of bit streams transmitted by several smart labels. In each synchronized time slot at the current bit index the bit information from all smart labels superimposes on the RF channel, and generates a specific overlaid signal. At the receiver side the superimposed signal in each time slot is captured and evaluated based on the collective communication algorithm (cf. mechanism in Figure 1).

In order to initiate every tag to start transmission at the same time the signaling can be done either by (i) turning off the reader device coil for a long time period and then start empowering the tags periodically with short intermissions, or (ii) begin with transmission by transmitting the start bit in a long time slot followed by transmitting the subsequently bit stream in regular sized time slots. Either way, the circuit logic in the clock & reset building block is tuned to interpret request orders sent from reader device based on capacitor discharge behavior and voltage comparator device. The circuit logic is connected with the tag rectifier shown in Figure 6. Parallel to the circuit logic that detects the external clock synchronization request, the internal clock counter in the clock & reset building block is reseting the bit index, and start increasing the count when the next intermission is registered. In this way, the smart label acquires the actual bit position in the bit sequence. In addition to the clock detection circuit a memory buffer realized through D-flip-flops preserves the bit index. This cache device

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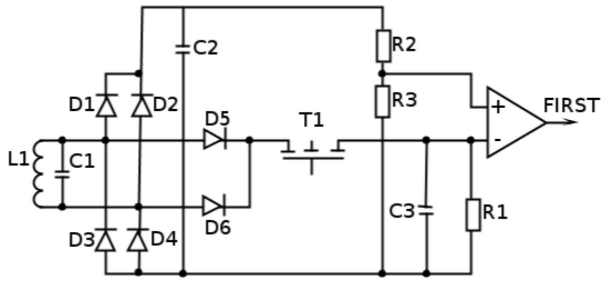

Figure 6. Schematic of the clock & reset building block.

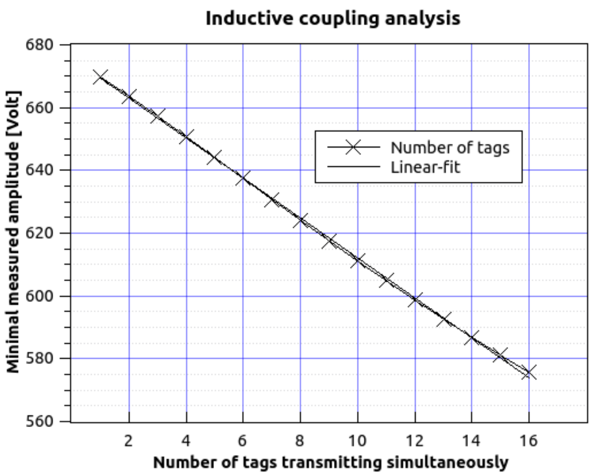

Figure 7. The overall signal analysis indicates the maximal amplitude difference between different trails with up to 16 simulated passive tags transmitting simultaneously.

keeps the storage contents even if the polymer tag is not powered for a short term, i.e., when the reader device causes an intermission to signalize the next time slot for transmission. Before increasing the bit index an additional memory buffer realized by D-latches stores temporarily the current bit index and induces the bit transmission. After increasing the bit index, it is delayed rewritten in the bit index buffer. The mono-flops in the circuit block provide the required delay for stabilized rewriting. The circuitry of the clock & reset block is depicted in Figure 5, whereby the external clock detection circuit is shown in Figure 6.

D. Feasibility assessment

The realization of printing electronic devices in mass production is one key issue of present-day research. With regard to organic and printed smart labels the state-of-the-art is described in Section II. All references indicate the feasibility of printing circuits with ultra-low hardware complexity, but non of them has yet enabled the printing of circuits implementing highly complex functionalities, such as an organic printed RFID chip with large number of transistors. With respect to current OE limitations the collective communication protocol was developed with the purpose to facilitate applications in the near future, though. The ability of exploiting concurrent and thus superimposed information transfer, has provided to move the hardware complexity from tag to the reader side. To the sake of completeness and, in order to indicate the hardware complexity of the proposed passive tag, the remaining of the circuitry is shown in Figure 8. It entails a 6-bit counter that enables to read out the hardwired 64 bit sequence shown partially in Figure 3. Due to lack of space the sensor unit is not shown here. As can be seen from the circuit block diagram in Figure 4, the depicted circuits in Figure 5, in Figure 6 and in Figure 8, the entire hardware complexity of the tag is reduced to about few hundreds of transistors. Considering the tag circuitry in relation to already manufactured printed electronics by other research facilities, the fabrication in a clean room of 64-bit ROM devices has been experimentally verified [11]–[13]. The printing of holistic 4-bit RFID tags employing load modulation for communication is described in [14]. A challenge for realizing the proposed passive tag into polymer electronics is to achieve hazard-free printed circuit devices. For example, the analog components in the clock & reset building block, such as the comparator and the RC-element for timekeeping (cf. Figure 6), need to be printed with high accuracy, so that the circuit characteristic remains constant. Further on, the transmission range regarding polymer-based printed transponders indicates low modulation index as reported in [15]. This may constrain the free scalability property of collective communications, i.e., to read-out many tags at once.

E. Simulation

The communication protocol collective communications is designed to allocate information instantly from a large number of nodes transmitting data simultaneously to a receiver. The communication relies on ON-OFF-Keying (OOK), and works generally for active reader systems. Here, we analyze the applicability of the collective transmission mechanism for passive reader systems. For our analysis, we established in LTspice a simulated passive reader system, where the antenna coil generates in HF an electromagnetic RF field providing up to 16 simulated passive transponder circuits with wireless power. Depending on passively switched on tags the change in the electromagnetic RF field, i.e., the amount of drawn energy from the RF field is recorded and evaluated at the reader side. With regard to parameterizing the simulation, we chose default parameters from standard RFID reader systems, such as $10\,\mathrm{cm}$ in diameter for the reader antenna coil, $2\,\mathrm{cm}$ in diameter for the tag antenna, which conforms to the inductive coupling coefficient of 0.025. The portability of the simulation with respect to polymer electronics is taken for granted, because the key parameter for inductance applies for printed antennas and circuits. In order to simulate different tag positions in relation to the reader antenna, respective, different sizes of tag antennas the coupling coefficient is varied. For the resonant circuit of the reader device generating the $13.56\,\mathrm{MHz}$ signal the hardware parameters are chosen according to Finkenzeller [16, Chapter 4.1]. The inductance is set by $2\,\mu\mathrm{H}$ with resistance of $2.5\,\Omega$. The capacitor is set by $68.8\,\mathrm{pF}$. Further on, for the tag coil we chose $100\,\mathrm{nH}$ and $0.1\,\Omega$. The results of the signal analysis are shown in Figure 7, that indicate the minimal measured amplitude strength for n simulated passive tags transmitting simultaneously. Therewith, the maximal amplitude difference is acquired for distinguishing different number of responsive tags. Further on, the simulations show the more passive tags being responsive the greater the distinctive features appear among the captured superimposed signals.

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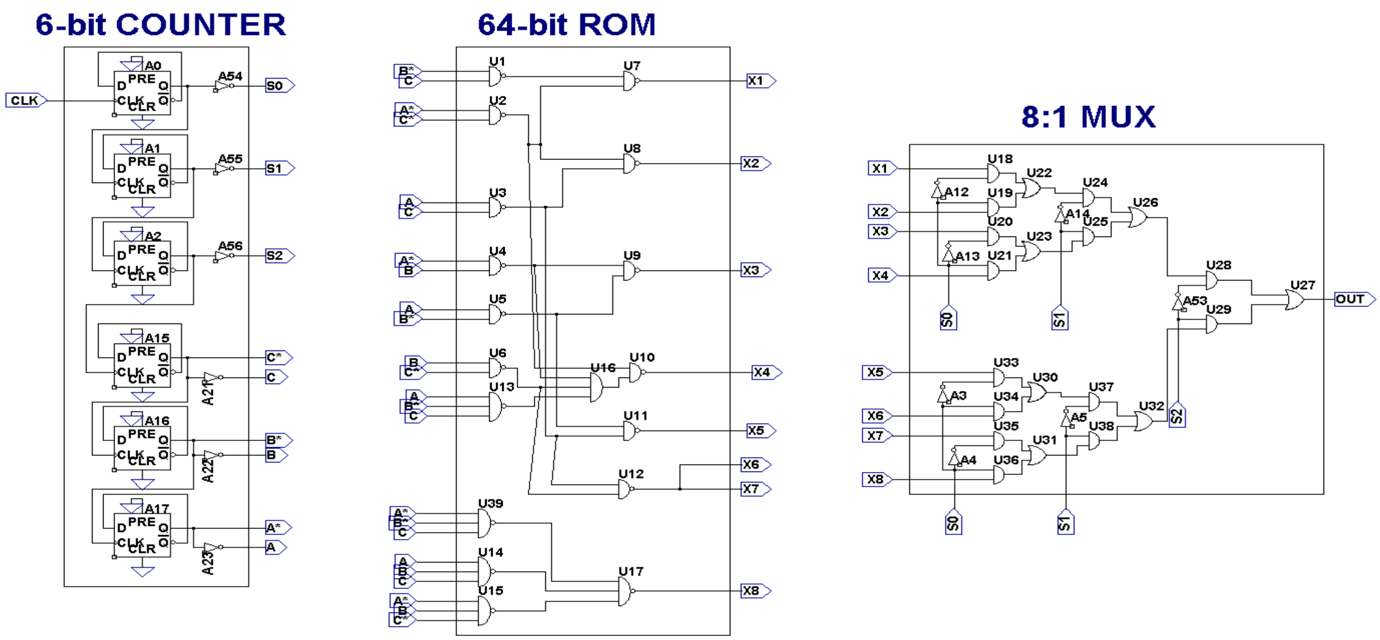

Figure 8. Schematic of the basic circuit arrangement realizing the part of circuit logic for a 64-bit polymer tag.

IV. Conclusion

With regard to smart packaging, item level tagging and organic printed smart labels, we described the implementation of one fully functional passive RFID tag, that is based on our earlier developed collective communication protocol and regards current organic electronics constraints. Apart from describing the state-of-the-art regarding printable smart labels and, putting this in relation to our smart label circuitry, we introduced with regard to reader-tag-communication an external and centralized clock synchronization strategy. Further on, we provided for the reader system a feasibility assessment, that indicates the printing of the proposed smart RFID label is in principle with present-day printing technology possible, but entails risks, such as low communication range and hazard-afflicted circuits that have been encountered by organic printed devices with similar hardware complexity. The causes for it were led back in the used conductive inks and fluctuations at the printing process. Hence, the specified hardware parameters may vary drastically, so that the printed polymer tags may exhibit unexpected and consequently unwanted behavior. However, the development and testing of novel conductive inks in material science, and improving the design rules for printing circuits on large area substrates, promises to resolve current issues of mass production in the near future.

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References

[1] Organic Electronics Association, "OE-A Roadmap for organic and printed electronics," White Paper, 2008.

[2] P. Jakimovski, F. Becker, S. Sigg, H. R. Schmidtke, and M. Beigl, "Collective communication for dense sensing environments," Intelligent Environments, International Conference on, vol. 0, 2011, pp. 157–164.

[3] K. Myny et al., "An inductively-coupled 64b organic rfid tag operating at 13.56mhz with a data rate of 787b/s," in Solid-State Circuits Conference, 2008. ISSCC 2008. Digest of Technical Papers. IEEE International, 2008, pp. 290–614.

[4] M. Jung et al., "All-printed and roll-to-roll-printable 13.56-mhz-operated 1-bit rf tag on plastic foils," Electron Devices, IEEE Transactions on, vol. 57, no. 3, 2010, pp. 571–580.

[5] P. Harrop. Sunchon university printed transistors. IDTechEx. [Online]. Available: http://www.printedelectronicsworld.com/print-articles.asp?articleids=2664 [retrieved: April, 2014]

[6] The kovio website. [Online]. Available: http://www.kovio.com/ [retrieved: April, 2014]

[7] M. Islam and N. Karmakar, "A novel compact printable dual-polarized chipless rfid system," Microwave Theory and Techniques, IEEE Transactions on, vol. 60, no. 7, 2012, pp. 2142–2151.

[8] B. Shao, Q. Chen, Y. Amin, R. Liu, and L. Zheng, "Chipless rfid tags fabricated by fully printing of metallic inks," annals of telecommunications - annales des tlcommunications, vol. 68, no. 7-8, 2013, pp. 401–413. [Online]. Available: http://dx.doi.org/10.1007/s12243-013-0378-3

[9] S. Preradovic and N. Karmakar, "Fully printable chipless rfid tag," in Advanced Radio Frequency Identification Design and Applications, D. S. Preradovic, Ed., 2011.

[10] P. Jakimovski, H. R. Schmidtke, S. Sigg, L. W. F. Chaves, and M. Beigl, "Collective communication for dense sensing environments," JAISE, vol. 4, no. 2, 2012, pp. 123–134.

[11] E. Cantatore et al., "A 13.56-mhz rfid system based on organic transponders," Solid-State Circuits, IEEE Journal of, vol. 42, no. 1, 2007, pp. 84–92.

[12] A. Ullmann, M. Bhm, J. Krumm, and W. Fix, "Polymer multi-bit rfid transponder," in ICOE, June 2007, pp. 4–7.

[13] K. Myny et al., "Plastic circuits and tags for 13.56 mhz radio-frequency communication," Solid-State Electronics, vol. 53, 2009, pp. 1220–1226.

[14] J. Krumm and W. Clemens, "Printed electronicsfirst circuits, products, and roadmap," in AACD Workshop, 2010, pp. 333–346.

[15] M. Böhm, A System Study for RFID, Transponders Based on Polymer Semiconductors. Cuvillier Verlag, 2007.

[16] K. Finkenzeller and D. Müller, RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication. Wiley, 2010.