SYSTEM INTEGRATION OF ELECTRONIC FUNCTIONALITY IN PACKAGING APPLICATION

Tomas Unander

Supervisors:
Hans-Erik Nilsson
Bengt Oelmann

Electronics Design Division
Department of Information Technology and Media
Mid Sweden University, SE-851 70 Sundsvall, Sweden

ISSN 1652-893X
Mid Sweden University Doctoral Thesis 112
ISBN 978-91-86694-49-4
Akademisk avhandling som med tillstånd av Mittuniversitetet i Sundsvall framläggs till offentlig granskning för avläggande av teknologie doktorsexamen fredag, 23:e september, 2011, klockan 13:00 i sal O102, Mittuniversitetet Sundsvall. Seminariet kommer att hållas på engelska.

SYSTEM INTEGRATION OF ELECTRONIC FUNCTIONALITY IN PACKAGING APPLICATION

Tomas Unander

© Tomas Unander, 2011

Electronics Design Division,
Department of Information Technology and Media
Mid Sweden University, SE-851 70 Sundsvall
Sweden

Telephone: +46 (0)60-19 38 71

Printed by Kopieringen Mid Sweden University, Sundsvall, Sweden, 2011
Dedicated to Malin and Wilma
SYSTEM INTEGRATION OF ELECTRONIC FUNCTIONALITY IN PACKAGING APPLICATION

Tomas Unander

Electronics Design Division, Department of Information Technology and Media
Mid Sweden University, SE-851 70 Sundsvall, Sweden

ABSTRACT

Sensor applications are becoming increasingly important as products are now being requested to be more and more intelligent and safe. As the costs involved in sensor technology decrease its usage will spread to new market segments including new areas with products that have never previously used such functionalities, including, wood fibre based products for packaging, hygiene or graphical use. Currently there is a significant interest in developing technology that will allow packages to become interactive and be integrated with digital services accessible on the Internet. In this thesis, the system integration of a hybrid RFID based sensor platform is presented. This proposed platform provides a trade-off between the communication performance and its compatibility with international standards and also includes flexibility in on-package customization, including the type and number of sensors. In addition it combines the use of traditional silicon based electronics with printed electronics directly onto wood fibre based materials so as to enable the possibility of creating smart packages. Together with the system integration of the sensor platform, five printed moisture sensor concepts that are designed to work with the sensor platform are presented and characterized. Firstly, there is a moisture sensor that shows a good correlation to the moisture content of wood fibre based substrates. The second one involves a sensor that detects high relative humidity levels in the air and the third is an action activated energy cell that provides power when activated by moisture. The fourth one deals with two types of moisture sensors that utilize silver nano-particles in order to measure the relative humidity in the air. The final one is a printable touch sensitive sensor that is sensitive to the moisture contained in the hand. A concept of remote moisture sensing that utilizes ordinary low cost RFID tags has also been presented and characterized.

The main focus is thus on system integration to, by combining silicon based electronics with printed electronics, find the most low cost solution with regards to flexibility, sensor functions and still meet the communication standards.

Keywords: sensor platform, RFID, printed electronics, moisture sensors
SAMMANDRAG


Fokus är således att på system integrationsnivå, med hjälp av att kombinera kisel elektronik med tryckt elektronik, hitta den mest kostnadseffektiva lösningen med avseende på flexibilitet, sensor funktionalitet och att även kunna möta kommunikationsstandarderna.
ACKNOWLEDGEMENTS

This work was carried out at SCA R&D Centre and at Mid Sweden University in Sundsvall, Sweden. The Knowledge Foundation is greatly acknowledged for their financial support.

I would like to thank my supervisors Professor Hans-Erik Nilsson and Professor Bengt Oelmann for their help and guidance during my time as a Ph.D. student. I would like to thank my colleagues at SCA R&D Centre for providing such a good working atmosphere. I would like my colleagues at Electronic Design Division at Mid Sweden University, especially Johan Sidén, Henrik Andersson and Anatoliy Manuilskiy for the help with work in some of the papers within this thesis.

I would like to thank my wife Malin and our daughter Wilma for the love and support. I would like to thank my mother Elsie and father Ronnie, my brother Håkan and his wife Jenny and their children Elin and Jesper, my grandparents Svea, Gunnar and Kickan, my parents in law Ingemar and Britt, my wife’s brother Martin and his wife Christine.

I would like to thank my friends Janne, Elona, Bengt, Jenny, Rikard, Linda, Tom, Anna, Martin and Erika and all my friends at Sundsvalls Orienteringsklubb and of course any of you that I have accidentally left out.

Sundsvall, June 2011

Tomas Unander
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................ V

SAMMANDRAG .................................................................................................................................. VI

ACKNOWLEDGEMENTS ................................................................................................................ VII

ABBREVIATIONS AND ACRONYMS ........................................................................................ XIII

GENERAL .......................................................................................................................................... XIII

LIST OF PAPERS ........................................................................................................................... XV

1 INTRODUCTION ............................................................................................................................. 1
  1.1 PROBLEM FORMULATION ...................................................................................................... 7
  1.2 MAIN CONTRIBUTIONS .......................................................................................................... 8
  1.3 THESIS OUTLINE .................................................................................................................... 8

2 RFID BASED SENSOR SYSTEM ............................................................................................... 11
  2.1 SYSTEM INTEGRATION OF THE RFID BASED SENSOR SYSTEM ..................................... 11
  2.1.1 RFID chip .......................................................................................................................... 13
  2.1.2 Microcontroller (sensor chip) ............................................................................................ 14
  2.1.3 Antenna design .................................................................................................................. 17
  2.1.4 Power source .................................................................................................................... 17
  2.2 PERFORMANCE OF THE RFID BASED SENSOR SYSTEM ............................................. 18
  2.2.1 Data storage in the RFID based sensor platform ............................................................... 18
  2.2.2 Reading range of the RFID based sensor platform ........................................................... 20
  2.3 APPLICATIONS FOR THE RFID BASED SENSOR SYSTEM ............................................. 22
  2.3.1 Moisture content sensor solution ...................................................................................... 22
  2.3.2 Tilt sensor solution ............................................................................................................ 26
  2.3.3 Tamper detection solution ................................................................................................. 29
  2.4 WIRELESS SENSOR PLATFORM COMPARISON ............................................................... 31
  2.4.1 Wi-Fi technology .............................................................................................................. 31
  2.4.2 Infrared technology .......................................................................................................... 32
  2.4.3 Impulse Ultra Wideband (I-UWB) .................................................................................. 32
  2.4.4 Passive RFID solution ...................................................................................................... 33
  2.4.5 Wirelessly-charged RFID ............................................................................................... 33
3 LOW COST MOISTURE SENSORS .................................................................35

3.1 MOISTURE CONTENT SENSOR FOR WOOD FIBRE BASED SUBSTRATES ..........36

3.1.1 Experimental results for the moisture content sensor .................................38

3.2 RELATIVE HUMIDITY SENSOR FOR HIGH HUMIDITY LEVELS .....................42

3.2.1 Experimental results for the sensor for high relative humidity levels ............43

3.3 PRINTED ACTION ACTIVATED MOISTURE SENSOR ........................................46

3.3.1 Experimental results for the action activated moisture sensor .....................47

3.4 REMOTE MOISTURE SENSOR THAT UTILIZES ORDINARY RFID TAGS ........42

3.4.1 Experimental results for the remote moisture sensor solution .......................55

3.5 PRINTED NANO PARTICLE BASED MOISTURE SENSOR ...............................59

3.5.1 Printed nano-particle based sensor for very dry moisture conditions ............59

3.5.2 Experimental results for nano-particle based sensor for dry moisture conditions .................................................................60

3.5.3 Single layer nano-particle based moisture sensor for high humidity levels ....62

3.5.4 Experimental results for single layer nano-particle based moisture sensor 63

4 PRINTED TOUCH SENSITIVE SENSORS .........................................................69

4.1 PRINTED SENSOR STRUCTURE FOR THE TOUCH SENSITIVE SENSOR SOLUTION ......70

4.2 READOUT ELECTRONICS FOR THE TOUCH SENSITIVE SENSOR SOLUTION .......72

4.3 COMMUNICATION INTERFACE FOR THE TOUCH SENSITIVE SENSOR SOLUTION ....73

4.4 EXPERIMENTAL RESULTS FOR THE TOUCH SENSITIVE SENSOR SOLUTION ........74

5 SUMMARY OF PUBLICATIONS .....................................................................79

5.1 PAPER I ...........................................................................................................79

5.2 PAPER II .........................................................................................................79

5.3 PAPER III .......................................................................................................79

5.4 PAPER IV .......................................................................................................80

5.5 PAPER V .......................................................................................................80

5.6 PAPER VI .......................................................................................................80

5.7 PAPER VII ....................................................................................................81

5.8 PAPER VIII ..................................................................................................81

5.9 PAPER IX .....................................................................................................82

5.10 AUTHOR’S CONTRIBUTIONS .............................................................................82

6 THESIS SUMMARY AND CONCLUSIONS .....................................................85

6.1 BAP RFID BASED SENSOR SYSTEM .............................................................85

6.2 PRINTED MOISTURE CONTENT SENSOR FOR WOOD FIBRE BASED SUBSTRATES ......86
6.3 PRINTED RELATIVE HUMIDITY SENSOR FOR HIGH RELATIVE HUMIDITY LEVELS ........................86
6.4 PRINTED ACTION ACTIVATED MOISTURE SENSOR ..........................................................86
6.5 REMOTE MOISTURE SENSING UTILIZING ORDINARY RFID TAGS ................................87
6.6 PRINTED NANO-PARTICLE BASED SENSOR MOISTURE SENSORS ....................................87
6.7 PRINTED TOUCH SENSITIVE SENSOR .............................................................................87
6.8 CONCLUSIONS .................................................................................................................88

REFERENCES ........................................................................................................................89

PAPER I ..................................................................................................................................99

PAPER II ................................................................................................................................107

PAPER III .............................................................................................................................117

PAPER IV ................................................................................................................................131

PAPER V ...............................................................................................................................139

PAPER VI ................................................................................................................................145

PAPER VII .............................................................................................................................159

PAPER VIII ............................................................................................................................165

PAPER IX ................................................................................................................................171
ABBREVIATIONS AND ACRONYMS

General

BAP .............. Battery-Assisted Passive
EIRP .............. Effective Isotropic Radiated Power
EPC .............. Electronic Product Code
ERP .............. Equivalent Radiated Power
GC-MS .......... Gas chromatography–mass spectrometry
Gen 2 .......... Class 1 Generation 2 UHF Air Interface Protocol Standard
HF ............... High Frequency
IC ............... Integrated Circuit
I-UWB .......... Impulse Ultra Wide Band
LF ............... Low Frequency
MD ............. Machine Direction
PCB ............. Printed Circuit Board
PVP ............ Polyvinylpyrrolidone
RFID .......... Radio Frequency Identification
RH ............ Relative Humidity
SAW ............ Surface Acoustic Wave
SPI ............. Serial Peripheral Interface
TTL .......... Transistor–transistor logic
UHF ............ Ultra High Frequency
WORM .......... Write Once and Read Many
VSWR .......... Voltage Standing-Wave Ratio
LIST OF PAPERS

This thesis is mainly based on the following papers, herein referred to by their Roman numerals:

**Paper I**  
*Printed touch sensor for interactive packaging and display*  
Tomas Unander, Hans-Erik Nilsson and Bengt Oelmann  

**Paper II**  
*Characterization of printed moisture sensors in packaging surveillance applications*  
Tomas Unander and Hans-Erik Nilsson  

**Paper III**  
*Design of RFID based sensor solution for packaging surveillance applications*  
Tomas Unander, Johan Sidén and Hans-Erik Nilsson  
Accepted for publication in IEEE Sensors Journal, DOI: 10.1109/JSEN.2011.2155055

**Paper IV**  
*Evaluation of RFID based sensor platform for packaging surveillance applications*  
Tomas Unander and Hans-Erik Nilsson  
Accepted for publication at RFID-TA2011, Barcelona, Spain, September 15-16, 2011

**Paper V**  
*Inkjet printed silver nanoparticle humidity sensor with memory effect on paper*  
Henrik A. Andersson, Anatoliy Manuilskiy, Tomas Unander, Cecilia Lidenmark, Sven Forsberg and Hans-Erik Nilsson  
Submitted for publication in IEEE Sensors Journal

**Paper VI**  
*Printed write once and read many memories in smart packaging applications*  
Hans-Erik Nilsson, Henrik A. Andersson, Anatoliy Manuilskiy, Tomas Unander, Krister Hammarling, Johan Sidén and Mikael Gulliksson  
Accepted for publication in IEEE Sensor Journal, DOI: 10.1109/JSEN.2010.2095496
Paper VII  **Characterization of moisture sensor based on printed Carbon-Zinc energy cell**
Hans-Erik Nilsson, Johan Sidén, Tomas Unander, Torbjörn Olsson, Peter Jonsson, Andrei Koptioug and Mikael Gulliksson
Proceedings of IEEE Polytronic 2005, Wroclaw, Poland, October 23-26, 2005

Paper VIII  **Remote moisture sensing utilizing ordinary RFID tags**
Johan Sidén, Xuezhi Zeng, Tomas Unander and Hans-Erik Nilsson

Paper IX  **System integration of electronic functions in smart packaging applications**
Hans-Erik Nilsson, Tomas Unander, Henrik A. Andersson, Anatoliy Manuilskiy, Johan Sidén and Mikael Gulliksson
In manuscript

Related articles, but not included in the thesis:

Paper 1  **Ink-jet printed thin-film transistors with carbon nanotube channels shaped in long stripes**
Jiantong Li, Tomas Unander, Ana López Cabezas, Botao Shao, Zhiying Liu, Yi Feng, Esteban Bernales Forsberg, Zhi-Bin Zhang, Indrek Jõgi, Xindong Gao, Mats Boman, Li-Rong Zheng, Mikael Östling, Hans-Erik Nilsson and Shi-Li Zhang
Journal of Applied Physics 109, 084915, 2011

Paper 2  **Electric and electromagnetic coupled sensor components for passive RFID**
Johan Sidén, Jinlan Gao, Tomas Unander, Henrik Andersson, Peter Jonsson and Hans-Erik Nilsson
In manuscript
1 INTRODUCTION

Sensor applications have become increasingly important as products are now being requested to be more and more intelligent and safe. As the costs involved in sensor technology decrease, its usage will spread to new market segments including new areas with products that have never previously used such functionalities, including wood fibre based products for packaging, hygiene or graphical use [1]. Currently, there is a significant interest in developing technologies that will allow packages to become interactive and be integrated with digital services accessible on the Internet [2-3]. The information harvested through the digital channel is useful for the further development of the product, building customer loyalty programs, and to further enhance the story around the product. The use of 2D graphical codes, such as the QR code or the Datamatrix code is being introduced into the market and this provides a communication channel for new services [4-6].

![Process to manufacture electronics in (a) roll to roll printing process, source: PolyIC [7] (b) traditional parallel wafer process, source: Infineon [8]](image)

Figure 1. Process to manufacture electronics in (a) roll to roll printing process, source: PolyIC [7] (b) traditional parallel wafer process, source: Infineon [8]

Another technology that could be used in order to connect packages to the digital service channels involves printed electronics. There are currently significant interests in the area of printed electronics, from partly printed to fully printed devices. These include, for example, printed displays on flexible substrates [9-14], printed thin film transistor circuits [7,15], printed memories [16], printed photovoltaic [17] and printed batteries [18-19] to name a few. When manufacturing low cost electronics on flexible substrates it is possible that this could lead to the
evolution of new market segments for electronic devices, which will most probably not be able to out-compete the traditional silicon based electronics but will rather work as a complement in very low cost applications such as smart packaging. Smart packaging solutions could be achieved by adding surveillance functions to the package in order to ensure that, for example, food quality is preserved [20]. Packaging logistics is another area where smart packaging solutions based on Radio Frequency Identification (RFID) technology with sensor functionality will provide transparency and traceability and, in this case it is the stakeholders along the entire supply chain who will be the major beneficiaries [21]. RFID is an identification technology that uses radio waves in the identification process instead of printed visible lines that are scanned by a reader as is the case with bar-codes. The RFID systems available at present can be divided into different categories. In Table 1 the typical frequencies used in RFID systems are presented.

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Frequency (LF)</td>
<td>&lt; 135 kHz</td>
</tr>
<tr>
<td>High Frequency (HF)</td>
<td>13.56 MHz</td>
</tr>
<tr>
<td>Ultra High Frequency (UHF)</td>
<td>860 – 960 MHz</td>
</tr>
<tr>
<td>Microwave</td>
<td>2.45 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EPC class</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class-1</td>
<td>Passive-backscatter tags with a few minimum features</td>
</tr>
<tr>
<td></td>
<td>• Electronic product code (EPC) identifier</td>
</tr>
<tr>
<td></td>
<td>• Tag identifier (Tag ID)</td>
</tr>
<tr>
<td>Class-2</td>
<td>Higher functionality tags with more features than those of Class-1</td>
</tr>
<tr>
<td></td>
<td>• Extended tag ID</td>
</tr>
<tr>
<td></td>
<td>• Extended user memory</td>
</tr>
<tr>
<td>Class-3</td>
<td>Battery-Assisted Passive (BAP) tags with more feature than those of Class-2</td>
</tr>
<tr>
<td></td>
<td>• A power source that may support power to the tag and/or its sensor</td>
</tr>
<tr>
<td></td>
<td>• Sensor with optional data logging</td>
</tr>
<tr>
<td>Class-4</td>
<td>Active tags that are able to work as both a tag and a reader</td>
</tr>
</tbody>
</table>
The different frequencies offer some advantages and disadvantages, for example, it is possible with UHF tags to have longer reading ranges and to have higher data rates than those for HF tags. However, on the other hand, the higher frequency in the UHF tag has proven to be a more challenging obstacle to overcome for printed electronics. Table 2 shows the different RFID classes defined by EPC Global, from the simple Class-1 passive tag to the very complex active Class-4 tags. Passive tags do not have any built-in batteries, they are, instead, using the transmitted power from the reader to power up the microcontroller and to transmit their identity and thus have an, in theory, unlimited lifetime.

Most of the items in the present day supply chain are tagged with bar-codes as the identification method. However, market forecasts [22] indicate that in 2022 more than 56 billion RFID tags will be sold annually to the retail and consumer goods business in Europe with a market share of at least 25% of the total identification volume in the supply chain. Thus, by using the EPCglobal UHF Class 1 Generation 2 (Gen 2) [23] and the ISO/IEC 18000-6C [24] air interface protocol, which are the current standards for RFID based item level tagging, it is possible for every item to have a unique identification number which will increase the traceability [25] of the items within the supply chain. Some other significant advantages associated with RFID systems as compared to bar-codes are that products marked with an RFID tag can be read without a line of sight and many tags can be read simultaneously. Thus an entire pallet with multiple packages can be read instantly. It also has the possibility to incorporate security features such as anti-theft and anti-counterfeiting and, in addition, different kinds of sensors. These sensors can be used to track the condition of the package or its content in the supply chain or to provide information with regards to whether or not the products are out of date. There are many advantages associated with RFID in comparison to those for the bar-codes but, a number of problems exists which needs to be overcome and one of these involves the cost. Whereas bar-codes are almost free of charge, electronic based RFID tags will incur a larger cost.

Market forecasts [22] indicate that if there is a breakthrough in the RFID tag technology with, for example, low cost (< 1 euro cent) printed chipless tags then the volume of RFID tags on food items can reach more than 500 billion annually by 2017. Today, there is research being carried out in relation to all-printed tags such as the work by Jung et al. [26], PolyIC [7] and Kovio [15]. These tags operate in the high frequency band of 13.56 MHz which means that they are unsuitable for item level tagging in the supply chain because it involves reading ranges which are in the order of centimetres. To increase the reading range, the operating frequency must be increased to the UHF frequency band of 860 – 960 MHz. However, the author has not yet seen any working all-printed RFID tags in this frequency band. Printed electronics is still in its infancy and there are many challenges both for
devices and system integration, but as stated by Subramanian et al. [27] “it is possible to realize printed systems that exploit the advantages of printing while working around the disadvantages of the same”. This means that it is meaningful to address the system integration of printed electronics in spite of the limitations of the present day technology.

At the present time both printing and roll to roll processing are the preferred manufacturing technologies used by the packaging industries. It is therefore a natural choice to envision printed electronics as the primary technology platform for adding electronic functions to packages. However, it is not obvious that printed electronics could provide the lowest possible total cost for the system integration. It is therefore worthwhile to analyse the specific constraints and demands set by the application in order to understand how the cost will be distributed for the entire function.

Subramanian et al. [27] provide an overview with respect to the different costs associated with printed electronics in comparison to those for the silicon technology. This can be summarized in the following bullet point list.

- The cost per function is higher for printed electronics than for silicon solutions.
- The capital expenditure is higher for printed methods compared to those for lithography for line widths above 1 μm.
- Printing has the very important advantage, in comparison to silicon manufacturing, of being additive.
- Printing allows for the efficient processing of the substrate material (roll to roll or sheet-feed) for large feature sizes.

The final conclusion is thus that silicon is more cost effective per function while printing is more cost efficient when large areas are involved in the integration [27]. This means that information regarding the application must to be known in order to decide which technology solution is optimal from a cost perspective. For example, tamper monitoring of a packaging unit is more advantageous for printed electronics as compared to temperature sensing in combination with RFID. In one case a large area is demanded while in the other a single point function provides the solution.

Another important aspect is the product volume. The additive process and possible use of direct print provides a strong advantage for printed electronics when there is a smaller product volume. Thus, printed electronics may provide a very cost effective production method for a smaller product series, where a high degree of customization is required. Although the temptation may be to compare printed electronics with standard printed circuit board (PCB) technology for electronics production this is, however, misleading, since printed electronics are
capable of providing complete integration on the product, for example, by adding electronic functions directly to the packaging material. As silicon technology demands large volumes in order to be cost efficient, standard integrated circuits (IC) are thus the backbone of modern electronics and will also be the primary means of incorporating complex functionalities and data processing capability into smart packaging applications. Thus, it becomes more important to develop hybridization methods and silicon device packages that are well suited for integration with printed electronics. It will then be possible to provide hybrid system integrations which are able to meet the complexity and high frequency demand associated with traditional silicon based technology and the large area to low cost issue associated with printing technology. It may also become possible to adapt new printed electronic devices and components, when they become more mature, into the hybridization solutions.

With the use of direct print by adding the electronic functions directly to the packaging material, it is very valuable to know the type of material that the electronic function will be added to. For packages, it is highly likable to be wood fibre based substrates since 40% of all packages used today are manufactured of wood fibres [28]. A wood fibre based substrate is very commonly used for graphical prints, in newspaper and packages, and is very suitable for the printing process. There are, however, some disadvantages associated with wood fibre based substrates that must be considered, namely the fact that it is a material that absorbs moisture and thus its conductivity may change [29-30] which could lead to problems when electronic circuits are printed directly onto the substrate. However, there has been research conducted by Rida et al. [31] and Siegel et al. [32] that shows working conductive tracks and antennas on wood fibre based substrates.

The potential problems associated with the physical property changes of wood fibre based substrates, when they are exposed to alternating moisture levels, can, on the other hand, be used as a moisture sensing feature for the printed electronic devices. Moisture sensing in wood fibre based packages is important since it is known that the strength of a wood fibre based package is considerably reduced when it is exposed to high relative humidity levels [33]. For example, Benson [34] shows that if the relative humidity is changed from 50% to 90% the strength of the wood fibre based paper is reduced to half its original value, which is shown in Figure 2. There could also be significant potentials for moisture sensors in many other areas including the monitoring of the condition of buildings. In this case, there is an increasing risk of microbial growth in building materials when the moisture content or relative humidity in wood based materials exceeds 20% or 80 – 85%, respectively [35].
In section 2 of this study, a system integration of a BAP RFID based sensor platform is presented. The proposed platform provides a trade-off between, communication performance, compatibility with international standards and flexibility in on-package customization by combining traditional silicon based electronic devices with printed large area components such as sensor, antenna and interfaces. Thus, the proposed architecture separates the high performance communication circuit and the low frequency sensor interface logic.

In section 3, some printed moisture sensor solutions are presented. They are intended for use in the monitoring of the moisture levels in, for example, the supply chain, as an indicator and not as a precision measuring solution. Therefore the associated cost is more important than the accuracy of the measurements. The reason for this is that if the costs can be very low, it would be possible to put these types of sensors on every package. By measuring the moisture from a pallet with multiple packages and by taking the average of all the sensors, it will be possible to greatly increase the attainable level of accuracy.

Another interesting area where printed electronic devices could prove to be a competitive technology is in printed low cost sensors for interactive paper displays, for instance, interactive point-of-sales displays. In this case, the large area sensor is required, which, as stated before, is where printed electronics provide the greatest benefits in comparison to traditional silicon based electronics. Interactive point-of-sales displays could be a good application since market research shows that 70% of all purchasing decisions are made in-store and the use of interactive
point-of-sales displays could increase the sales by up to 400% [36]. By integrating a printed low cost touch sensitive sensor into a high quality image on a point-of-sales display, together with a loud speaker, the ordinary point-of-sales displays will have interactive capabilities. In section 4 a more detailed description of a printed touch sensitive sensor solution is presented. The targeted applications for the sensor solution are large area touch sensitive commercial stands, flat keyboards at the point of purchase and touch and manipulation surveillance in logistic chains.

1.1 Problem formulation

The thesis is focused on two main areas. Firstly, there is the system integration of a hybrid BAP RFID platform with sensor functionalities that shows the potential of combing traditional silicon based electronic, which are more cost effective per function, with printed electronics, which are more cost effective when using large area integration. The second area involves printed sensors made out of conductive inks which respond to moisture in nearby media. In relation to the printed sensors, the focus is on moisture sensors that react to the moisture in wood fibre based substrates or in the ambient air and touch sensitive sensors in which it is the moisture in the hand that is detected. In this case, single layer conductive structures are preferred because each additional layer will increase the total cost of the sensor. It is preferable that the sensor substrates are low cost printable materials. The readout electronics associated with the sensors are to be a simple, low cost and low power solution that could be integrated into the RFID sensor platform. The main discussion of the thesis involves the following four problem formulations.

- System integration of hybrid BAP RFID platform on wood fibre based packaging materials.
- Low cost moisture sensors to be integrated into smart packages.
- Characterization of a remote moisture sensing concept.
- Integration of printed low cost touch sensitive sensor into point-of-sales displays.

These problems are discussed because it is possible, in these cases, to combine the advantages associated with both traditional silicon based electronics and printed electronics, since both large areas and high complexity are required.

The system integration of the hybrid BAP RFID sensor platform is discussed because, with the hybridization technology, it is possible to meet the complexity and high frequency demands with silicon based electronics and to solve the large area to low cost issues with printing technologies. The hybridization technology
also has the possibility of being able to adapt new printed electronic devices and components when they become more mature.

The integration of moisture sensor for use in smart packages is discussed, as by logging the moisture in the transportation of packages, detailed information concerning the variations in the transports can be achieved. These variations can, for example, be caused by season variations. Knowledge concerning how these variations affect a package means that it is possible to optimize them with regards to material consumption. In seasons where there are only small variations, a lighter package with less material can be used.

The remote sensing concept is discussed because it shows the possibility to, with ordinary RFID tags, measure the moisture in moisture absorbing materials. The concept could be used in moisture detection in building materials but also with regards to moisture detection in smart packaging.

The touch sensitive sensor for interactive point-of-sales displays is discussed because it is a simple means of turning an ordinary display into an interactive display, which, according to market research, will cause an increase in sales [36]. In this case it is the moisture in the human hand which interacts with the sensor.

1.2 Main contributions

The main scientific contributions of this thesis are:

- System integration of RFID based sensor platform directly on wood fibre based substrates that combine the advantages of traditional silicon based electronics and printed electronics.
- Low power management for increasing battery lifetime of the RFID based sensor platform.
- Utilizing low cost manufacturing processes and materials to create sensing features for wood fibre based packages and displays.
- Characterization of low cost moisture sensors that together with simple electronic devices enables smart packages.
- Characterization of low cost screen printed moisture activated energy cells.
- Concepts regarding how to set-up low cost moisture sensors utilizing commercial available RFID tags.

1.3 Thesis outline

The main focus of this thesis is on the design and system integration of a hybrid RFID sensor platform and the fabrication and characterization of low cost sensors, which together can be used in smart packaging applications. The RFID platform shows that it is possible to combine traditional silicon based electronics, which is more cost effective per function, with printed electronics, which is more cost
effective when using large area integration, in order to achieve the benefits associated with these two technologies.

The sensors can be divided into two groups, namely, moisture sensors and touch sensitive sensors. The goal here has been to integrate silicon based electronics and printed electronics with wood fibre based substrates so as to enable sensing features on smart packages. Wood fibre based paper is used as the sensor substrate as far as possible, basically because of the associated costs. However, if a sensor requires other types of substrates because of manufacturing properties or sensor features, a more suitable substrate is used. In section 2 the system integration of the BAP RFID sensor platform is presented. In section 3 the low cost moisture sensors are presented. The touch sensitive sensors and their system integration are presented in section 4. Section 5 summarizes the work covered by all the papers included in the thesis. Section 6 summarizes and concludes the contributions of the thesis. The papers presenting the original contributions to this thesis can be found in the appendix.
2 RFID BASED SENSOR SYSTEM

In this section the system integration of a hybrid sensor system is presented. The proposed RFID platform provides a trade-off between, communication performance, compatibility with international standards and flexibility in on-package customization including type and number of sensors. The proposed design separates the high performance communication circuit and the low frequency sensor interface logic. The design enables the possibility that, in the future, the sensor interface could be integrated using printed logics to further enhance the flexibility and to allow low cost customization features. In the design, all the pieces in the system integration, except for the silicon based components, are designed to meet the printing requirements. For example, in this case, two dimensional antenna structures are used instead of the more complex three dimensional structures with more layers and vias connecting the different layers because such a complex structure will make the printing process more complicated.

2.1 System integration of the RFID based sensor system

The sensor platform is designed in such way that the RFID communication interface, which is compatible with the EPC Gen 2 standard [23], and the sensor interface are handled by conventional silicon based electronics in order to meet the complexity and high frequency demands set by the Gen 2 standard. For such system integration, there are basically three different RFID systems concepts available.

![Figure 3. Example of a one-chip passive RFID tag with sensor capability](image)

The first concept, called one-chip passive RFID sensor solution, is based on a passive RFID tag system where the RFID chip has been designed to have sensor inputs as seen in Figure 3. This solution does not have any built-in power supply so the sensor can only be read instantaneously, in other words the sensor cannot store any data when outside the range of the RFID reader. However the associated
cost for this sensor solution will be relatively low because no built-in power supply is required.

The second concept, called a two-chip battery assisted passive (BAP) RFID sensor solution, is based on an RFID tag where the system has two chips, one RFID chip and one sensor chip as seen in Figure 4. Here the sensor chip is powered by some sort of built-in power supply. There are many examples with regards to how such a set-up could work and one idea is to use some kind of slow modulation of the backscattering power, for example a pulse-width modulation of the backscattered power back to the reader, where the pulse width is dependent on the sensor output. Another idea is to use the user programmable memory in the RFID chip in order to store the sensor data. This set-up means that it is possible to store sensor data even when the system is not powered by an RFID reader.

![Figure 4. Example of a two-chip BAP RFID tag with sensor capability](image)

The third concept, called the one-chip BAP RFID sensor solution, is based on a BAP RFID tag but, as opposed to the two-chip solution presented above, the RFID chip is designed is such way that the sensor is connected directly to the RFID chip as seen in Figure 5. Apart from that it works in a similar manner to that for the two-chip solution.

There are some advantages and disadvantages associated with these three RFID sensor concepts. The BAP solutions have the advantage that they can collect and store sensor data during, for example, a transport even when no RFID reader is
present. In a one-chip solution the RFID chip and the sensor chip are integrated into the same chip and therefore the size and cost of the chip can be relatively low. The advantage associated with the two-chip solution is that both the RFID chip and the sensor chip can be standardized regardless of the type of sensor that it is connected to. Thus, every application can have the same RFID chip and sensor chip and only the firmware in the sensor chip is required to be specially designed for the application. It is also possible to replace the RFID chip to work in another frequency band, for example change from UHF to HF, and still use the same sensor chip.

The sensor system in this study is intended for measuring and logging of the sensor data in the supply chain, in order to have both knowledge regarding the condition of the package or its content and to be able to track the point within the supply chain at which a particular incident has occurred. This is the reason why a BAP sensor platform with a built-in power source has been chosen. It should be relatively simple to tailor the sensor platform to work with different types of sensor and thus the choice to use the two-chip sensor solution. This means that in the proposed sensor platform the RF communication part and the sensor interface part are divided into two separate components, in which the Gen 2 RF communication is handled by a commercially available RFID chip and the interface to the sensor is handled by a microcontroller (sensor chip). This two-chip set-up enables the sensor tag to be more easily tailored to work with any type of sensors, regardless of whether the sensor is interfaced through a serial peripheral interface (SPI) or a non-standard interface.

Today, the silicon based components and the battery part of the two-chip solution will be the most costly because of the specially designed small scale and prototype production of the RFID chip and the small scale production of the printed batteries. However, as the production of the RFID chip and the batteries scale up in volume and become standard component, the cost of these components could be greatly reduced, and thus the total cost of the sensor system will be reduced.

2.1.1 RFID chip

In the proposed sensor platform the EM4325 [37-38] RFID chip from EM Microelectronic [39] has been chosen. The chip is currently under development and it is both read and writeable and has 3072 bits of user programmable memory, which are divided into 48 pages of 64 bits each. The chip also has a manufacturer programmed serial number in accordance with the Gen 2 standard. The EM4325 chip was chosen because it can be programmed with a DC voltage which means that data can be written directly from a microcontroller via SPI. To the author knowledge only a few Gen 2 compatible RFID chips exists that have SPI capability
and these include the EM4325, the SL900A [40] from IDS Microchip and WM72016 [41] from Ramtron Corporate, thus making them unique chips. The EM4325 and the SL900A also have the feature of a built-in temperature sensor.

2.1.2 Microcontroller (sensor chip)

The microcontroller in the proposed sensor platform is the interface between the sensor and the RFID chip. The microcontroller interacts with the sensor, makes calculations on the sensor data, if required, and stores the data in the memory of the RFID chip. The sensor platform is designed in such way that it should be able to collect sensor data at all times, which means that the microcontroller will be powered by an external power source built into the sensor platform. In order for there to be a long battery lifetime for the system the microcontroller must to have as low power consumption as possible.

The PIC18LF13K22 [42] microcontroller from Microchip Technology [43] was chosen as the microcontroller in the proposed sensor platform. This particular microcontroller was chosen because it has a voltage range from 1.8 to 3.6 V and has a programmable internal oscillator which can be altered from 31 kHz up to 16 MHz during operations. It also has a relatively low power consumption, which means that all the criteria set by the platform are satisfied.

2.1.3 Antenna design

In relation to the designing of RFID antennas, one of the most important aspects is to design the antenna to conjugate match the RFID chip in order to maximize the power transfer to the chip and thus maximize the read range. When calculating the antenna and the chip efficiency, the voltage standing-wave ratio (VSWR) [44] can be used. The VSWR is a measure of how much of the incident power is delivered into the load, in this case the RFID chip, and how much is reflected back. The VSWR is calculated from the antennas and the chip input impedances in accordance with (1) and (2).

\[ VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (1) \]

\[ \Gamma = \frac{Z_{\text{Antenna}} - Z_{\text{Chip}}^*}{Z_{\text{Antenna}} + Z_{\text{Chip}}} \quad (2) \]
where $\Gamma$ is the reflection coefficient, $Z_{\text{Antenna}}$ is the impedance of the antenna, $Z_{\text{Chip}}$ is the impedance of the chip and $Z^*_{\text{Chip}}$ is the complex conjugate of the chip impedance.

When the impedance of the antenna and the chip are complex conjugates, such as $Z_{\text{Antenna}} = Z^*_{\text{Chip}}$, then the reflection coefficient in (2) is zero and this gives a VSWR equal to one, which means that all the power is delivered to the chip. Another challenge involves in designing antennas for RFID is that the bandwidth of the antenna should be sufficiently large for global compatibility with the Gen 2 standard [23] which is 860 – 960 MHz.

Antennas for printed or partly printed tags should preferably consist of only one layer in order to avoid the complexity of vias through the substrate or between the layers. Another aspect to be considered when designing antennas for printing is that the line width and the print thickness must allow for a certain sheet resistance in order to provide good antenna efficiency [45]. Another challenging aspect of RFID antenna design is that the object that the RFID tag will be attached to is seldom known at the time of the antenna design. In the supply chain it is likely that this will be wood fibre based materials but the content is still most probably unknown. Bearing this uncertainty in mind, the antenna bandwidth should be sufficiently large to withstand some interference from the substrate it is placed on. A drawing of the antenna and its dimensions is shown in Figure 6. This particular antenna design is optimized for a rigid FR-4 substrate, which is a glass reinforced epoxy laminate sheet, which is commonly used in printed circuit boards (PCB). However, reading range measurements show that the antenna layout also works when it is printed on coated paper substrates.

![Figure 6. Layout of antenna design for the RFID based sensor platform](image)

The antenna design has its origins based on an ordinary dipole, but the dipole structure has been equipped with an inductive load whose purpose is to lower the real part of the dipole antenna’s input impedance while simultaneously increasing
its imaginary part. The combination of a relatively low real part and a relatively high imaginary part is otherwise difficult to achieve with an ordinary dipole [46]. Ordinary thin dipoles often have bandwidths of only a few percent and are therefore easily detuned when placed next to materials that they are not designed for. The impedance matching inductive loop introduced to the antenna in Figure 6 partly overcomes this by also increasing the bandwidth by about 20%. To further increase the bandwidth, capacitive loads are placed at the ends of the antenna elements [47].

In Figure 7 the simulated VSWR of the antenna structure and the RFID chip impedance are shown. The antenna is optimized for a frequency of 868 MHz which is the standard frequency for UHF RFID in the EU. Marker 3 in Figure 7 shows that the VSWR is almost one at 870 MHz which shows that, according to the simulations, the antenna and the RFID chip are almost matched. A custom estimation of the antenna functionality is to measure the bandwidth where the VSWR is less than 1.5, which corresponds to an input return loss below -14 dB. This in turn corresponds to the fact that a minimum of 96% of the incident power is transferred to the chip. Marker 1 and 2 in Figure 7 mark the frequencies where the VSWR is 1.5 and it is possible to see that the bandwidth of the RFID system is about 770 MHz to 1045 MHz, which corresponds to almost 32% bandwidth around the central frequency.

Figure 7. Simulated VSWR as a function of the operating frequency for the designed antenna structure. Marker 3 marks the frequency 870 MHz. Marker 1 and 2 shows the bandwidth for VSWR < 1.5
2.1.4 Power source

The proposed sensor platform is designed in such way that it should be able to collect sensor data even when the tag is not powered by a reader, which means that the sensor platform must to have some sort of internal power source. Many different types of RFID based sensor solutions exists, for example, passively powered as presented by Cho et al. [48-49] and Sample et al. [50]. However, these sensor platforms are passively powered which means that they can only collect sensor data when being powered by a reader, which means that they have to be in the vicinity of a reader. There is also some research in the area of hybrid solutions, such as the work by Yeager et al. [51], where a tag is wirelessly charged by the reader to provide sufficient power to be able to collect sensor data when the tag is outside the reading range of the reader. The hybrid technology is a promising technology for the future, however, at the present time, it appears that the operational time is too short and the charging time is too long. In the proposed sensor platform presented in this thesis, the sensor is powered by batteries in order to achieve a long energy lifetime. The batteries, which only power the microcontroller and the sensor, must provide a voltage of between 1.8 and 3.6 V in order to power up the microcontroller and to be able to store the sensor data in the memory of the RFID chip. The sensor platform is designed to be used with small button cell batteries [52] and flexible or printed batteries, such as, ST3-102 from Blue Spark [18] or the Reg 3.0V SoftBattery from Enfucell [19].

Table 3. Description of batteries [18-19, 52]

<table>
<thead>
<tr>
<th>Battery</th>
<th>Voltage (V)</th>
<th>Capacity (mAh)</th>
<th>Peak current (mA)</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg 3.0V</td>
<td>3</td>
<td>10</td>
<td>6*</td>
<td>Zn / MnO₂</td>
</tr>
<tr>
<td>CR1216</td>
<td>3</td>
<td>30</td>
<td>1</td>
<td>Li / MnO₂</td>
</tr>
<tr>
<td>ST3-102</td>
<td>3</td>
<td>33</td>
<td>2</td>
<td>Zn / MnO₂</td>
</tr>
<tr>
<td>CR1620</td>
<td>3</td>
<td>68</td>
<td>1</td>
<td>Li / MnO₂</td>
</tr>
<tr>
<td>CR2032</td>
<td>3</td>
<td>235</td>
<td>3</td>
<td>Li / MnO₂</td>
</tr>
</tbody>
</table>

* For maximum 50 ms

Table 3 shows a description of some example of batteries that could be used with the sensor platform. The possibility is, of course, to print the batteries directly onto the sensor platform together with the antenna and the interfaces between the different components or directly onto the packaging material together with the sensor. However, in this study the focus is on system integration, and therefore a commercially available battery solution is used.
2.2 Performance of the RFID based sensor system

In this section the system performance of a laboratory set-up of the RFID based sensor system is evaluated and characterized. The laboratory set-up of the sensor system is manufactured on a rigid FR4 substrate in which the antenna and the interfaces between the components are etched copper. The reason for this is in order for there to be easier mounting of the components and testing of the system.

2.2.1 Data storage in the RFID based sensor platform

The EM4325 RFID chip chosen for the sensor platform has 3072 bits of user programmable memory. These 3072 bits are divided into 48 pages of 64 bits each. This is a rather limited amount of available data storage for a logging device. This section is focused on how to achieve as high data storage in the RFID system as is possible with a sufficient resolution of the measured data. In this case, a storage solution is used, in which only a small amount of the total sensor data is stored in the sensor platform while the remainder is stored in the RFID reader infrastructure. This is achieved by dividing the memory into two parts, one containing an identification number, which basically is a counter that increments each time the memory in the RFID chip is full, and the other part contains the sensor data.

\[
N = \frac{3072 - m}{n}
\]  
\( (3) \)

Figure 8 shows the memory map of the system where \( N \) is the number of samples that can be stored in the RFID chip, in accordance with equation (3), and \( M \) is the total number of increments of the identification number, in accordance with equation (4).
\[ M = 2^n \]  

where \( n \) and \( m \) are the number of bits dedicated to the sensor data and the identification number, respectively.

If, for example, the identification number is 4 bits long (\( m = 4 \)) and the sensor data values are 4 bits long (\( n = 4 \)) then \( M \) equals 16 in accordance with (4) and \( N \) equals 767 in accordance with (3), which means that the whole system can store a total of 12272 sensor values.

When the sensor data is read from the RFID chip, the data is fitted into the correct position in the RFID readers database with the assistance of the factory programmed RFID id number, in accordance with the Gen 2 standard, and the by the sensor system programmed id number (the counter described earlier). The Gen 2 id of the RFID chip is used in order to determine from which RFID chip the data has been collected and the counter is used as a time reference.

When a new sensor value is sampled from the sensor, the new value is programmed into the memory of the RFID chip followed by a zero sensor value. The zero sensor value represents invalid data and is an indicator that the sensor values after the invalid sensor data are old sensor values and should be inserted before the newer sensor values when added to the reader database. This is illustrated in Figure 9, where the example shows the sensor data in the reader database system before and after two reads (at time \( t = 1 \) and \( t = 2 \)).

![Figure 9. Example of how the data from the RFID tag is fitted into the reader database. The old sensor data (data number 9) at read time \( t = 2 \) is stored before the id number (counter) 1. ID: X is the Gen 2 id of the RFID chip.](image-url)
With this method the RFID system can store a great deal more data than the RFID sensor platform itself. One drawback is that data can be lost if the time between two consecutive reads of the RFID tag is too long. However, the time reference (counter) can determine the time interval for which the sensor data is missing.

Table 4 shows the amount of data the RFID system can store for different sensor data and identification (counter) bit sizes. The table only shows a selection of possible combinations.

The number of bits required to represent the sensor data is highly dependent on the characteristics of the sensor and how accurate the measurement should be. In some applications, such as, surveillance of cold food it may only be important to know whether the temperature has been above +5°C [53] or not, and in this case one bit should be sufficient. However, if the application is to monitor a temperature span from -18°C to 46°C with a resolution of 0.25°C then at least 8 bits are required.

Table 4. Data storage in the sensor based RFID system for different data and id settings

<table>
<thead>
<tr>
<th>Data bits (n)</th>
<th>Id bits (m)</th>
<th>Number of samples in RFID chip memory (N)</th>
<th>Total number of samples (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>1 534</td>
<td>24 544</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>1 532</td>
<td>392 192</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>1 530</td>
<td>6 266 880</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>1 528</td>
<td>100 139 008</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>767</td>
<td>12 272</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>766</td>
<td>196 096</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>765</td>
<td>3 133 440</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>764</td>
<td>50 069 504</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>383</td>
<td>98 048</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>382</td>
<td>25 034 752</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>191</td>
<td>12 517 376</td>
</tr>
</tbody>
</table>

2.2.2 Reading range of the RFID based sensor platform

One important parameter when discussing the performance of RFID system is the reading range because, firstly the tag will be readable at longer distances and secondly because it is more robust against objects that are partially blocking the radio wave. The reading range in this section is measured as being the maximum distance where it is possible to read a tag in an approximated open space with as
little interference as possible. The set-up for the open space read range measurement is illustrated in Figure 10, where the reader to tag distance $r$ can be varied from approximately 0 to 9 meters with as little interference as possible.

![Figure 10. Setup for measuring maximum read range in open space](image)

Table 5. Maximum reading range measurements in open space

<table>
<thead>
<tr>
<th>RFID tag system</th>
<th>Reading range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFID based sensor platform on rigid FR-4 substrate</td>
<td>3.4</td>
</tr>
<tr>
<td>Reference Gen 2 RFID tag from UPM Raflatac</td>
<td>2.7</td>
</tr>
<tr>
<td>RFID platform with antenna printed on flexible wood</td>
<td>2.7</td>
</tr>
<tr>
<td>fiber based substrate</td>
<td></td>
</tr>
</tbody>
</table>

The measurements for the maximum read range were conducted using the EMDB412 evaluation kit [54] which is based on the UHF RFID reader module SkyModule M9 [55] from SkyeTek [56] and with an external UHF broadband antenna [57]. The reader module has an adjustable output power of between 10 and 27 dBm in steps of 0.1 dBm. The maximum read range measurements were conducted with an output power of 27 dBm. This, together with the external antenna, which has a gain of about 6.25 dBi (at 868 MHz), provides an estimated output power of 2.11 W EIRP (effective isotropic radiated power) which is below the allowed output power level in the EU of 2 W ERP (equivalent radiated power), which corresponds to 3.28 W EIRP. This could be compared to the corresponding output power regulation in the US which is 4 W EIRP. In the measurements, the tag was attached to a corrugated board with an approximate size of 20 cm x 30 cm. In Table 5 the result from the reading range measurement is shown. In this case, the sensor platform on the rigid FR-4 board is compared to a reference tag.
consisting of a Gen 2 tag from UPM Raflatac. In Table 5 the reading range is also compared to a printed antenna. For the printed antenna the maximum reading range was decreased to 2.7 m because the antenna layout was optimized for a rigid FR-4 substrate and also because of a higher sheet resistivity in the antenna structure which leads to ohmic losses. The sheet resistivity of the printed antenna was estimated to be approximately 120 mΩ/□.

2.3 Applications for the RFID based sensor system

In this section the RFID based sensor platform is evaluated for three smart packaging concepts for packaging surveillance applications.

2.3.1 Moisture content sensor solution

In this section the RFID based sensor platform is evaluated using a moisture content sensor. The moisture content sensor solution is described in greater detail in section 3.1. For this study three samples were produced by screen printing [58] the two-dimensional sensor structure (an example which can be seen in Figure 18) with conductive silver ink (26-8204) from Coates Screen [59] on a 100 μm thick plastic film from MACtac [60]. These plastic films were then laminated onto wood fibre based substrates. The substrate was a C-flute corrugated board made out of testliner [61] where the liner and the fluting had a base weight of 140 g/m² and a total thickness of 4 mm. The two-dimensional conductive structure had an electrode width of 4 mm and an electrode spacing of 1.2 mm and had a total size of 40x53 mm in a rectangular shape. The sensors were preconditioned at 20% relative humidity and then exposed and logged at the following relative humidity levels: 30%, 50%, 70%, 85% and back to 70% at a constant temperature of 23°C. All the measurements were made at equilibrium condition, which means that the samples were exposed to the corresponding relative humidity level for 24 hours. The moisture content in the wood fibre based substrates was measured using a HB45 halogen moisture analyser from Mettler Toledo [62]. The moisture content sensor is a capacitive sensor which is read by charging the sensor to a fixed potential and then measuring the discharge time. The readout solution is described in greater detail in section 3.1.

In the evaluation of the moisture content sensor application, eight bits are used for the sensor data values and for the identification number. This determined that the RFID chip can store 383 data values while the whole system can store a total of 98048 sensor values as seen in Table 4. The moisture content changes in wood fibre based materials is a rather slow process so a fast sampling rate is not necessary. A sampling time of between 10 and 30 minutes between each sample is sufficient. Figure 11 shows how long it takes to fill the RFID chip and the whole system, respectively, for different sampling rates. As can be seen in Figure 11 if the system
has a sampling rate of 0.556e-3 Hz, which corresponds to 30 minutes between samples, the RFID chip can store sensor values for almost 8 days before the memory is full, and the whole system can store data for 5.5 years.

The battery lifetime for the moisture content application greatly depends on the sampling rate and the energy capacity of the battery. In Table 6 the current consumption of the evaluated moisture content sensor system is presented. Here, the different modes are shown together with the length of time that the system is in the particular mode.

![Graph](image)

Figure 11. The total amount of time to fill the RFID chip memory and the entire RFID sensor system respectively as a function of the sampling rate for the moisture content sensor application

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current (μA)</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep</td>
<td>0.7</td>
<td>*</td>
</tr>
<tr>
<td>Sensor charge</td>
<td>500</td>
<td>1</td>
</tr>
<tr>
<td>Sensor discharge</td>
<td>1840</td>
<td>0.2</td>
</tr>
<tr>
<td>Data handling</td>
<td>500</td>
<td>5.4</td>
</tr>
<tr>
<td>SPI write sensor data</td>
<td>500</td>
<td>2**</td>
</tr>
<tr>
<td>SPI wait</td>
<td>7.8</td>
<td>20**</td>
</tr>
</tbody>
</table>

* Depends on the sampling rate

** Data storing (SPI write and SPI wait) is only active when 16 bit (word) of sensor data is available. For a setup with 8 sensor bits, 2 sensor values (16 bits) are needed before the data is stored in the RFID chip
Figure 12. The estimated battery lifetime of the moisture content sensor setup as a function of the sampling rate for different battery energy capacities with a self-discharge of 10% per year.

Figure 13. Normalized discharge time as a function of the moisture content in the substrates for three moisture content sensors.

In Figure 12 the estimated battery lifetime of the moisture content sensor is shown for two different battery energy capacities, a self-discharge of 10% per year for the battery has been included in the calculation. As can be seen in Figure 12 for
a battery with an energy capacity of 33 mAh, the sensor platform should have an estimated battery lifetime of 3.4 years with a sample rate below 0.1 Hz.

In Figure 13 the normalized discharge time is plotted as a function of the moisture content. The discharge time is normalized against the response when no sensor is connected to the microcontroller. As can be seen, the sensors in the particular set-up are unable to distinguish between moisture content levels below six percent. However, this sensor is designed to be used at higher moisture content levels, which correspond to 50% relative humidity and above.

Table 7. Temperature measurements on the moisture content sensor at 70% relative humidity (mean of 3 sensors)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Moisture content (%)</th>
<th>Discharge time (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>11.01</td>
<td>27.0</td>
</tr>
<tr>
<td>23</td>
<td>10.74</td>
<td>26.0</td>
</tr>
<tr>
<td>30</td>
<td>10.50</td>
<td>25.5</td>
</tr>
</tbody>
</table>

In Table 7 the temperature dependency of the sensor and the moisture content of the substrate are shown for a constant relative humidity of 70%. As can be seen in the measurements, the moisture content is decreasing with a higher temperature, which corresponds to earlier observations [34]. However, when the temperature increases the amount of water in the air increases for a constant relative humidity level, for example, when the temperature reduces from 18°C to 30°C the vapour density almost doubles [63]. The decrease for the moisture content is because it is the chemical potential that determines the quantity of moisture or water vapour. As the temperature of a two phase system is increased, the concentration in the vapour phase increases at the expense of that in the condensed/adsorbed phase but the chemical potentials remain the same between the two phases at equilibrium [64]. Large variations in temperature could lead to false moisture content measurements. However, the sensor set-up has a built-in temperature sensor which, together with the moisture content sensor, could give both a more accurate moisture response and also the possibility to estimate the relative humidity.

As can be seen in the results in Figure 13 it is possible to reduce the number of sensor levels to, for example, seven (instead of 256) and still obtain a rather good estimation of the moisture content level. This should decrease the number of sensor data bits \( (n) \) to 3 which should increase the number of sensor bits that could be stored in the RFID chip to 1021, if nine id bits \( (m) \) are used, and thus greatly increase the memory lifetime of the sensor system.
Figure 14. Picture of a laboratory setup of the RFID based sensor platform with printed antenna and sensor. The components and the battery are mounted directly on the paper substrate with anisotropic conductive tape.

Figure 14 shows a picture of a laboratory setup of the RFID based sensor platform. In this case, the antenna, the sensor and the interfaces are inkjet printed using silver based ink. The RFID chip, the sensor chip and a printed battery are mounted on the paper substrate with the assistance of anisotropic tape. One Reg 3.0V printed battery from Enfucell [19] is used in the set-up.

2.3.2 Tilt sensor solution

Tilt and shock sensors could be used on packages with contents which are sensitive to impact or must be stored in a certain direction (this side up). In this case, the shock and tilt is registered by an accelerometer that is connected to the sensor platform. The accelerometer is a three axis accelerometer that provides information about the acceleration in three axes (x, y and z). If the accelerometer is static it will only be influenced by gravity. From the response of the accelerometer, vibrations and tilt in all three axes can be calculated. This means that it could be used to detect both shock and tilt. However, in order to detect shock and tilt, different types of accelerometers, with different working regions, are necessary to establish a high accuracy or not to saturate at too low g levels. For a tilt sensor a low g measuring range is preferable to obtain accurate tilt estimations, whereas a range between ±1.5 to ±2 g is preferable for the sensor platform. For a shock sensor, the g measuring range should be higher so as not to trigger it at very low impacts.
The commercially available shock indicators, for example from ShockWatch, are designed to have a triggering level from 10 g to 100 g [65]. Thus, for the shock sensor application that should work in the same region as the indicators, the accelerometer should have a measuring range of at least 100 g.

In this case, a low g accelerometer from Freescale is used for the tilt sensor application. The MMA7260Q [66] is a three axis accelerometer with three analogue outputs (x, y and z). The accelerometer has a selectable measuring range with the following ranges, ±1.5, ±2, ±4 and ±6g. In this set-up the analogue outputs is connected to three ADC channels on the microcontroller in order to measure the acceleration in all three axes.

For commercially available tilt indicators, a few different types exists, for example, TiltWatch XTR [67] that indicates if the tilt has been more than 80° or the TiltWatch Plus [67] that indicates angles with an increment of 10° from a 30° tilt and above. The tilt sensor described is intended to be used in, for example, tilt detection in packages. For a performance test of the tilt sensor set-up a tilt detector is proposed that detects tilt angles from 0° to 360° in increments of 45°. For this specific application set-up, four bits are used to represent the tilt angle and eight bits are used for the identification number. Thus, the RFID chip can store a total of 766 sensor values while the entire sensor system can store a total of 196096 sensor values as seen in Table 4.

![Figure 15. The total amount of time to fill the RFID chip memory and the entire RFID sensor system respectively as a function of the sampling rate for the tilt sensor application](image)
To in order to obtain an idea in relation to the number of hours the sensor system can be work until the RFID chip is full and the sensor system has an overflow, the operating time in hours as a function of the sampling rate in Hertz is shown in Figure 15. For example, if the system has a sample rate of 1 Hz it will take around 12.8 minutes before the memory is full and 2.27 days before the entire system has an overflow. However, if the tag is known to be read at least once a day then the sampling rate must be below 0.0089 Hz which corresponds to a time between samples of around 2 minutes and above in order to be able to store sensor data in the RFID chip for at least 24 hours until it is full.

Table 8. Power consumption for the tilt sensor application

<table>
<thead>
<tr>
<th>Mode</th>
<th>Current (μA)</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep</td>
<td>0.7</td>
<td>*</td>
</tr>
<tr>
<td>Sample sensor</td>
<td>1170</td>
<td>12</td>
</tr>
<tr>
<td>Data handling</td>
<td>630</td>
<td>40</td>
</tr>
<tr>
<td>SPI write sensor data</td>
<td>500</td>
<td>2**</td>
</tr>
<tr>
<td>SPI wait</td>
<td>7.8</td>
<td>20**</td>
</tr>
</tbody>
</table>

* Depends on the sampling rate
** Data storing (SPI write and SPI wait) is only active when 16 bit (word) of sensor data is available. For a setup with 4 sensor bits, 4 sensor values (16 bits) are needed before the data is stored in the RFID chip

Figure 16. The estimated battery lifetime of the tilt sensor setup as a function of the sampling rate for different battery energy capacities with a self-discharge of 10% per year
The battery lifetime for the tilt application is highly dependent on the sampling rate and the energy capacity of the battery. In Table 8 the current consumption of the evaluated tilt sensor system is presented. Here, the different modes are shown together with the length of time that the system is in the particular mode.

In Figure 16 the estimated battery lifetime of the tilt sensor is shown for two different battery energy capacities, a self-discharge of 10% per year for the battery has been included in the calculation. As can be seen in Figure 16, for a battery with an energy capacity of 33 mAh, the sensor platform should have an estimated battery lifetime of 2.6 years with a sample rate of 0.0089 Hz. If, on the other hand, the sample rate should be 1 Hz then the battery lifetime should be around 30 days for the battery with 33 mAh of energy capacity.

In Table 9 the results from the tilt evaluation measurements are shown and the measurements are made within the ±1.5g measurement range. As can be seen, the measurement show a good relationship between the tilt angle and the calculated angle from the response of the accelerometer. The measurements were made in a static set-up only and do not take any impacts on the accelerometer from other sources other than from the gravitation into consideration. Measurements show that the set-up has a tilt resolution of around 2°.

### Table 9. Accelerometer tilt measurement study

<table>
<thead>
<tr>
<th>Tilt angle (°)</th>
<th>Accelerometer angle (°)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>45</td>
<td>46</td>
<td>2.22</td>
</tr>
<tr>
<td>90</td>
<td>91</td>
<td>1.11</td>
</tr>
<tr>
<td>135</td>
<td>134</td>
<td>0.74</td>
</tr>
<tr>
<td>180</td>
<td>174</td>
<td>3.33</td>
</tr>
<tr>
<td>225</td>
<td>224</td>
<td>0.44</td>
</tr>
<tr>
<td>270</td>
<td>269</td>
<td>0.37</td>
</tr>
<tr>
<td>315</td>
<td>313</td>
<td>0.63</td>
</tr>
</tbody>
</table>

#### 2.3.3 Tamper detection solution

Another important application for packaging surveillance is tamper evidence, for example, to be sure that a package has not been opened during transportation. Some security aids do exists, such as, security tape that delaminates when being removed and leaves a text on the package stating that the package has been opened [68]. In this case, the idea is that a photovoltaic cell is connected to the sensor platform and the photovoltaic supplies power to the platform when it is exposed to light. The concept works in such way that when the package is opened the microcontroller, which is powered by the photovoltaic, will register the event in
the RFID chip. From the registered events it is possible to determine how many times and for how long time the package has been opened.

In the evaluated set-up the XOB17-04x3 XOLAR SolarBITs [69] from IXYS Corporation [70], which provide a maximum of 1.53 V, have been used. In the measurements two photovoltaic cells are required in order to provide above 1.8 V to the platform which is necessary to power up the microcontroller and to store the event in the RFID chip. The photovoltaic cells have an estimated active area of 1.08 cm² each.

In Figure 17 the result from the measurements on the photovoltaic cells are shown for different loads. In the measurements, fluorescent lamps are used, which are commonly used in warehouses. The measurements show that the incident light from the fluorescent lamps must have intensity above 500 lux to provide sufficient voltage to power up the microcontroller and sufficient energy to be able to perform a write instruction to the RFID chip at the lowest microcontroller oscillator frequency. This is based on a voltage of 1.86 V and a 50 kΩ resistor which corresponds to a current consumption of 37 μA. The intensity necessary to power up the platform could of course be reduced by increasing the active area of the photovoltaic cells.

![Figure 17. Output voltage from the photovoltaic cells as a function of incident light intensity for different loads. Solid line no external resistor, dash-dotted line R = 1130kΩ, dash-dash line R = 560kΩ, dotted line R = 100kΩ, (□) R = 50kΩ and (◊) R = 10kΩ.](image-url)
Table 10. Photovoltaic cells measured under incandescent light bulb with a light intensity of 610 lux

<table>
<thead>
<tr>
<th>Load</th>
<th>Output voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No external resistor</td>
<td>3.070</td>
</tr>
<tr>
<td>1 130kΩ</td>
<td>3.063</td>
</tr>
<tr>
<td>570kΩ</td>
<td>3.072</td>
</tr>
<tr>
<td>100kΩ</td>
<td>3.041</td>
</tr>
<tr>
<td>50kΩ</td>
<td>3.017</td>
</tr>
<tr>
<td>10kΩ</td>
<td>2.666</td>
</tr>
</tbody>
</table>

As can be seen in Table 10 if an ordinary incandescent light bulb is used instead of a fluorescent lamp, the output voltage from the photovoltaic cells is much higher, for example, 610 lux can power a 10 kΩ load to 2.7 V which corresponds to a current of 0.27 mA. The high increase in energy when using an incandescent light bulb, instead of a fluorescent light, is highly likely to be because an incandescent light bulb has a smoother intensity curve with a higher energy over the whole visible wavelength spectra.

As seen in the results, the sensor platform together with the photovoltaic cells can be used to create a tamper evidence solution for packages that shows whether the package has been opened. The technique, naturally, has some disadvantages, such as an opening event can only be detected if the light intensity is sufficient to power up the microcontroller from the photovoltaic cells. However, there is the possibility to use the photovoltaic cells as a trigger for a system powered by a battery. Then, a much lower light intensity is required in order to detect the event.

2.4 Wireless sensor platform comparison

In this section the proposed RFID based sensor platform is compared to other wireless sensor platform solutions. The platforms are both based on RFID technology and on other types of communication technologies.

2.4.1 Wi-Fi technology

Folea et al. [71] have presented an ultra low power Wi-Fi sensor platform which is based on the IEEE 802.11b standard operating at 2.4 GHz. The sensor platform has a reading range of up to 50 m in an indoor environment. The IEEE 802.11b standard also makes it feasible to work with a very high data rate of up to 11 Mbps. One downside associated with the Wi-Fi solution is that it is an active tag, which means that the sensor platform requires power from a battery, or similar, to be able to transmit the sensor data to the reader (or access point). The sensor platform consumes 700 mA for 1 – 5 ms while it transmits the sensor data.
However a sensor platform is at sleep for the majority of the time and during sleep it consumes between 4 and 10 μA. The power consumptions above are based on a 3V power supply.

2.4.2 Infrared technology

Mattoli et al. [72] have presented a flexible data logger based on the IrDA (infrared) communication standard. The sensor platform has a reading range of 10 cm and because it is based on infrared communication the tag must be in line of sight of the reader. The communication between the tag and the reader occur at a speed of 19.2 kbps. The infrared sensor platform is, as the Wi-Fi, based on an active sensor platform, which means that the transmitter must have energy from an internal power source, for example a battery. The infrared sensor platform consumes 1.8 mA (3 V) for 5.5 ms while transmitting the sensor data. As with all sensor platforms the power consumption during sleep is very important for a long battery lifetime of the sensor platform. The infrared sensor platform has a sleep power consumption of 1.3 μA (3 V).

2.4.3 Impulse Ultra Wideband (I-UWB)

The impulse ultra wideband (I-UWB) technology can be seen as a hybrid version of the ordinary passive UHF RFID technology. The I-UWB technique presented by Baghaei-Nejad et al. [73] uses an ordinary EPC class 1 protocol for the downlink communication (reader to tag) and for the remote powering of the tag. However, in the uplink communication (tag to reader), it uses short pulses for data transmission which provides a higher data rate. According to Baghaei-Nejad et al. [73] the I-UWB technology can reach an uplink data rate of up to 10 Mbps. Since the majority of the data in a sensor platform is sent from the tag to the reader, the technology might be a suitable candidate for a sensor platform. The I-UWB technology is, however, not a standard communication protocol, which means that it will not work with the existing Gen 2 readers and infrastructure. The platform has an input sensitivity of -18.5 dBm which gives an estimated reading range of 13.9 m considering 4W EIRP and 0 dB gain of the antenna. The low input sensitivity and the long reading range is, according to Baghaei-Nejad et al. [73], mainly due to the use of a voltage sensor which reduces the power consumption during the harvesting time. The voltage sensor activates the tag only when the storage capacitor reaches a certain voltage (2.75V) and when the voltage drops below 1.9V the operation is stopped and the storage capacitor is recharged [73]. The tag consumes 51 μA (1.8V) at 10 MHz pulse rate while transmitting data to the reader. One downside associated with the I-UWB tag solution is that it is remotely powered which means that the sensor can only store sensor data when the tag is within the reading range of the reader.
2.4.4 Passive RFID solution

A few sensor enabled passive RFID tags exists [48-50, 74]. Passive RFID tags use the energy from the reader to power the tag. This means that the passive RFID technology has an almost unlimited lifetime. However, it also means that they can only store sensor data when the tag is powered by the reader. An ordinary passive RFID tag has a return link (tag to reader) data rate up to 640 kbps and a reading range up to 4.5 m (4 W EIRP) [50].

2.4.5 Wirelessly-charged RFID

A wirelessly-charged RFID tag basically means a semi-passive tag without batteries. Instead, the tag harvests the energy it acquires from the reader and stores it in a capacitor to be used when the tag is away from the reader. Yeager et al. [51] have presented a wirelessly-charged UHF tag for sensor data collection. The tag uses the Gen 2 standard for communication. The presented RFID tag has a reading range of 4.5 m. However, they state that the tag can be charged at a distance of up to 10 m from the reader. The tag uses the Gen 2 standard and has a return link (tag to reader) data rate of up to 640 kbps. The tag is a semi-passive tag which means that the tag works in a similar manner to a passive tag while communicating with the reader, and does not consume any (or very little) of the stored energy when communicating. The sensor platform has a sleep power consumption of 1.8 μA operating at 1.8V. The tag is designed so that when the tag is within the vicinity of the reader, it charges the capacitor and when no reader is in the vicinity the tag uses the stored energy to read out the sensor and store the data in the memory. The tag presented by Yeager et al. [51] is designed to work for 24 hours when the capacitor is fully charged. The charge time for the tag is dependent on the distance to the reader, according to Yeager et al. [51] the predicted charge time for 1 m distance is about 20 minutes.

2.4.6 Summary of comparison between different wireless sensor platforms

The different wireless sensor solutions presented in this section all have some advantages and disadvantages. However, it is highly unlikely that some of them will be used for packaging surveillance in the supply chain. In Table 11 the different communication technologies are listed with some notes stating how suitable they are for packaging surveillance applications in the supply chain.
Table 11. Comparison between different wireless sensor solutions

<table>
<thead>
<tr>
<th>Technology</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiFi</td>
<td>WiFi is an active radio tag and is not suitable to be used in the supply chain. The technology is not compatible with the current standard for item level tagging.</td>
</tr>
<tr>
<td>IrDA</td>
<td>IrDA must have line of sight in order to be read which makes it not suitable to be used in the supply chain.</td>
</tr>
<tr>
<td>I-UWB</td>
<td>I-UWB is an interesting technology which allows high data rate for a short period of time. However, it is not fully developed for sensing functionality and it is not compatible with the Gen 2 standard.</td>
</tr>
<tr>
<td>Passive RFID</td>
<td>Passive RFID is not possible to use as a logger because it needs energy from the reader in order to gather sensor data.</td>
</tr>
<tr>
<td>Wirelessly-charged</td>
<td>Wirelessly-charged RFID is an interesting solution in sensor data logging. However, the short operation time and long charging time makes it not suitable to be used in the supply chain. The technology could, however, together with other energy harvesting solutions be very interesting.</td>
</tr>
<tr>
<td>RFID</td>
<td></td>
</tr>
<tr>
<td>Two-chip semi-</td>
<td>The two-chip solution presented in this study could very well be used in data logging in the supply chain, with a long lifetime and the possibility to be tailored to work with many different types of sensors.</td>
</tr>
<tr>
<td>passive RFID*</td>
<td></td>
</tr>
</tbody>
</table>

* This work
3 LOW COST MOISTURE SENSORS

The introduction of the Gen 2 standard as a replacement for traditional bar-codes in packaging has opened up new markets for intelligent packaging. Not only will it be possible to read many packages simultaneously, it will also be possible to incorporate different types of sensors into the packages. It is of significant interest to be able to track the condition of a package during its transportation through the supply chain. This makes it possible to guarantee that the package has not been exposed to the wrong conditions or climate, for example, to check that frozen food has not been exposed to temperatures that are too high.

Today around 40% of all packages used are manufactured of wood fibres [28] and moisture has a large influence on the board strength of wood fibre materials. Thus, measuring the moisture could provide vital information with regards to dimensioning the package in the right way. It is known that the strength of a wood fibre based package is considerably reduced when exposed to high relative humidity levels [33]. For example Benson [34] shows that if the relative humidity is changed from 50% to 90% the strength of the wood fibre based paper is reduced to half its original value. Since wood fibre based paper is a hygroscopic material it absorbs and desorbs moisture according to the relative humidity in its surroundings. However, the moisture content (the amount of water in the paper) is not only determined by the present relative humidity level but rather depends on the history of the relative humidity changes in the surroundings [33]. When many of the paper properties are plotted against the relative humidity they display hysteresis phenomena [75]. However, these hysteresis phenomena can be removed if the paper properties are instead plotted against the moisture content of the paper. One of the most critical moisture situations with reference to wood fibre based packages involves the relative humidity cycles between dry conditions and high moisture levels when the package is under a constant load [76]. This situation is significantly more crucial than for the case in which the package is exposed to a constant high humidity level. Thus, moisture sensing in packages and moisture logging is very important in order to determine the condition of the package.

In this section five different types of moisture sensors are presented. The first involves a moisture content sensor for wood fibre based substrates based on a capacitive measuring technique, the second is a relative humidity sensor for high humidity levels based on a resistive measuring technique. The third is an action activated moisture sensor that is producing a voltage signal when exposed to moisture. The fourth is a remote moisture sensor utilizing ordinary passive or semi-passive RFID tags in order to measure the moisture. Finally there are two types of moisture sensors that are utilizing silver nano-particles as a moisture sensing substance.
The first three and the fifth sensor solutions, which are printed sensors, are designed to be easily integrated into the RFID based sensor platform described in section 2 whereas the fourth, the remote moisture sensor solution, utilizes ordinary RFID tags for moisture detection. The concept of dual measurements in moisture sensor could be integrated into the RFID based sensor system for higher accuracy.

3.1 Moisture content sensor for wood fibre based substrates

In this section a moisture content sensor for wood fibre based substrates is presented, and this is the same sensor as was presented previously in section 2.3.1. Typical applications are moisture detection in smart packages and in building materials. The sensor is based on a two-dimensional conductive structure and could be shaped for example as seen in Figure 18.

![Figure 18. Example of a layout of a sensor structure shaped as a circle](image1)

By measuring the capacitance between the two electrodes of the two-dimensional structure the moisture level in the surroundings can be detected. By applying the structure on a wood fibre based substrate with an insulation or
dielectric layer in between, as seen in Figure 19, the moisture level in the substrate can be measured.

There are different ways of measuring capacitances. In this case, in packaging surveillance, the intention is to allow simple integration in an all digital circuit solution and therefore the capacitance is measured by charging the sensor to a fixed potential and then measuring the discharged time over a resistor to a predetermined level. The discharge time is proportional to the capacitance value of the sensor. In equation (5) the discharge equation of a capacitor in series with a resistor can be seen. In Figure 20 typical discharge curves from two capacitors, one of 10 pF and one of 20 pF over a 100kΩ resistor can be seen. The marked values are the time taken to discharge the capacitors to 37% of the initial value. A discharge time, which is twice as long, can be observed for the larger capacitor.

$$u(t) = Ee^{-\frac{t}{RC}}$$  (5)

where E is the initial voltage, R and C are the resistor and capacitor values respectively and t is the time from the start of the discharge.

![Figure 20. Typical discharge curves from two capacitors over a 100kΩ resistor. The dashed lines mark the discharge time to 37% of the initial voltage value](image)

When the moisture content in the wood fibre based substrates changes, its conductivity will also change, as seen in earlier observations [29-30]. As the
conductivity in the substrate changes, $R_2$ in Figure 19, the measured capacitance value between the two conductive electrodes will change.

![Figure 21. Simulated discharge time as a function of the substrate resistance ($R_2$) in the moisture content sensor, $R = 100k\Omega$, $C_1 = 7.6pF$ and $C'_2 = 194.1\ pF$](image)

Figure 21 shows a simulated capacitance response from the sensor as a function of the substrate resistance $R_2$. Here the $C_2$ value is the sum of the $C_2$ capacitances, between the conductive electrodes and the substrate as seen in Figure 19, when the $R_2$ resistance is close to zero. The result shows a peak when the substrate resistance is in the region of $100k\Omega$. At lower resistances the measured capacitance value will tend towards the sum of the capacitances ($C_1$ and $C'_2$) and at higher resistances the measured capacitance value will tend towards the capacitance value between the electrodes in the conductive two-dimensional structure ($C_i$). For the sensor to have a high response the substrate resistance ($R_2$) should be in the region of $100k\Omega$ to $1M\Omega$ for the region of particular interest as defined by the application.

### 3.1.1 Experimental results for the moisture content sensor

In this section the results from the moisture content measurements are presented. The description of the sensor samples are presented in Table 12. In the sensor samples evaluated, a plastic sheet layer was used as the dielectric layer because of an easier manufacturing procedure in this particular case. The conductive two-dimensional structures had an electrode width of 4 mm and an electrode spacing of 1.2 mm with a total size of 40x53 mm in a rectangular shape. For the measurements a microcontroller from Microchip [43] was used which
charges the sensor to a fixed potential, in this case 5V, and measures the discharge time to a low TTL level. In the evaluated sensor set-up, the charge time was set to 1 millisecond. The oscillator frequency of the microcontroller was 16 MHz and the discharge time was measured with a 16 bit counter which provides a time resolution of 0.25 μs and a maximum measurable discharge time of 16.4 milliseconds. The measurements were made in a climate chamber where the humidity and the temperature could be held at a predetermined constant level. Moisture content measurements are a slow process because it takes a particular time for the substrate to absorb or desorb the moisture in the surroundings [33]. All the measurements in this study were made at equilibrium conditions, i.e. the substrates were exposed to a given relative humidity level for at least 24 hours [33].

Table 12. Description of the moisture content sensor samples evaluated

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Dielectric</th>
<th>Conductive</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>Single wall C-flute [77] corrugated board made out of kraftliner [61]</td>
<td>100 μm thick plastic film from MACtac [60]</td>
<td>Screen printed [58] conductive silver ink (26-8204) from Coates Screen [59]</td>
</tr>
<tr>
<td>MC2</td>
<td>Single wall C-flute [77] corrugated board made out of testliner [61]</td>
<td>100 μm thick plastic film from MACtac [60]</td>
<td>Screen printed [58] conductive silver ink (26-8204) from Coates Screen [59]</td>
</tr>
</tbody>
</table>

In Figure 22 the discharge time of the sensor samples MC1 and MC2, described in Table 12, are presented as a function of the relative humidity in the range from 50% to 90%. As can be seen the sensor samples show a hysteresis effect, this is because wood fibre based material is hygroscopic [33]. In Figure 23 the discharge time for the sensor samples is, instead, plotted as a function of the moisture content in the wood fibre based substrate. The result shows that there is a good correlation between the sensor output and the moisture content in the substrate, both in the absorption and desorption stage.
Other results, not presented, show that at higher moisture content levels, namely above 13%, the discharge time for the two sensor samples decreases. This is explained in Figure 21 as when the substrate resistance ($R_s$) is below 100kΩ it decreases to a level which corresponds to the sum of the capacitance values $C_1$ and $C'_2$. This means that at moisture content levels of approximately 13% in the
samples evaluated the substrate resistance is around 100kΩ and at even higher moisture content levels the substrate resistance will decrease further [29-30] and thus the measured capacitance value will be reduced as seen in Figure 21. As this could, unfortunately, give false readings from the sensors, it is preferable to manufacture the sensor in such way that the substrate resistance (R_s) should be in the region of 100kΩ to 1MΩ for the region of particular interest as defined by the application.

A study to determine whether the temperature had any influence on the moisture content sensor samples was conducted. These measurements were made in a climate chamber where the relative humidity was held at a constant level of 50% and the temperature was altered from 18°C up to 30°C. The results displayed in Table 13 show that the sensor solution has no significant temperature dependency. However, a small drop in the moisture content can be observed with higher temperatures, which corresponds to earlier observations [34]. However, when the temperature increases the amount of water in the air also increases for a constant relative humidity level. For example, when the temperature increases from 18°C to 30°C the vapour density almost doubles [63]. The decrease of the moisture content is because it is the chemical potential that determines the quantity of moisture or water vapour. As the temperature of a two phase system is increased, the concentration in the vapour phase increases at the expense of that in the condensed/adsorbed phase but the chemical potentials remain the same between the two phases at equilibrium [64].

Table 13. Temperature measurements on the moisture content sensor samples, described in Table 12, at 50% relative humidity

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>MC1 Moisture content (%)</th>
<th>Discharge time (μs)</th>
<th>MC2 Moisture content (%)</th>
<th>Discharge time (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>7.45</td>
<td>27.6</td>
<td>7.18</td>
<td>27.4</td>
</tr>
<tr>
<td>23</td>
<td>7.45</td>
<td>27.8</td>
<td>7.16</td>
<td>27.6</td>
</tr>
<tr>
<td>28</td>
<td>7.43</td>
<td>27.8</td>
<td>7.15</td>
<td>28.0</td>
</tr>
<tr>
<td>30</td>
<td>7.38</td>
<td>27.8</td>
<td>7.11</td>
<td>28.0</td>
</tr>
</tbody>
</table>

The result in this section shows that it is feasible to manufacture a sensor solution that monitors the moisture content in wood fibre based substrates. The evaluated sensors had a measuring accuracy with a coefficient of variance of 0.22% and a temperature difference of 0.36%.
3.2 Relative humidity sensor for high humidity levels

In this section a relative humidity sensor solution for high relative humidity levels is presented. There are many ways to manufacture a relative humidity sensor solution including for example, surface acoustic wave (SAW) sensors [78], capacitive-type [79] sensors and resistive-type [80] sensors. In this study the focus is on a low cost all printed sensor solution and therefore a resistive-type relative humidity sensor solution has been chosen. The relative humidity sensor solution is an extension of ideas used in earlier work conducted by Norberg [81] and has been influenced by the Wetcorr instruments developed by the Norwegian Institute for Air Research [82]. The Wetcorr instruments are used to measure humidity conditions in the micro-environments on surfaces and within building materials. Typical applications for the relative humidity sensor are moisture detection in packages and in buildings.

![Figure 24. A cross section of the sensor solution for high relative humidity levels](image)

The sensor has the same basic geometrical structure as the moisture content sensor described in the previous section. However, in this case the sensor is built up of two active layers, see Figure 24. The conductive two-dimensional structure is applied directly to a substrate, for example, a plastic sheet. By measuring the resistance between the two electrodes in the two-dimensional conductive structure the relative humidity in the surroundings can be measured. The measured resistance depends on the water absorbed on the surface of the substrate. Here, no cover layer is used which could lead to the sensor being sensitive to external strains, from different types of contaminations on the sensor or by electro-migration in the conductive layer. There are different ways of reducing these problems, one of which is to hide the sensor in the package so that it is not directly exposed to the external strains. Another method is to apply a thin dielectric layer on top of the finger structure which will act as a sensing layer and which will also encapsulate the printed layers from external strains. Such a concept has been shown in earlier work by Jachowicz et al. [83]. However an additional layer for the sensor may drive up the total costs for the sensor solution. The relative humidity sensor solution is intended to be used to monitor the moisture levels in the supply chain as an indicator, not as a precision measuring solution. In addition the
associated costs are very important, as if the costs can be very low it would be possible to put these types of sensors on every package. By measuring the moisture from a pallet with multiple packages and by taking the average of all the sensors, it will be possible to greatly increase the attainable level of accuracy.

The sensor solution in this section is based on a resistive measuring technique. The idea is to measure the resistance between the electrodes in the conductive two-dimensional structure. The gap between the electrodes can be considered as being a resistor in parallel with a capacitor, as seen in Figure 24. One method of measuring the resistance between the electrodes in the sensor (Rs in Figure 24) is to insert a pulse on one side of the sensor and then measure the DC current through the sensor. This is performed in this sensor solution by measuring the voltage over a resistor in series with the sensor, see Figure 25. The pulse that is inserted into the sensor is centred around zero volts, i.e. it has both a positively and a negatively charged pulse, so that the sensor does not become charged and thus changes its response over time. The pulse inserted into the sensor, is 1.55 V for 2 s, 0 V for 2 s, -1.55 V for 2 s and then 0 V for 2 s, which is then repeated. The DC current is measured 2 seconds after the 0 to 1.55 V transition. The fastest frequency response from the sensor solution will thus be 0.125 Hz. However this is highly dependent on the sensor design (Rs and Cs in Figure 24 and Figure 25). In packaging surveillance applications such a fast response is not necessary, as in this case it is the power consumption that is required to be as low as possible, thus a time period of at least one minute may be preferred. This can be achieved by increasing the length of the zero volt parts of the sensor pulse.

![Schematic picture of the relative humidity sensor for high humidity levels](image)

**Figure 25.** Schematic picture of the relative humidity sensor for high humidity levels

### 3.2.1 Experimental results for the sensor for high relative humidity levels

In this section the results from measurements with the resistive-type relative humidity sensor solution are presented. The description of the sensor samples are presented in Table 14. Here, three different substrates have been used. Photo paper from HP [84] was used for the inkjet printed sensor samples. Transparency sheets
from Xerox [85] were used for the flexography printed samples. A sensor with gold electrodes on alumina substrate was used as a reference sensor.

Table 14. Description of the relative humidity sensor samples for high humidity levels evaluated

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sheet resistivity</th>
<th>Substrate</th>
<th>Conductive layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH1</td>
<td>110 mΩ/□</td>
<td>Advanced Photo Paper from HP [84]</td>
<td>Inkjet printed [86] conductive silver ink (CCI-300) from Cabot [87]. Line width and line spacing 0.2 mm.</td>
</tr>
<tr>
<td>RH2</td>
<td>110 mΩ/□</td>
<td>Advanced Photo Paper from HP [84]</td>
<td>Inkjet printed [86] conductive silver ink (CCI-300) from Cabot [87]. Line width and line spacing 0.3 mm.</td>
</tr>
<tr>
<td>RH3</td>
<td>480 mΩ/□</td>
<td>Transparency sheet from Xerox [85]</td>
<td>Flexography printed [58] conductive silver ink (CFW-105X) from Jetrion [88]. Line width and line spacing 0.3 mm.</td>
</tr>
<tr>
<td>RH4</td>
<td>13100 mΩ/□</td>
<td>Transparency sheet from Xerox [85]</td>
<td>Flexography printed [58] conductive carbon based ink (CFW-201L) from Jetrion [88]. Line width and line spacing 0.3 mm.</td>
</tr>
<tr>
<td>RH5</td>
<td>10 mΩ/□</td>
<td>Alumina</td>
<td>Gold electrodes. Line width 0.15 mm and line spacing 0.1 mm.</td>
</tr>
</tbody>
</table>

In Figure 26 the results from the five sensor samples measured in a climate chamber are presented. In this case, the relative humidity was altered from 20% up to 90%. The results show that sensor samples RH1 and RH5 have almost the same response within the entire range. Sensor samples RH2 and RH3 have a slightly worse response than RH1 and RH5 at lower relative humidity levels. This is because sensor samples RH1 and RH5 have smaller line spacing between the electrodes in the two-dimensional structure, which gives a higher current through the sensor. Sensor sample RH4 has almost no response at all within the entire relative humidity range. This is because of the high resistance in the printed electrodes. In order to improve the sensitivity of sensor sample RH4 the serial resistor in the readout electronic device can be increased. However, an increasing serial resistance will increase the noise in the system and the signal to noise ratio will be reduced.
Figure 26. Output voltage as a function of the relative humidity for the sensor solution for high relative humidity levels. The bar at 70% RH shows the scattering between the samples presented in Table 15.

None of the sensor samples shown in Figure 26 had any response at 40% relative humidity and lower. This is because of the resolution of the analogue to digital (A/D) converter. The current through the sensor samples are so small that the results are rounded off to zero. A better resolution in the A/D conversion could probably lead to a higher sensitivity at lower relative humidity levels. However, the currents are so small that the signal to noise ratio will be very low and it may be difficult to detect the signal. There are ways of increasing the sensitivity in the sensor samples by applying a humidity sensing film over the finger structure as has been seen in the earlier work by Jachowicz et al. [83], Wang et al. [80] and Oprea et al. [89]. However, an additional layer will drive up the total cost of the sensor solution.

A brief study was conducted to determine whether it was possible to achieve good repeatability. For the measurements ten new samples were produced in the same way as RH3 (see Table 14) and they were named RH11-RH20. The repeatability measurements presented in Table 15 show that there is a small amount of scattering between the printed sensor samples with a coefficient of variance of 13% (if neglecting RH20). It is the opinion of the author that this is rather good without any calibration of the single sensor samples. Other measurements show that the sensor samples evaluated do not have any significant temperature dependency. The evaluated sensor solution has a measuring accuracy with a coefficient of variance of 0.28% and a temperature dependency of 9% both
measured at 70% relative humidity. It has a cyclic stability of 15% at 50% relative humidity and 0.08% at 85% relative humidity. The better stability at 85% relative humidity is because of the higher current which gives a higher signal to noise ratio.

Table 15. Repeatability measurements on the relative humidity sensor samples at 70% relative humidity

<table>
<thead>
<tr>
<th></th>
<th>RH11</th>
<th>RH12</th>
<th>RH13</th>
<th>RH14</th>
<th>RH15</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH11</td>
<td>0.75 V</td>
<td>0.63 V</td>
<td>0.78 V</td>
<td>0.60 V</td>
<td>0.85 V</td>
</tr>
<tr>
<td>RH16</td>
<td>0.85 V</td>
<td>0.86 V</td>
<td>0.87 V</td>
<td>0.84 V</td>
<td>1.55 V</td>
</tr>
</tbody>
</table>

The result shows that it is feasible to manufacture a two layer relative humidity sensor, with a substrate and a conductive layer. It also shows that in order to make a good sensor with as high sensitivity as possible, the spacing between the electrodes in the conductive two-dimensional structure should be as short as possible and the conductivity in the electrodes should be as high as possible in order to increase the DC current through the sensor.

3.3 Printed action activated moisture sensor

The action activated moisture sensor concept is based on a dry energy cell that provides power to the readout electronic when activated by moisture. The concept is based on the Action Activated Tags (AAT) concept described by Sidén et al. [90]. This means that when the detector is triggered, it powers up an electronic circuit that initiates communication with an alarm server. Typical applications are moisture and leakage detection in buildings and water pipes, moisture detection and control of frozen food in smart packages and moisture and leakage detection in health care systems.

For the moisture sensor concept to be competitive in the market segments outlined, there are a number of demands which must be satisfied. Ideally, it should have a long life time (i). It should be very low cost (ii). It should be possible to hide or incorporate the device inside objects, for example, inside walls or in diapers (iii). An active system that logs the moisture [91] and reports back if the moisture content is too high could satisfy conditions (ii) and (iii), but fails to satisfy condition (i) because of a built in energy source. Humidity indicators [92-95] that visually show whether the sensor has been exposed to harmful conditions easily satisfies conditions (i) and (ii), but fails on condition (iii), because it is required to be read visually. The action activated moisture sensor concept utilizing printed energy cells described in this section meets the three conditions.
The concept is based on a printed energy cell that provides power to a readout device when activated by moisture. There are many energy cell types using different chemical compounds to store and provide power that could be used in the outlined applications. For example lithium-ion energy cells [96-97], nickel-metal hydride energy cells [98-99], zinc-carbon energy cells [100-101] and zinc-air energy cells [102]. The energy cells named cover the full range from partially printable to fully printable. In the proposed concept, one of the most important aspects is the cost. For a sensor to be placed in, for example, every diaper the associated cost must be low. For this reason a zinc-carbon type of energy cell is used in the sensor concept presented in this section. The zinc-carbon type is chosen because it can be fully printed in conventional printing processes, which can drive down the cost. The energy cell provides sufficient power to drive the readout electronics and the necessary cost for the chemical components are relatively low, which, all in all, offers a low cost energy cell.

The energy cell is a multilayer structure with two layers of paper. One paper is printed using an ink mixture of zinc and carbon and the other by an ink mixture of carbon and manganese dioxide. An electrolyte is placed between these two paper layers. Normally printed energy cells have a well controlled electrolyte usually including salts, such as zinc chloride or sodium chloride. In this case, water is used as the electrolyte and thus the current driving capability will be much lower for the dry cells than for normal printed batteries. When the moisture is entering into the moisture absorbing separator layer of the energy cell structure, an electrochemical reaction starts and the energy cell provides power to the readout electronics. Different moisture absorbing substances can be used to tune the humidity sensitivity of the dry energy cell. For example, in a diaper application, the trigger level should be very close to 100% humidity while in moisture detection in buildings the trigger level may be in the relative humidity level of 80 – 85% [35]. The moisture absorbing material can be doped with a mixture of ammonium chloride and zinc chloride to increase the sensitivity of the sensor at low relative humidity levels.

3.3.1 Experimental results for the action activated moisture sensor

In this section, the results from measurements on carbon-zinc energy cell samples are presented. The description of the sensor samples are presented in Table 16. The sensor samples are produced by screen printing [58] the said substrates (as seen in Table 16) with the carbon-zinc and carbon-manganese dioxide ink mixtures. In between the substrates the said electrolyte (as seen in Table 16) is placed. The active part of the evaluated energy cell samples has a dimension of 15x30 mm. A picture of an energy cell can be seen in Figure 27. The energy cell sensor will always be connected to some sort of readout device with a
resistive load. The measurements for the energy cell samples were made using a data acquisition tool from Keithley [103] over a 500kΩ resistor. The measurements were made with single energy cells in a climate chamber where the humidity and the temperature could be maintained at a constant level.

In Figure 28 the sensor signal from the four sensor samples (EC1 – EC4) are presented after a long exposure time in a climate chamber with 90% relative humidity. The different samples are built up of different materials for different types of applications. For example, sample EC3 only responds to direct contact with water i.e. humidity levels near 100% (diaper products) while, as can be seen in Figure 29, sample EC1 has a response at levels around 70% relative humidity and above (moisture detection in buildings).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Electrolyte</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC1</td>
<td>Paper substrate with mix of synthetic fibres</td>
<td>Porous electrolyte made out of cellulose fibres soaked in moisture absorbing substances</td>
</tr>
<tr>
<td>EC2</td>
<td>News-paper</td>
<td>Porous electrolyte layer made out of cellulose fibres with a top layer of moisture absorbing substances</td>
</tr>
<tr>
<td>EC3</td>
<td>Paper substrate with mix of synthetic fibres</td>
<td>Electrolyte made out of porous plastic</td>
</tr>
<tr>
<td>EC4</td>
<td>Paper substrate with mix of synthetic fibres</td>
<td>Porous electrolyte layer made out of cellulose fibres</td>
</tr>
</tbody>
</table>
In Figure 29 samples EC1 and EC2 are exposed to a cyclical humidity from 50% relative humidity to 90% and back to 50% again. Each step was scheduled for 8 hours. It can be seen that the sensor samples have some sort of memory effect resulting in hysteresis of the sensor signal. The origin of the hysteresis effect is a
thermodynamic process in the moisture absorption in the wood fibres [104], which is the same process as for the moisture content sensor previously described. The strength of the memory effect can be adjusted by selecting different materials in the porous electrolytic layer. It is desirable to possess the hysteresis effect in an action activated sensor, since it allows time for the registration to take place when the sensor is triggered by a peak in the humidity. The memory effect provides energy for data processing during a longer time than actually provided by the event itself.

The sensor solution can effectively be used as a “defrosting” alarm, for example in frozen article monitoring systems in the supply chain. In this case the sensor is preloaded with water and frozen together with the item to be monitored. When the article is removed from the freezer or the temperature control fails the inner electrode releases moisture and the sensor is triggered. Even when the sensor is frozen some sensor signal (voltage) can be registered but the driving capability (current) is extremely low. As can be seen in Figure 30, if the sensor sample is maintained at room temperature, the signal increases and sensor becomes a power generating element within a minute or less. The sensor sample evaluated in Figure 30 has been slightly modified in order to reduce current leakage when frozen and thus the sensor sample only has a maximum signal level of 1.2 V.

![Graph showing sensor signal as a function of time after exposure to room temperature](image)

**Figure 30.** Sensor signal from frozen sensor sample (EC4) as a function of time after exposed to room temperature

The power driving capability from a single carbon-zinc energy cell sensor depends on the volume of the sensor. A typical sensor has a driving power of a few mA and provides between 1.1 V to 1.5 V as a single cell. The difference in the voltage level depends on the design of the sensor with respect to its chemistry and layout. In order to reach the levels necessary to power the sensor platform
presented in section 2 the energy cells must provide above 1.8V in order to power up the device. Thus, the dry energy cells are required to be stacked in series in order to reach the power up level. One way of implementing the stacked dry energy cells is by printing a top and a bottom substrate layer, which are then laminated together to form the actual dry energy cell structure. In Figure 31 and Figure 32 the different layers involved in the bottom and top substrates for a four cell energy cell are presented. In Figure 33 a 3D picture of the four cells stacked energy cell is shown. A two cell solution can easily be derived using half as many cells as the structure shown in Figure 33.

![Layer 1, silver paste](image1)

![Layer 2, solvent based carbon paste](image2)

![Layer 3, solvent based carbon ink doped with Zn](image3)

![Layer 4, solvent based carbon ink doped with MnO	extsubscript{2}](image4)

**Figure 31. Description of the bottom substrate layer of a four cell stacked energy cell**

The stack of dry cells will not be completely isolated electrically which means that this configuration relies on the fact that the charge transport over the separator is much stronger than the leakage between dry cells. The leakage between cells can be minimized by the geometrical design of the stack.
An initial study of the stacked dry cell structures was conducted using a lamination technique and hand assembly. The different ink layers were screen printed and laminated together as seen in Figure 33. As the separator layer, a low
cost filter paper with micrometer pores was used. The hand assembled energy cell had an active area of 14 mm by 30 mm. In Table 17 the results from the initial measurements using 3 ml of water can be seen.

Table 17. Current and voltage from typical hand assembled four cell stacked dry cells structure. The open circuit voltage was 3.9V.

<table>
<thead>
<tr>
<th>Load resistance</th>
<th>Voltage</th>
<th>Current</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 kΩ</td>
<td>2.78 V</td>
<td>1.26 mA</td>
<td>3.5 mW</td>
</tr>
<tr>
<td>441 Ω</td>
<td>1.33 V</td>
<td>3.0 mA</td>
<td>4.0 mW</td>
</tr>
<tr>
<td>46 Ω</td>
<td>0.17 V</td>
<td>3.7 mA</td>
<td>0.63 mW</td>
</tr>
</tbody>
</table>

The results shown in Table 17 shows that stacked energy cells can be used to power up the sensor platform to be used as a watch-dog timer for moisture.

Sensor samples of single energy cells produced in batches show that the sensor solution is very stable with less than 10% variation in signal for the same humidity level using simple manual printing techniques. This value can of course be improved by using better printing techniques. The sensors can be configured in such a way that they provide substantial levels of electric power. For example, a thin sensor the size of square decimetre can provide as much as 0.5 W in power over several minutes.

The result shows that the concept of using carbon-zinc energy cells as an action activated moisture sensor is feasible. It also shows that the sensor can be manufactured with different trigger and signal levels to enable it to be optimized towards specific applications. The sensor can utilize the hysteresis effect of hygroscopic materials, such as wood fibre based paper, to provide a stable triggering signal.

3.4 Remote moisture sensor that utilizes ordinary RFID tags

The moisture sensing concept presented in this section has the ability to be read remotely. Typical applications are remote moisture sensing and leakage detection inside a building, for example, inside walls. Some technologies do exist in which it is possible to remotely monitor the humidity inside walls. There are, for example, microwave technologies [105-106] in which a hole in the wall has to be drilled. There are also surface acoustic wave (SAW) based sensors [78,107] and a resonant frequency sensor [108], which has a reading range of about one centimetre. Active wireless humidity loggers [109], require built-in power supply, which means that they possess a limited life time.

In this section a remote moisture sensor concept is proposed which utilizes ordinary RFID tags. Two tags are incorporated into one label in which one of the
tags is embedded in a moisture absorbent material and the other is left open. In a humid environment the moisture concentration is higher in the absorbent material than in the surrounding environment, which causes degradation to the antenna of the embedded tag in terms of dielectric losses and a change of input impedance. The amount of water in the absorbent material is determined for a passive RFID system by comparing the difference in the output power required to power up the open and embedded tags respectively. For a semi-passive RFID system the difference in the backscattered signal strength is proportional to the moisture in the absorbent material.

The sensors can be constructed at a very low cost because ordinary low cost passive RFID tags can be used as remote moisture sensors, i.e. sensor signal inputs are not required on the RFID chip. Figure 34 shows how a remote moisture sensor label inside a wall could work. The idea is that the sensor label is inserted inside the wall during the manufacture of the wall. The tag’s location is somehow registered, for example, on the outside of the wall. The tags can then be read periodically by means of a hand-held reader and it is thus possible to prevent costly damage due to mould or putrefaction in the building. By using passive RFID tags that, in theory have an unlimited (in practice very long) life-time (no built-in power supply), the remote moisture sensor concept can be used throughout the entire life-time of the building.

Figure 34. Remote moisture sensor label incorporating two RFID tags where one is embedded in moisture absorbing material and the other is open
3.4.1 Experimental results for the remote moisture sensor solution

In this section the results from measurements for the remote moisture sensor concept are presented. The measurements were made using two different RFID systems. Firstly, a passive system was used, which was operating at a frequency of 865-868 MHz and secondly, a semi-passive system, operating at a frequency of 2.45 GHz was used. The passive measurements were made using EPC Gen 2 tags from Alien Technologies [110] and which measured 95 mm x 8 mm. The embedded tag was covered with papers whose dimensions were 103 mm x 20 mm. The semi-passive measurements were made using tags from TagMaster [111] measuring 85 mm x 54 mm. In this case the embedded tag was covered with papers that had a dimension of 90 mm x 58 mm. In the passive system the measurements were made using two tags simultaneously, one open and one embedded according to Table 18. By comparing the power difference required to power up the two tags respectively, the moisture content in the absorbing material could be determined. The measurements for the semi-passive RFID system were made using only one tag at a time because the reader set-up only allowed a direct readout of the backscattered signal. Since this is the total received strength, the investigation could only be made for one tag at the time and not for pairs of tags. The concept is, however, directly applicable for pairs of tags if a reader can be constructed which is able to extract individual backscattering powers. At present, the difference in backscattered power is extracted from the same tag when it is open and when it is embedded in paper and not simultaneously for two backscattered tags.

Table 18. Description of the remote moisture sensor samples evaluated

<table>
<thead>
<tr>
<th>Sample</th>
<th>RFID system</th>
<th>Tag 1 (embedded tag)</th>
<th>Tag 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Passive - 868 MHz</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>P2</td>
<td>Passive - 868 MHz</td>
<td>5 mm blotting paper in front</td>
<td>Open</td>
</tr>
<tr>
<td>P3</td>
<td>Passive - 868 MHz</td>
<td>5 mm blotting paper in front and behind</td>
<td>Open</td>
</tr>
<tr>
<td>SP1</td>
<td>Semi-passive - 2.45 GHz *</td>
<td>2.5 mm blotting paper in front</td>
<td>Open</td>
</tr>
<tr>
<td>SP2</td>
<td>Semi-passive - 2.45 GHz *</td>
<td>5 mm blotting paper in front</td>
<td>Open</td>
</tr>
<tr>
<td>SP3</td>
<td>Semi-passive - 2.45 GHz *</td>
<td>5 mm of Luna Core [112] paper in front</td>
<td>Open</td>
</tr>
</tbody>
</table>

* Measurements with one RFID tag at a time

Figure 35 and Figure 36 show the results from measurements on the remote moisture sensor samples described in Table 18 as a function of the relative humidity. The measurements were made in a climate room where the relative humidity and temperature could be maintained at a constant predetermined level.
The time intervals between the measurements were 24 hours. The results in Figure 35 show that at 50% relative humidity there is no difference between the open and the embedded tags. However at 90% relative humidity there is about a 5 dB difference. The sensor sample that is embedded with blotting paper both in front and behind (P3) shows a little higher difference than the sensor sample with only the blotting paper in front (P2).

![Figure 35](image)

Figure 35. Minimum output power difference required for the RFID reader to read the open and the embedded passive tags as a function of the relative humidity

The semi-passive RFID system shown in Figure 36 shows an increased backscattered power at higher humidity levels. This is the reason for the inclusion of negative numbers. The phenomenon of increased backscattering is possibly because the impedance of the tags becomes even closer to a perfect matching than for the original tag antenna, which leads to an increased reading range. The introduced ohmic losses would then have a smaller effect than the increase in impedance match. The result shows a 1.5 dB stronger backscattering power for the embedded tag at 50% relative humidity and 4 dB at 90% for sensor sample SP2. This provides a 2.5 dB difference between 50% and 90% relative humidity as opposed to the passive system which had a 5 dB difference.
Figure 36. Backscattering power difference between open and embedded semi-passive RFID tags as a function of the relative humidity.

Figure 37. Minimum output power difference required for the RFID reader to read the open and the embedded passive tags as a function of the amount of added water to the moisture absorbing material.

Figure 37 and Figure 38 show the results from measurements on the sensor samples, presented in Table 18, in situations of real wetness. In this case, water is applied directly onto the moisture absorbing material. Water drops are added one
drop at the time with the aid of a pipette and distributed at about five drops per gram. The measurements were conducted approximately two minutes after the application of the water. A real life comparison to this real wetness situation could be when the labels are placed in locations inside walls or in floors and where there is a risk of water leakage, for example, from leaking water pipes.

For the measurements with the passive sensor samples shown in Figure 37 there is a 13 dB difference of the transmitted power required to power up the embedded tag when 12 grams of water is applied to the paper sheets in comparison to dry paper sheets.

For the measurements on the semi-passive sensor samples shown in Figure 38 the same behaviour can be seen as in the case for climate room measurements (Figure 36) where there is an increased backscattering power for a small amount of added water to the paper sheets. However, when the amount of water exceeds five grams the system shows a decreased backscattered power. If the initial negative values are ignored, the difference for the semi-passive system is slightly smaller than for the passive system. It should, however, be remembered that the semi-passive tag is covered by paper sheets of a larger area than the passive tags, but the comparison is made using the same amount of water.

![Figure 38. Backscattering power difference between open and embedded semi-passive RFID tags as a function of the amount of added water to the moisture absorbing material](image)

The results show that the concept for remote moisture sensors using ordinary RFID tags is feasible. The difference in power level is of the order of approximately
two to three decibels at 80% relative humidity, and this is the humidity level at which is the starting point for the source of mould. The results may be improved by using embedding materials that change their dielectric properties even more at moderate humidity levels. The hysteresis effect of paper materials could be a source of a problem since it may give incorrect readings due to memory effects. However, an incorrect reading due to hysteresis still indicates that the humidity level has been high.

3.5 Printed nano particle based moisture sensor

In this section some initial studies on printed nano-particle based moisture sensors are presented. In this case, two different structures are evaluated, one is a horizontal single layer structure and the other is a two layer structure. The initial study presented in this section shows that it is possible to manufacture a moisture sensor with nano-particle based inks. With the two-layer structure concept it is possible to manufacture a sensor for very dry conditions. A typical application for the sensor solution is in relation to moisture detection in smart packages.

3.5.1 Printed nano-particle based sensor for very dry moisture conditions

The printed nano-particle based sensor for very dry moisture conditions is basically based on the same two-dimensional structure as has been presented previously in the moisture content sensor solution. However, in this case, an additional layer is applied on top of the conductive electrodes to act as a moisture sensing layer. Similar ideas of using sensing layers have been conducted in previous research by Jachowicz et al. [83], Wang et al. [80] and Oprea et al. [89]. In this study, a layer of unsintered silver nano-particle suspension is used as the moisture sensing layer. A cross section showing the different layers can be seen in Figure 39. The first layer is the substrate, the second layer is the conductive two-dimensional structure and the third layer is the unsintered silver nano-particle layer. The silver nano-particle ink, applied over the conductive finger structure, is dried at a low temperature and is thus not sintered. By measuring the DC resistance between the electrodes in the structure, the relative humidity in the surroundings can be measured.

The humidity sensitivity is related to an effect in the charge transport between the nano-particles. The effect in the unsintered nano particles causes the resistance to increase with increasing moisture levels. This is rather surprising since increased moisture levels are usually attributed to reduced resistance. However, the mechanism appears to be related to a reduced tunnelling probability between neighbouring silver nano-particles with an increased moisture level, possibly caused by an increased inter-particle distance (swelling). The overall result is a distinctive change in the charge transport properties.
Silver Conductors

Figure 39. A cross section of the printed nano-particle based sensor for low moisture levels. With the substrate, the conductive sensor layer and the layer of unsintered silver nano-particles.

The output of the nano-particle sensor solution is a change in the DC resistance. The DC resistance change can be measured by several different methods using, for example, an ordinary multi-meter or similar tools. This means that the readout electronics can be constructed using standard components or can be integrated into a single chip solution that is compatible with the RFID based sensor platform described in section 2. In the future, when the technology becomes more mature, the readout electronic may be printed together with the printed sensors. In the evaluation of the sensor samples presented in section 3.5.2 an ordinary multi-meter has been used.

Table 19. Description of nano-particle based sensor for dry moisture conditions samples evaluated

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Conductive</th>
<th>Sensing layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP1</td>
<td>Kapton [113]</td>
<td>Inkjet printed [86] conductive silver ink (CCI-300) from Cabot [87] sintered at 180°C. Line width and line spacing 0.3 mm</td>
<td>Inkjet printed [86] conductive silver ink (CCI-300) from Cabot [87] dried at 70°C.</td>
</tr>
<tr>
<td>NP2</td>
<td>Kapton [113]</td>
<td>Inkjet printed [86] conductive silver ink (CCI-300) from Cabot [87] sintered at 180°C. Line width and line spacing 0.4 mm</td>
<td>Inkjet printed [86] conductive silver ink (CCI-300) from Cabot [87] dried at 70°C.</td>
</tr>
</tbody>
</table>

3.5.2 Experimental results for nano-particle based sensor for dry moisture conditions

In this section the results from the measurements associated with the nano-particle sensor for dry moisture levels are presented. The description of the sensor samples are presented in Table 19. The sensor samples have been produced by inkjet printing [86] with silver based ink from Cabot on Kapton [113] sheets from DuPont. Kapton sheets have been used because of the high thermal stability [114].
The printed conductive two-dimensional structure is sintered at a temperature of 150°C, while the moisture sensitive nano-particle layer applied on top is dried at 70°C to prevent the nano-particle suspension from sintering, which will cause the sensor to lose its moisture sensing properties.

![Graph](image)

Figure 40. Resistance as a function of the relative humidity for sample of the nano-particle based sensor for dry moisture levels from Table 19

![Graph](image)

Figure 41. Resistance scattering between the forty printed nano-particle based sensor for dry moisture levels
In Figure 40 the results from the nano-particle sensor samples measured in a climate chamber in which the relative humidity was altered from 10% up to 50% and back to 10% are presented. The sensor samples have a slow response time with a saturation time of about 12 hours. To ensure that the sensor samples are stable at the corresponding relative humidity level they were stored in the chamber for 24 hours between each measurement. The results show that the sensor samples are linear from 10% to 50% relative humidity. However, when the relative humidity level is reduced down to 10% again the sensor samples shows a hysteresis effect. The measurements could only be conducted at relative humidity levels up to 50% because the unsintered nano layer becomes liquefied at higher relative humidity levels.

A brief study was conducted to determine whether it was possible to achieve good repeatability. In this study, 40 sensor samples were produced in a batch. As can be seen in Figure 41, there is some scattering between the sensor samples and, in fact, between the 40 samples there is a coefficient of variance of 56% which was not felt to be good. However, between 30 of the samples there is a variance of 8% which is rather good without calibration of the single sensor samples.

The sensor samples show no significant temperature dependency over the measured range. However, at very high temperatures namely above 100°C the unsintered silver nano-particle layer will be sintered and the moisture sensitivity will be lost.

The result shows that it is feasible to manufacture a printed relative humidity sensor for very low humidity levels. 75% of the sensor samples had a variance of 8% without calibration of the single samples. The sensor samples show a linear response as the relative humidity is increased from 10% to 50%. However, the sensor shows a hysteresis effect when the relative humidity is reduced down to 10%.

### 3.5.3 Single layer nano-particle based moisture sensor for high humidity levels

In this section a printed single layer nano-particle based moisture sensor is presented. The sensor is based on a short and narrow line of silver nano-particles, as seen in Figure 42(a). When the silver nano-particle is exposed to water or humidity, the resistance of the sensor is decreased and remains at that level after drying. The sensor can, for example, be used to monitor humidity in the transportation of packages or in buildings. The observed reduction of the resistance in the nano-particle ink line is related to the sintering of the nano-particles. The sintering of nano-particle inks is usually performed by heating in an oven or electrically [115-118], although some results on chemical sintering have
been reported [119-120]. The active sizes for the width and the length of the thin line in Figure 42(a) are 40 μm and 125 μm respectively between the contact pads. If the initial or final resistance in the sensor requires to be lower for a particular application, then multiple lines can be used as shown in Figure 42(b). All the measurements in this study are based on the single line version of the nano-particle based moisture sensor as seen in Figure 42(a).

The single layer nano-particle structure described in this section was initially designed as a printed write once read many times (WORM) resistive memory that can be programmed using a 1.5 V printed battery and to be used as a wireless watch-dog alarm function. However, in this case it is used as a moisture sensitive sensor.

3.5.4 Experimental results for single layer nano-particle based moisture sensor

In this section the results from moisture measurements on the single layer nano-particle based moisture sensor are presented. The sensor evaluated in this study was inkjet printed [86] with Silverjet DGP 40LT-15C [121] ink from Advanced Nano Products (ANP) [122] on HP Advanced photo paper [84]. In Figure 43 the layout of the printed sensor samples with eight sensor elements can be seen. The layout is designed to fit into a standard SD [123] memory card reader for easy characterization and evaluation of the sensor. The samples evaluated were prepared by printing the silver nano-particle ink with a Dimatix DMP-2831 [124] inkjet printer using 10 picoliter printing heads. After being printed, the resistance of the print was usually very high (above 15 MΩ) so the samples where dried for a

![Figure 42. Photographs showing single line single layer nano-particle based moisture sensor (a) and multiple line single layer nano-particle based moisture sensor (b). Both with an active length of 125 μm](image-url)
short time in the oven at 80 – 90°C so that the resistance reduced to around 2 MΩ to 10 MΩ. After the oven treatment, the samples were electrically sintered down to the desired initial resistance value. The electrical sintering, in comparison to heat sintering, makes it easier to control the resistance value in the preparation of the samples.

Figure 43. Layout of the single layer nano-particle moisture sensor with eight sensor elements

It has been observed that the initial resistance value affects how large the relative resistance change is when the sensors are subjected to humidity. In Figure 44 sensor samples with different initial resistance values were subjected to 90% RH and 23°C for a period of 24 hours. The resistance was measured before they were

Figure 44. Measured relative resistance change of single layer nano-particle based sensors with different initial resistance values subjected to 90% RH for 24 hours
placed in the climate chamber and after they have been removed and dried in 30% RH.

In Figure 45 the final resistance for the sensor samples shown in Figure 44 is plotted with respect to the initial resistance. It can be seen that the final resistance is very consistent and varies only from 40Ω to 105Ω although the initial resistance is within the range from 1kΩ to 10MΩ. For values below 1kΩ the final resistance slowly decreases until it reaches a value of 2Ω for an initial value of 5Ω.

Figure 45. Final resistance as a function of the initial resistance for the single layer nano-particle based moisture sensor shown in Figure 44

Measurements performed on single layer nano-particle based moisture sensor samples in different humidity levels can be seen in Figure 46. Here, the sensor samples were electrically sintered down to between 3kΩ and 5kΩ. After the electrical sintering, the samples were exposed to different relative humidity levels where the resistance was logged using a Kiethley 2410 sourcemeter [103]. The measurements were made in a climate chamber where the temperature was held at a constant level of 23°C. As can be seen, the resistance decreases more rapidly at higher humidity levels. Thus, by logging the resistance change in the sensor and by calculating the slope of the resistance change the relative humidity can be determined. After the moisture measurements in the climate chamber the samples were exposed to a low relative humidity level of 30% which causes the resistance decrease to stop and the resistance in the samples remained at the corresponding resistance level from the end of the measurements.
Figure 46. Measurements showing resistance change in different humidity levels for single layer nano-particle sensors printed on HP Advanced photo paper

Figure 47. Measurements showing resistance change in different humidity levels for single layer nano-particle based sensors printed on Canon PT-101 photo paper

It has been observed that when using other photo paper brands, such as the Canon PT-101 photo paper [125], the resistance change when exposed to high humidity levels is completely different as seen in Figure 47. This is felt to be very likely due to different coating layers in the photo papers.
Nano-particle inks are usually stabilized with one or more capping agents that create an electrostatic and/or steric barrier that prevents the nano-particles from aggregating. Polyvinylpyrrolidone (PVP), which is a well known capping agent, was established to be present in the ANP ink by pyrolysis GC/MS [126]. In earlier work in chemical sintering [119, 120] of silver nano-particles it has been shown that when neutralizing the charges in the capping agent this leads to particle coalescence and sintering of the silver nano-particles. When examining the results in Figure 46 it can be seen that the humidity threshold at which the resistance starts to decrease is in the same humidity range as when the PVP is known to soften and therefore the resistance decrease could be explained by particle coalescence. However, this does not explain the different results obtained from different photo paper brands. It could be that that one portion of the PVP is bound to the particle and the excess can be pulled into the coating by the capillary forces and therefore the pore structure will determine the amount of polymer retained in the ink layer. Also, when the moisture content in the PVP is raised, the ability for there to be ion transport is created within the polymer [127] and ions from the paper coating can be transported into the ink layer. It is a possibility that the chemistry of the paper is also of importance for the sintering process. Therefore, the observed variation in moisture sensitivity on papers of different brands could possibly be explained by variables in the coatings. More research is required to be able fully understand the humidity sintering effect on the silver nano-particle inks and the role of the substrate in the process.

A short study conducted shows that when using Cabot CCI-300 [87] on HP Advanced photo paper the resistance will instantly become very low and that either none or only a very small moisture sensitivity could be seen when there was exposure to high moisture levels.

The single layer nano-particle moisture sensor is an irreversible sensor and can therefore only be used once. This could be a drawback, but, on the other hand, the sensor has a memory effect that provides information that the sensor has been exposed to a high humidity level, which is very crucial information in certain applications.

The result in this section shows that it is feasible to manufacture printed single layer and two-layer nano-particle based relative humidity sensors. However, more research is required in order to fully understand the moisture sintering of the silver nano-particles and the influence by the substrate. For further understanding of the moisture sintering the reference is to future work within the “New system integration tools for printed intelligence in packaging applications” project at Mid Sweden University [128].
4 PRINTED TOUCH SENSITIVE SENSORS

The printed touch sensitive sensor concept is based on the idea of integrating sensors into a high quality image. The idea is that when someone touches the image with the integrated sensor the user receives some sort of response, for example, a sound is played. Typical applications are touch sensitive information displays and interactive point-of-sales displays, which according to market research can increase sales by up to 400% [36]. One particular application for the sensor solution concept is to use it on ordinary wood fibre based point-of-sales displays used in a store. The idea is to create added value for the point-of-sales display. Therefore wood fibre based substrate is used as the base substrate for the sensor solution. The printed touch sensitive sensor solution is an extension of the moisture content sensor solution for wood fibre based substrates but it is reacting to the moisture in the finger instead of the moisture in the substrate.

![Figure 48. Schematic picture of the touch sensitive sensor solution](image)

For a sensor solution to be competitive in the outlined market segments it must satisfy several demands. It should be low cost (i). It should be flat (ii). It should be flexible (iii). It should be possible to integrate it in high quality images (iv). It should be possible to make large touch sensitive areas (vi). Capacitive and resistive touch screens [129-130] satisfy condition (ii), could satisfy conditions (i), (iv), (vi) and (v). But fail on conditions (iii). Surface acoustic wave (SAW) touch screens [131-132] satisfy condition (ii), could satisfy conditions (i), (iii), (iv) and (vi), but fail on condition (v). An ordinary light switch could satisfy conditions (i), (ii) and (v), but will fail on conditions (iii), (iv) and (vi). The printed touch sensitive sensor solution presented in this section satisfies all six conditions.

The sensor solution is based on a capacitive measuring technique and can be divided into three subsystems as seen in Figure 48. Firstly there is the printed
sensor structure which is connected to a detection or readout electronic device. The readout electronic device converts the analogue capacitive sensor signal into a digital format which is sent to an external device through the communication interface. The external device can be any type of electric device, for example a computer, an mp3 player or a light switch.

4.1 Printed sensor structure for the touch sensitive sensor solution

The first part of the touch sensitive sensor solution is the printed sensor structure. The sensor structure is based on a capacitive measuring technique. There are many ways of manufacturing capacitive sensor structures from a single layer [133] to multilayer structures [134]. One aim associated with this sensor solution is to produce low cost sensor structures and therefore a single layer structure is preferred in order to reduce the manufacturing cost. When using a single layer capacitive touch sensor solution the sensor is triggered by the capacitance created between the human hand and the sensor structure. By using a parallel pair electrode concept in the sensor the sensitivity can be increased, as the human hand is touching both of the electrodes. This is the reason why the sensor is based on a two-dimensional conductive structure, of which an example can be seen in Figure 18.

The printed sensor structure is fabricated using conductive ink on paper substrates. The sensor structure is built up of four layers. Firstly there is a wood fibre based substrate, secondly there is a dielectric or insulating layer, thirdly there is a conductive layer and finally there is a cover layer, see Figure 49.

![Diagram of Capacitive Sensor Structure](image)

Figure 49. A cross section of the capacitive touch sensitive sensor solution

The first layer, namely the wood fibre based substrate, is used because it is a low cost material with good printability. However the disadvantage associated with wood fibre based substrates is that it changes its conductivity when the
moisture level in the surroundings change [29-30], as has been described in section 3.1. Thus a dielectric or insulating layer is placed between the wood fibre based substrate and the conductive third layer. If this is not the case, then it is possible that a short circuit can occur in the conductive layer at high moisture levels and this will cause the touch sensitive sensor to cease working. The third layer, namely the conductive layer, is structured as a two-dimensional pair electrode structure as seen in Figure 18. A pair electrode structure is used because the sensor should work both when touched by a hand but also when touched by a small finger. The sensor must therefore be able to handle touch from a square centimetre up to several square decimetres. The sensor samples manufactured had an electrode width of 4 mm and a gap of 1.5 mm between the electrodes, as shown in Figure 50. The gap between the electrodes was chosen to be 1.5 mm so as not to create any problems in the printing process.

![Figure 50. Overview of the capacitive touch sensitive sensor with a pair of parallel electrodes](image)

The fourth layer is applied on top of the conductive layer to firstly hide the conductive layer but also to prevent the conductive lines from being short circuited by a conductive material. The cover layer can be printed with a high quality print, which means that the sensor is integrated into a graphical layout. Figure 51(b) shows an example of a sensor layout designed to be integrated into a high quality image Figure 51(a).

The measured capacitance value in the sensor is dependent on the capacitance between the electrodes in the pair electrode structure (C₁ in Figure 49), the capacitance through the surrounding air (here part of C₁) and the capacitance through the dielectric material (C₂ in Figure 49). The sensor set-up can be viewed as three capacitors in parallel, and the total capacitance value is the sum of the capacitances. When a conductive material, for example, a human hand, touches the sensor area, an additional parallel capacitance is created and the total capacitance value is the sum of the four capacitances, i.e. an increase in the measured capacitance. By measuring this capacitance change, a touch event can be registered.
This sensor solution can be thought of as a means of producing low cost touch sensitive paper. An additional advantage involved from the use of printing techniques, apart from its cost efficiency, is the possibility of easily producing sensor structures of any printable size and shape, for instance, in the form of a large star, a football or a gigantic lion. The size of the sensor structure can be as small as a square centimetre up to several square decimetres. The printed sensor structure can be manufactured in any conventional graphical printing process, for example, flexographic printing, screen printing and inkjet printing [58, 86].

4.2 Readout electronics for the touch sensitive sensor solution

The touch sensitive sensor solution is, as has been previously described for the moisture content sensor solution, based on a capacitive measuring technique. There are different ways to measure the capacitance of a touch sensitive sensor. One way is to use some sort of charge transfer sensing solution used by commercial companies such as the Atmel Corporation [135] and Microchip Technology [136]. However, in this case the readout electronic device is working in a similar manner to that for the moisture content sensor solution, described in section 3.1, in other words by means of a microcontroller that measures the discharge time of the sensor over an external resistor. However, in order to increase the signal-to-noise ratio, it has been decided to construct a slightly more advanced readout electronic device consisting of an instrumental amplifier and two resistors. The instrumental amplifier, together with the printed sensor structure using the electrode pair concept, enables the readout electronics to filter
out the noise picked up in the sensor structure, which leads to an increased signal-to-noise ratio. The readout electronic device used in the evaluation of the sensor samples is charging the sensor structures to five volts and is measuring the discharge time over a 100kΩ resistor. The sensors are discharged to a low TTL level (0.8 V) and thus an all digital electronic device is used. The readout electronic device can easily be integrated into standard electronics solutions or into a single chip solution.

4.3 Communication interface for the touch sensitive sensor solution

When the readout electronic device has detected a touch on the printed sensor, an event has to be sent to an external device which gives a feedback to the user. The feedback could, for instance, be to play a sound or switching a light bulb on or off. To be able to communicate with the external device a communication interface is required. The communication interface can be divided into two system groups. Firstly, there is a simpler version with a simple analogue wire solution, which means that a wire is placed between the readout electronic device and the external device. This is useful when the distance between the printed sensor and the external device is short. The whole system can, for example, be integrated into the same unit. However, for longer distances, it may prove difficult to have a wired communication and, in this case, it is more beneficial to use a more advanced sensor concept which is based on a distributed sensor network with wireless communication links. In a wireless system, the readout electronic device (sensor node) is working alone and communicates with a central node that triggers the external device when a touch has been registered. More than one sensor node can be used in this set-up. In Table 20 there is a comparison between four possible wireless standards for use in creating a distributed sensor network.

Table 20. Comparison of different wireless standards [137-139]

<table>
<thead>
<tr>
<th>Name</th>
<th>Wi-Fi</th>
<th>Bluetooth</th>
<th>Semi-active RFID</th>
<th>Zigbee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>IEEE 802.11b</td>
<td>IEEE 802.15.1</td>
<td>EPC</td>
<td>IEEE 802.15.4</td>
</tr>
<tr>
<td>Network Size</td>
<td>30</td>
<td>7</td>
<td>&gt; 100</td>
<td>65536</td>
</tr>
<tr>
<td>Data Rate</td>
<td>11 Mbps</td>
<td>1 Mbps</td>
<td>30 kbps</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Range</td>
<td>100 m</td>
<td>10 m</td>
<td>5 m</td>
<td>30 m</td>
</tr>
<tr>
<td>Power Consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Active</td>
<td>100 mW</td>
<td>48 mW</td>
<td>1 mW</td>
<td>40 mW</td>
</tr>
<tr>
<td>- Sleep</td>
<td>180 μW</td>
<td>1 μW</td>
<td>40 μW</td>
<td></td>
</tr>
</tbody>
</table>
In a distributed sensor network the sensor nodes are working by themselves and therefore the power consumption is very important for a sensor network to work efficiently. In an interactive point-of-sales display system the data rate of the sensor network is not overly important because a relatively small amount of data will be sent through the network. However the network size may by very important if the sensor network is working in, for example, a supermarket with multiple displays. In the case of a point-of-sales display solution with multiple displays the ZigBee communication interface would be preferred because of its large network size, long communication range and low power consumption. In other applications, such as, packaging solutions where the sensor is printed on a package and when the package is picked up, an event will be activated. A semi-active RFID communication system is better for this scenario as it has very low power consumption.

4.4 Experimental results for the touch sensitive sensor solution

Table 21. Description of the touch sensitive sensor samples evaluated

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Dielectric</th>
<th>Conductive</th>
<th>Cover layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td>Single wall C-flute [77] corrugated board made out of kraftliner [61]</td>
<td>100 µm thick plastic film from MACtac [60]</td>
<td>Screen printed [58] conductive silver ink (26-8204) from Coates Screen [59]</td>
<td>100 µm thick plastic film from MACtac [60]</td>
</tr>
<tr>
<td>TS2</td>
<td>Single wall C-flute [77] corrugated board made out of testliner [61]</td>
<td>100 µm thick plastic film from MACtac [60]</td>
<td>Screen printed [58] conductive silver ink (26-8204) from Coates Screen [59]</td>
<td>100 µm thick plastic film from MACtac [60]</td>
</tr>
<tr>
<td>TS3</td>
<td>Single wall C-flute [77] corrugated board made out of kraftliner [61]</td>
<td>100 µm thick plastic film from MACtac [60]</td>
<td>Screen printed [58] conductive carbon ink (26-8203) from Coates Screen [59]</td>
<td>100 µm thick plastic film from MACtac [60]</td>
</tr>
</tbody>
</table>

In this section the results from measurements on three touch sensitive sensor samples are presented. The description of the sensor samples are presented in Table 21 with the different layers presented in Figure 49. In the evaluated sensor samples, a plastic film was used as the dielectric layer because of an easier
manufacturing procedure in this particular case. The dielectric layer could otherwise have been printed using a dielectric ink. The conductive two-dimensional finger structure had an electrode width of 4 mm and an electrode spacing of 1.5 mm, as seen in Figure 50, and a total size of 150x100 mm shaped in a rectangular fashion. The measurements were conducted in a climate chamber where the temperature and the humidity could be held at a constant level.

As the touch sensitive sensor solution is based on a capacitive measuring technique, the touch can be seen as a parallel-plate capacitor between the finger and the conductive layer. The measured capacitance is dependent on the area that it is touched with. This can be seen in equation (6) for parallel-plate capacitors:

\[ C = \varepsilon_r \varepsilon_0 \frac{A}{d} \]  

(6)

where C is the capacitance in farads [F], A is the area of each plate in square metres [m²], \( \varepsilon_r \) is the dielectric constant of the material between the plates, \( \varepsilon_0 \) is the permittivity of free space [8.854e-12 F/m] and d is the separation between the plates in metres [m].

![Figure 52](image.png)

**Figure 52.** Sensor response from two printed touch sensitive sensor samples touched with one, two and three fingers, respectively. The relative humidity was held at 50% and the temperature at 23°C.

This means that a higher response is obtained when the sensor is touched with a larger area, thus three fingers give a higher response than one finger, which can
be seen in Figure 52. The result also shows that there is no significant influence of the sheet resistivity of the conductive layer. This is an important fact because the price of the carbon based ink is approximately 10% of the silver based ink. The carbon based ink has a sheet resistivity of $18\,\Omega/\square$ and the silver based ink has a sheet resistivity of $0.02\,\Omega/\square$. Both of these cases involve a layer thickness of 15 $\mu$m.

In Figure 53 a change can be seen in the base value (when the sensor sample is untouched) in comparison to Figure 52. The difference is that the measurement shown in Figure 53 is made with a relative humidity of 85% in comparison to 50% in Figure 52. As seen in the moisture content sensors for wood fibre based substrates (section 3.1.1) and research by Simula et al [59] and Murphy [30] that the conductivity of wood fibre based substrates is dependent on the moisture content of the paper. The conductivity change in the evaluated substrate has changed the base value of the sensor sample. However, the touch sensitivity still remains the same. There is, however, a small tendency for a higher noise level at 85% relative humidity in comparison to 50% because of the higher capacitance value. However, this is possible to take care of in the readout electronic device by means of, for example, different types of filtering methods.

As can be seen in Figure 54, the sensor response which depends on the moisture content in the substrate is a very slow process with a long time constant and involves approximately 20 hours until saturation, which is in comparison to a
touch that has a response time in the range of seconds. This means that the sensor solution can both detect a touch and simultaneously monitor the moisture.

Figure 54. Discharge time as a function of the time exposed to different relative humidity levels. The relative humidity was altered from 50% up to 90% and back to 50% in 10% steps, with variable time length.

Figure 55 shows an example of a non-distributed interactive point-of-sales display solution integrated into an aluminium frame with integrated loud speakers. The wood fibre based sheet with the integrated touch sensitive sensors is replaceable and the sound is reprogrammable. The display works in such a way that, when one of the three characters is touched then the corresponding sound will be played. This kind of interactive point-of-sales display can be introduced into supermarkets in order to promote products or provide information about certain groceries.

The result in this section shows that it is feasible to manufacture a touch sensitive sensor integrated into a high quality image on wood fibre based substrates. It has been shown that the touch sensitivity is the same at both 50% and 85% relative humidity. However, there is a tendency for there to be higher noise level at 85%. The sensor solution shows no difference in touch sensitivity between the sensor samples printed with silver or carbon based ink which is a significant advantage.
Figure 55. Example of a non-distributed interactive point-of-sales display solution with integrated loud speakers
5 SUMMARY OF PUBLICATIONS

The nine papers in this thesis deal with low cost sensors, some printable and others which are applications of low cost commercial tags. System integration of a hybrid BAP RFID based sensor system.

5.1 Paper I

The performance of a capacitive printed touch sensitive sensor is investigated and compared to other commercially available touch screens. The advantage associated with the proposed sensor solution is that it is a low cost sensor that can be integrated into a high quality print. The targeted applications are large area touch sensitive commercial stands, flat keyboards at the point of purchase and touch and manipulation surveillance in logistic chains. The study also compared different kinds of communication links between the readout electronic circuit and external devices, from high-end wireless systems that are utilizing RFID or ZigBee to simple analogue wire solutions.

5.2 Paper II

This work presents a study related to the performance of printed low cost moisture sensors fabricated using conductive ink on paper substrates. The sensors are intended to add value to the surveillance of packages. Two different kinds of sensors are evaluated and characterized. The two sensors have similar geometrical shapes, but different measuring principles are employed. The first sensor measures the moisture content in cellulose based substrates, while the second measures the high levels of relative humidity in the surroundings. The sensors have been developed so that they can be integrated into Radio Frequency Identification (RFID) systems for surveillance in logistic chains. A laboratory set-up of a RFID tag with sensor capability based on an ordinary passive RFID tag has been shown.

5.3 Paper III

In this work a two-chip battery assisted Radio Frequency Identification (RFID) based sensor platform is presented. The radio frequency communication interface is based on the EPC Gen 2 standard. A laboratory set-up of the platform has been shown and characterized for a moisture content sensor application. The laboratory set-up of the sensor platform has a reading range of 3.4 meters which is in comparison to commercially available Gen 2 tags. The laboratory platform has an average power consumption of 2.1 μW operating at 3 V, which together with a printed battery gives an estimated lifetime for data logging of several years.
The proposed RFID platform provides a trade-off between, communication performance, compatibility with international standards and flexibility in on-package customization including type and number of sensors. The proposed architecture separates the high performance communication circuit and the low frequency sensor interface logic. In the future the sensor interface may be integrated using printed logics to further enhance the flexibility and low cost customization features of the architecture.

5.4 Paper IV

In this work the two-chip battery assisted passive RFID based sensor platform presented in Paper III is evaluated for two different packaging surveillance applications. The results show that the sensor platform can easily be tailored to be used with different types of sensors to achieve the desired solution, such as, shock, tilt and tamper evidence sensors and detectors. For a tilt sensor solution the sensor platform can have a battery lifetime above 3 years when being powered by a battery with an energy capacity of 33 mAh.

5.5 Paper V

In this work the design and manufacturing of an inkjet printed resistive type humidity sensor on paper is reported. After having been exposed to humidity above a threshold level the resistance of the sensor decreases substantially and remains at that level when humidity is reduced. This sensor can be used in various applications for environmental monitoring where the memory effect means that the highest humidity exposure is recorded. The humidity level can be deduced by monitoring the rate of change. A possible cause for this behaviour is the presence of polyvinylpyrrolidone (PVP) which can enable ionic transport within the polymer when exposed to humidity. The simple manufacturing procedure makes it a good and versatile low cost sensor solution that can be integrated with printed flexible electronics.

5.6 Paper VI

A horizontal printed Write Once Read Many (WORM) resistive memory has been developed for use in wireless sensor tags targeting single event detection in smart packaging applications. The WORM memory can be programmed using a 1.5 V printed battery. An alternative programming method is to use chemical sintering which allows the development of exposure time triggered single event tags that can be accessed wirelessly. The new WORM memory has very low losses in the ON-state which allows direct integration into RF antenna structures. A sensor tag architecture that utilizes the WORM memory functionality and the well
established Electronic Article Surveillance (EAS) communication standard has been outlined. Both active (printed battery powered) and fully passive sensor tag solutions have been proposed. The role of printed electronics in smart packaging applications has been reviewed and discussed. Important enabling factors for the future development have been highlighted, such as the need for hierarchical design and test tools, better printed interconnect technologies as well as better components that allow communication with existing information and communication technology (ICT) standards. This is illustrated and underlined by the presented smart packaging concept demonstrators. Finally, we conclude that the new horizontal WORM memory technology provides an important additional tool to reach future fully printed smart packaging wireless communication platforms. The ongoing research on resistive memory structures with multiple read and write functionality could further advance such technology platforms.

5.7 Paper VII

A simple printable moisture sensor that is based on a carbon-zinc type energy cell is characterized. The energy cell based sensor provides power to a readout electronic circuit when activated by moisture. Typical applications are moisture and leakage detection in buildings, water pipe lines, smart packages and health care systems. In the study some critical parameters are characterized such as power driving capability and internal memory effects. In addition a specific application for the surveillance of frozen articles during transport is examined.

5.8 Paper VIII

The paper presents a concept where pairs of ordinary RFID tags are exploited for use as remotely read moisture sensors. The pair of tags is incorporated into one label where one of the tags is embedded in a moisture absorbent material and the other is left open. In a humid environment the moisture concentration is higher in the absorbent material than in the surrounding environment which causes degradation to the embedded tag’s antenna in terms of dielectric losses and change of input impedance. The amount of water in the absorbent material is determined for a passive RFID system by comparing the difference in the RFID reader output power required to power up the open and embedded tag, respectively. It is similarly shown how the backscattered signal strength for a semi-active RFID system is proportional to the amount of water in the absorbent material. Typical applications include moisture detection in buildings, especially from leaking water pipe connections hidden within walls. The presented solution has a cost that is comparable to ordinary RFID tags. The passive system also has infinite life-time since no internal power supply is needed. The concept is characterized for two
commercial RFID systems, one passive operating at 868 MHz and one semi-active operating at 2.45 GHz.

5.9 Paper IX

The paper presents a review in relation to existing system integration technologies relevant for smart packaging applications. The objective is to summarize and to outline possible future technology directions for system integration of electronic functionalities in paper based packaging solutions. Recent advances in printed electronics, RFID tag production and standardization of communication protocols are factors that increase the design freedom for new applications. As in all new technology fields the first products are expected to appear in the high cost segment attracting early adopters in the form of niche products. A reasonable assumption is that these products will come from hybridization of different types of technologies. Such a scenario is likely since no technology solution available can provide all the features that these types of applications demand.

There is a requirement for standard solutions for the hybridization of silicon devices and printed (or foil type) components. Conductive ink technology is a powerful tool for hybridization and customization of large area electronics providing 3D integration and large area customization. However, high performance communication and advanced processing demands the use of silicon. Smart hybridization solutions allow for a combination of the best from both worlds.

This work provides a technology review and an analysis of the requirements for a hybridization technology suitable for smart packaging applications. To illustrate the concepts discussed we also present design examples on intrusion surveillance solutions for cellulose based packaging applications.

5.10 Author’s contributions

The contribution of the author of this thesis has been essential to all the papers listed in Table 22.
Table 22. Author’s contribution (M = Main, C = Co-author)

<table>
<thead>
<tr>
<th>#</th>
<th>TU</th>
<th>HN</th>
<th>BO</th>
<th>JS</th>
<th>HA</th>
<th>AM</th>
<th>CL</th>
<th>SF</th>
<th>KH</th>
<th>MG</th>
<th>TO</th>
<th>PJ</th>
<th>AK</th>
<th>XZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>M</td>
<td>C</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Main writer and measurements (70%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>M</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Main writer and measurements (95%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>M</td>
<td>C</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Main writer and measurements (90%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>M</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Main writer and measurements (98%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>C</td>
<td>C</td>
<td>M</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Writer and measurements (24%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>C</td>
<td>M</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Measurements and discussion (10%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VII</td>
<td>C</td>
<td>M</td>
<td>C</td>
<td></td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Measurements (32%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>C</td>
<td>C</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Measurements, writing and discussion (30%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IX</td>
<td>C</td>
<td>M</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TU: Writer and discussion (20%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TU: Tomas Unander  HA: Henrik Andersson  KH: Krister Hammarling  AK: Andrey Koptyug  
BO: Bengt Oelmann  CL: Cecilia Lidenmark  TO: Torbjörn Olsson  
JS: Johan Sidén  SF: Sven Forsberg  PJ: Peter Jonson
6 THESIS SUMMARY AND CONCLUSIONS

The design and characterization of a battery assisted passive RFID sensor platform together with the fabrication and characterization of printed low cost sensors have been presented in this thesis. An introduction to the research area has been provided in section 1. In section 2 the BAP RFID sensor platform is presented and evaluated for three smart packaging applications. In section 3 six different moisture sensor solutions are presented. Some of these are printed whilst others utilize ordinary commercial available systems to give moisture sensing features. The moisture sensor solutions are targeting applications such as the moisture monitoring of wood fibre based packages, moisture and leakage detection in buildings and health care systems.

In section 4 a printed touch sensitive sensor solution has been presented. The targeted applications for the touch sensitive sensor solution are large area touch sensitive commercial stands, flat keyboards at the point of purchase and touch and manipulation surveillance in logistic chains. Section 5 gives a brief summary of the original papers that this thesis is based on.

The low cost sensor solutions evaluated show a good correlation to the targeted specification set by the applications. In the following sections a more detailed summary and conclusion for the different sensor solutions are presented.

6.1 BAP RFID based sensor system

In section 2 a battery assisted passive RFID sensor system is presented. The proposed RFID platform provides a trade-off between, communication performance, compatibility with international standards and flexibility in on-package customization including type and number of sensors. The proposed architecture separates the high performance communication circuit and the low frequency sensor interface logic. In the future the sensor interface maybe integrated using printed logics to further enhance the flexibility and low cost customization features of the architecture.

Smart packing applications demand large volumes, and low cost production as well as low cost customization for each product. A trade-off between all these demands is necessary in order to obtain a competitive technology platform. The proposed structure has the advantage of providing the required communication performance and the design flexibility for the specific application. The forecast in relation to printed electronics indicates that low frequency digital circuits (sensor interfaces) are ready for large scale commercialization within the foreseeable future [26, 140]. Such technology could very well replace the sensor chip in our platform and thus provide low cost customization solutions with high performance communication by the silicon RFID Gen 2 chip.
The study shows that it is possible to manufacture a laboratory RFID based sensor platform with a reading range within the same range as a commercially available Gen 2 tag. The laboratory set-up of the sensor platform has been shown to be readily tailored to work with different types of sensors.

6.2 Printed moisture content sensor for wood fibre based substrates

In section 3.1 a printed moisture content sensor has been presented. The sensor solution is based on the same capacitive sensor concept as the touch sensitive sensor solution presented in section 4, but, in this case, the effect of the moisture dependency is characterized.

The result shows a good correlation between the sensor response and the moisture content in cellulose based substrates. The evaluated sensor solution has a measuring accuracy with a coefficient of variance of 0.22% and a temperature difference of 0.36%. A laboratory set-up of a two chip semi-passive RFID tag with moisture content sensing features has also been presented.

6.3 Printed relative humidity sensor for high relative humidity levels

In section 3.2 a relative humidity sensor has been presented. The sensor solution is based on a resistive measuring technique that measures the DC current through a sensor. The DC current is determined by measuring the voltage over a resistor in series with the sensor two seconds after a 0 to 1.55 V transition.

The experimental results show that in order to manufacture as good a sensor as possible the sensor should be manufactured with a highly conductive material and the line spacing between the electrodes in the two-dimensional structure (Figure 18) should be as short as possible to increase the DC current through the sensor.

6.4 Printed action activated moisture sensor

In section 3.3 a printed action activated moisture sensor has been presented. The sensor is based on an energy cell that provides power when activated by moisture.

The result shows that the concept of using carbon-zinc energy cells as an action activated moisture sensor is feasible. It also shows that the sensor can be manufactured with different trigger and signal levels to be optimized towards specific applications. The sensor can utilize the hysteresis effect of hygroscopic materials, such as cellulose based paper, to provide a stable triggering signal. A defrosting alarm for the monitoring of frozen articles has been presented. The sensor is triggered after approximately a minute or less after the sensor
temperature rises above zero degrees centigrade. By stacking four energy cells in series it is possible to power up and program the RFID based sensor platform presented in section 2.

6.5 Remote moisture sensing utilizing ordinary RFID tags

In section 3.4 a remote moisture sensor that utilizes ordinary RFID tags has been presented. The concept is based on an idea in which a pair of RFID tags is used, where one is embedded in a moisture absorbing material while the other remains open. The power difference required to power up the tags is used to determine the humidity in the moisture absorbing material.

The results show that the concept with remote moisture sensing using ordinary RFID tags is feasible. The difference in power levels for the different levels of relative humidity proved to be of the order of approximately two to three decibels for the 80% relative humidity and it is possible that this humidity level might prove to be the starting point for the source of mould. The hysteresis effect of paper materials could be the source of a problem since it may make incorrect readings due to memory effects. However, an incorrect reading due to hysteresis still indicates that the humidity level has been high.

6.6 Printed nano-particle based sensor moisture sensors

In section 3.5 an initial study on a printed nano-particle based relative humidity sensor has been presented. In the study two different types of sensor structures are investigated, one being a horizontal single layer structure for high humidity levels and the other being a two-layer structure for very dry moisture conditions. The printed single layer solution utilizes short and narrow lines of silver nano-particles for humidity detection. The two-layer solution utilizes an effect in unsintered silver nano-particles to measure the relative humidity in the surroundings. The measurements in both of the solutions are conducted by measuring the DC resistance in the printed nano-particle based sensors.

The result shows that it is possible to manufacture printed moisture sensors with silver nano-particles. For the two-layer relative humidity sensor for very low humidity levels 75% of the samples had a variance of 8% without calibration of the single samples. The sensor solution shows a linear response as the relative humidity is increased from 10% to 50%. However, the sensor shows a hysteresis effect when the relative humidity is again reduced down to 10%.

6.7 Printed touch sensitive sensor

In section 4 a printed touch sensitive sensor has been presented. The concept of the sensor solution is to incorporate a touch sensitive sensor into a high quality
image. The sensor solution is based on a capacitive measuring technique. The building blocks of the sensor solution are presented with the printed sensor structure, the readout electronics and the communication interface.

The result shows that it is feasible to manufacture a touch sensitive sensor integrated into a high quality image on cellulose based substrates. It has been shown that the touch sensitivity is the same at 50% as 85% relative humidity. However, there is a tendency towards higher noise level at 85%. The sensor solution shows no difference in touch sensitivity between sensor samples printed with silver or carbon based ink.

6.8 Conclusions

The work in this thesis has shown the possibility associated with combining printed large area components, such as, antenna, sensor and interface, with traditional silicon based electronics in order to achieve a two-chip BAP RFID based sensor platform directly on wood fibre based substrates. A theoretically long battery lifetime of the platform has also been shown by using commercially available printed batteries. The thesis also show the possibility to, with printed means, create moisture sensing features on wood fibre based substrates, such as, moisture content sensor, relative humidity sensor and AAT sensor. Concepts, using commercially available RFID tags, in order to create moisture sensitive sensors that can be read remotely, have also been discussed.
REFERENCES

[16] ThinFilm Electronics, [Online], Available: http://thinfilm.se
[23] UHF Class 1 Gen 2 Standard v. 1.2.0, [Online], Available: http://www.gs1.org/sites/default/files/docs/uhfc1g2/uhfc1g2_1_2_0-standard-20080511.pdf


Presentation of EM4325 RFID chip (under development), [Online], Available: http://www.stech.cz/download.php?id_document=401158198&at=1


3V lithium battery technical overview, [Online], Available: http://www.renata.com/content/3vlithium/overview.php


SkyeTek, [Online], Available: http://www.skyetek.com


Coates Screen, [Online], Available: http://www.coates.com

MACtac, [Online], Available: http://www.mactac.com


Mettler Toledo, [Online], Available: http://www.mettler-toledo.com


Ramarao V. Bandaru, Professor & Associate Director, Department of Paper & BioProcess Engineering, Empire State Paper Research Institute, State University of New York College of Environmental Science & Forestry, private communication, 2009


[70] IXYS Corporation, [Online], Available: http://www.ixys.com


[79] P. M. Harrey, B. J. Ramsey, P. S. A. Evans, D. J. Harrison, “Capacitive-type humidity sensors fabricated using the offset lithographic printing process”,

93


[112] SCA Luna core, [Online], Available: http://www.sca.com/en/pulp/Products1/Luna1/Luna-Grades/Luna-Core


[128] Mid Sweden University project “New system integration tools for printed intelligence in packaging applications”, MIUN 2010/1802
[137] RF Solutions Ltd., [Online], Available: http://www.rfsolutions.co.uk
PAPER I

Printed touch sensor for interactive packaging and display
PAPER II

Characterization of printed moisture sensors in packaging surveillance applications
PAPER III

Design of RFID based sensor solution for packaging surveillance applications
PAPER IV

Evaluation of RFID based sensor platform for packaging surveillance applications
PAPER V

Inkjet printed silver nanoparticle humidity sensor with memory effect on paper
PAPER VI

Printed write once and read many memories in smart packaging applications
PAPER VII

Characterization of moisture sensor based on printed Carbon-Zinc energy cell
PAPER VIII

Remote moisture sensing utilizing ordinary RFID tags
PAPER IX

System integration of electronic functions in smart packaging applications