Intelligent and Interactive Package
Based on RFID and WSN

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I would like to dedicate this thesis to my family!
ABSTRACT

An intelligent and interactive package can interact with people smartly, safely and friendly. It involves many technologies such as electronics, optics, biologic, magnetics and electro-mechanics. By combined with Radio Frequency Identification (RFID) and Wireless Sensor Network (WSN), intelligent and interactive packaging technology has been an emerging and global research topic over the years.

In this thesis, a new technology, named Controlled Delamination Material (CDM), is introduced. It was primarily used in aerospace applications in the past and further developed by Stora Enso AB. A CDM product can delaminate easily in a controlled way by the use of electrical current. This concept opens up many interesting application possibilities for the traditional packaging industry. In order to understand the delamination mechanism, some related work on the electrochemical characteristics of the material showed the possibility to facilitate the interactive packaging system design.

A paper-based package which is integrated with RFID system and CDM is presented to realize an intelligent and interactive system. It can be opened automatically through a finger touch. The opening action is controlled electrically by RFID system. The test results of the demonstration have proved feasibility of the solution and shown the potential for mass production.

Following this solution, an interactive pharmaceutical package for pervasive healthcare is proposed by using EPCglobal Gen2 RFID technology. A Gen2 RFID system significantly increases the efficiency of information exchange, and reduces the medication error rate and the possibility of sale counterfeit drugs. It makes the medication accessible for patient only at the prescribed dose and time, and at the same time, the information for the action of taking medication will be delivered to the doctor as well. Such interactive pharmaceutical package not only gives unprecedented high patient compliance, but also improves the communication between patients and healthcare staffs.

By integrating WSN with various bio-chemical sensors, in addition to temperature and moisture sensors, more kinds of information can be involved in the intelligent and interactive packaging communication system. It enhances the functionalities of the package such as protecting the integrity and effectiveness of product, providing safety information details, and being child resistance, senior friendliness.
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Although my name stands alone on the book cover, this thesis and the included researches would not exist without the supports of many other people. Now I have the opportunity to extend my sincere gratitude to them.

First of all, I would like to thank my parents who always encourage and support me in ever decision with infinite patience and endless love. They make my life wonderful and meaningful!

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Thanks to the CDM project, Fresh Food project, and VINNOVA (The Swedish Governmental Agency for Innovation Systems) for the financial support.

Last but not least, to all of my family and friends, nothing will be possible without you. Thank you for reminding me of everything that life is all about.

To everybody mentioned, and those I forgot – Thank you!!!

Jie
Stockholm, September 2010
List of Publications

Paper included in this thesis


In this paper, an interactive and intelligent packaging solution integrating RFID and CDM technology is first presented. A package sealed off with CDM product could be opened automatically and electrically in 20 seconds. Passive RFID technology is used to control the opening action. Test results of the demonstration have proved the feasibility of the proposed interactive packaging solution. Based on this basic solution, an interactive medical package of unprecedented high patient compliance for pervasive healthcare is suggested. Combining RFID with CDM, the medicine packages are senior-friendly, automatic to open with authorization for right dose and right time, and resistant without approval.

Author’s contributions: The author proposed an intelligent and interactive package solution, finished the first demonstration of it, set up the related tests, and wrote the paper.


In this paper, a CDM product named Sinuate® is introduced. It is a metal/glue material with a sandwiched structure which will delaminate if giving a DC or AC power supply for a while. In opening process, the maximum current on the material at a DC power supply is almost 1 mA/cm², which is similar with the results in the previous researches. When being applied to an AC pulse supply, just little time more needed to open the material. Because more processes will start following with the electrochemical reactions to realize the opening action of the material. Though the opening time is litter longer, using AC pulse power supply is a more feasible way than the one using DC. It is easier to design more application circuits based on CDM by provided an AC pulse power supply.

Author’s contributions: For the further development of Sinuate®, the author set up the related experiments to test and analyze its electrochemical characteristics, and wrote the manuscript.

In this paper, an enhanced dual-layer dual-directional wide area wireless sensor network system is applied in fresh food tracking application. An essential set of useful measurements is provided to monitor the environmental conditions during fresh food transport. Since 3-axis acceleration data account for 99.89% data amount out of all collected data, we propose in this work a novel lossy acceleration compression scheme. The source acceleration data are extracted into three components, and then each component is compressed separately according to its distinct characteristic and then packetized as an encoded frame. Field test data are used for acceleration data compression experiment. Experimental results confirm that the compression scheme proposed in this work could achieve a high compression ratio with the acceptable distortion.

Author’s contributions: As a study case of the thesis, the author was involved in the work for a further developed demonstration and its related testing.


In this paper, a novel WAN-SAN Coherent Architecture is proposed to enhance the mobility, deployment and capability of wireless sensors for networked services. A system based on the proposed architecture is developed, including hardware modules, protocols, application interfaces, and system software. Due to the dual-layer dual-directional wireless communication capability and the removal of fix-installed gateway, all sensor nodes are mobile, remotely controllable and wide area deployable for networked services. An application example of the system has been successfully deployed and tested in field for Fresh Food Tracking service.

Author’s contributions: As a study case of the thesis, the author was involved in the work for a further developed demonstration and its related testing.
LIST OF FIGURES

Fig. 2.1: The structure of an RFID system. ................................................................. 30
Fig. 2.2: Near-field communication via inductive coupling at less than 100 MHz. .... 31
Fig. 2.3: Far-field communication via backscattering at greater than 100 MHz. ... 32
Fig. 2.4: The structure of a sensor node. ................................................................. 36
Fig. 2.5: The operation of sensor nodes ................................................................. 37
Fig. 2.6: Hierarchical layer of WSN. ................................................................. 38
Fig. 3.1: The structure and opening action of a CDM product ................................ 44
Fig. 3.2: Way to definite the delamination ............................................................ 44
Fig. 3.3: System concept for a smart packaging solution ...................................... 45
Fig. 3.4: Flow chart of operation ................................................................. 46
Fig. 3.5: PCB view of Watcher ........................................................................... 48
Fig. 4.1: Current waveform on Sinuate® at 30V DC voltage. .............................. 51
Fig. 4.2: Current waveforms at different DC power supplies. ............................ 52
Fig. 4.3: The total opening time at different DC power supplies. .......... 53
Fig. 4.4: Test circuit for AC pulse opening behaviors ........................................ 54
Fig. 4.5: AC pulse behaviors (I_{top} vs. T_{o}) ......................................................... 55
Fig. 4.6: The peak current at different frequency and duty cycle. .................... 55
Fig. 4.7: The average current at different frequency and duty cycle ................. 56
Fig. 4.8: The total opening time for CDM at AC pulse supply. .......................... 56
Fig. 4.9: The charging time at different frequency and duty cycle .................. 57
Fig. 4.10: The quantity of electrical charges in CDM product ......................... 58
Fig. 4.11: Demonstration for an interactive packaging solution ....................... 59
Fig. 4.12: Voltage pulse generation ................................................................. 59
Fig. 5.1: Logical Memory structure for EPC Gen2 RFID Tag ......................... 64
Fig. 5.2: System concept for a interactive medical packaging solution ............ 64
Fig. 5.3: Information flow chart for MedSystem .............................................. 66
Fig. 5.4: Programmable multi-outputs waveform ............................................. 67
Fig. 5.5: Fresh food tracking system in one truck ........................................... 68
Fig. 5.6: Medical care network ................................................................. 69
Table 2-1: RFID operating frequencies and characteristics..............................32
LIST OF ABBREVIATIONS

Alternating Current ................................................................. AC
Analog-to-Digital Converter .................................................... ADC
Automatic Identification System .............................................. Auto ID
Complementary Metal–Oxide–Semiconductor ................................ CMOS
Controlled Delamination Material ............................................ CDM
Direct Current ......................................................................... DC
Free Space Optical .................................................................... FSO
Frequency Hopping Spread Spectrum ....................................... FHSS
General Packet Radio Service ................................................ GPRS
Global System for Mobile Communications .............................. GSM
Industrial, Scientific and Medical ............................................. ISM
Integrated Circuit ..................................................................... IC
Internet of Things ..................................................................... IoT
Near-Field Communication ..................................................... NFC
Micro-programmed Control Unit ............................................. MCU
Optical Character Recognition ................................................ OCR
Personal Digital Assistants ...................................................... PDA
Printed Circuit Board ............................................................. PCB
Radio Frequency Identification ................................................ RFID
Radio Frequency ...................................................................... RF
System in Package .................................................................... SiP
System on Chip ........................................................................ SoC
Ultra High Frequency ............................................................. UHF
Ultra-Wideband ......................................................................... UWB
Wide Area Network ............................................................... WAN
Wireless Sensor Network ......................................................... WSN
Worldwide Interoperability for Microwave Access ................. WiMAX
# Contents

Abstract ................................................................................................................................... V
Acknowledgments ............................................................................................................... VII
List of Publications ................................................................................................................ IX
Summary of The Included Papers ......................................................................................... XI
List of Figures ..................................................................................................................... XIII
List of Tables ...................................................................................................................... XIV
List of Abbreviations ........................................................................................................... XV

1 Introduction ................................................................................................................... 19
  1.1 Project Motivation .................................................................................................. 21
  1.2 Outline of the Thesis ............................................................................................... 21

2 Background .................................................................................................................... 25
  2.1 Interactive Packaging .............................................................................................. 27
  2.2 Radio Frequency Identification ............................................................................... 28
    2.2.1 Auto ID Technology ........................................................................................ 28
    2.2.2 RFID System ................................................................................................... 29
    2.2.3 Applications ..................................................................................................... 33
    2.2.4 Challenges ....................................................................................................... 35
  2.3 Wireless Sensor Network ........................................................................................ 35
    2.3.1 Fundamentals ................................................................................................... 36
    2.3.2 Applications ..................................................................................................... 39
    2.3.3 Challenges ....................................................................................................... 39
  2.4 Summary ................................................................................................................. 40

3 Material and Solution .................................................................................................... 41
  3.1 Controlled Delamination Material .......................................................................... 43
    3.1.1 Physical Structure and Features ....................................................................... 43
    3.1.2 Way to Define Delamination ........................................................................... 44
  3.2 Interactive Packaging Solution ............................................................................... 45
    3.2.1 System Concept ............................................................................................... 45
    3.2.2 Functional Description .................................................................................... 46
    3.2.3 Hardware ......................................................................................................... 47
  3.1 Summary ................................................................................................................. 47

4 Tests and Results ........................................................................................................... 49
  4.1 Sinuate® with CDM Technology ........................................................................... 51
    4.1.1 DC Opening/Debonding Behaviors ................................................................. 51
    4.1.2 Pulse Opening Setup and Behaviors ................................................................. 53
  4.2 Demonstration for the Interactive Packaging Solution ........................................... 58
    4.2.1 Voltage Pulse Generation ............................................................................... 58
    4.2.2 Reading Distance ............................................................................................. 59
    4.2.3 Programmable Control ................................................................................... 59
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.4</td>
<td>Current on the Material Surface</td>
<td>60</td>
</tr>
<tr>
<td>4.3</td>
<td>Summary</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Discussion</td>
<td>61</td>
</tr>
<tr>
<td>5.1</td>
<td>Medical Package with High Compliance</td>
<td>63</td>
</tr>
<tr>
<td>5.1.1</td>
<td>System concept</td>
<td>63</td>
</tr>
<tr>
<td>5.1.2</td>
<td>EPCglobal Gen2 RFID Tag</td>
<td>63</td>
</tr>
<tr>
<td>5.1.3</td>
<td>System Concept</td>
<td>64</td>
</tr>
<tr>
<td>5.1.4</td>
<td>Functional Description</td>
<td>65</td>
</tr>
<tr>
<td>5.2</td>
<td>Fresh Food Tracking</td>
<td>67</td>
</tr>
<tr>
<td>5.3</td>
<td>Medical Care Network</td>
<td>68</td>
</tr>
<tr>
<td>5.4</td>
<td>Summary</td>
<td>69</td>
</tr>
<tr>
<td>6</td>
<td>Conclusions and Future Work</td>
<td>71</td>
</tr>
<tr>
<td>6.1</td>
<td>Conclusions</td>
<td>73</td>
</tr>
<tr>
<td>6.2</td>
<td>Future Work</td>
<td>73</td>
</tr>
<tr>
<td>Bibliography</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>Appended Papers</td>
<td></td>
<td>79</td>
</tr>
</tbody>
</table>
Chapter One

1 INTRODUCTION

In this chapter, the motivation of the research project will be provided first. The outline of the thesis and the contribution of the author will be followed.
1.1 Project Motivation

This project is a part of the iPack VINN Excellence Centre at KTH.

CDM is a new material technology developed by the Stora Enso. Consumer packages, joined together using CDM, can delaminate in a controlled way by the use of electrical current. A package sealed with CDM product will open in several seconds, when the surface of the CDM product is applied to enough voltage. This concept creates many interesting ideas for the packaging industry, especially for interactive packaging.

The goal of this project is to develop integrated electronics for an interactive package concept which can be opened electronically (E-Open), based on the physical and chemical mechanisms of the material. Over 30V power supply is needed in order to electronically open the package in reasonable time. According to a better understanding of the study results from related projects about the material delamination mechanism and electrochemical system characterization, the aims of this project are including:

- To integrate CDM technology with electronic systems and realize innovative interactive packaging solutions based on RFID technology.
- To find solutions to achieve ultra-low power and logic electronics integrated in low cost.
- To further explore the CDM applications combined with other technologies e.g. WSN.

1.2 Outline of the Thesis

The remainder of the thesis is structured as followed:

Chapter Two: Background

This chapter gives an overview on the three hot technologies in the world nowadays, which are Interactive Packaging, Radio Frequency Identification (RFID), and Wireless Sensor Network (WSN). At first, a short overview shows a clear picture of the development for the interactive packaging technology. After that, several kinds of automatic identification systems are briefly introduced. Among them, RFID is proved to be one of the friendliest and the most popular technologies which have been widely used all around recent years. Then some applications are followed. Due to large potential benefits and low cost, the vantages of RFID are obvious. After that, the principle and structure of a WSN system is given with several applications. Although these three technologies have many challenges in optimization and improvement, with the growing needs from market, more and more research centers and companies pay much attention on them.

Chapter Three: Material and Solution

This chapter introduces a CDM product, Sinuate®, in details, such as the physical structure and some chemical features. An interactive and intelligent packaging solution
sealed with Sinuate® and RFID is presented followed. The system concept, software platform and hardware circuit are also given.

The detailed parts have been published in:


Jie Gao, Zhibo Pang, Qiang Chen and Li-Rong Zheng, "A Study on Electrical Properties of Controlled Delamination Materials", Manuscript

Chapter Four: Tests and Results

This chapter presents some related experiments on the material and demonstration. In order to make the delamination mechanism clear, several related tests on Sinuate® were performed at first, such as DC opening behaviors and pulse opening behaviors. With the results of tests, the delamination phenomenon and data are analyzed. After that, the test results on the demonstration indicate that the system works pretty well.

The detailed parts have been published in:


Jie Gao, Zhibo Pang, Qiang Chen and Li-Rong Zheng, "A Study on Electrical Properties of Controlled Delamination Materials", Manuscript

Chapter Five: Discussion

This chapter suggests an interactive medication package solution for pervasive healthcare at first. Based on the previous interactive and intelligent packaging solution, it will use the EPCglobal Gen2 RFID technology which allows much more information involved during the system operating process. After that, two related study cases are followed. The fresh food tracking system can improve the transportation scheme, and further protect the fresh food. The medical care network can work collaboratively to supply the safe, comfortable and efficient medical care service.

More details can be found in:


**Chapter Six: Conclusions and Future Work**

This chapter summarizes the thesis and outlines the future work.
Chapter Two

2 BACKGROUND

In this chapter, three related technologies of this thesis, Interactive Packaging, RFID and WSN, are introduced briefly and individually.

First of all, interactive packaging technology is an emerging technology and around us everywhere for years. A short overview of the interactive packaging technology development shows that the intelligent package with lower cost can bring us an easy and smart life.

Secondly, although 2D barcode has taken a large part in retail and logistics areas near two decades, other Auto ID technologies are also developed rapidly. Especially for RFID, it is a convenient method for identification. It can be easily embedded in objects, and has bigger reading range and faster data transfer speed. Due to these advantages, RFID is extensively studied and used in many different research and industry areas, such as logistics, pharmaceutical management, keyless entry, item identification and tracking, etc.

At last, based on the sensor and network technologies, WSN technology has developed fast in recent years. The advantage of lower power consumption makes it widely used in many fields. But it also has challenges in lifetime extension, and high self-adapting, etc.
2.1 Interactive Packaging

A common packaging of health and beauty product usually costs three times as much as to make the content itself [1]. Normally, product packaging is used to protect goods to improve its quality and safety. It makes the product easy and quick to be stored, delivered and transported. The packaging cost consists of advertisement, raw material, direct and indirect labor, warehousing, quality control, and related machinery, etc., which will be folded into the sale price of the goods. For the commercial market, it is always regarded as an extra overhead, and most of the customers do not want to pay for it.

With the rapid increase of the requirements from customers and packaging industries, including the safety of products, the cost of raw materials and the energy needed for production, product packaging cost becomes higher and higher steadily during the past decade. A study about the new US industry forecasts shows that the US foodservice packaging demand reached $7.6 billion in 2008, and the number was $6.2 billion in 2003 [2].

On the other hand, packaging design not only has effects on whether a new product can enter the market for commodity circulation successfully or not, but also affects the sale price and sales volume. A unique packaging design can make the product different from the other competitors, stimulate consumers’ interest to buy it, and improve its competitiveness. When the goods are on the shelf, their packages are also advertising itself on the shelf, which means the packaging acts as a “silent salesman”. Therefore, the packaging is regarded as the fifth "P" factor of the marketing mix which also includes Product, Price, Place, and Promotion.

Equipped with some modern technologies, an attractive and smart packaging solution makes consumers tend to be willing to pay much more to buy the product. With wireless communication technology, additional content, coupons, or promotions can be sent directly to the consumer and tailored to meet their needs and concerns from the product packaging in time. In addition, a product accompanied good packaging can have a higher price, so that the corporations can obtain much more profit.

Recent years, besides the packaging and forest industries, more and more companies have been looking for new ways to lower their costs on packaging and logistic processes in order to raise the profit margins. Some companies have shown the ability to place smart tags on a variety of packaging surfaces. Graphic Packaging International (GPI) announced the first commercial application of its integrated mobile marketing system, Snap2C, on a US chicken processor’s paperboard containers in 2008, which created real-time marketing connections between consumers and products at the point of sale in the store and at the point-of-use in the home [3]. Wal-Mart unveiled a "Packaging Scorecard" program in 2006 to improve packaging, reduce emissions and save energy [4]. Ericsson’s packaging engineers created a simple calculation model that can calculate the total packaging cost and compare different packaging solutions in order to find the most effective packaging solution [5].

As mentioned above, interactive and intelligent packaging is an emerging research area nowadays. It is one of the new methods to improve product price/performance ratio. It puts emphasis on effective protective packaging designs to protect products, and also to promote,
identify and communicate corporate information. It brings people convenient and smart life, reduces consumption of traditional packaging materials and direct or indirect labor costs as well. At the same time, the needs from users are increasing, such as to know more information about the product like what is in the package, how to use it, where and how the product has been stored and transported, etc. With the development of the technology, more societal factors are likely to aid the growth of interactive and intelligent packaging in the near future.

2.2 Radio Frequency Identification

2.2.1 Auto ID Technology

Auto ID technology has been spread and promoted rapidly for items identification, distribution, management and tracking in the fields of production, logistic, sale, transportation and related service for decades. It provides a platform for information collection, processing and identification. It is a technology which integrates semiconductor manufacturing, computer software and hardware, optical, communications, electronic circuits and engineering, electromagnetic, network technology, automatic control, security, and business processes. The main Auto ID applications include Barcode, Smart Card, Biometrics, Optical Character Recognition (OCR) and RFID [6]. All of them can be seen almost everywhere in our daily life.

Barcode

After got a patent, barcode was primarily used commercially in a US supermarket in 1967. The first generation of barcode was combined with a series of narrow or wide black lines and write blank, which represented some basic information of the product in the width and the spacing of parallel lines such as name, manufacturer and location, and category, etc. It has been developed quickly in forty years. Till now, there are dozens of linear barcodes and a wide variety of matrix (2D) barcodes (which is similar to a 1-dimensional barcode, but has more information capability). On the other hand, barcode is very cheap to produce, but it has lots of limitations. It requires an optical readable machine, a short distance and a clear line of sight between the code and reader, and it can only be obscured by greased and nearby object.

Smart Card

A smart card, also known as an integrated circuit card (IC card), looks like a poker card in shape. Without any power supply inside, instead, it has an embedded microprocessor, some I/O ports and memories. The processor uses a limited instructions set for the smart applications, and may be up to 16 bits. A smart card gets power to work from a card reader, and the data on it can be easily read, written, or deleted by communication between card and reader through the bidirectional I/O ports. It provides identification, authentication and data storage for many applications such as mobile phone, electronic cash, security system, wireless communication, and bank business, etc. But it also has some disadvantages. The vulnerability of the contacts between card and reader is very easy to wear, corrosion and dirt, and the reader cannot be completely protected against vandalism as well [6].
**Biometrics**

Previously, biometrics means the statistical and mathematical methods applicable to data analysis problems in the biological sciences. In recent years, according to the diversification of biological traits, biometrics is also used in the field of individual identification, such as fingerprinting procedures (dactyloscopy), voice identification, retina (or iris) scanning, and face recognition, etc. With the help of the biological sensors on high accuracy, the biometric identification of high-precision is widely used in security, detection and tracking systems. But the cost of the related equipment is very high, which may affect the spread of the biometrics in the commercial market.

**OCR**

OCR is the recognition of scanned images of printed or handwritten text, which includes photo scanning of text character, analysis for scanned image, translation from image to code, and manual check. In the recognition process, the scanned character image is analyzed for light and dark areas in order to identify each alphabetic letter or number. Once a character is recognized, it will be converted into a corresponding code. It avoids the trouble to reenter data for the printed materials, and it is easy to convert paper documents into electronic files. To speed up the OCR process, special designed circuit and software is needed, which will increase the system cost. Many research fields are involved in OCR system, such as pattern recognition, artificial intelligence and computer vision. It is no doubt that the information in OCR system is in high density, but the high price and complexity discourage its promotion.

**RFID**

In addition to those above, RFID technology is regarded as a fundamental Auto ID technology for universal services of our everyday life. According to the latest RFID annual market overview from ABI Research, the total revenue earned from RFID transponders, readers, software and services would amount to more than $5.6 billion in 2009 [7]. Comparing with other automatic identification technologies like barcode and OCR, an RFID system has a higher data density and provides much more information. An RFID tag can be read and recognized manually by an RFID reader which can be a simple and portable installation. The reading process is rid of the influences from light, humidity, direction, location and pollution, but whether reader can get the information from the tag or not is determined by the reading distance between them. Among all the Auto ID systems, the RFID system has the longest reading range, which is suitable for some large-scale and long-distance applications. Comparing to biometrics (like fingerprinting and voice recognition) and OCR, the cost of an RFID system is really much lower. That is why the RFID system is considered as the next generation of wireless communication system, and its influence exceeds that of other Auto ID systems by far [8].

2.2.2 **RFID System**

Invented in 1940s, RFID technology was used in World War II for aircraft identification for foe or friend in its initial trials. After that, the studies on RFID system and its applications became hotter and hotter. When a passive RFID transponder was patented in
1963, the researchers made a great breakthrough. Due to the low cost and small size, this technology has soon been fully implemented in commercial and specific applications from 1980s [9].

Recently, with the widespread of RFID, more and more people all over the world came to accept this applied technology which can completely change their daily lives. At the same time, the standardization setting activities appear to meet the needs of the RFID commercial use. Many organizations have made great contributions to the birth of the standards, such as International Standards Organization (ISO, a global organization which concentrates on industry-wide standards) [10], International Electrotechnical Commission (IEC, a global organization which forces on electrical, electronics and related fields) [11, 12] and EPCglobal (an organization set up to achieve worldwide adoption and standardization of Electronic Product Code - EPC technology) [13]. Some of these standards have been used for many years, and some are still being formed and perfected, e.g. ISO/IEC 11784 &11785 for animal identification, ISO/IEC 10536 for close coupled cards, ISO/IEC 18000 for a series of diverse RFID technologies, and EPC Gen1/Gen2. Nowadays, RFID applications are widely promoted with the development of these standards.

An RFID system is fundamentally constituted of two key parts: tags (also called transponders), reader or writer. For further development, a processor and related application host (like local software and infrastructure) are needed in the whole RFID system, as shown in Fig. 2.1. In wireless range, using electromagnetic waves at radio frequencies, the reader/writer collects and exchanges data stored by tags attached on the objects. The reader/writer system communicates with tags via an antenna in order to harvest information for the system applications. The information will be processed by the processor in reader/writer system in order to support further applications.

According to the operating principle, there are three kinds of RFID tags: passive, semi-passive, and active. Among them, a passive tag has the simplest structure which doesn’t have power source inside, and obtains energy only by receiving electromagnetic radiation from reader/writer system to power up its operation [9, 14, and 15]. Although the communication distance is short, long life cycle and low cost make it considered as one of the largest commercial potential [15]. A semi-passive tag has its own power supply, and works by using backscattering [12]. Different from the two above, an active tag has the power source internal and on-tag transmitter. It can realize more complex operations and has a longer reading distance, but it is larger in size and much more expensive.

Due to the lower cost and small size, passive tags are widely used in many fields and have a large market share. Passive RFID tags located on the objects to be identified can also be regarded as transponders. There are two main components present in the RFID tag: an
antenna and a small Integrated Circuit (IC) chip. The antenna is used to receive and send radio frequency waves. The IC chip contains a unique identification number which is utilized as a kind of important data in the process of system communication.

Based on the different communication methods to transfer energy from reader/writer to tags, there are two kinds of passive tags: near-field and far-field coupling.

For its simplicity, near-field inductive coupling is the initial and straighter way to realize a passive RFID system. While a large alternating current flowing through the coil of a reader, an alternating magnetic field appears around it, which is shown in Fig. 2.2. The field generates a small current in the coil of the tag, when the tag is in the magnetic field. After the tag is powered up via the small current, it sends data back to the reader by load modulation. In this process, any current variation of the tag will be detected by the reader and cause a corresponding current variation in the reader.

Compared with the near-field coupling, far-field RFID tag operates at long range which is out of the range of reader’s near field. So the communication between reader and tags cannot be established by information transmitting back via load modulation. The electromagnetic wave is captured by the tag via the antenna attached on the reader, which will create a potential difference to be the energy of the tags, given in Fig. 2.3. In this process, backscattering is used, which means varying the loading on the antenna can change the reflected energy [12]. The reading range for a far-field RFID system depends on the amount of the energy the tag get from the reader and the reflected signal sensitivity of the reader [16]. The advantages of using a far-field RFID system include high operating frequency, small antenna size, and low tag cost, etc.

The reader/writer, as another important part of the RFID system, is a fixed unit or handheld machine. The reader/writer can interrogate nearby RFID tag and get information on it via Radio Frequency (RF) communication. When a passive tag is powered up within the reading range of the reader/writer, the reader/writer can receive or write data on it. A semi-passive tag and an active tag can communicate with the reader/writer directly within a certain range.

Fig. 2.2: Near-field communication via inductive coupling at less than 100 MHz.
Taking advantage of radiate electromagnetic waves, RFID is fundamentally based on wireless communication. When other radio services are also needed to be considered, RFID restricts the suitable operating frequency range for an available system which operates in unlicensed spectrum space. That is why RFID system has its own frequency range which has been reserved specifically for different applications like industrial, scientific or medical and short range devices, as shown in Table 2-1.

<table>
<thead>
<tr>
<th>Band</th>
<th>Low Frequency (LF)</th>
<th>High Frequency (HF)</th>
<th>Ultra-High Frequency (UHF)</th>
<th>Microwave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>30–300kHz</td>
<td>3–30MHz</td>
<td>300 MHz–3GHz</td>
<td>2–30 GHz</td>
</tr>
<tr>
<td>Features</td>
<td>Penetrates water</td>
<td>Penetrates water</td>
<td>Cannot penetrate water or metals</td>
<td>Cannot penetrate water or metal</td>
</tr>
<tr>
<td></td>
<td>but not metal</td>
<td>but not metal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical RFID</td>
<td>125–134 kHz</td>
<td>13.56 MHz</td>
<td>433 MHz 865 – 956MHz 2.45 GHz</td>
<td></td>
</tr>
<tr>
<td>Frequencies</td>
<td></td>
<td></td>
<td>2.45-5.8 GHz</td>
<td></td>
</tr>
<tr>
<td>Read Range</td>
<td>Short</td>
<td>Medium</td>
<td>Long</td>
<td>Very Long</td>
</tr>
<tr>
<td>Read Rate</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>very fast</td>
</tr>
<tr>
<td>Impact of Humidity</td>
<td>None</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Impact of Direction &amp; Location</td>
<td>None</td>
<td>None</td>
<td>Partially</td>
<td>Yes</td>
</tr>
<tr>
<td>Accepted World-Wide</td>
<td>Yes</td>
<td>Yes</td>
<td>Partially (EU &amp; US)</td>
<td>Partially (not EU)</td>
</tr>
<tr>
<td>Typical Applications</td>
<td>Access Control, Security, Animal Tracking, Car immobilizer, Chip Cards, Identification, Public Transport, Smart Labels, Contact-less Cards, ...</td>
<td>Libraries, Ticketing, Tracking &amp; Tracing, Airport Baggage, Parcels, Pharmaceuticals, ...</td>
<td>Specialist Animal Tracking, Logistics, Trucks, ...</td>
<td>Road Toll, ...</td>
</tr>
</tbody>
</table>

Table 2-1: RFID operating frequencies and characteristics.
2.2.3 Applications

For the past decades, RFID technology came to be one of the most popular technologies. It has been widely used by manufacturing industries, logistic providers, supply chain managements, retails, banks and exhibitions for the purpose of status identification, whereabouts tracking and process detection on products or animals. According to the recent RFID market forecasts of IDTechEx, the value of RFID systems and its related services has been increasing from $2.77 billion in 2006 to $12.35 billion in 2010, and it will tend to be $26.23 billion in 2016 [17]. On the other hand, the consumption of RFID tags was 1.3 billion in 2006, and it will rocket to more than half a trillion tags in 2016. It means the RFID market value will increase almost ten times over that period [17], since their potential cost is only $0.05 per tag now[18].

Following the history of RFID technology, it is no doubt that the trend of the development for RFID commercial applications mainly contains size miniaturization, cost reduction, energy saving, and large-scale production, etc. In the coming years, RFID will be expected to be a ubiquitous technology which is helpful in solving a variety of problems in a wide range of industries. The RFID applications have fostered large-scale implementations in the livestock or pets tracking, personal identification, access controls, ticketing system, automatic payment, supply chain, pharmaceutical tracking and management, etc.

Livestock or Pets Tracking

Livestock tracking is one of the oldest RFID applications. It is used to help farmers to make sure the number and location of their livestock, and get accurate information for providing feed and water at optimal location and time at all times. This technology is widely utilized to promote pets tracking nowadays. The RFID tag attached on the pet provides the name of the pet and its owner, as well as its contract information. The information can be read by a wireless RFID reader which may be a small box carried by the owner. Besides, due to helping animal protection organizations to track migration patterns, monitor population growth or decline, and evaluate breeding locations, it is also a tool for valuable wild life conservation.

Personal Identification

After the RFID animal tracking experiments have been proved to be safe and successful, more and more ideas on personal identification are emerging. A student in school can borrow a book in the library, have a lunch in the dining-hall, and book a venue for tennis in gymnasium with only a student ID card which has an RFID chip inside to prove who he/she is.

After Malaysia issued the world first passport with RFID chip embedded in 1998, many countries followed, involving Norway, Japan, Spain, Australia, the United Stated, Serbia, and Korea, etc. But the report in May 2005 from the United States Government Accountability Office (U.S. GAO) pointed out that "Without effective security controls, data on the tag can be read by any compliant reader; data transmitted through the air can be intercepted and read by unauthorized devices; and data stored in the databases can be accessed by unauthorized users" [19]. Also, in 2006, a report named “The Use of RFID for Human Identity Verification”, from U.S. Department of Homeland Security (DHS) Data Privacy and Integrity Advisory Committee, mentioned that using RFID-enabled systems to
track materiel was proved to be feasible and safe, but “The case for using RFID-enabled systems by the government to identify and record the presence of individuals requires a more careful analysis involving the mission to be accomplished, the alternative technologies available, and the practicability of employing safeguards to protect the privacy and security of information collected from and about individuals.” [20]. Because of these insecure factors, the report recommend that US government should ponder whether to use RFID for identifying individuals or not, and it is better to find other solutions.

**Access Controls**

Nowadays, many companies and organizations require an efficient access control system. Based on the item and person identification system of RFID application, the RFID access control system can easily realize the keyless entry, identification of the access card holder, time record and person counting. It is very useful to improve loss prevention, enhance security for limiting access to restricted areas, and track activity of the card holder. However, the security risk is still a problem which needed to be solved as soon as possible.

**Ticketing System**

In 2005, all of the 100,000 tickets for the Tennis Master Cup in Shanghai China were supported by the RFID ticketing system. The tickets were fixed with TI’s Tag-it™ HF-I RFID tag. At the same time, the system was required to distinguish different types of tickets, and the chips inside are numbered and accordant with ticket number. It was the largest RFID-based anti-counterfeit ticketing applications for sporting events in China until 2005[21]. It was serviceable to protect ticket revenues, prevent the use of counterfeit tickets, and speed up the entrance. After that, from 2006, Premiership football club started issuing RFID-enabled season-tickets to cut queues at the turnstiles on match days and increase safety around the stadium [22].

**Automatic Payment**

Primitively, the idea of automatic payment comes from the credit card companies. The name and account number of the customer always appear on the surface of the credit card, which makes it very easy for thieves to clone the card and make fraudulent purchases. That is the reason why the credit card companies wanted to find new methods for safe payment. With the technical support from the mobile phone companies, automatic payment by mobile phone was realized through a microSD card which was specialized developed and could be both a passive tag and an RFID reader. In other fields, like transportation payment, RFID technology also has played a great role for automatic payment. In Norway, all public toll roads are equipped with AutoPass. It is an RFID electronic payment system that allows collecting road tolls automatically from cars when they are passing. In Shanghai, China, an RFID public transportation card lets user credit money in advance. The card can be used to pay for almost all the public traffic in the city, such metro, bus, and taxi.

**Supply Chain**

In the next few years, RFID is foreseen to appear in many fields of supply chain to offer substantial economic benefit and significant commercial value via monitoring product flow and capturing data in an efficient manner [23]. The advantages of using RFID in supply
chain have been presented in many papers and reports, including increasing operational efficiencies, integrating supply chains, providing detailed data to improve forecast accuracy, reducing the rate for out of stock, improving operator efficiency and product security, etc [24]. Many companies have full confidence in the usage of RFID system. Though only around 30% of Wal-Mart’s top suppliers achieved 100% full-scale RFID implementation in 2005, Wal-Mart started a “Packaging Scorecard” program in 2006 [24]. However, there are still many problems to promote the process for using RFID, such as cost, reliability, size, failure rate, and data management, etc.

Pharmaceutical Tracking and Management

Pharmaceutical, thanks to its medicinal function, is so special which make it different from other ordinary products. The supply chain of pharmaceutical is more complex than others, and always catches more public attention. From manufacturer to the end user, the supply chain for drugs can change hands multiple times. Using RFID to track the movement of drugs will lower the risks of loss of products, protect them from theft and replacement, and ensure patient take the right tablets as much as possible. It will be effective to resist counterfeit pharmaceuticals and improve drugs safety. During the tracking process, much data will be created, which is invaluable to facilitate patient diagnosis and business decisions.

2.2.4 Challenges

Although the potential benefits of RFID technology are tremendous, there are still two most critical problems, cost and security, both of them are the bottlenecks in RFID development. Compared with barcode, though the information can be used in RFID system is much larger, the cost increases several times more. This problem can be solved by using printed RFID tags, but it needs widely adopted and strong support from the printing technology. On the other hand, RFID chips can send malicious data to unsecured back-end databases and other systems which are susceptible to common attacks such as viruses, buffer overflows [25]. It will cause big security issues if happens. The security risk is one of the most serious problems which prevent people from enjoying the RFID products with ease.

However, the applications based on RFID still have many challenges including the usage of base material with flexible/m Metals/biomaterials, antenna miniaturization, reading range and data transfer speed enhancement, integration of low-power integrated circuits and sensors on low-cost systems, operation on multiple frequency bands, system security and reliability, etc. Obviously, these challenges discourage the development of RFID applications, but encourage the researchers from related fields to improve the technology.

2.3 Wireless Sensor Network

In the foreseeable future, all the things will be connected and addressed [26]. More information could be obtained to supply the intelligent ambient, comfortable life and low energy consumption. Internet of Things (IoT) is thought to be the successor of the traditional Internet. The concept is attributed to the Auto-ID Center of Massachusetts
Institute of Technology (MIT) [27, 28, 29]. It refers to the network interconnection of everyday objects, and is described as a self-configuring wireless network of sensors whose purpose would be to interconnect all the things [30]. In an IoT system, sensors are equipped to the railways, bridges, tunnels, roads, buildings, water systems, oil and gas pipelines, and other appliances. Through Internet and remote control, the direct communication among objects in different places will be achieved by running a special program. IoT can be used in many applications such as retail, logistics, pharmaceutical, food, health, and intelligent home, etc. From a coffee cup to a yacht, one can easily get their location via a laptop with Internet.

To realize the communication between people and object (even between object and object) via WSN, RFID and sensor technologies, IoT makes things "smart". As the infrastructure of IoT, WSN plays a very important role in the implementation of IoT. The information needed for IoT is provided by WSN, which are responsible for sensing and the first stages of the processing hierarchy. WSN initially started to be used in military applications. Today, it is spread in many civilian areas, such as environmental and ecological monitoring, health surveillance, home automation, and traffic control.

A modern sensor network system is composed of a large number of inexpensive, low-power, multi-function miniature sensor devices that are densely either insider the phenomenon or very close to it [31]. Sensing is the most important function of the WSN. Sensors for temperature, humidity, gases, and acceleration, etc., should be miniaturized to be integrated into the node. Instead of sending the raw sensing data, pre-processing should be performed in the node as well. At last, the useful information is sent through the communication network. Such a WSN system could greatly improve information transmission and resource utilization.

2.3.1 Fundamentals

In different applications, the structures of WSN are different, which normally includes signal collection, information processing, data transfer, and power management. Most WSN devices have following hardware components: several sensors, a microcontroller for computation, a small RAM for dynamic data and flash memories which keep the program code and long-lived data, a wireless transceiver, an Analog-to-Digital Converter (ADC), and a power source, as shown in Fig. 2.4.

![Fig. 2.4: The structure of a sensor node.](image-url)
Normally, the operation of the WSN sensor node consists of three steps: sensing for information collection, processing for data calculation and analysis, and communication for signal dissemination and exchange. The relations of them are shown in Fig. 2.5.

![Fig. 2.5: The operation of sensor nodes.](image)

**Sensing**

The sensors can be integrated to nodes in three ways. Firstly, an antenna of the communication module could be used as the sensing part. For example, inductive coupling technology can be utilized for a humidity sensor [32]; the far-field backscatter coupling technology can be adopted to implement the humidity sensor as well [33]; besides, some other sensors can also be implemented using the antenna as the sensing part, such as accelerometer sensor [34] and displacement sensor [35], etc. The second way is to integrate the sensor into the node IC directly, such as the pressure and temperature monitoring sensor [36], temperature and photo sensor for environmental monitoring [37], etc. The third method is to use external sensors with programmable microcontroller [38]. In addition to the traditional CMOS technology to implement the sensors, printed sensor is emerging as a low-cost and flexible solution, such as printed humidity sensor [39].

**Processing**

A simple processor with limited memories is used for the computation task. Instead of sending the raw sensing data to other nodes, the sensor node should process (such as analyze or compress) the raw data and send out the processed data to decrease the volume of communication data. Normally, the sensor network is a multi-hop network. The sensor nodes should also forward the data from other sensor nodes. To finish the simple scheduling between different processing tasks, an embedded operating system is needed to run on each sensor node. TinyOS is one of them. By written in the network embedded systems C (nesC) programming language as a set of cooperating tasks and processes, it is a free and open source component-based operating system and platform targeting WSN [40].

**Communication**

In Fig. 5.3, it shows the typical structure of WSN. Multi-hop WSN constitutes the low layer communication network, while wireless or wired Wide Area Networks (WAN) form the high layer communication network. The wireless transmission medium can be optical, infrared or radio according to the bandwidth requirement, environment condition, and implementation cost, etc. An optical communication method, using laser source and Corner Cube Retroreflector (CCR), is proposed to lower the node complexity caused by the communication part and solve the security problem between sensor nodes or between the base and node [41]. Free Space Optical (FSO) is used for communication when the light of sight exists between the transmitter and receiver [42]. Infrared can also be used for inter node communication. Infrared instrument have already been widely used in computers, mobiles and Personal Digital Assistants (PDA). The advantages of infrared instruments are
low-cost and easy to deploy. Its main drawback is that the system has some requirements for the line of sight between the transmitter and receiver.

The most widely used transmission method is that the RF signal works at the band of Industrial, Scientific and Medical (ISM), which is license free in most countries. A lot of technologies can be used for WSN, such as RFID, Bluetooth, Zigbee, Near-field Communication (NFC), Ultra-Wideband (UWB), and so on.

- RFID technology is proposed to identify and track persons, animals and products. It can operate at low frequency, high frequency and Ultra High Frequency (UHF) band. For a passive tag, the communication distance is under a few meters; for an active one, the distance can be further extended. (Details in Chapter 2.2.2)

- Bluetooth is developed for wireless personal devices to replace the data cables. The Frequency Hopping Spread Spectrum (FHSS) technology is adopted at the 2.4 GHz frequency. The communication distance ranges from 1 meter to 100 meters.

- Zigbee is a low-cost and low-power consumption solution for low data rate RF applications together with the requirement of long battery life. It operates in the band of 2.4 GHz, as well as 868 MHz in Europe, and 915 MHz in the USA and Australia, corresponding data rates of 250 Kbps, 20 Kbps and 40 Kbps respectively.

- NFC is a short-range wireless communication technology, which let the devices exchange data within 10 centimeters distance. It uses the frequency of 13.56 MHz, and the data rate is up to 424 Kbps.

- UWB is a radio technology that can be used at a very low energy level for short-range high-bandwidth communications by using a large portion of the radio spectrum. It used to be utilized in non-cooperative radar imaging. Recently, it has developed a lot in sensor data collection, precision locating and tracking applications.

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![Hierarchical layer of WSN](image.png)

Fig. 2.6: Hierarchical layer of WSN.
2.3.2 Applications
The WSNs system can be utilized in military, home, and transportation applications, etc.

Military
In military applications, WSNs can be used for monitoring the friendly forces, battle field surveillance, considering the rapid deployment, self-organization, and fault tolerance features, etc. The soldiers and equipments attached with wireless sensors are monitored by the commanders. Based on the status collected by the sensors, the commanders can make the suitable decision timely. The wireless sensors can also be rapidly deployed in the target field. The commander can evaluate the situation of battle field according to the collected surveillance information. It’s especially useful when the target filed may be attacked by the nuclear, biological and chemical weapons.

Home
WSN is used to constitute the smart home and activities of daily living. By connecting all the electrical equipments, people can control them through a uniform terminal such as a computer or mobile phone, which also makes it possible to remotely and easily operate domestic appliances. Before going back home, one can remotely operate the air condition to supply a comfortable home environment. Besides, the domestic appliances can also work in an intelligent way. Based on the surveillance data from the sensors, such as temperature, humidity, lightness, and oxygen gas, etc., the corresponding equipments will run automatically to adjust the home environment.

Transportation
Cars with wireless sensors can form a network for transportation. The traditional surveillance system deploys the monitors at the fix points. The information of roads and cars is not sufficient enough and normally unidirectional to the supervisors, which means that the drivers cannot utilize the information efficiently in time. By embedding the wireless sensors into cars, the vast number of sensor nodes constitutes a large sensor network for transportation surveillance. The system can also be integrated with the Global Positioning System (GPS). The road conditions and other information are exchanged among cars and surveillance points. If accident happens or any road is blocked, the coming cars will be noticed timely to change the path. Besides, the parking information can also be supplied by this transportation system.

2.3.3 Challenges
Although sensor nodes may prone to failures and have no global identification, WSN improves sensing accuracy by offering vast quantities of sensing information, provides coverage of a large area via scattering of numbers of sensors, localizes discreteness to lower power consumption, decreases manual intervention and management, works in abominable surroundings, and reacts dynamically to face the changes from networks.

With the development of applications and research work, the demand on WSN increases higher and higher, and the challenges are emerging gradually as well at the same time. A high efficient WSN system is required to have: a large number of cheap small-sized sensors
for good scalability and management, nodes with long lifetime, low energy expenditure and
time consuming, small memories to fit sensor nodes, data aggregation by some special
sensors, periodically self-organization of networks to avoid nodes failure and new entry that
may occur, and collaborative signal processing to improve the detection performance, etc
[43].

In addition to those mentioned above, sensors are limited in power and computational
capacities as well [44]. For the networks, it is also not easy to extend its lifetime, build an
intelligent data collecting system, and adapt the dynamic environmental conditions. All of
them are tough problems which are needed to be solved as soon as possible.

2.4 Summary

Interactive Packaging, RFID and WSN are three hot technologies which are widespread
applied in many fields. All of them have a rapid development and significant future
potential. But they also have some weak points and bottlenecks. The material cost and needs
for more information will limit the development of interactive packaging industries. Most of
the RFID tags typically keep no history of past reading, which will lead to privacy and
security risks. On the other hand, with the popularization in the commercial market, the cost
of RFID is expected to become lower and lower. Besides, lifetime extension and high self-
organization are big problems for WSN system improvement.
Chapter Three

3 MATERIAL AND SOLUTION

In this chapter, Controlled Delamination Material (CDM) technology is introduced at first. It was primarily used in aerospace applications. A CDM product, named Sinuate®, consists of two aluminum foils bonded together with a conductive epoxy adhesive. The adhesion strength at one of the conductor/adhesive joints decreases sharply when a voltage is applied on, which makes the material opened easily. An interactive and intelligent packaging solution which integrating a passive RFID system with Sinuate® is proposed. The package opening action is electrically controlled by the RFID system.
3.1 Controlled Delamination Material

Because of the low cost and a wide variety of usage, adhesives play an important role in many traditional industries like packaging industry. CDM is a new technology with which a special adhesive can be released when having an applied voltage. In order to achieve lower the production expenses and less the cost of reparations, CDM was first used in aerospace applications to temporarily bond monitoring instruments to aircrafts, and permitting dismantling quickly without surface damage or marking [45]. A CDM product contains electrically induced debonding adhesive and metal substrates, such as aluminum, steel, copper, and titanium, etc. [46].

Recently, CDM has drawn attention from the traditional packaging industry due to its characteristics of low-power and electrically controlled debonding. It could be a new option to replace the common adhesive, with the developments of new interactive and intelligent packaging solutions.

3.1.1 Physical Structure and Features

Further developed by Stora Enso AB [47] (a Finnish packaging, paper and wood products company), a CDM product called Sinuate® is used here. It is a glassfiber reinforced epoxy based CDM adhesive sandwiched between two pieces of aluminum foil. The fundamental structure of Sinuate® is shown in Fig. 3.1(a).

The top layer and bottom layer are two pieces of aluminum foils. Between these two layers, a layer with dark color is a thin layer of glue epoxy that has a strong adhesion against pulling force. With the fiberglass net in the adhesive mixture, the tensile strength is 8 MPa, the shear strength is 3.5 MPa and the peel strength is 8 N/cm at room temperature [49]. When a 10-50V DC voltage is applied to the structure for a short period of time, the bond strength will be reduced, and the adhesive will become unstuck [50, 51]. It enables the material could be easily separated by little extra pulling force. In addition to the material properties, the total time for debonding also depends on the power supply voltage and some environmental conditions like humidity. Water is an important conductor for the conductive mechanism. An increased amount of moisture content in the material will have a great effect on the change in resistance and aid the debonding processes when a voltage is applied [46]. Therefore, with higher humidity, the material will separate faster.

In order to make the laminate open, a sufficiently high voltage is needed to apply to the sandwiched material structure, as shown in Fig. 3.1(a). After applying such bias for a while, the electrochemical reaction weakens one of the interface joints between the glue epoxy and aluminum foils, and finally leads to debonding of that interface. As shown in Fig. 3.1(b), when a power source is applied on the both layers of the aluminum foils, the bottom aluminum foil layer which is connected to the anodic side of the power source will depart from the rest part of the material (including the top aluminum foil layer and the epoxy glue layer).

According to the related research on the electrochemical characterization of Sinuate® [46], a picture of the electrochemical reaction for delamination mechanism is presented clearly. The debonding including the electrochemical reactions is a multi-step process. Once
a suitable voltage around 5-50V is applied on the material, the debonding process will start. At the same time, a polarization on the anodic interface occurs, which brings two results: aluminum oxidation and electrochemical reaction. The reaction products contain aluminum ethyl sulfate/oxide/hydroxide and little water. Most of the products perform weakly in cohesion, and induce a resistance and volume increase at the anodic interface. The increasing volume brings an increase stress between the aluminum surface and adhesive, which ultimately leading to delamination of the material. Although a fiberglass net is used to strengthen the material structure, the net does increase in volume and cannot stop the debonding process. On the other hand, the production of water decreases the pH-value and may aid the processes leading to delamination. After some related experiments, the material kept in a higher humid environment will make the deboding process faster [51, 52].

![Aluminum Foil](image)

Fig. 3.1: The structure and opening action of a CDM product.

### 3.1.2 Way to Define Delamination

The polarization of laminate progresses gradually. In the DC opening/debonding behavior test (Details shown in Chapter 4), the stickiness on the material seems to disappear over time when applying a DC power source. However, some bonding strength still remains, after charging for a certain time. The measured current through the material does decrease but never come down to zero, if there is no external force to clear this residual adhesive strength. Therefore it is hard to define an exact time point for the delamination only by naked eyes instead of test instrumentations.

To simplify the way to define the delamination, a small weight like 100g is needed to be applied on the bottom layer of the aluminum foils as Fig. 3.2 [52]. When the bond strength is weak enough, the aluminum foil will delaminate and the measured current will directly drop to zero. In most cases, the current will reduce to less than 10% at that time, which makes it convenient to measure the time and the charges needed for delamination.

![Aluminum Foil](image)

Fig. 3.2: Way to definite the delamination.
3.2 Interactive Packaging Solution

3.2.1 System Concept

Sealed off with the CDM product, the interactive packaging can be electrically opened following with several prompting functions if the specified conditions are satisfied.

As shown in Fig. 3.3, a low-cost interactive packaging solution combining Sinuate® laminate with a passive RFID tag may be useful in the fields of logistic, healthcare, security, toll system and other identification systems. RFID technology is used to determine and control when and whether an opening action should take place. The whole system includes three parts: Tag, Watcher and Package.

- **Tag**: A passive RFID tag is used here, which has an antenna, a microchip, and without any extra power supply. The only information on the microchip is an 8-bit ID number. The number is unique, and has been set in the factory during the manufacturing and installing process. The tag will send data out once it captures the electromagnetic wave under at frequency from the RFID reader to power up.

- **Watcher**: Five modules constitute the Watcher: an antenna, an RFID reader, a Micro-programmed Control Unit (MCU), a charge pump, and a power unit. The antenna is a bridge between the RFID tag and reader by communicating with another antenna on the tag. The reader communicates with the tag and MCU separately to exchange data between them, and also supplies energy to the tag by sending electromagnetic wave at radio frequency through the antenna. The MCU compares the authentication key stored on it with the ID number received from the reader, and sends the corresponding commands for further operations. The charge pump is used to convert the output signal from the MCU to a higher voltage to drive the laminate debonding (the package opening action). The power unit provides the system with the power supply only when a press switch is pressed, or a touch sensor is touched respectively.

![Fig. 3.3: System concept for a smart packaging solution.](image-url)
Package: The Package is connected with Watcher, and sealed off with Sinuate®. There are some other external devices attached on it. The output voltage from Watcher will be connected to both layers of the material. After being electrically biased with enough high voltage for a certain time, Sinuate® will debond and make the Package open automatically. The external devices can provide more prompting functionalities other than just opening, e.g. audio or video functions at the time while the package is opening.

3.2.2 Functional Description

The operational flow chart of the system function is presented in Fig. 3.4. The firmware platform is written in computer programming language C, and it is programmed to the MCU in advance, which is easy to reprogram anytime through a compiler.

![Flow chart of operation](image)

Fig. 3.4: Flow chart of operation.

Following the flow chart, when the Watcher is turned on by pressing the press switch or touching the power button, the RFID reader starts to work. The reader sends signals out to find out whether there are any available tags nearby or not. If a tag is presented within the reader’s reading distance, the reader will check whether there is any response from the tag or not. Without any tags, the reader will turn to power off. If the tag replies an 8-bit ID number to the reader, the number will be sent to the MCU and then compared with the authentication key that was pre-stored/programmed into the memory of the MCU. Once these two numbers are not the same, i.e. mismatching, the Watcher will power off after a while. When these two numbers are the same, i.e., matching, the MCU will wait for a while to allow the RFID reader to read the ID again in order to confirm the matching. After the matching is confirmed, the MCU will enable the charge pump, and later send a 30V DC output signal to Package to open the laminate which could sealed off the package. Meanwhile the MCU will trigger other functionalities as well, such as sound notification.

For the tag, when obtains electric power by its antenna from electromagnetic wave sent by the reader within the reading distance, it is powered up. After getting the reading command from the reader, it starts to send ID number to the reader.
3.2.3 Hardware

The tag is an electronic read-only RFID card. It combines a coil antenna with a Complementary Metal–Oxide–Semiconductor (CMOS) IC. The circuit is powered by the antenna placed in an electromagnetic field, and obtains its master clock from the same field via one of the antenna terminals. By turning on and off the modulation current, the chip will send back an 8-bit ID number which is coded as Manchester and stored in the factory pre-programmed memory array. For its small chip size and low power consumption, the passive RFID tag is widely used in logistics automation, anti-counterfeiting, access control, and industrial transponder, etc.

The main components in the Watcher are an RFID reader, a MCU chip and a charge pump. The Watcher system in Printed Circuit Board (PCB) is 5.1cm×9.7cm in size, which is shown in Fig. 3.5. Since the components used in this solution are very common in use and cheap in price, the cost of the whole system is very low (less than $8 US dollar).

The RFID reader is a CMOS integrated RFID transceiver circuit. Without any external crystal oscillators, a resonant frequency which is suitable for the antenna that can be obtained by the internal phase-locked loop PLL. It is used as a base station to perform antenna driving at carrier frequency, AM synchronous modulation and demodulation of the antenna signal modulation induced by the transponder. While working with a 5V DC power supply and at a low frequency ranging from 100 kHz to 150 kHz, the RFID reader communicates with a microprocessor via simple interface. For its small plastic package and low cost, the RFID reader is very widely used in the fields of car immobilizers and handheld readers.

The MCU is an 8-bit single-chip microcontroller designed for applications demanding high-integration, low-cost solutions over a wide range of requirements. It is based on a high performance processor architecture that executes instructions in 6 times the rate of standard 8051 devices. It is the core of the system to analyze data and make operation decisions.

The charge pump is a current-mode pulse-width modulation step-up DC/DC converter. The input voltage ranges from 2.5V to 10V, and the adjustable output voltage is up to 30V. Because the output voltage from the MCU is only 3V and the power needed to open a CDM normally should be 20V or more, a DC-DC converter is necessary in this solution. Once the charge pump is enabled, it will convert the input voltage from 3V to 30V and send the 30V DC signal out to Package.

As one of the key parts of this system, several pieces of CDM products are attached on the sealing edges of the packages instead of normal sealing compound. The two aluminum layers of the material bonding the package connect to the output voltage end (\(V_o\)) and ground (GND) of Watcher system separately. It makes the package much stronger, and uneasy to open without the confirmation by a matched RFID tag.

3.1 Summary

Sinuate®, a CDM product, is an adhesive/aluminum material with a sandwich structure. When having a suitable voltage on the sandwich structure for a while, the adhesive loses most of its viscosity. To simplify the debonding process, a small mechanical force is needed to make the material delaminated completely.
Sealed off with Sinuate®, an interactive packaging solution is presented. Based on RFID technology, the system concept and solution of software and hardware are introduced as well.

Fig. 3.5: PCB view of Watcher.
Chapter Four

4 Tests and Results

In this chapter, several experiments are setup for the studies on the electrochemical characteristics of the CDM product, Sinuate®, and the verification for the demonstration of an interactive packaging solution. The studies on Sinuate® contain results and analysis of the DC and AC opening behaviors. On the other hand, the test results of the demonstration system are proved the feasibility of the solution and show the potential of low cost for mass production.
4.1 Sinuate® with CDM Technology

4.1.1 DC Opening/Debonding Behaviors

As mentioned in many previous studies, a CDM product, Sinuate® will open automatically in few seconds if given a voltage in 10-50V DC voltage [49, 50]. There are also some environment parameters will affect the electrochemical characteristics of the material. The following tests are performed at a temperature around 22°C -25°C and a humidity of 30%-37%. All the tests are finished within the safe voltage of 36V DC power supply for the human being.

When the material is subjected to a 30V DC power supply, the waveform of the current flowing through a piece of 1 cm$^2$ Sinuate® is given in Fig. 4.1. In order to compare with the following tests, neither layers of the material is added an extra mechanical force here.

![Fig. 4.1: Current waveform on Sinuate® at 30V DC voltage.](image)

The DC behavior of Sinuate® in 200 seconds can be analyzed by being divided into four steps as below:

I. 0 – 5s: No power supply, no reaction.

II. 6 – 15s: Once a voltage is applied on the material, the current reaches its maximum value within 10 seconds. The Peak Current ($I_{peak}$) nearly reaches 0.95 mA/cm$^2$.

III. 16 – 100s: During the polarization process of the material, the current drops down substantially and finally will be reduced by over 90%. At this moment, the material is so weak that just a slight tough can make it peel off.

IV. 100 – 200s: After the current drop down to around 10% of $I_{peak}$, without any external force, the current through the material is very small. It will infinitely close to zero but never turn to zero.
Depending on the different DC supply voltages applied, the debonding/opening time of the material greatly varies. The waveforms of the current flowing through the material under different bias voltages from 5V DC up to 30V DC are shown in Fig.4.2. If no other force is added, the current will never turn to zero and the material will not be separated completely as shown in Fig. 4.1. In order to define the delamination of the material, in following tests (includes Fig.4.2), a 100g weight will be hanged to the bottom surface of the material (details are given in 3.1.2 “Way to Define Delamination”).

![Fig. 4.2: Current waveforms at different DC power supplies.](image)

In Fig. 4.2, after reaching $I_{\text{peak}}$, the current flowing through the surface of the material decreases slowly during the following several seconds, and the adhesive strength of glue becomes more and more weak. When the strength could not afford the weight added on the material, the material will be debonded immediately. The current at that moment is called Turn-off Current ($I_{\text{off}}$). It signifies the moment that the current is turn to zero and the material is delaminated. The total opening time ($T_o$) is the time elapsed during opening process. $T_o$ is defined as the time interval from the point the power supply is applied on the surface till the point the turn-off current comes out. If the power supply is lower than 5V, the material will not open within 2 minutes without any extra-large force. According to Fig. 4.2, when the voltage of power supply increases from 5V to 30V, $T_o$ will decrease monotonically.

For different pieces of the materials, $T_o$ is not always the same. The test results for $T_o$ of 4 different samples of the material under different DC power supply voltages ($V_{\text{out}}$) from 5V to 30V are shown in Fig. 4.3. A, B, C and D are four pieces of different Sinuate® samples with the same shape and size. Only judged from the surface of material, since many air bubbles are added on the surface of the material in the production process with no intention, there is a significant difference from the aluminum substrate plane of these samples. A 100g weight is also used in this test to define the delamination process. In Fig 4.3, the material cannot be opened automatically in less than 2 minutes under a 5V power supply voltage. As a contrast, the worst case is that it takes 20 seconds for the material to open at a 30V DC supply voltage for sample A.
For samples with different material size but from the same piece, the difference of $T_o$ is little. It means that the size of the material is almost unrelated with $T_o$. On the other hand, the time for the material debonding action is much dependent on individual properties of each piece.

To summarize, with a DC power supply, the material can open by given a voltage ranges from 5V to 50V in several seconds. $T_o$ mainly depends on the voltage supplied on the surface of material. When the voltage is higher than 30V or is lower than 5V, it will take much more time to delaminate or even no opening action happens without any external strong force. According to these tests, 30V DC power supply is proved to be more efficient than the others. The test results also show that the way to define delamination is feasible and easy to handle with.

4.1.2 Pulse Opening Setup and Behaviors

With an enough power source not only supplied by DC but also AC, Sinuate® works well and open quickly. To get the AC pulse opening behaviors, the test circuit is setup as Fig. 4.4. As the same with the DC power supply tests, the environment temperature is around 22°C-25°C, and the humidity is around 30%-37%.

In the test circuit, two voltage sources, $V_{\text{in1}}$ and $V_{\text{in2}}$, are combined together to provide a 30V AC pulse supply via a high voltage transistor $M_1$. The amplitude of the pulse can be changed through the 30V DC voltage source $V_{\text{in1}}$, and the frequency and duty cycle are also changeable by the pulse signal source $V_{\text{in2}}$. $R_1$ is a divider resistance to protect the circuit from over current. $D_1$ is a diode to block the negative current which may occur to affect the opening process in the loop circuit. Lower the value of capacitance will make $D_1$ works better at high frequency. $R_2$ is a resistance used to measure the current. The current flow through $R_2$ is equal to the current flow through the laminate.
4.1.2.1 AC Opening Behaviors at Different Voltage Supplies

When the circuit is supplied by a 30V AC pulse signal at 1M Hz frequency and 50% duty cycle, the material is charging during the half period of $T_o$. Based on the test results from the DC behaviors of the material, we may predict that $T_o$ at 50% duty cycle should be doubled than that with full time charging, because the charge time of the material is just half of the DC behaviors. However, the experimental results are not that simple and the same as what we have expected.

When an AC pulse power supply is applied on the material, the electrochemical reactions of the material will happen immediately and quickly. Once the pulse time is over in a cycle time, the current drops to zero, which makes the floating charged ions stop participating in the polarization. However, the chemical reactions will still be continued. Because the chemical reactions happen in the whole cycle time, this could save some time for the material debonding process. The extra operating time in non-pulse time makes $T_o$ cannot be calculated simply by duty cycle based on that of DC power supply. That is the reason why $T_o$ at 50% duty cycle is much less than just doubled on that of DC behavior.

The waveform in 30 seconds of the top current ($I_{top}$) in one pulse cycle flows through the materials at a 30V AC pulse supply with a frequency of 1M Hz and 50% duty cycle is given in Fig. 4.5. Compare with the 30V DC power supply (Fig. 4.2), $I_{peak}$ at 30V AC is close to 0.7 mA/cm$^2$, which is smaller than that at 30V DC. On the other hand, $T_o$ is not doubled. The whole process only takes about 5-6 seconds more, nearly 130%, than the one at 30V DC.

The detail of the current waveform is shown as zooming in the Fig. 4.5. The material is charging during the half period cycle of signal. $I_{top}$ of each cycle will be lower and lower with the time goes on. While the pulse time is going over, the current drops to zero at once, and then come up until the next charging pulse. The current turns up and down in an instant, which causes some sharp waves at the end of each half period cycle. The waveform will look more smoothly at a lower frequency, and the amplitude of the sharp waves will be smaller.
4.1.2.2  AC Opening Behaviors at Different Frequencies and Duty Cycle

When the material is charging at different frequencies (ranging from 1 Hz to 80M Hz) and different duty cycles (ranging from 20% to 80%), $I_{\text{peak}}$, the maximum of the current in the whole debonding process, is shown in Fig. 4.6. Most of results distribute erratically from 0.4 mA to 1.1 mA. It means no matter the frequency is low or high, $I_{\text{peak}}$ does not depend on the duty cycle, but are evenly distributed in the value range mentioned above. According to Fig. 4.6, $I_{\text{peak}}$ is very low at opening process, which makes Sinuate® safe and friendly to be used in the applications for human being.
Meanwhile, we can get the average current \( I_{\text{avg}} \) of the laminate during the whole charging time as

\[
I_{\text{avg}}(t) = \frac{\int_0^{T_o} I(t) \, dt}{T_o},
\]

where \( I(t) \) is the momentary current with a time variable of \( t \), \( T_o \) is the total time for the material open.

In Fig. 4.7, most of the results for \( I_{\text{avg}} \) range intensively from 0.2 mA to 0.4 mA, at the frequency and duty cycle which change within the same range mentioned above. Obviously, frequency and duty cycle almost have no influence on the average current. However, the current will be greatly affected by some elements of the material itself, like some air bubbles on the material surface and any significant changes in humidity.
Actually, the AC pulse opening solution of the CDM product is more feasible for commercial use than DC opening, though there are no related reports on it from the internet. It just needs a simple transformation of AC voltage as a voltage source to realize the opening action. For a battery charged CDM system, it only needs a DC-AC voltage boost-up instead of a DC-DC one.

After several seconds pass, the material will delaminate by electrochemical reactions while getting a certain amount of electric charges. Assuming the quantity of electric charge to debond the material for each square centimeter can be regarded as a constant, then the debonding time will be controllable.

During the tests, \( T_o \) of the whole delaminating process at different frequencies and duty cycles can be plot in Fig. 4.8. Obviously, most of \( T_o \)s range from 5s to 13s, expect the ultra low frequency, like 1Hz and 10Hz.

For the AC pulse supply, the total charging time of the material in the pulse time until delamination can be called \( T_c \). It depends on the duty cycle and \( T_o \). For example, at the same frequency, the material is charging during half period of \( T_o \) at pulse supply with 50% duty cycle; and \( T_c \) at 20% duty cycle is four times more than that at 80% duty cycle with the same opening time.

Therefore, \( T_c \) can be deduced from the total opening time, as shown in Fig. 4.9:

\[
T_c = D \times T_o,
\]

where \( D \) is the duty cycle of the AC pulse supply.

The total quantity of the injected electric charge the material gets during \( T_c \) can be concluded as

\[
Q_e = \int_0^{T_o} I(t) dt,
\]

as shown in Fig. 4.10. Obviously, \( Q_e \) is entirely decided by duty cycle. However, frequency has almost no effect on \( Q_e \).
To summarize, for AC pulse power supply, the variable frequency and duty cycle could hardly effect on $T_o$ for the laminate debonding. Only if the frequency is extremely low, most cases of $T_o$ range from 7s to 13s. Besides the electrochemical reactions, there is one or more processes that cause the debonding action [52]. The electrochemical reactions and uncertain processes happen both in the pulse period and non-pulse period. It will only cost a little more time for the material to separate than by DC power supply, no matter what duty cycle and frequency the AC pulse supply has. As supposed at the beginning, the quantity of electric charge needed to debond the material can be regarded as a constant in most cases. The material will delaminate quickly when obtaining a certain amount of electric charge quantity, which is 20-30 mC/cm$^2$. Obviously, it needs enough time to achieve delamination.

![Quantity of the Injected Electrical Charge](image_url)

Fig. 4.10: The quantity of electrical charges in CDM product.

### 4.2 Demonstration for the Interactive Packaging Solution

A demonstration for the interactive packaging solution is shown in Fig. 4.11. Following the commands stored previously in an RFID card in front of it, a small box sealed with Sinuate® is electronically opened.

#### 4.2.1 Voltage Pulse Generation

If the ID number in RFID tag is the same with the authentication key stored in MCU, the Sinuate® sealed with the package will be opened automatically in several seconds after receiving a 30V DC voltage from Watcher as Fig. 4.12 (a). If the two IDs are not the same, the output voltage is about 5V which is too low to open Package as Fig. 4.12 (b). There is a flow voltage to keep RFID reader and MCU work during the test process. It is about 4.3V-5V.
4.2.2 Reading Distance

The reading distance between the tag and the package is mainly determined by the RFID system. It is about 5cm in this solution, which is suitable for the application scenarios.

4.2.3 Programmable Control

The authentication key stored in the MCU can be reprogrammed via connecting to a computer. By replacing the opened Sinuate® to a new one, it is convenient for users and manufactures to recycle the smart package.

Due to the characteristics instability of the material, the time duration of the output voltage pulse from Watcher is also programmable to ensure a reliable opening for Sinuate®.

(a) Two IDs match                             (b) Two IDs do not match.

Fig. 4.12: Voltage pulse generation.
4.2.4 Current on the Material Surface

The current flowing through the material surface of the package in the experiments decreases from 680µA to 320µA in 19 seconds at a 30V DC voltage pulse. For an intelligent packaging solution, such a small current on the material surface is safe to be used for human beings.

4.3 Summary

Sinuate® is an adhesive/aluminum material with a sandwich structure. When having a DC or AC power supply, it will delaminate after a while. The opening time and current flowing through the material surface is unrelated with the area of the material, but closely related to some environment elements. The maximum current on the material at a DC power supply is almost 1 mA/cm² in opening process. When an AC pulse supply is connected, just a little time is needed to open the material, because more processes will start following with the electrochemical reactions to realize the opening action of the material. On the other hand, duty cycle and frequency have almost no efforts on the AC behaviors. Obviously, though the opening time is litter longer, using AC pulse power supply is a more efficient way than using DC, and it is easier to design more application circuits based on CDM with an AC pulse power supply.

As an interactive and intelligent packaging solution integrating RFID technology and Sinuate® is presented in Chapter 3, a package which sealed off with Sinuate® is expected to be opened automatically and electrically in 20 seconds. Passive RFID technology is used to control the opening action. The test results of the demonstration have proved the feasibility of the proposed interactive packaging solution.
5 DISCUSSION

In this chapter, based on the primal simple solution, an interactive medication package for pervasive healthcare is proposed, using EPCglobal Gen2 RFID technology. It will make the medication being accessible for patient only at the prescribed dose and time, and medication taking information will be delivered as well. Such medication package will not only give unprecedented high patient compliance, but also improve the communication between patients and healthcare staffs. After that, two study cases with WSN based systems are briefly introduced: fresh food tracking and medical care network.
5.1 Medical Package with High Compliance

5.1.1 System concept

From big bottle to small unit dose package, a traditional medical package is usually utilized to protect, inform and distribute the drugs inside. However, it brings a lot of problems for pharmaceutical noncompliance, such as skipping a dose, taking too much/less or wrong drugs or at wrong time, mixing fresh pills with the old ones, prematurely discontinuing medication, and storing medicine improperly, etc [53]. A study from the Healthcare Compliance Packaging Council (HCPC, which was established in 1990 to promote the many benefits of unit dose packaging) shows that every year in the United States only, over 125,000 death cases are attributed to pharmaceutical noncompliance, and 10% of all hospital admissions and 23% of all nursing home admissions are due to people’s inability to take their medications as prescribed, which costs an estimated $180 billion [54]. Besides these direct costs of noncompliance, the indirect costs cannot be ignored as well, such as reduction in worker productivity, more sick days and less efficient work, and premature death, etc [53]. The invention of unit dose package for medication helped to relieve these problems, and gave a certain improvement for pharmaceutical noncompliance.

Based on the aforementioned low-cost interactive packaging solution, an intelligent medical packaging solution is proposed to reach unprecedented high patient compliance for pervasive healthcare. It assists patients in taking medicine more correctly and effectively. In addition, automatically opening makes the packages smart and easy to use for seniors, and being sealed off with CDM products makes the intelligent packages locked strongly enough to be childresistant. Moreover, a more powerful generation II (EPCglobal Gen2) RFID tag is utilized to enhance the whole medical treatment process. Through networks, medication information will be delivered in time to improve the information exchange between patients and healthcare staffs, and enable the monitoring of patient compliance. It will be helpful for reducing the growing incidence of medical errors, decreasing the medication costs, and relieving the insufficiency of staff resources, etc.

5.1.2 EPCglobal Gen2 RFID Tag

By being built on the original specification framework, the EPCglobal Class1 Gen2 RFID tag has a large extensibility to many high-performance system applications. Compared with the first generation (Gen1) of RFID tag, Gen2 has been greatly enhanced in data capacity, transmission rates, and information security, etc. The reading speed is close to four times as many as that of Gen1. Gen2 can be rewritable many times. There are also four reader "sessions" allowing parallel communication by multiple readers with one Gen2. Due to security issues, Gen2 has 32-bit lock and kill passwords. For further extensibility, the user memory depends on the manufacturer and can be as little as 0 bits to 64 bits and going as high as 2048 or more now [55]. Texas Instruments has such kinds of HF tag products for 64-bit factory programmed read only number and 2M-bit user programmable memory.

The memory part of EPCglobal Gen2 RFID tag is logically combined with four banks separately as shown in Fig. 5.1. Each bank may comprise zero or more memory words [56, 57]. The large user memory (Bank 11) allows users to define, organize and store user data.
5.1.3 System Concept

The MedSystem is made up of three parts: MedPackage, MedCard and MedTerminal. The concept for the main parts of MedSystem is shown in Fig. 5.2.

5.1.3.1 MedPackage

In addition to the several parts used in the previous single interactive packaging solution, MedPackage has a selector and several individual packages sealed off with Sinuate®. The RFID reader is replaced by an RFID reader/writer. Each individual Sinuate® sealed package could contain a given amount of a specific medicine or a specific mixture of multiple medicines.
When a MedPackage is powered up and starts to work, the RFID reader will find out if there is any MedCards nearby to confirm the identity of the MedCards at first. When the ID in a MedCard does not match with the authentication key kept in the MCU of the MedPackage, which means MedCard meets the wrong MedPackage, and then the MedPackage will turn off. Once they match, the reader will accept all the information/prescription kept on MedCard. Then the MCU will follow the prescription and send commands to the selector in order to control when and how many individual packages should be opened. When the time is up, a certain amount of medicine packages will be gradually opened in turn with some visible or audible reminder functions. For the hard package sealed off with Sinuate®, it is difficult to open without any tools for children or unauthorized opening, or if it is not the time.

Each time after a package opened, the MCU will create an opening report, and send it to the RFID writer. By the connection with MedCard, the report will be written on the MedCard.

5.1.3.2 MedCard

MedCard is a Gen2 RFID tag that has a large programmable memory for users. It is different from the basic Tag in the previous solution.

Before receiving any signal from a MedPackage, the MedCard is disabled. Once it is activated by a reading signal from the RFID reader, MedCard sends out its ID number at first. If the ID is confirmed, another reading signal from the MedPackage will let MedCard send all its information to the RFID reader. Then MedCard will turn off. Once the RFID writer in MedPackage gets a report from MCU, a writing signal activates the MedCard again. Then the information stored on MedCard will be updated.

5.1.3.3 MedTerminal

The MedTerminal could be a networked terminal equipped with RFID reader/writer. It can be deployed in pharmacies, healthcare organization, and/or patient’s home. The information from patients and healthcare organization will be processed and saved. Through the networks, the communication between patients and healthcare staffs will be highly improved.

5.1.4 Functional Description

The main function of MedSystem is to improve the communication between patients and healthcare staffs. Due to having a Gen2 RFID tag, MedSystem has much more data to be involved in the interaction of the whole patient treatment process. These data are invaluable information, not only for the patients themselves, but also for the healthcare organization and pharmaceutical industries. The information flow chart is shown in Fig. 5.3.
5.1.4.1 Open – Counterclockwise Flow

Following the counterclockwise flow in Fig. 5.3, an opening route for a MedPackage is presented. The detailed standard instruction about the medicine inside will be pre-set by pharmaceutical manufactures, and it can be adjusted by hospital or pharmacy staffs. Once a patient receives his diagnosis, the MedTerminal could retrieve information through networks. The information may include the basic personal information and status, codes of the healthcare organization and doctor, case number of previous records and doctors’ diagnosis, codes of the medicine, and the time and dosage to take drugs, etc. The prescription is one of the most important information, such as the name of the medicine, when the patient should take drugs and how many pills should be taken, etc. These data will be written on a MedCard by the RFID reader/writer of a MedTerminal. When receiving or delivering a MedCard and MedPackages, the patient and medical staff could check the matching between MedCard and Med Packages. It is effective to avoid mistakes in receiving/issuing card and/or packages. Once a matching status is confirmed, the prescription will be read and operated by the MCU in MedPackage. The right medicine packages sealed by CDM will be opened automatically following the instructions from the MCU, which is child-resistant and senior-friendly.

5.1.4.2 Report – Clockwise Flow

A report route is given following the clockwise flow in Fig. 5.3. With the gradually opening of the packages, reports on opening success are created by MCU. They are the new records in patient’s medication history. Through the communication loop from MedPackage to MedCard and then to MedTerminal, the reports will be updated in the whole MedSystem. Through the networks, the healthcare staffs could then timely retrieve these updates. They can monitor the cure plan remotely and have a decision for whether following the previous plan or doing some adjustments. Once a new decision is made, the old instruction will be renewed through the networks, following again the counterclockwise flow in Fig. 5.3. The ways of opening MedPackages will be changed immediately. These reports will follow the whole medical treatment process, and reduce the medical errors caused by poor communications as much as possible.
5.1.4.3 Functional Verification

According to the different ID numbers getting from MedCards, MedPackage operates in different ways. The operation rules are programmable and easily controlled by the MCU in MedPackage.

In Fig. 5.4, two multi-output cases show the sequence of three 30V DC pulse outputs are changed with different IDs and rules. The holding times for each output to keep the 30V DC voltage are changed as well, which is utilized to meet the variable needs to open the MedPackage CDM sealed.

![Multi-output cases](image)

(a) Multi-output case A.                         (b) Multi-output case B.

Fig. 5.4: Programmable multi-outputs waveform.

5.2 Fresh Food Tracking

According to the report from Billerud AB for fresh food services, ten percentages of all the fruit and vegetables delivered in Europe are damaged and destroyed on the way to the consumer, and the losses reach to ten billion every year [58]. It’s really a long and tough journey for fruits and vegetables from growers to consumers, which may experience harvest, packaging, delivery, transportation, storage, and sale, etc. Mechanical damage, temperature and humidity all have a significant impact on the life time of the fresh foods. If the fruit and vegetables are treated in a suitable way, the life time will be prolonged to avoid the waste and save the cost. To achieve the target, the status of the fresh foods should be monitored timely.

Fig. 5.5 shows a WSN based system deployed in one truck. When the sensor networks provide a suitable coverage and accuracy, the wireless sensors attached on the packages of fresh foods are used to measure the tri-axis acceleration, environment temperature, humidity, gas concentration of carbon dioxide, oxygen, and ethylene, etc. The data from sensors are collected by the master nodes. On one hand, the driver can take actions according to these sensing data, such as lowering the temperature, increasing the relative humidity through the truck system, or driving the truck more steadily to avoid the mechanical damage. On the other hand, the sensing data are also sent to the supervisors through the wide area network, such as Global System for Mobile Communications (GSM), General Packet Radio Service (GPRS), and Worldwide Interoperability for Microwave Access (WiMAX), etc. The supervisors can also adjust the conditions remotely. The
recorded information is very important and useful to improve the transportation scheme to further protect the fresh food.

![Fig. 5.5: Fresh food tracking system in one truck.](image)

In order to enhance the mobility, deployment and capability of wireless sensors for networked services, an enhanced dual-layer wide area WSN system has been developed and applied in fresh food tracking application [59]. During the fresh food transportation, the sensor nodes of the system provide a set of useful and efficient measurements on the environmental conditions. In this WSN system, all sensor nodes are mobile, remotely controllable and wide area deployable for networked services because of the dual-layer dual-directional wireless communication capability and the removal of fix-installed gateway. The system architecture and the implementation of sensor nodes and sensor network are described in detail in [59]. A case study, a transportation of fresh melon fruit in 20 days from Brazil to Sweden, is performed to verify the feasibility.

Considering the large volume data generated by continuously sensing for each sensor node, the efficient compression approach is necessary to lower the data rate between the sensor nodes. A novel compression scheme is proposed to compress the acceleration data [60]. The experimental results show that a high compression ratio with the acceptable distortion could be achieved. It confirms an effectiveness of the compression scheme for a WSN application for resource and cost saving.

### 5.3 Medical Care Network

The medical care network integrated with the interactive medical packaging and WSN presented previously is proposed in Fig. 5.6, which includes monitoring and treatment.

In the monitoring part, the situation of the patient is monitored completely, automatically and continuously by the medical care system. The patient’s position can be located by the position sensor. The medical items of patient are monitored by the wearable wireless sensors, such as heart rate, body temperature, and blood pressure, etc. These data will be recorded and analyzed via microcontroller or computer. The information processed is also sent to customer terminal for further processing and storage. If needed, the doctors can make a diagnosis based on the monitored information timely.
The other part of the network is the treatment. The interactive medical packaging solution proposed can be used for the medicine taking procedure. The prescription is stored in the customer terminal after the face-to-face examining or the telemedicine service. According to the prescription, through the networks, the suitable medical packages will open automatically at the suitable time. Then the suitable dosages are prepared for the patient at the right time. The system can also send audio or video signals to prompt for the patient. This is especially useful and important for the elder people or forgetful men to prevent the unsuitable dosage. If the medicine is taken, the system will record it. The history can be reviewed and checked for further medical care. Based on the condition of the patient, the prescription can be adjusted and updated timely through the networks. Besides, other simple treatment equipments are also embedded to the treatment part for a suitable treatment.

Combining the proposed interactive medical packaging with WSN, the two parts of the medical care system can work collaboratively to provide a safe, comfortable and efficient medical care service.

5.4 Summary

Based on the basic solution, an interactive medical package solution of unprecedented high patient compliance for pervasive healthcare is suggested. Combining RFID with Sinuate®, the medicine packages are senior-friendly, automatic to open with authorization for right dose and right time, and resistant without approval. By using a Gen2 RFID tag, a
large information flow could be utilized to improve the communication between the patients and healthcare staffs.

Two case studies of WSN applications are proposed followed. The fresh food tracking system with a successful real case study has proved to be efficient. The medical care network solution based on the interactive packaging solution is proposed in order to develop more applications for combining these technologies.
Chapter Six

6 CONCLUSIONS AND FUTURE WORK

This chapter concludes the thesis and outlines the future plan.
6.1 Conclusions

RFID technology is one of the hottest technical topics nowadays. It can be widely used without professional knowledge. It is low in cost, and almost away from the impact of the outside surrounding. However, the working range of an RFID system depends on the operation frequency and the properties of RFID devices. Similar with RFID, WSN is also a popular technology which plays an important role in our daily life.

With the combination of CDM, some interesting interactive packaging solutions are presented in this thesis. A CDM product, named Sinuate®, has a sandwiched structure of mental/glue and can delaminate automatically with little electricity within a certain time. The first simple solution is to integrate CDM with RFID. Through the related experiments, this solution is proved to be feasible. Once the power button is pressed, the demonstration which is a paper box sealed with Sinuate® opens automatically without any box surface damage or marking. Based on this basic solution, an interactive medical package of unprecedented high patient compliance for pervasive healthcare is further suggested. This medicine packages will use a Gen2 RFID tag instead. In such a system using Gen2 RFID technology, a large information flow could be utilized to improve the communication between patients and the healthcare staffs. This solution is senior-friendly and automatic to open for right dose at right time with right authorization, and resistant without adequate authorization.

Besides what mentioned above, two study cases worked on combination between CDM, RFID and WSN are proposed. The fresh food tracking system is designed to monitor and record the status of fresh food in real-time during transportation, which is useful to improve the transportation quality and protect the fresh food. The medical care solution can work collaboratively to supply the safe, comfortable and efficient medical care service.

6.2 Future Work

In order to further develop the intelligent and interactive packaging solutions, the initial discrete component design for demonstrating the proposed solutions would be replaced by a System in Package (SiP) solution to miniaturize the system and reduce the cost. Such SiP solution might be even built on multi-layer paper based board by using printed electronics. Integrating DC/DC converter, RFID reader/writer circuits and MCU on an application specific System on Chip (SoC), in combination with paper battery, printed antennas and printed CDM package sealing-off, is another interesting direction towards realizing intelligent and interactive packaging solutions of low cost and small size.


[40] TinyOS, http://www.tinyos.net/


APPENDED PAPERS