ROYAL INSTITUTE
OF TECHNOLOGY

Technologies and Architectures of the Internet-of-Things (IoT) for Health and Well-being

ZHIBO PANG

Doctoral Thesis in Electronic and Computer Systems
KTH – Royal Institute of Technology
Stockholm, Sweden, January 2013

Zhibo Pang

Technologies and Architectures of the Internet-of-Things (IoT) for Health and Well-being

ISBN 978-91-7501-736-5

TRITA-ICT/ECS AVH 13:11

ISSN 1653-6363

ISRN KTH/ICT/ECS/AVH-13/11-SE

Royal Institute of Technology (KTH)

School of Information and Communication Technology

Department of Electronic Systems

Forum 120

Isafjordsgatan 39

SE-164 40 Kista

Sweden

ABSTRACT

The emerging technology breakthrough of the Internet-of-Things (IoT) is expected to offer promising solutions for food supply chain (FSC) and in-home healthcare (IHH), which may significantly contribute to human health and well-being. In this thesis, we have investigated the technologies and architectures of the IoT for these two applications as so-called Food-IoT and Health-IoT respectively. We intend to resolve a series of research problems about the WSN architectures, device architectures and system integration architectures. To reduce the time-to-market and risk of failure, business aspects are taken into account more than before in the early stage of technology development because the technologies and applications of IoT are both immature today.

The challenges about enabling devices that we have addressed include: the WSN mobility and wide area deployment, efficient data compression in resource-limited wireless sensor devices, reliable communication protocol stack architecture, and integration of acting capacity to the low cost intelligent and interactive packaging (I2Pack). Correspondingly, the WAN-SAN coherent architecture of WSN, the RTOS-based and multiprocessor friendly stack architecture, the content-extraction based data compression algorithm, and the CDM-based I2Pack solution are proposed and demonstrated.

At the system level, we have addressed the challenges about effective integration of scattered devices and technologies, including EIS and information integration architectures such as shelf-life prediction and real-time supply chain re-planning for the Food-IoT, and device and service integration architectures for the Health-IoT. Additionally, we have also addressed some challenges at the top business level, including the Value Chain Models and Value Proposition of the Food-IoT, and the cooperative ecosystem model of the Health-IoT. These findings are generic and not dependent on our proprietary technologies and devices.

To be more generalized, we have demonstrated an effective research approach, the so-called Business-Technology Co-Design (BTCD), to resolve an essential challenge in nowadays research on the IoT -- *the lack of alignment of basic technology and practical business requirements.* We have shown its effectiveness by our design practice. It could be an instructive example of "*the change of mindset*" which is essential for the IoT research in the future.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervisors, Prof. Lirong Zheng, Dr. Qiang Chen and Prof. Elena Dubrova for providing me the opportunity to study and research in the excellent group of iPack Center of KTH. They helped me so much in positioning my research topics, resolving research challenges, and even in everyday life. They are great scientists, smart leaders, patient guidance, and warm friends!

My gratitude goes to our partners in iPack Center, Lucas Åhlstrom, Lars Sandberg, and Per Norman. I have learnt a lot of cross-industry knowledge from them. Wish their continuous success in business and career. Special thanks to Prof. Hannu Tenhunen for his great efforts on forming the research areas and enabling the MBA-for-PhD program which has deeply changed my mindset. Special thanks to Prof. Axel Jantsch and Prof. Mikael Östling for their efforts on project procedures which have ensured my research to progress smoothly. Special thanks to the management and administration team of iPack Centeer, Fredrik Johnson, Agneta Herling, and Alina Munteanu.

Deepest thanks to Mikael Gidlund and Johan Akerberg for their instructive comments on this thesis. Many thanks to Peter Lofgren, Stefan U Svensson and Helena Malmqvist for their supports, as well as all other friends, Eva Stenqvist, Ewa Hansen, Gaetana Sapienza, Gargi Bag, Jonas Neander, Krister Landernas, Linus Thrybom, Mikael Davidsson, Morgan E Johansson, Niclas Ericsson, Roger N Jansson, and Tomas Lennvall, Xiaojing Zhang, Alf Isaksson, Xiaodong Zhu, Zhiyong Wei, Kan Yu.

Also many thanks to my dear classmates, Jun Chen, Zhuo Zou, Ning Ma, David Sarmiento Mendoza, Yasar Amin, Awet Yemane Weldezion, Ana Lopez, Zhi Zhang, Jian Chen, Jia Mao, Liang Rong, Yi Feng, Jue Shen, Botao Shao, Zhiying Liu, Huimin She, Geng Yang, Peng Wang, and Li Xie. You have made the group like a big family. We have had a lot of fun together.

My dear friends please forgive me if any of you is missing here.

I would also express my thanks to the opponent and committee members, Prof. Lida Xu, Dr. Tiberiu Seceleanu, Prof. Cristina Rusu and Prof. Xiaoming Hu.

Dedicated thanks to my parents, brother and his family, parents in law, and brother in law and his family for their endless supporting. Finally, I would say to my wife Tingting Ma and my dear daughter Xiaohan, you are the most important in my life, and you make everything meaningful!

Zhibo Pang

Västerås, April 2013

-- *For my family*

TABLE OF CONTENTS

ABBREVIATIONS

3C	Consumer Communication Computing
3GPP	Third Generation Partnership Project
BTCD	Business-Technology Co-Design
CDM	Controlled Delamination Material
EHR	Electronic Healthcare Record
EIS	Enterprise Information System
EPC	Electronic Product Code
ES	Enterprise System
Food-IoT	IoT solution for food supply chain
FSC	Food Supply Chain
Health-IoT	IoT solution for healthcare (specifically refers to in-home healthcare)
HIS	Hospital Information System
I2Pack	Intelligent and Interactive Packaging
ICT	Information and Communication Technologies
IHH	In-Home Healthcare
IHHS	In-Home Healthcare Station
IIIE	Industrial Information Integration Engineering
iMedBox	Intelligent Medicine Box (of the proposed IHHS solution)
IoT	Internet-of-Things
MN	Main Nodes (of the proposed WSN platform)
RFID	Radio-Frequency IDentification
RTOS	Real Time Operation System
SAN	Sensor Area Network
SN	Sub Nodes (of the proposed WSN platform)
SOA	Service Oriented Architecture
USN	Ubiquitous Sensor Networks
WAN	Wide Area Network
WSN	Wireless Sensor Network

LIST OF PUBLICATIONS

Papers included in this thesis:

1. **Zhibo Pang,** Jun Chen, David Sarmiento M., Zhi Zhang, Jie Gao, Qiang Chen, Lirong Zheng, “Mobile and Wide Area Deployable Sensor System for Networked Services”, *IEEE Sensors Conference 2009*, pp1396 – 1399, Oct 2009, Christchurch, New Zealand.

2. Jie Gao, **Zhibo Pang,** Qiang Chen, Lirong Zheng, “Interactive Packaging Solutions Based on RFID Technology and Controlled Delamination Material”, *The 2010 IEEE International Conference on RFID,* April 2010, pp158-165, Florida, USA.

3. **Zhibo Pang,** Jun Chen, Zhi Zhang, Qiang Chen, Lirong Zheng, "Global Fresh Food Tracking Service Enabled by Wide Area Wireless Sensor Network", *IEEE Sensors Applications Symposium (SAS-2010),* pp6-9, Feb 2010, Limerick, Ireland.

4. **Zhibo Pang,** Qiang Chen; Junzhe Tian, Lirong Zheng, Elena Dubrova. “Ecosystem Analysis in the Design of Open Platform-based In-Home Healthcare Terminals towards the Internet-of-Things”. *International Conference on Advanced Communications Technology (ICACT).* Jan 2013, Pyeongchang, Korea. **Outstanding Paper Award.**

5. **Zhibo Pang,** Qiang Chen, Lirong Zheng. “Content-Extraction-Based Compression of Acceleration Data for Mobile Wireless Sensors”, *IEEE Sensors Conference 2012*, Oct 2012, Taipei, Taiwan.

6. **Zhibo Pang,** Kan Yu, Johan Åkerberg, Mikael Gidlund, “An RTOS-based Architecture for Industrial Wireless Sensor Network Stacks with Multi-Processor Support”, *IEEE International Conference on Industrial Technology (ICIT2013),* Feb 2013, Cape Town, South Africa.

7. **Zhibo Pang,** Qiang Chen, Lirong Zheng. “Value creation, Sensor Portfolio and Information Fusion of Internet-of-Things Solutions for Food Supply Chains”, *Information Systems Frontiers,* Aug 2012, DOI: 10.1007/s10796-012-9374-9. **IF 1.596**.

8. **Zhibo Pang,** Lirong Zheng, Junzhe Tian, Sharon Kao-Walter, Elena Dubrova , Qiang Chen. “Design of a Terminal Solution for Integration of In-home Healthcare Devices and Services towards the Internet-of-Things”, *Enterprise Information Systems*, DOI:10.1080/17517575.2013.776118, April 2013. **IF 3.684.**

Papers not included in this thesis:

9. Kan Yu, **Zhibo Pang,** Mikael Gidlund, Johan Åkerberg, Mats Björkman, "REALFLOW: Reliable Real-time Flooding-based Routing Protocol for Industrial Wireless Sensor Networks". *IEEE **Transactions** on Wireless Communications,* Jan 2013, **submitted**.

10. Ma, Ning; Lu, Zhonghai; **Pang, Zhibo**; Zheng, Lirong, "A Hybrid Circuit- and Wormhole-switched Router for Scalable and Flexible NoCs", *IEEE **Transactions** on Computers* Nov 2012, **submitted**.

11. Kan Yu, Tao Zheng, **Zhibo Pang,** Mikael Gidlund, Johan Åkerberg, Mats Björkman, "Reliable Flooding-based Downlink Transmissions for Industrial Wireless Sensor and Actuator Networks", *IEEE International Conference on Industrial Technology (ICIT2013)*, Feb 2013, Cape Town, South Africa.

12. **Zhibo Pang,** Qiang Chen; Lirong Zheng, Elena Dubrova. "An In-home Medication Management Solution Based on Intelligent Packaging and Ubiquitous Sensing". *International Conference on Advanced Communications Technology (ICACT).* Jan 2013, Pyeongchang, Korea. **Outstanding Paper Award.**

13. **Zhibo Pang,** Qiang Chen, Lirong Zheng, "Scenario-based Design of Wireless Sensor System for Food Chain Visibility and Safety", Advances In Computer, Communication, Control and Automation. *Lecture Notes in Electrical Engineering,* 2012, Volume 121, 541-548, DOI: 10.1007/978-3-642-25541-0_69.

14. Ning Ma, Zhonghai Lu, **Zhibo Pang**, Lirong Zheng, "System-Level Exploration of Mesh-based NoC Architectures for Multimedia Applications", *2010 IEEE International SOC Conference,* pp 99-104, Sep. 2010, Las Vegas, USA.

15. Sarmiento M, David; **Zhibo Pang;** Sanchez, Mario F.; Qiang Chen; Tenhunen, Hannu; Li-Rong Zheng; "Mobile wireless sensor system for tracking and environmental supervision", *IEEE Inte. Symp. on Industrial Electronics (ISIE2010),* pp470-477, Jul. 2010, Bari, Italy.

16. Zhi Zhang, Zhonghai Lu, **Zhibo Pang,** Xiaolang Yan, Qiang Chen, Li-Rong Zheng, "A Low Delay Multiple Reader Passive RFID System Using Orthogonal TH-PPM IR-UWB", *19th Inte.l Conf. on Computer Communications and Networks (ICCCN*2010*),* pp1-6, Aug. 2010, Zurich, Switzerland.

17. **Zhibo Pang,** Qiang Chen, Lirong Zheng, "A Pervasive and Preventive Healthcare Solution for Medication Noncompliance and Daily Monitoring", *2nd International*

Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL2009), pp1-6, Nov 2009, Bratislava, Slovak Republic.

18. Ning Ma, **Zhibo Pang,** Jun Chen, Hannu Tenhunen, Li-Rong Zheng, “A 5Mgate/414mW Networked Media SoC in 0.13um CMOS with 720p Multi-Standard Video Decoding”, *IEEE Asian Solid-State Circuits Conference (ASSCC),* pp385-388, Nov 2009, Taipei, Taiwan.

19. **Zhibo Pang,** Jun Chen, Zhi Zhang, Qiang Chen, Lirong Zheng, “A Global Fresh Food Tracking Service Based on Novel Wireless Sensor and RFID Technologies”, *The 6th annual International New Exploratory Technologies Conference (NEXT2009),* Oct 2009 Shanghai China.

20. Zhi Zhang, **Zhibo Pang,** Jun Chen, Qiang Chen, Hannu Tenhunen, Li-Rong Zheng, Xiaolang Yan, “Two-Layered Wireless Sensor Networks for Warehouses and Supermarkets”, *3rd Inte.l Conf. on Mobile Ubiquitous Computing, Systems, Technologies (UBICOMM 2009),*pp220-224, Oct. 2009, Malta.

21. Jun Chen, **Zhibo Pang,** Zhi Zhang, Jie Gao, Qiang Chen, Lirong Zheng, “A Novel Acceleration Data Compression Scheme for Wireless Sensor Network Application in Fresh Food Tracking System”, *9th Inte.l Conf. on Electronic Measurement & Instruments (ICEMI2009),* pp3.1- 3.5, Aug. 2009, Beijing, China.

22. **Zhibo Pang**, Majid Baghaei-Nejad, “TouchMe System - RFID Solution for Interactive Package with Mediated Service”, *RFID Nordic EXPO and Conference 2008*, **winning the first place award in scholarship competition**, Oct. 2008, Stockholm, Sweden.

23. Ning Ma, **Zhibo Pang,** Hannu Tenhunen, Li-Rong Zheng, “An ASIC-Design-Based Configurable SOC Architecture for Networked Media”, *IEEE Inte. Symp. on System-on-Chip (SOC2008),*pp1-4, Oct. 2008 Tampere Finland.

Others:

24. Mikael Gidlund, Johan Åkerberg, **Zhibo Pang**, Kan Yu, “Determination of communication routes in a wireless communication network”, **European Patent Application**, No. 12175093.9-1249.

25. **Zhibo Pang**, “Business Model Design for Personal Mobile Healthcare Service: the Methodology and Case Study”, **MBA Thesis,** University of Turku, June 2012.

26. **Zhibo Pang**, “FreshVision: a food chain visibility service”, **Business Plan**, Aug, 2010. not published.

PART I:
Thesis

1. INTRODUCTION

1.1 The Internet-of-Things

1.1.1 The Vision

To improve human health and well-being is the ultimate goal of any economic, technological and social development. The rapid rising and aging of population is one of the macro powers that will transform the world dramatically, it has caused great pressure to food supply and healthcare systems all over the world, and the emerging technology breakthrough of the Internet-of-Things (IoT) is expected to offer promising solutions (National Information Council 2008). Therefore the application of IoT technologies for the food supply chain (FSC) (so-called Food-IoT) and in-home healthcare (IHH) (so-called Health-IoT[1]) have been naturally highlighted in the strategic research roadmaps (European Commission Information Society 2009). To develop practically usable technologies and architectures of IoT for these two applications is the final target of this work.

The phrase "Internet of Things" (IoT) was coined at the beginning of the 21st century by the MIT Auto-ID Center with special mention to Kevin Ashton (Ashton 2009) and David L. Brock (Brock 2001). As a complex cyber-physical system, the IoT

[1] Many relevant concepts have been introduced to describe the future healthcare powered by emerging information and communication technologies, such as pervasive healthcare (pHelath), ubiquitous healthcare (uHealth), mobile healthcare (mHealth), electrical healthcare (eHealth), telehealth, telemedicine, etc. (Pawar *et al.* 2012). In this work, we don’t intend to distinguish them pedantically and these concepts are looked as alternative expressions of the Health-IoT. Additionally, without special state, the Health-IoT more specifically refers to the in-home healthcare application of IoT.

integrates all kinds of sensing, identification, communication, networking, and informatics devices and systems, and seamlessly connects all the people and things upon interests, so that anybody, at any time and any place, through any device and media, can more efficiently access the information of any object and any service (ITU 2005, European Commission Information Society 2008 and 2009). "*Ubiquitous*" is the distinct feature of IoT technologies, so the IoT is often related to *ubiquitous* identification (Sheng *et al.* 2010), *ubiquitous* sensing (ITU-T, 2008), *ubiquitous* computing (Friedewald and Raabe 2011), *ubiquitous* intelligence (Zheng *et al.* 2008), etc. As shown in Figure 1-1, a vivid description of this vision has been illustrated in a report by *The Economist* in 2007 (The Economist 2007).

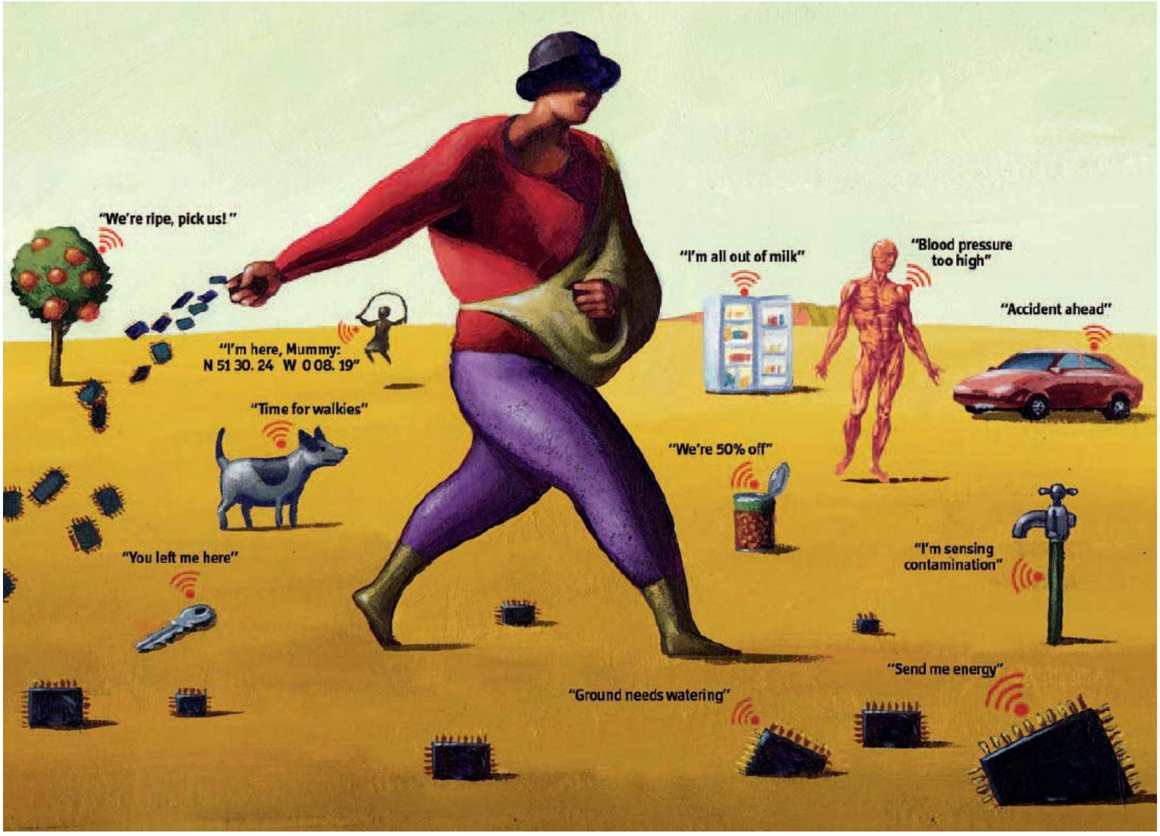

Figure 1-1 A vivid description of the vision of Internet-of-Things (Authorized by Jon Berkeley)

The impact caused by the IoT to human life will be as huge as the internet has caused in the past decades, so the IoT is recognized as "the next of internet". A part of the enabling technologies are sensors and actuators, Wireless Sensor Network (WSN), Intelligent and Interactive Packaging (I2Pack), real-time embedded system, MicroElectroMechanical Systems (MEMS), mobile internet access, cloud computing, Radio Frequency IDentification (RFID), Machine-to-Machine (M2M) communication, human machine interaction (HMI), middleware, Service Oriented Architecture (SOA), Enterprise Information System (EIS), data mining, etc. With various descriptions from various viewpoints, the IoT has become the new paradigm of the evolution of information and communication technology (ICT) (Atzori *et al.* 2010, Miorandi *et al.* 2012).

1.1.2 Research Space

It is broadly accepted that the technologies and applications of IoT are both in early stage and distant from mature (Atzori *et al.* 2010, Miorandi *et al.* 2012). Research challenges are distributed in almost all aspects of a solution, ranging from the enabling devices to the top level business models. So the research space for a complete IoT solution shows a cross-layer and multidisciplinary pattern (Figure 1-2).

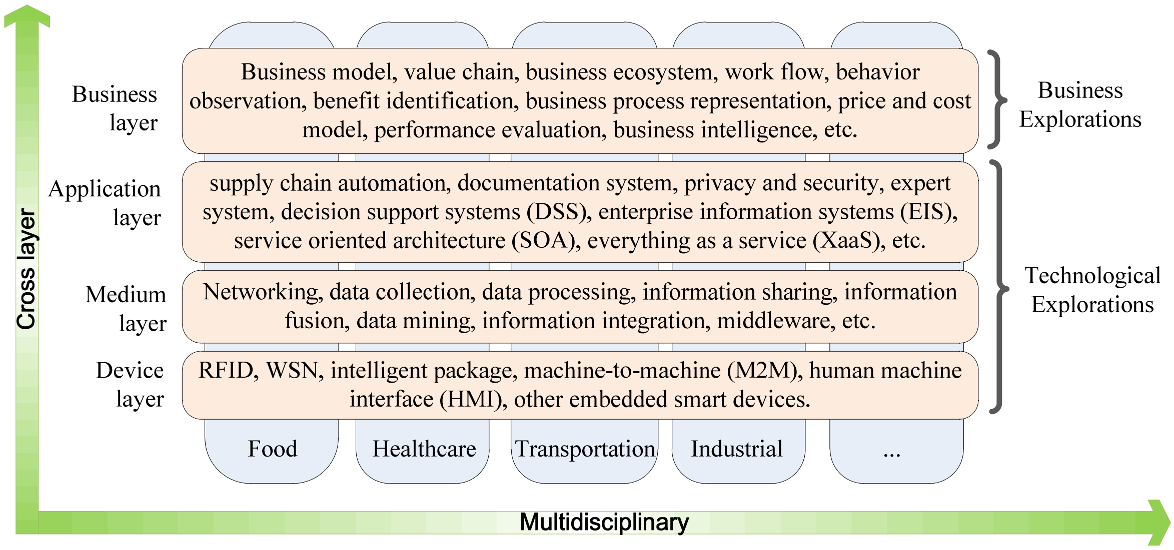

Figure 1-2 Research space of the IoT

On one hand, the explorations should cover all the layers from the bottom device layer, through the medium networking and data processing layer, and application layer, up to the top business layer. The bottom layer of the solution is a series of innovative wireless sensor devices; the data from the devices are collected through specific networking protocols; the data is processed at different layers and integrated into valuable information to users; and business model and work flow are designed at the top layer to maximize the added values towards sustainable business. Innovations are distributed at all the layers, and cross-layer design and optimization is required.

On the other hand, to develop a complete solution for a particular application, developers must at least integrate multidisciplinary knowledge of ICT, management, business administration, and the target application. Moreover, the specific knowledge of the target application often covers multiple disciplines too. For example, in the application of food supply chain, to decide the environmental parameters that the wireless sensor devices should measure, we need to analyze the causes of food damages during the food supply chain. To deliver valuable information to users, e.g. to predict shelf life, we need to exploit the meaning of the huge amount of raw data. These works need a fusion of expertise in food engineering, biology, and agriculture.

1.1.3 Conmen Challenges

The IoT research is facing an essential challenge: *the alignment of enabling technology and practical business requirements*. In other words, *there is a huge gap between the technology development and business innovation*.

The setbacks of some big initiatives have confirmed the critical challenges in business design of IoT innovations. For example, Wal-Mart's adoption of RFID has been delayed so much that some critics even announced the "death" of RFID technology (McWilliams 2006, Visich *et al.* 2011), and the failure of Google Health is related to the unsuccessful value chain establishment (Dolan 2011). We have read many "affirmative conclusions" in technological papers on the feasibility of such business, but the reality is cruel! In particular, this gap results in two major barriers for the development of IoT market. So it is crucial not only for commercialization efforts but also for enabling technology development.

1. **Unattractive Value Proposition**. This is the primary limitation of mass volume adoption. For example, the RFID-based food trace system (in which RFID tags are used to record the operators and time over the supply chain) is one of the most common IoT applications. It can reduce labor cost and process time of food distributors and retailers. But this added-value is not attractive enough to drive the entire supply chain. "*The suppliers were reluctant to adopt the RFID because their initial investment cost, required by the third party logistics firm, has produced the minimum level benefits for themselves, which, in turn, has a cascading effect on the minimum level business benefits realized by the third party logistic firm*" (Wamba and Chatfield 2010). And Visich et al. (2011) have also observed that, actually most of the profitable RFID applications today are out of the prioritized targets when this technology was firstly invented. Similarly, the lack of value-chain attractiveness also exists in Health-IoT. Many of existing solutions hasn't provided enough opportunity for the primary healthcare service providers (e.g. hospitals) to get involved in the value chain. This has caused "*the lack of trust from patients and the absence of financial support from public authorities to such services*" (Limburg et al. 2011). Therefore, more added-values should be delivered, and new functionalities and capacities should be developed directly aiming for such new values,.
2. **Lack of Device and Service Integration**. Many appreciated technologies have been developed in recent year for the two applications, covering nearly all the key elements of a solution. But many reviews (WHO 2011, Ruiz-Garcia *et al.* 2009, 2011, Lee *et al.* 2010, Alemdar and Ersoy 2010), as well as our investigation, have indicated the *scattered pattern* of the existing research.That is, there are a mass of sperated technologies and devices, but there are few integrated services. Just as Ludwig *et al.* (2012) has pointed, "*focused services for selected diseases might not meet the real life requirements of multimorbid seniors; and thus, a combination of several telehealth services might be advisable to support people in a more holistic way; and to do this, a lot of interdisciplinary work between all stakeholders and the engineers has to be*

done". The World Health Organization (WHO) (2011) also highlights this issue: *"A common pattern for the introduction of ICT and mobile technologies in countries is their entrance to health markets in pockets, a plaster here or a bandage there, to fix a particular problem"; "the most common result is a profusion of non-interoperable islands of ICT"*. Therefore, a holistic design framework is demanded to effectively integrate the scattered devices and technologies into more valuable services.

1.1.4 Change of Research Mindset

Essentially, such gap is caused by the technology-driven research tradition or *mindset*. That is, technology developers often create a new technology first and then find what it could be used for. For the research on a mature application, the business model and application scenario are clear and have already been mapped into technical requirements. So the technology developers just need to focus on the technology aspects of particular functionalities or performances. They don't necessarily need to spend much time on business-related aspects. But obviously, if the technology and application are both immature, like the IoT, this is inefficient in terms of business-technology alignment. There are too many possibilities and uncertainties equivalently, in business models and application scenarios. One solution can never fit all these possibilities. To reduce the time-to-market and risk of failure, business aspects should be taken into account more than before in the early stage of IoT technology development. If the inventors still hold the traditional mindset, the feedback from business practice is usually too late for them to survive in the cruel business world.

A wiser approach for IoT developers is to carry out business design in the early stage of technology development (Limburg *et al.* 2011, Michahelles 2011). This implies a change of mindset from technology-driven to business-technology joint research, the so-called Business-Technology Co-Design (BTCD). Ideally, the BTCD can essentially overcome the aforementioned common challenges. In the BTCD, by drawing a whole picture of the target business use cases first, developers can discover more attractive value proposition to drive the whole value chain indeed. Then they can make better architectural tradeoffs for the device and service integration, because only the *business design* can be used as the *top criteria* of these tradeoffs.

For example, as the access network of WSN, wireless local area network (WLAN) is more attractive if the independence to telecom operator is prioritized in the business design; on the contrary, wireless cellular network like GSM/GPRS/3G/4G is more attractive if the mobile and wide area deployment is emphasized first. For another example, the third-party device and service interface of the IHH terminal is determined by the form of business ecosystem prior to the technical functionalities. A close system prefers proprietary interfaces which might have better security, higher performance, and simpler development procedure. But if the business is established upon an open and cooperative ecosystem, standardized interfaces (e.g. USB, Bluetooth, Zigbee, NFC, etc.) and data formats should be applied even though they might increase the complexity due to the critical interoperability specifications. This principle is also applicable to many other architectural aspects such as the security and authentication scheme for patient privacy, sensor integration for wireless sensor devices, the selection of operation system (OS) and computation platform, data-processing and information fusion, etc.

Moreover, the BTCD is important to ease the integration of the IoT solution into the entire Enterprise Information System (EIS). The IoT technologies have been recognized as enabling infrastructure of future EIS for food supply chain and healthcare (Sinderen and Almeida 2011). Numerous techniques of EIS and Industrial Information Integration Engineering (IIIE) have been applied e.g. Business Process Management (BPM), information integration and interoperability, enterprise architecture and enterprise application integration, and Service Oriented Architecture (SOA) (Xu 2011a, 2011b). Obviously successful adoption of these techniques relies on deep insight business design.

1.2 Overview of the Target Applications

1.2.1 The Food-IoT

Today's food supply chain (FSC) is extremely distributed and complex. It has large geographical and temporal scale, complex operation processes, and large number of stakeholders. The complexity has caused many issues in the quality management, operational efficiency, and public food safety. IoT technologies offer promising potentials to address the traceability, visibility and controllability challenges. It can cover the FSC in the so-called *farm-to-plate* manner, from precise agriculture, to food production, processing, storage, distribution, and consuming. Safer, more efficient, and sustainable FSCs are expectable in the future.

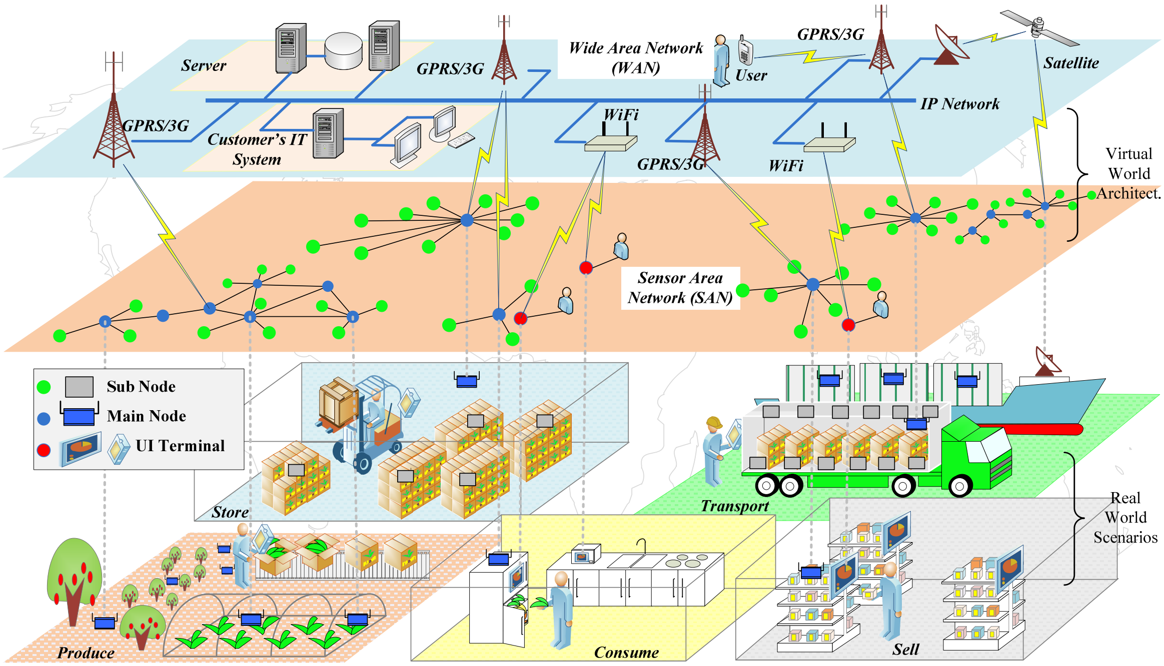

Figure 1-3 A whole picture of food supply chains in the era of Internet-of-Things

Figure 1-3 is an illustration of a typical IoT solution for FSC (the so=called Food-IoT). It comprises three parts: the field devices such as WSN nodes, RFID readers/tags, user interface terminals, etc., the backbone system such as databases, servers, and many kinds of terminals connected by distributed computer networks, etc., and the communication infrastructures such as WLAN, cellular, satellite, power line, Ethernet, etc. As the IoT system offers ubiquitous networking capacity, all these elements can be distributed throughout the entire FSC. And it also offers powerful but economy sensing functionalities, all the environmental and event information during the lifecycle of food product can be gathered on a 24/7 basis. The vast amount of raw data can be refined into high level and directly usable information for the decision making of all stakeholders.

1.2.2 The Health-IoT

In the coming decades, the delivery model of healthcare will transform from the present hospital-centric, through hospital-home-balanced in 2020th, to the final home-centric in 2030th (Koop *et al.* 2008). The future healthcare system should be organized in a layered structure, e.g. from low to high comprising the personal, home, community, and hospital layer; and the lower layer has lower labor intensity and operational cost, higher frequency of usage for chronic disease, and lower frequency of usage for acute disease (Poon and Zhang 2008). So the in-home healthcare (IHH) service enabled by the IoT technology (the so-called Health-IoT) is promising for both traditional healthcare industry and the ICT industry. The Health-IoT service is ubiquitous and personalized and will speed up the transformation of healthcare from career-centric to patient-centric (Liu *et al.* 2011, Klasnja *et al.* 2012, Plaza *et al.* 2011). A typical application scenario of the Health-IoT is shown in Figure 1-4.

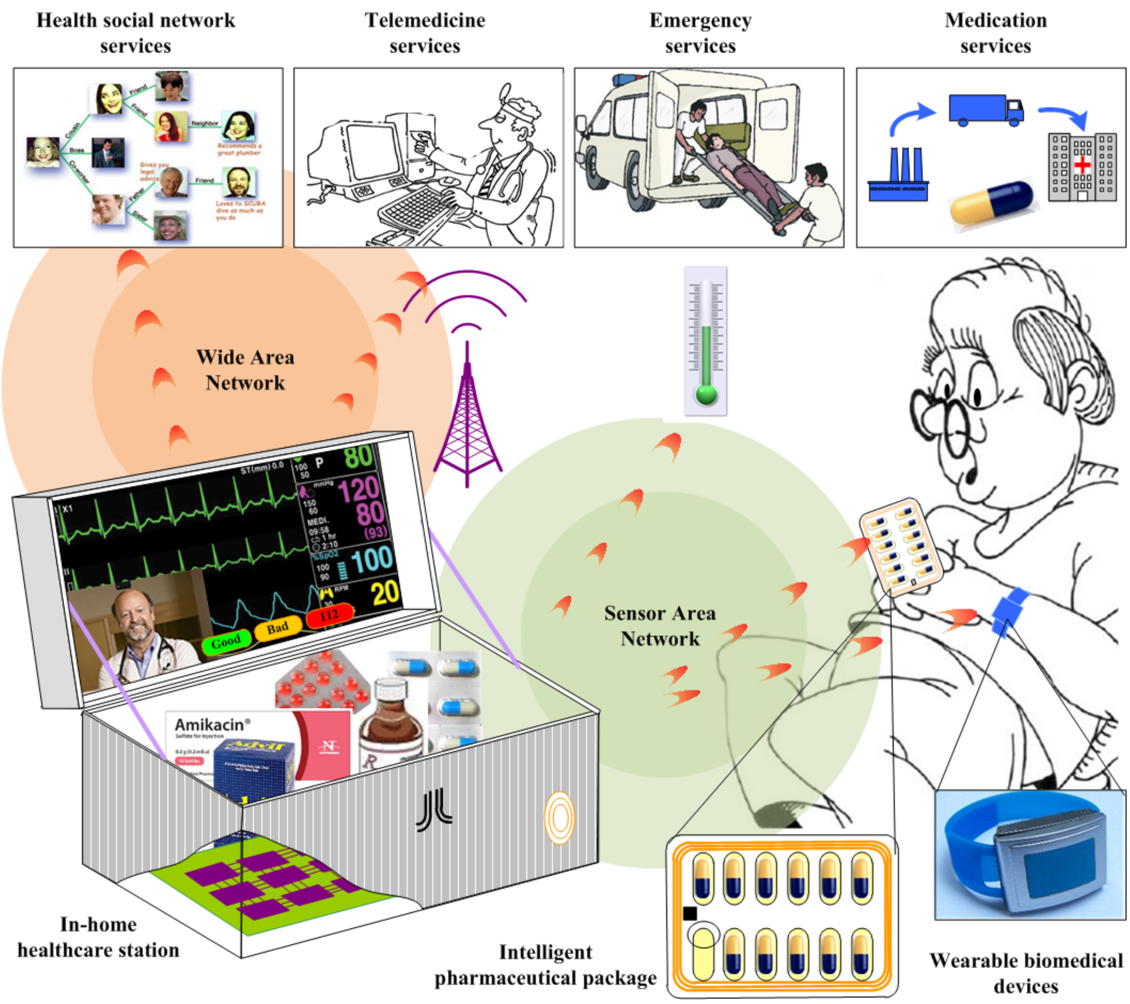

Figure 1-4 Application scenario of the proposed In-Home Healthcare Station

Typically, a Health-IoT solution includes the following functions:

1. Tracking and monitoring. Powered by the ubiquitous identification, sensing, and communication capacity, all the objects (people, equipment, medicine, etc.) can be tracked and monitored by wearable WSN devices on a 24/7 basis (Alemdar *et al.* 2010).
2. Remote service. Healthcare and assist living services e.g. emergency detection and first aid, stroke habitation and training, dietary and medication management, telemedicine and remote diagnosis, health social networking etc. can be delivered remotely through the internet and field devices (Plaza *et al.* 2011, Klasnja and Pratt 2012, Ludwig *et al.* 2012).
3. Information management. Enabled by the global connectivity of the IoT, all the healthcare information (logistics, diagnosis, therapy, recovery, medication, management, finance, and even daily activity) can be collected, managed, and utilized throughout the entire value chain (Domingo 2012).
4. Cross-organization integration. The hospital information systems (HISs).are extended to patient' home, and can be integrated into larger scale healthcare

system that may cover a community, city or even state (Serbanati et al. 2011, Yin et al. 2009, and Liu et al. 2008).

1.3 Research Problem

Our work originates from the initiative of the iPack VINN Excellence Center (iPack Center) funded by the Swedish Governmental Agency for Innovation Systems (VINNOVA), KTH, and industrial partners. The mission of iPack Center is "to develop innovative electronics in vision of Internet-of-Things, through close collaboration with industry, leading research centers, and early adopters internationally" [2]. When the work in this thesis was started, we had just some initial technologies (e.g. real-time embedded system, RFID, WSN, functional material), some initial business demands from industrial partners, and a general vision. These business demands are mainly about two target applications, 1) fresh food tracking for food supply chain (FSC), and 2) patient medication management and monitoring for in-home healthcare (IHH),. So, the task of this work in general is to develop valuable and usable IoT solutions for the FSC and IHH. To be short, in our work the IoT solution for the application of FSC is called "Food-IoT", and the IoT solution for the application of IHH is called "Health-IoT". In particular, we intend to address the following research problems:

1. WSN architectures. As the objects in FSC and IHH are mostly mobile and widely distributed, the WSN system must support mobile and wide area deployment. Reliable communication is also needed to work with poor radio signal propagation through water-rich food and human body. Moreover, efficient data compression is essential to reduce the power consumption as well as traffic load especially for high data rate sensors. All these should be implemented with inexpensive chips and meet the long life cycle requirement of industrial applications.
2. Device architectures. The above two applications both require the WSN and I2Pack devices to integrate very rich functionalities including numerous sensors, actors, and storage. All these should be implemented under restrict limit of power consumption.
3. System integration architectures. These architectures should enable the seamless integration of the proposed WSN and I2Pack devices in practical EIS. Efficient information integration algorithms are needed to deliver the most compact information for decision making. Interoperability of devices and services from different suppliers, operational workflow, and proper security schemes should fit in business practices. Finally, the architectures should be verified by implemented prototypes and trials in field.

1.4 The BTCD-based Research Approach

First of all, a whole picture of the target application should be drawn**.** Since the value chains of the target applications involve a large number of stakeholders, if

[2] Home page of iPack Center: http://www.kth.se/en/ict/forskning/centra/ipack

developers take into account only a short segment of the entire value chain, business failures may happen due to the lack of acceptance by upstream or downstream stakeholders. So, comprehensive whole picture of the value chain of the target application is the base of successful added-value creation. The whole picture is also a representation of practical work flow for EIS integration. All the important architectural requirements for system integration are derived based on the top layer business design. It is also used for knowledge fusion between business developers and technology developers in terms of business intelligence to manage the great dimensionality and complexity of such applications (Xu 2011a, Duan and Xu 2012). Therefore, drawing the whole picture of the target application by means of value chain analysis is an appropriate start point of the IoT solution development.

The business requirements will be translated into technical specifications by the value-centric cross-layer design**.** For example, the architectures about sensor portfolio, networking, information integration, security, and interoperability may impact all the layers of the solution. So these aspects are the main concern of developers when integrate scattered devices. The system architecture should be optimized by considering all these aspects, instead of a part. The v*alue creation and distribution* based on the Application Whole Pictures will be the leading design criterion. In other words, For example, in the application of food supply chain the sensor portfolio is primarily determined by the added-values of the service. The technical constrains like power consumption, traffic load, complexity and cost are secondary factors which only affect the density of these sensors. Moreover, the information integration is also determined by the values to user, i.e. to deliver only the information that is useful in decision making instead of the raw data. And specific algorithms are implemented hierarchically according to the constraints at different layers.

Finally, the technical specifications are implemented by the enabling devices of WSN and I2Pack. New functionalities are added, such as sensing and data processing capacity of the WSN node, and the acting capacity of the I2Pack device. Key performances are also improved such as the system mobility, communication reliability and battery life. Some new data processing algorithms are developed. Guided by the proposed BTCD framework, the development of these enabling technologies can align better to the practical business. Finally the enabling devices and technologies are integrated into two specific solutions for FSC and IHH.

It is necessary to mention that, this work is driven by concrete application cases rather than basic research or pure theoretical study. It starts from the problems introduced by industrial partners, we seek and propose proper techniques to resolve these problems and the proposed solutions are assessed by experiments and field trials. The generic models and methodologies are verified by case studies. Analytical calculation and simulation are used as supplementary methods. Additionally, this work is carried out in an evolutionary manner. Both the enabling devices and technologies, and the design methodologies are refined round-by-round. For every round, corresponding proof-of-concept prototypes are developed and verified. A sketch of the research approach and evolution of the techniques are shown in Figure 1-5.

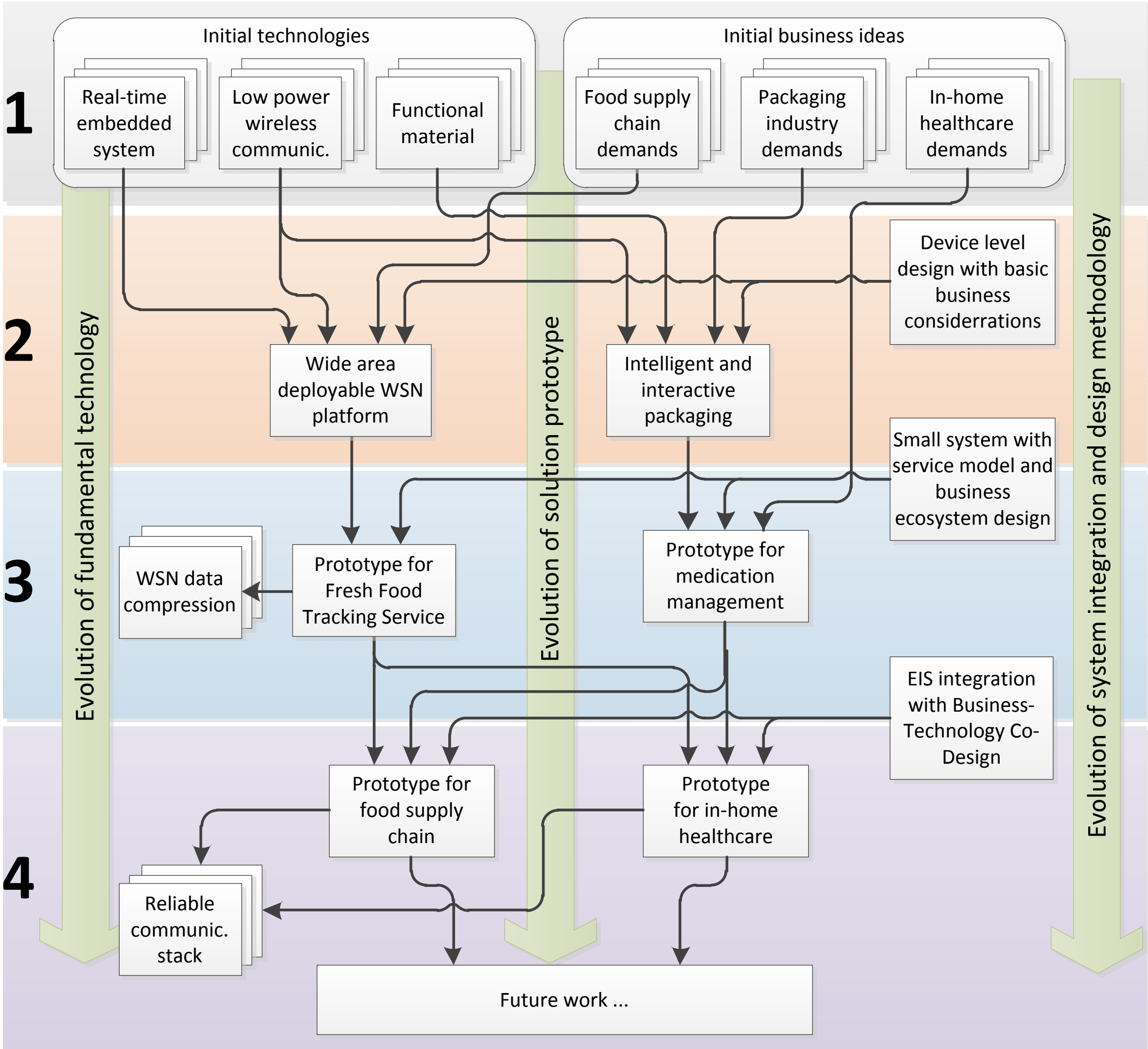

Figure 1-5 The research approach of this work

In particular, the project on Food-IoT was brought up by Billerud AB, a world leading food packaging solution provider. They had noticed the serious damages and loss during the food supply chain and intended to offer some new services to improve it. Then we together carried out a multi-disciplinary pre-study on the causes of damages and the best service models. An initial technical requirement (e.g. sensor portfolio, information fusion algorithms, networking architecture, etc.) was derived based on the pre-study. Then hardware and software prototypes were developed and tested in field. The prototypes have been incrementally refined and extended for four versions. At the same time, the design methodology and theoretical models have been extracted and refined.

The work on the I2Pack was initiated by StoraEnso AB, the largest paper and pulp manufacturer in the world. They had a strong vision to extend the functionality and capacity of traditional paper-based packages, and further develop innovative value-added services. They had noticed that, the emerging RFID technology and newly invented functional material called CDM (controlled delamination material) are promising towards this vision. However, in the beginning neither feasible technical architecture nor clear business scenario were in place. So we started with the technical development (e.g. to characterize the CDM material and design the driving circuits) and the business design (e.g. to identify the business values, and application scenarios) in parallel. Finally, we reached the I2Pack solution and its application scenario in pharmaceutical packaging.

The project on in home healthcare was triggered by the demands from AstraZeneca, one of the world largest biopharmaceutical companies. They had noticed the issues of medication noncompliance and the huge market potential of in home healthcare. But comprehensive solution with affordable cost and sustainable business models were not in place. So we started to investigate feasible business models and system integration architectures at the same time. The WSN system developed for the fresh food tracking is extended to a multi-purpose platform. And the I2Pack solution is also integrated. Then three versions of IHHS prototypes are implemented and tested. After that, the proposed design methodology and theoretical models become more generic and mature.

1.5 Summary of Contributions

Corresponding to the research problems, the contributions of this work are summarized in the following subsections. By mapping to the BTCD framework, these contributions and their logical relationship are illustrated in Figure 1-6.

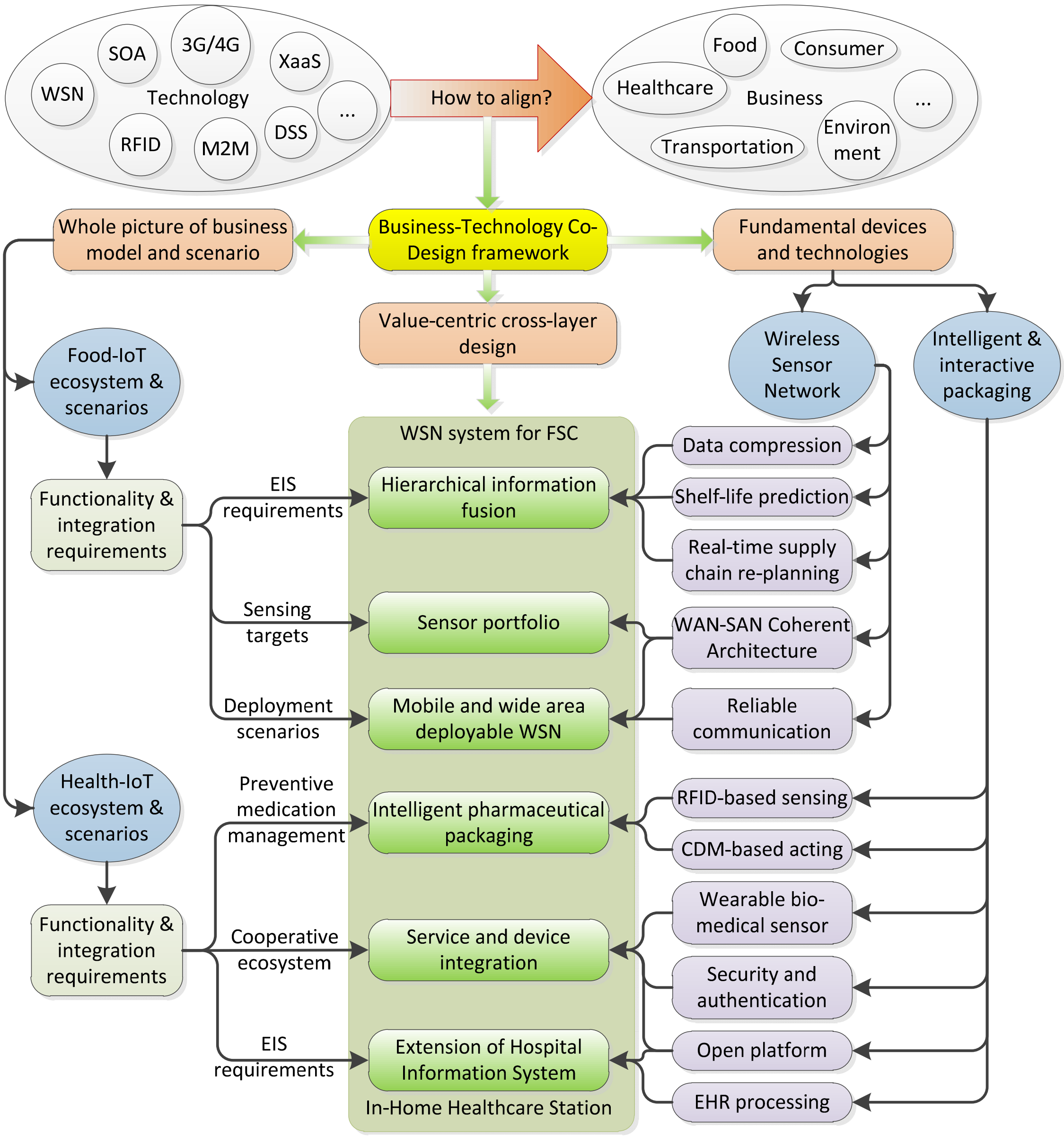

Figure 1-6 Interpretation of the research problem and answer from this work

1.5.1 WSN Architectures

We propose a mobile and wide area deployable WSN communication architecture, the so-called WAN-SAN Coherent Architecture, and successfully apply it in both the Food-IoT and Health-IoT solutions. It converges the wireless wide area networking and sensor area networking into the miniaturized and battery-powered Main Node, and thus the mobility is enhanced by avoiding the fix installed power supply and access network. Optimized power consumption enables all the devices to work with small batteries. More details are presented in section 2.2 and the included **Paper I**. Its application in Food-IoT and Health-IoT are presented in the included **Paper VII and VIII** respectively.

It was a “radical” design when we firstly proposed this architecture even though it has become quite popular today. This indirectly indicates its feasibility too.

We propose a new WSN stack architecture for reliable and secure communication, and demonstrate it in a functional implementation of the WirelessHART stack. It meets the critical requirements on reliability, security, and platform-independency of the target industrial systems by natively supporting the RTOS (real time operation system) and multiple processors. Layer-to-layer dependency and timing overhead are minimized by the novel Normalized Inter Layer Interface (NILI) and Inter-Processor Communication (IPC). More details are presented in section 2.3 and the included **Paper VI**. To the best of our knowledge, this is the first time that this architecture was explicitly and systematically presented.

We propose a novel acceleration data compression algorithm for WSN with significantly improved performances in terms of compression ratio, complexity, and scalability. It splits the raw data into Shock, Vibration, and Tilt components by low-complexity time-domain analysis, and the three components are compressed by the Adaptive Run-Length Coding, Adjustable Quantization, and Adjustable DPCM respectively. The coding parameters are automatically adjusted by the Application Concern Model. More details about the algorithm and experimental performances are presented in section 2.4 and the included **Paper V**. Although it was originally designed for Transportation Quality Monitoring (TQM) in the FSC application, the key scheme is applicable for many other WSN systems e.g. the vital signal monitoring and structure health monitoring (SHM).

1.5.2 Device Architectures

We propose a comprehensive sensor portfolio for the FSC applications and demonstrate it in a functional solution. The full list of sensing targets is derived by deep insight investigation of the physical, mechanical, biochemical, and microbiological causes of food damages throughout the FSC. The sensing technology alternatives, their maturity, availability, and costs (power consumption, price, and traffic load) are analyzed in a systematic manner. More details are presented in section 3.3 and the included **Paper VII**. This result is instructive for all the WSN and IoT developers for FSC despite the diverse devices and technology they choose.

We propose a novel I2Pack device solution and demonstrate it for the pharmaceutical packaging. Sensing and communication capacities are added to the traditional packages by integrating RFID, and acting capacity is added by the Controlled Delamination Material (CDM). The electrical characteristics of CDM are experimentally characterized, and the DC-DC driving and wireless controlling circuits are optimized. Use cases and system functionalities are also proposed. More details of the I2Pack device are presented in section 2.5 and the included **Paper II**. Its application in the Health-IoT is presented in the included **Paper VIII.** This is the first time that such idea is presented and implemented.

1.5.3 System Integration Architectures

We propose comprehensive system integration architectures for the Food-IoT and Health-IoT applications and verify them by implemented prototypes and field trials. They have offered the community a more comprehensive design case which addresses the technical challenges and business challenges at the same time. So the results are instructive to both the technology developers and the business developers. More background about these two applications is presented in section 3.3 and 3.4 respectively.

For the Food-IoT, we propose a Fresh Food Tracking Service including the operational workflows and SOA-based backend interfaces (**Paper III**). The whole picture of IoT-powered FSC is modeled by Value Chain Analysis and scenario modeling (**Paper VII**).The WSN devices are integrated to EISs through the so-called Cooperative Food Cloud (**Paper VII**). We also propose the 3-layer Hierarchical Information Fusion model for efficient information integration. It is demonstrated through an example for every layer, including the shock, vibration and tilt extraction for On-Site Information Fusion, Shelf Life Prediction models and self-learning algorithm for In-System Information Fusion, and Real Time Supply Chain Re-planning for the In-Cloud Information Fusion (**Paper VII**).

For the Health-IoT, we propose the In-Home Healthcare Station (IHHS) architecture to integrate the scatted devices and services into operable business. The new value-chain model of IoT-based in-home healthcare services is established by deconstructing the traditional mobile internet services and healthcare services. Corresponding authentication and security shames are designed to guarantee the fair distribution of benefit throughout the value-chain (**Paper IV**). The Hospital Information Systems (HIS) are extended and interconnected at patient's home through the so-called Cooperative Health Cloud (**Paper VIII**). The hardware architecture of IHHS is based on an open 3C (Consumer Communication Computing) platform, and it is enhanced with specific Health Extension which converges most of mainstream communication interfaces of biomedical devices. The interfaces among software apps are isolated by the local embedded Data Base and interoperability is guaranteed by standard EHR (Electronic Healthcare Record) data formats (**Paper VIII**).

1.6 Reflection on the Research Approach

Being more generic, the BTCD approach that we use in this work is an effective approach to resolve the aforementioned challenge of IoT research: *the alignment of enabling technology and practical business requirements.* We have proven this point from the flowing angles:

1. The necessity of concurrent business design in the early stage of technology development is clarified. Convincing evidence is presented from the lessons of failures and the latest results of business research.
2. Practical operations of the BTCD are demonstrated through detailed cases. We demonstrate how to utilize the theories of Value Chain Analysis and Stakeholder Analysis to derive technical specifications e.g. the sensor portfolio of Food-IoT

and the software and hardware architecture of IHHS. These specifications are so concrete that they can be the guidance of electronic engineers.

3. The effectiveness of the proposed BTCD framework has been demonstrated by the changes it makes. We draw more comprehensive models of the Value Chains and application scenarios of FSC and IHH applications. More attractive Value Proposition is derived and assessed. The latest knowledge of agricultural and food engineering has been effectively fused in the Food-IoT solution, the adoption of RTOS in WSN stack becomes convincing when prioritize the product lifecycle costs, the open OS platform for the IHHS becomes natural when the cooperative ecosystem has been formulated, etc.

Finally, it is necessary to mention that, we don't expect the BRCD to be the only research approach to resolve this challenge. Instead, we believe there should be different approaches. Therefore, it is good enough that our approach has made some positive changes in the research mindset of IoT area. Of course, if these changes can be proven by business success in the future, it could be even better, but this is out of the scope of this thesis work.

1.7 Thesis Outline

The thesis is organized in two parts. In Part I, the research problems are described as well as an overview of relevant research areas, and a summary of contributions. In the end of Part I, conclusions and future work are presented. Part II includes relevant papers which contains details of this work.

The rest of Part I is organized as follows. An overview of relevant research areas and related work is presented in two chapters in which the state-of-the-arts, challenges, and the relevance to our work are introduced. In particular, in chapter 2, we briefly review the enabling devices and technologies including basic concept of wireless sensor network, wide area deployable architectures, reliable communication stack, data compression, and intelligent and interactive packaging. In chapter 3, we briefly review the aspects about system integration including value-centric business innovation, Enterprise Information Systems and information integration, and IoT solutions design for food supply chain and in-home healthcare. Then in chapter 4, the contributions of the included papers are highlighted. Finally the conclusions are drawn and future works are discussed in chapter 5.

2. BASIC DEVICES AND TECHNOLOGIES

2.1 Wireless Sensor Network Overview

Wireless Sensor Network (WSN) is a key enabling technology of IoT (Li *et al.* 2013). It connects a number of sensor and/or actuator[3] nodes into a network through wireless communication, and integrates this network into a higher level system through a network gateway. The sensor nodes are normally lightweight, inexpensive, easy to deploy and maintain, but the capability and functionality are limited by resources (sensors, processors, memories, energy sources, etc.). Akyildiz *et al.* (2002) and Yick *et al.* (2008) have thoroughly reviewed the architectures, applications, protocols and challenges. Among them, the challenges about energy efficiency, communication reliability, and system mobility are emphasized in the design of our WSN platform for Food-IoT and Health-IoT.

When the WSN is integrated in an application system of IoT, it is extended to be the Ubiquitous Sensor Networks (USN). According to (ITU-T 2008), the main components or layers of USN are:

1. Sensor Networking: also called Sensor Area Network (SAN), comprising sensor/actuator, processor, communication interface, and power source (e.g., battery, solar power, or passive). The sensors can be used for collecting and transmitting information about their surrounding environment;
2. Access Networking: also called Wide Area Network (WAN), intermediary or "sink nodes" or gateway collecting information from a group of sensors and facilitating communication with a control center or with external entities;

[3] Sometimes the term of Wireless Sensor and Actuator Network (WSAN) is used to emphasize the support of actuators in WSN. But in this thesis, we don't distinguish the WSN and WSAN explicitly.

3. Network Infrastructure: likely to be based on a next-generation network (NGN);
4. Middleware: for the collection and processing of large volumes of data;
5. Applications Platform: to enable the effective use of a USN in a particular industrial sector or application.

Many alternative technologies have been developed in recent years for SAN. Some of them have been standardized such as the Bluetooth Low Energy[4], IEEE802.15.6[5], Zigbee[6], WirelessHART[7], ISA100[8], WIA-PA[9], and 6LoWPAN[10]. The Zigbee, WirelessHART, ISA100 and WIA-PA are all utilizing the IEEE802.15.4[11] radio. Some are not open standard but have been widely applied in certain industry such as the Z-Wave[12]. Some are not specifically designed for WSN but are also applied in many cases after certain optimization such as IEEE 802.11 WLAN[13] (Ferrari *et al.* 2006). At the same time, many proprietary technologies are proposed too. Despite the diversity of technical details, all these alternatives are commonly featured by low power consumption, short range communication, flexible networking capacity, and light weight protocol stack. These are the key features required by WSN.

The aim of USN Access Networking is to connect the small area WSN to the wide area internet. It has many alternatives and they can be grouped into two types. One type is wired WAN such as the IEEE 802.3 Ethernet[14] and broadband power line communication[15]. Another type is wireless WAN such as IEEE 802.11 WLAN, 3GPP wireless cellular communication (GSM, GPRS, EDGE, UMTS, LTE, LTE-A, etc)[16], and satellite[17] [18] [19] [20]. One common feature of these technologies is the infrastructure

---

[4] Bluetooth SIG, http://www.zigbee.org/

[5] IEEE 802.15 WPAN™ Task Group 6 (TG6) Body Area Networks, www.ieee802.org/15/pub/TG6.html

[6] ZigBee Alliance, http://www.zigbee.org/

[7] HART Communication Foundation, http://www.hartcomm.org/

[8] The International Society of Automation, http://www.isa.org

[9] IEC62601 (WIA-PA), http://www.iec.ch

[10] IETF 6LoWPAN, http://datatracker.ietf.org/wg/6lowpan

[11] IEEE 802.15 WPAN™ Task Group 4 (TG4), www.ieee802.org/15/pub/TG4.html

[12] Z-Wave Alliance, http://www.z-wave.com

[13] IEEE 802.11WLAN, http://www.ieee802.org/11/

[14] IEEE 802.3 Ethernet. http://www.ieee802.org/3/

[15] HomePlug Powerline Alliance, https://www.homeplug.org

[16] 3rd Generation Partnership Project (3GPP), http://www.3gpp.org/

[17] INMARSAT, http://www.inmarsat.com/

dependency. Different access types are quite diverse in terms of connectivity, mobility and cost (as shown in Table 2-1).

Table 2-1 Comparison among USN Access Networking types

Access Type	**Cost**	**Coverage** Indoor	Outdoor	**Mobility**
Ethernet	Very Low	High	Very Low	Very Low
Power Line	Low	Medium	Very Low	Very Low
WLAN	Very Low	High	Low	Medium
3GPP	Medium	High	High	High
Low orbit satellite	Very High	Very Low	Very High	High
	(Xue *et al. 2006*)			

2.2 Wide Area Deployable WSN

For the WSN solutions for the Food-IoT and Health-IoT applications, one core value of such services is the real-time monitoring (sensing) and tracking of mobile and distributed objects such as the goods and patients. The objects that the system should track are highly mobile and distributed. Thus, high mobility and wide area deployment of WSN nodes are significant to realize this value. This was the first challenge that we face when we started the work in 2008.

As a enabling technical challenge, the mobility and deployment area is mainly limited by the WAN networking approach and power supply of the WSN gateway. After we did the survey on existing gateway architectures, we found three typical types of gateway architectures and they are introduced below.

1. In industrial applications which require critical real-time and reliability, wired Ethernet and/or field buses are often chosen as the access networking. One typical example is the WSN system for factory automation in the SOCRADES project (Sollacher *et al.* 2009). Fixed power supply is also required (and normally available) to support the large power consumption of the powerful gateway. The gateway is typically based on an industrial computer or programmable logic controller (PLC). The mobility of such kind of WSN system is very low due to the fix installed gateway, and it is not suitable to be deployed in wide area as limited by the availability of wired internet access.

2. In consumer applications, access networking is often based on the 3GPP wireless cellular networks. An example is the Bluetooth and mobile phone-based patient monitoring system (Zhang and Xiao 2009). By reusing the patient's existing mobile phone or personal digital assistant (PDA) as the WSN gateway, the initial

---

[18] ORBCOMM, http://www.orbcomm.com/

[19] Quake Global, Inc. http://quakeglobal.com/

[20] Iridium Communications Inc. http://www.iridium.com/

cost of deployment could be minimized. Good coverage and reasonable service cost of cellular network are available at most places. The mobility of such systems is enhanced due to the elimination of fix installed gateway, and it can be deployed to wherever the cellular network is available. But the functionality of such systems is limited since the mobile phone and PDA are not specifically designed for such professional sensing applications.

3. If the WSN system is deployed in rural environments (such as farms, forest, river), a powerful base-station is used as the gateway to access the internet through wireless cellular or Ethernet. An example is the remote irrigation management system for precision agriculture application (Kim *et al.* 2008). Although the access networking of such systems could be mobile, its mobility is still very low due to the fixed power supply. To deploy in the places where mains power is not available, autonomous power generation should be equipped (e.g. solar panels, wind power generators, etc.). All these autonomous power generation systems are often fixed too.

The existing architectures cannot meet our requirements. At one polar, the fixed buck gateways (example 1, 3) are very powerful in functionality. But they are too bulky and expensive for our applications. At another polar, the mobile-phone or PDA-based gateways (example 2) are light-weight and less expensive. But the functionality is limited because they are mainly designed for consumer applications instead of such professional applications.

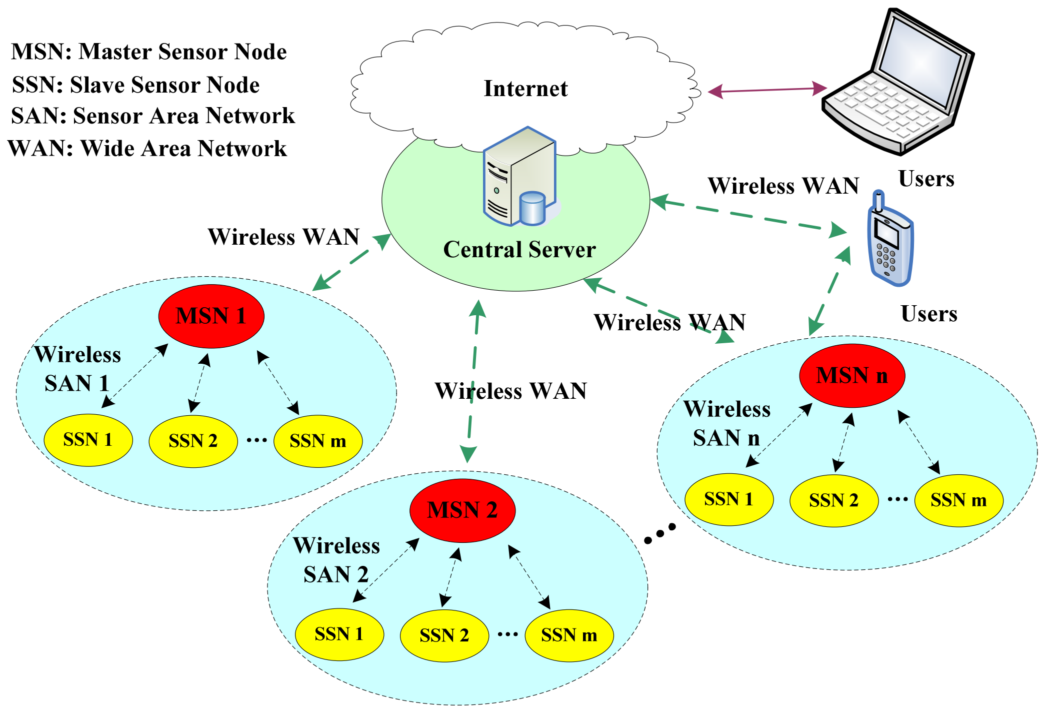

Figure 2-1 The proposed WAN-SAN Coherent Architecture of WSN

With enhanced mobility, Munir *et al.* (2007) has proposed the “three-tiered” mobile WSN architecture. Its lowest tier is composed of randomly deployed sensor nodes with ad hoc networking. The mobile agents (mobile phones, laptops, internet equipped cars, etc) in the medium tier can move to anywhere at any time. The highest tier is a number of fixed installed access points (WLAN access points, cellular networks base stations, etc.). This has inspired us to propose our gateway architecture called WAN-SAN Coherent Architecture as shown in Figure 2-1 (**Paper I**). Comparing to example 1 and 3, the mobility of the proposed architecture is enhanced significantly by removing the fixed installed or powered gateways. Comparing to example 2, the proposed system is customized for wireless sensing applications which supports more sensor types, higher performance data processing, and lower power consumptions. Comparing to the above "three-tiered" architecture, the medium layer of mobile agents (e.g. laptop) is eliminated and this has reduced system complexity and cost of deployment. When we look at the WAN-SAN Coherent Architecture again today in 2013, we find that this architecture has become a trend in practice. This trend confirms the feasibility of our architecture that was firstly proposed in 2008.

2.3 Reliable and Secure Communication of WSN

In our target applications, the working environments for the WSN nodes are mostly critical for radio signal propagation. For example, in the Food-IoT application, the WSN devices will be deployed in the warehouses and containers filled with water-rich foods like fruits and vegetables. In the Health-IoT application, the devices are worn on human body. The conductive materials in these environments may cause serious path loss and reflection of radio signal. The mobility of objects makes these effects even worse due to the dynamic fading. To guarantee the reliability of communication under the constraints of power consumption is very challenging. At the same time, the communication security is also crucial for these applications. Any miss-record or miss-access of the sensor information may cause serious accident to human health, privacy and safety. So the communication between sensor nodes and gateway, and between gateway and backend system should be well secured.

Many efforts have been done to strengthen the existing standards. For example, Chen *et al.* (2012) have introduced new mechanisms to the conventional Zigbee protocol to enhance the communication reliability with reduced traffic overhead. As a more essential pathway, new specific standards have been developed for such professional or industrial WSN (IWSN) applications. Superior reliability, determinism, timeliness, and security can be achieved by the enhancement of low layers. For example, the three mainstream IWSN standards, the WirelessHART, ISA100.11a, and WIA-PA, are all based on the IEEE 802.15.4 radio but apply new TDMA (time division multiple access) -based media access control (MAC) mechanisms. In the TDMA-based MAC, all communication among nodes is allocated and limited within corresponding timeslots. For example, the length of timeslot in WirelessHART is 10 ms, and acceptable timing error is sub-millisecond. ISA100.11a applies flexible timeslot, and WIA-PA uses 802.15-4-2006 super-frame with configurable timeslot too. TDMA is essential to reduce the possibility of collision and make good use of temporal diversity of the physical channels. Then the schedule of every node is properly planned according to the traffic load and task priority. This is the foundation of timing determinism which is the basic requirement of industrial applications. TDMA-based MAC requires all the nodes to be synchronized precisely, and the jitter of synchronization should be much smaller than the length of time slot. Moreover, many complex packet processing tasks should be finished within one timeslot.

The timing critical requirement has been recognized as the primary challenge of IWSN design (**Paper VI**). Firstly, the processor of the node has very limited resource and capacity, such as CPU frequency, memory space, and power source. The processing of IWSN protocol (e.g. packet parsing, encryption, decryption, authentication, etc.) has very large computation complexity for such resource-limited processor. Secondly, the processor of the node is often occupied by many other tasks like data processing, motor driving, and safety. That is, the IWSN stack is only a part of the timing critical tasks. This makes it even more challenging to guarantee timing integrity in such multi-task system.

Another critical challenge of our work is the adoption of real time operation system (RTOS) and the support of multiprocessor technology. The adoption of RTOS and support of multiple processors is required from the business viewpoint, but it makes it more challenging to guarantee the timing integrity.

In our Food-IoT and Health-IoT applications, the WSN system will be deployed as a part of the infrastructures that have very long life time. It is necessary to adopt a mature RTOS in the WSN node to meet the critical requirements of Product Lifecycle Management (PLM) including compatibility, scalability, reusability, safety, security, and system integration (Akerberg *et al.* 2011). Moreover the support of multi-processor (and/or multi-core) architecture is an effective way to improve the system scalability, manage the complexity and reduce cost. Additionally, dedicated high performance chips for IWSN are rare, but low cost (also low performance) IEEE802.15.4 system-on-chips (SoCs) are very common in commercial markets (Zhu *et al.* 2011). It could be a good balance if we can use low cost commercial IEEE802.15.4 chips combining with high performance industrial processors. So an optimized architecture is needed.

However, existing studies on this topic are rear and lack of specific solution. Edmonds *et al.* (2005) and Roedig *et al.* (2010) have presented the benefits of modular and multiprocessor design for the wireless sensor nodes but they haven’t given concrete solution for IWSN. Chen *et al.* (2010) have presented concrete communication architecture of WirelessHART stack, but they have little concern about hardware and software architecture. Song *et al.* (2008) have presented an implementation of the stack but haven’t mentioned the adoption of RTOS and the support of multiprocessor. Zhu *et al.* (2011) have compared multiple generations of chips for the IWSN, but the software architecture of the stack, especially RTOS and multi-processor support, is still not presented in detail. And in their suggestions for chip vendors, they haven’t considered the combination of low cost commercial IEEE802.15.4 chips and high performance industrial processors..

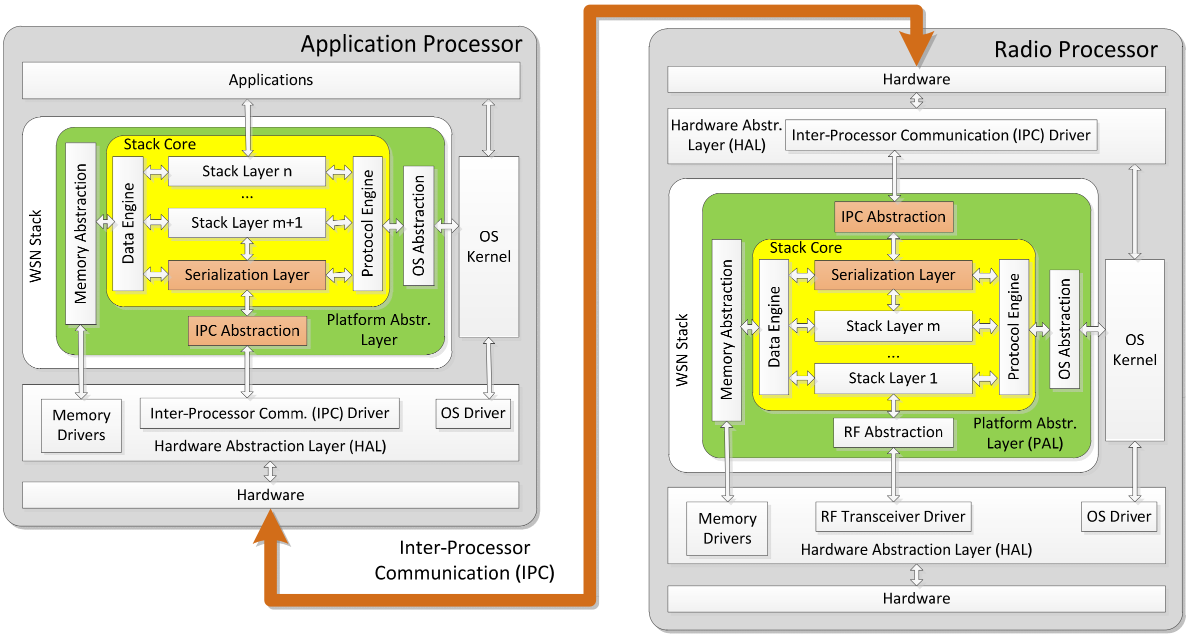

Figure 2-2 The proposed RTOS-based WSN stack architecture with multiprocessor support

As shown in Figure 2-2, we have proposed an RTOS-based architecture for IWSN stacks with multi-processor support (**Paper VI**). This architecture offers significant benefits in terms of platform independency, product life cycle, safety and security, system integration, and performance scalability. Furthermore, we have found that, the existing network management mechanisms of WirelessHART are very inefficient. Too many packets are transmitted between network manager and device, and between high layers and low layers. According to the BTCD framework, the compatibility with industrial practice is rather important to introduce the new WSN to traditional systems. The adoption of RTOS is a basic requirement for the WSN stack to be integrated in a complete industrial system. So, our findings have suggested us to improve the existing IWSN standard to be friendlier to the proposed RTOS-based architecture. The proposed BTCD has offered us sufficiently strong motivations to do so: the business requirement (e.g. PLM) is prior to technical expense (e.g. timing overhead). So it is an example of the changes that the proposed BTCD can make to the research paradigm of IoT.

2.4 Sensor Data Compression

Data compression is an emerging topic in WSN area. The communication bandwidth and energy are the two most critical resources for the WSN system. So data compression for WSN is crucial due to a number of requirements and challenges.

1. More data can be transmitted (i.e. net throughput) within the same bandwidth if the original data is effectively compressed. Or equivalently, the traffic load created by the same data source, as well as the energy consumed for this traffic,

can be reduced. This requires the algorithm to be very effective, i.e. its compression ratio should be big enough.

2. At the same time, to reach positive net saving, the energy consumed by the data compression and decompression should be less than the energy saved from the reduced communication. This requires the compression (and sometimes decompression) algorithm to be very efficient, i.e. the computational complexity should be low enough. This is also required by the limited capacity and memory space of the lightweight sensor nodes.
3. In many cases, the algorithm is needed to be scalable. This means the system developer can get different distortion (SNR), compression ratio (CR) and computational load by only adjusting the coding parameters without changing the overall architecture.

In short, the data compression algorithm for WSN should be effective, efficient, low complexity, and scalable. It is very challenging to meet all these requirements at the same time.

Traditionally, the data compression is a computation-intensive task. For example, many data compression algorithms have been developed since Ziv and Lempel (1977) invented the dictionary-based loss-less algorithm (so-called LZMA algorithm). The LZMA algorithm and variants are too complex for WSN due to the large memory usage and computation load. They are mainly used as performance benchmark in new algorithm development for the WSN (Marcelloni and Vecchio 2008, Cheng *et al.* 2008).

Dedicated data compression schemes for WSN have been proposed during the history of WSN (Kimura and Latifi 2005). Some algorithms are generic for WSN without optimization for specific application scenarios. For example, Wang *et al.* 2009 propose a joint special and temporal coding framework with adjustable resolution, but it is more effective when the number of nodes is very large. The Huffman-based variable length coding (VLC) by Marcelloni and Vecchio (2008) is simple but the compression ratio is just round 3. But our system, from business point-of-view, requires the compression ratio at the order of 10^2-10^3, so that the data rate of compressed acceleration data is at the same level of that of the other sensors like temperature and humidity. Greenstein *et al.* (2006) has proposed a generic framework for sensor nodes to capture higher frequency phenomena based on differential coding combined with time domain filtering and classification. It is attractive due to its low computational complexity. Cheng *et al.* (2008) have proposed a specific acceleration data compression algorithm based on wavelet transformation and adaptive differential pulse coding modulation (ADPCM) for body motion monitoring applications. But the huge complexity of wavelet transformation makes it unfeasible in our application.

Our solution is inspired more or less by these studies, but we more deeply exploit the distinct characteristics of the application. The origin of our work is the transportation quality monitoring application as a part of the Food-IoT solution. As shown in Figure 2-3, by making the best use of the characteristics of original data, we have proposed a content-extraction based acceleration data compression algorithm for the WSN system (**Paper V**). The original acceleration data is extracted into three components: Tilt, Shock, and Vibration. Different compression strategies and parameters are applied to different components.

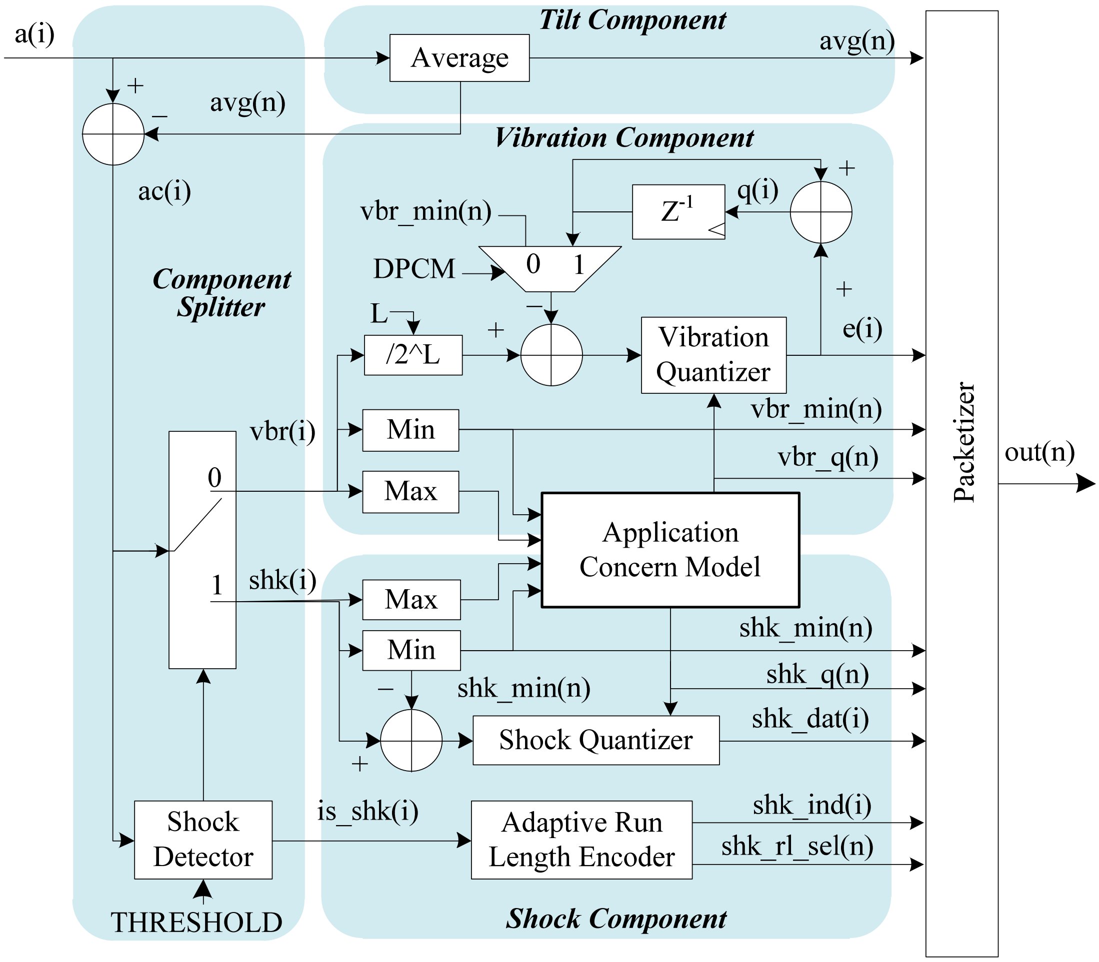

Figure 2-3 The proposed content-extraction based data compression algorithm for WSN

The proposed algorithm was originally developed for the Transportation Quality Monitoring (TQM) application. One specific scenario is the aforementioned food supply chain tracking system as shown in Figure 1-3. The fresh food distributed by ships, trains, and trucks for very long distance is often damaged due to poor transportation quality. The proposed WSN-based TQM solution is used to monitor the vibrations and shocks, identify potential damages and responsibility, and finally improve the quality of transportation. According to the proposed BTCD framework, only the valuable information from user's viewpoint needs to be transmitted by the WSN devices. Not only the statistical characteristics of original data, but also the physical meanings of the components of the original data are exploited. Their physical meanings and values for users are recognized by deeply analyzing the cause of mechanical damages in transportation. The more important data component, the Shock and Tilt, are compressed with lower compression ratio and less distortion, and the less important data component, the Vibration, are compressed with larger compression ratio and more distortion. This strategy is implemented by the so-called Application Concern Model which is used to derive compression parameter based on the characteristics of raw data. Higher compression ratio (up to 142 with acceptable distortion), lower complexity and better scalability are achieved simultaneously. With acceptable loss, the data rate of compressed acceleration data may approach the other sensors of the system. This is an essential improvement from the business viewpoint since it makes long term and real-time monitoring possible in practice. Moreover, although this algorithm has been verified only by the acceleration data, the proposed scheme is generally applicable for other WSN applications.

2.5 Intelligent and Interactive Packaging (I2Pack)

2.5.1 The Vision

As mentioned, "*ubiquitous*" is the distinct feature of IoT technologies. Ideally, it should be able to reach every item of the objects. For example, the Food-IoT system should be able to identify every package of perishable food, record its surrounding conditions, derive precise and shelf-life of this package, and present this information to consumers in their kitchen. Similarly, the Health-IoT system should be able to track every package of medicine, record the medication activity of every tablet of capsule, and present all prescription information related to the patient. To realize this feature, a suitable format of a smart device is demanded. It should be able to carry the capacities and benefits of IoT with *affordable* cost and in a *natural* manner. According to the vision of iPack VINN Excellence Center (2010), the Intelligent and Interactive Packaging (I2Pack) is a suitable format of smart device for this purpose.

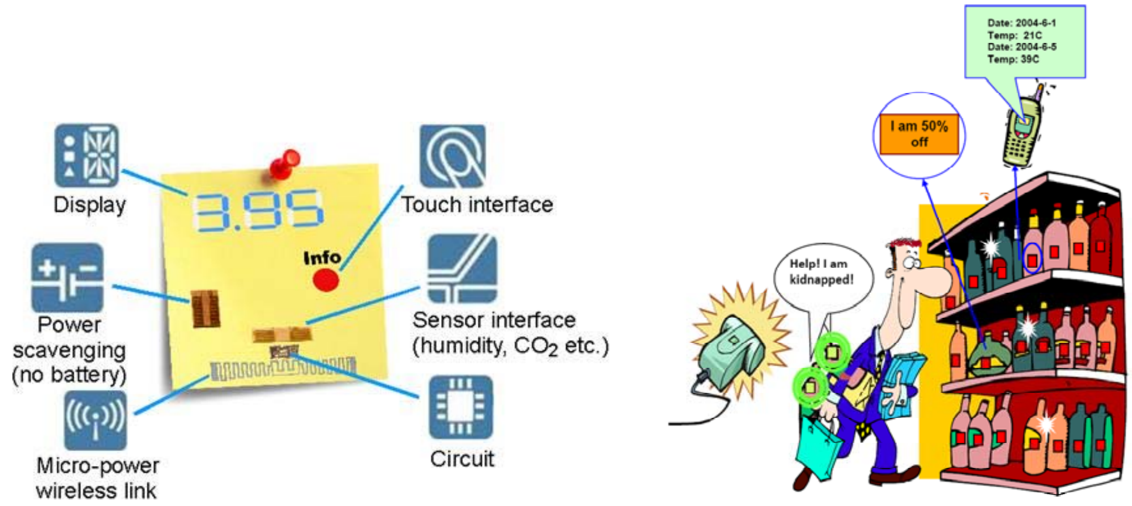

Figure 2-4 Vision of the intelligent and interactive packaging (iPack VINN Excellence Center 2010)

As shown in Figure 2-4, the I2Pack is the next generation of packaging which can interact with customers by integrating RFID, sensing, energy harvesting, communication, display, acting and other functions onto traditional packaging (Zheng *et al.* 2008). When paper-based actuators and display are integrated, the packaging can not only be aware of the presence of customers, but also be able to inform the customer what's on.

The vision of I2Pack may make big transformations to the business world. The information carried by the packaging will transform from static to dynamic, the flow of information will transform from single-directional (product-to-consumer only) to dual-directional (both product-to-consumer and consumer-to-product), and the role of packaging will transform from "passive" (only controlled by consumer) to "active" (self-controlled or remotely controlled). So the I2Pack can be assigned more responsibilities in addition to the containing and protecting of goods. The role of packing becomes "communication medium" between suppliers and consumers. It is expected to be a seller on-site, an information presenter, an information collector, and even an executor of particular operations. For example, in the retailing application scenario, the I2Pack with a touch sensor knows who has touched it, and if integrated with a price tag, it can inform the customer "today's special offer". In the Food-IoT application scenario, it can inform customer the quality and freshness of the food automatically. In the Health-IoT application scenario, an intelligent pharmaceutical packaging glued can be electrically opened through finger touch.

2.5.2 Research Challenges

Invented in 1948, the RFID technology 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. Besides the efforts on miniaturization, cost-down, and mass-production, the integration of sensing capacity of convenient RFID tag is a promising direction of the technology evolution. Much more added values can be created without losing the ubiquitous and low cost feature of traditional RFID technologies (Lee and Özer 2007, Gartner Research 2005, Véronneau and Roy 2009). These advantages make it an attractive technical approach for the I2Pack. Towards the vision of IoT, some progresses in basic components of the I2Pack have been archived in recent years, including:

1. Printed sensors on paper or flexible substrate, e.g. the touch sensors (Unander *et al.* 2007), humidity sensors (Unander and Nilsson 2009, Feng *et al.* 2009), optical sensors (Yuan *et al.* 2009), and thin film gas sensors (Wang and He 2008).
2. Functional materials, e.g. the printed display on paper (PaperDisplay 2012) and Controlled Delaminating Material (CDM) (Jeffry 2003).
3. RFID-based wireless sensing, e.g. temperature sensor (Pardo *et a;/* 2007) acceleration sensor (Philipose *et al.* 2005), ethylene sensor (Shrestha *et al.* 2009), pressure sensor (Tetu *et al.* 2009) and force sensor (Ikemoto *et al.* 2008), the wireless passive sensor network (WPSN) (Akan *et al.* 2009), and data cleaning for RFID and WSN integration (Wang *et al.* 2013).

However, the existing progresses are still in early stage and are mostly on the basic technologies. High level design issues like application scenario, operation model, service integration, and application specific solutions, are rarely studied. EPCglobal has specified the EPC Information Service (EPCIS) as a standard interface for cross-organizational information sharing and service integration (EPCglobal 2007). But EPCIS was specified mainly based on the traditional identification function of RFID technology, and the intelligent sensing, acting, and interaction are not considered in depth. Moreover, the immature components and materials have made the top level design more challenging. So the BTCD must be emphasized again.

2.5.3 Intelligent Pharmaceutical Packaging

Traditional medical package is usually utilized to protect, inform and distribute the drugs inside. However, it has a lot of problems for pharmaceutical noncompliance, such as skipping a dose, taking more or less, taking wrong items or at wrong time, mixing fresh pills with the old ones, prematurely discontinuing medication, adverse effects, etc. (Mayberry 2009). From big bottle to small unit dose package, a single dose packaging helps to relieve these problems, and gave a little improvement for pharmaceutical compliance (MTS Medication Technologies 2012). In the RFID-based pharmaceutical packaging (Cypak AB 2008, there is a conductive wire on the seal of blister for each tablet or capsule. All the conductive wires are connected to the RFID chip which is also embedding in the packaging. When the seal is broken, the wire is broken too, implying the tablet or capsule has been taken. An RFID reader reads the status of these wires through the RFID tag chip. In this way, the medication activities can be recorded.

Inspired by the above idea, we have proposed a more comprehensive intelligent pharmaceutical packaging solution by combining the CDM and RFID technologies (**Paper II**). Furthermore, we have developed its application scenario in the Health-IoT (**Paper IV**). Comparing to the Cypak's solution, the most significant imprudent in our solution is the acting capacity of the CDM. The open of the package is controlled by a backend system through the CDM. Without permission according to prescription, the package cannot be open. Thus, the medication management is accomplished in a preventive way (preventing from mistakes), instead of only passively recoding what has happened.

Since cost has been identified as an important barrier for the adoption of RFID (Visich *et al.* 2011), the pharmaceutical packaging market is a better business entrance for the I2Pack technologies because it is less sensitive to the cost. According to the BTCD, to deliver the added-value of "preventive medication management", the CDM material is the key of the proposed intelligent pharmaceutical packaging.

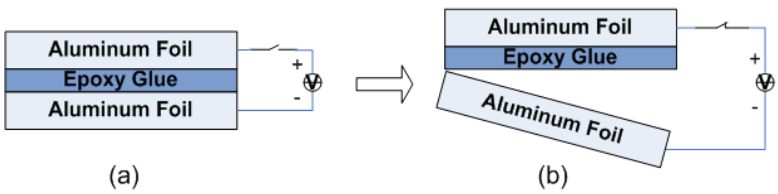

Figure 2-5 Illustrated structure and delaminating behavior of the CDM

As shown in Figure 2-5, the CDM is typically a sandwiched structure (Jeffry 2003, United States Patent 2003 and 2008). The top and bottom layer are two pieces of metal substrate like aluminum foil. Between them, there is a thin layer of adhesive epoxy that has a strong adhesion against pulling force. The strong adhesion can afford a weight of 211 kg/cm^2. After a 10-50V DC voltage being applied to the structure for a short period of time, the bond strength will reduce, and the adhesion becomes unstuck. This makes it easy to separate the CDM by a little extra force (EIC Laboratories 2004, Jeffry 2003). Its distinct low-power and electrically controlled delaminating characteristic has made it an attractive functional material for the I2pack (PCT International Patent 2007). To optimize the driving circuits, we have thoroughly characterized the material with regards for opening voltage, current, time and waveform of power supply (**Paper II**). According to these results, it is technically feasible to integrate the CDM material into a package. To the best of our knowledge, this is the first time that the CDM is characterized and used for the intelligent pharmaceutical packaging.

3. SYSTEM INTEGRATION FOR INNOVATIVE BUSINESS

3.1 Value-Centric Business Innovation

The revolution of IoT is boosting up a change to the philosophy of business innovation and people's mindset. "*Changing business strategies is the name of the game*" and "*Firms are embracing the underlying technologies of the Internet of Things to optimize their internal processes, expand their traditional markets and diversify into new businesses*" (ITU 2005). The business model design has become the central topic of business innovation since the rise of internet-based e-businesses in the last decade (Zott *et al.* 2011), and it has been emphasized even more than ever in the era of IoT (Limburg *et al.* 2011). However, up till now, the systematic research on the business model design is mostly in "business schools", and research on this topic in engineering area is still rear. The primary challenge is the "*knowledge gap*" between business research and engineering research. The main motivation for us to apply the BTCD approach is to cross this gap. To do so, the BTCD framework is established on the latest research results about business innovation.

There are many different business modeling methodologies based on different classification criteria, such as the degree of innovation, degree of integration, profit making activity, relative position on the price-value continuum, degree of economic control, degree of value integration, strategy of objectives, source of value, critical success factors, core competencies, and resources /sales /profit /capital models, etc. (Lambert 2006). Morris *et al.* (2005) have deconstructed as many as 19 different frameworks and then provided a coherent component list. From the entrepreneur's viewpoint, Mullins and Komisar (2009) have deconstructed the business model into 5 key elements: the revenue model, gross margin model, operating model, working capital model, and investment model. Osterwalder and Pigneur (2010) have created a famous Business Model Canvas which describes a business model by nine building blocks: key partners, key activities, key resources, value proposition, customer relationships, distribution channels, customer segments, cost structure, and revenue model. Lin *et al.* (2011) have applied a simplified variant of this framework in the telemedicine service in Taiwan and internal relationships of the building blocks are analyzed. With a step closer to the ICT industry, Gordijn *et al.* (2001) have created an "e3-Value model". And it has been broadly applied in requirement engineering of e-businesses, such as e-publication (Gordijn *et al.* 2001), distributed electricity generation (Gordijn and Akkermans 2007), mobile payment (Pousttchi 2008), service supply chain (He *et al.* 2010), IoT-powered drug supply chain (Liu and Jia 2010), and e-health service (Mettler and Eurich 2012).

Stakeholder Analysis is another approach for business innovation, in which the stakeholders' influences, interests, and satisfactions are quantized by a scoring matrix. In a value chain of IoT service, a large number of stakeholders are involved ranging from individual consumers, to enterprises and public authorities. From different stakeholder's viewpoint, the main concerns and expectation are usually different. Correspondingly, different values should be created and promoted. José álvarez-Gil *et al.* (2007) and Goff-Pronost and Sicotte (2010) have applied stakeholder-analysis methods in opportunity-challenge assessment in logistics and telemedicine industries respectively.

Despite the differences in details, all these approaches are based on the theory of Value Chain Analysis which was firstly described by M. E. Porter (1985, 1996, 2008) and now has become a paradigm of business research today. From the business viewpoint, the users only intend to pay for the "added values" that a particular application can offer, rather than the "technologies" that it applies. Therefore, value creation and distribution is at the center of business model design (Zott *et al.* 2011, Ueda *et al.* 2009). Uckelmann *et al.* (2011) have systematically summarized the new progress on these aspects for the IoT including the value creation, the role of IoT, and business model candidates. One important principle in the value creation is that, the business value of an IoT solution is determined by the *refined information* that it offers (Uckelmann *et al.* 2011). The *refined information* is not the raw data from sensors; instead, it must be mined according to business requirements and must be able to support the users' decision making.

In general, the BTCD framework is based on the theory of *value chain analysis*. First of all, the business whole picture of target application is drawn by deconstructing and reconstructing the value chain(s). Then concrete value proposition are derived and assed by quantitative stakeholder analysis. Finally, specific technical requirements are derived to guarantee the sustainable benefit distribution among all stakeholders in the value chain. In particular, these aspects of our Food-IoT solutions are systematically presented in **Paper III** and **Paper VII,** and those of the Health-IoT are presented in **Paper IV** and **Paper VIII**. Moreover, we have also developed concrete business models for the Food-IoT and Health-IoT applications in (Pang 2010) and (Pang 2012) respectively, and more business design theories and tools are applied such as the SWOT/TOWS strategy and financial analysis, but the details are out of the scope of this thesis.

This work is instructive for both business researchers and technology researchers. On one hand, our results are typical application cases of the above business theories. We have demonstrated to the business researcher what changes the theories can make. On the other hand, our results have offered a comprehensive thinking framework for the technology developers. Even without deep business knowledge about the Food-IoT and Health-IoT, they still can reach better technology-business alignment by following the proposed design principles. So, we could say, this work has significantly reduced the gap between the both sides.

3.2 Enterprise Information System and Information Integration

Another theoretical foundation of this work is the Enterprise Information System (EIS) and Industrial Information Integration Engineering (IIIE). As mentioned above, the information offered by an IoT system is the main carrier of business values. So, effective and efficient information integration is the foundation for the success of an IoT solution. This is a challenging work due to the scattered pattern of existing research on IoT technologies and devices (WHO 2011, Ruiz-Garcia *et al.* 2009, 2011, Lee *et al.* 2010, Alemdar and Ersoy 2010). Fortunately, the recent progresses on EIS and IIIE have offered powerful approaches for this purpose, e.g. the Business Process Management (BPM), workflow management, Service Oriented Architecture (SOA), etc.

In the last decade, the EIS, also called ES (Enterprise System), has emerged as a promising tool for integrating and extending business processes across the boundaries of business functions at both intraorganizational and interorganizational levels (Xu 2011a). The IIIE is an emerging topic in this area by emphasizing the information integration for industrial sectors. From the EIS viewpoint, the IoT system will be a enabling component of the infrastructures of future enterprises (Sinderen and Almeida 2011, Xu 2011a, 2001b). For example, Li *et al.* (2012) have proposed a framework to effectively integrate hybrid wireless networks, typically WSN and RFID, into the cloud based EIS. In this cloud-based architecture, frontend devices are integrated into backend services over medium layer networks. Data collection, processing, and mining should be realized and optimized through all the layers.

Three design principles are highlighted in the BTCD framework and our solutions for Food-IoT and Health-IoT.

Firstly, an IoT solution should be modeled as a cross-boundary integration of EISs rather than a closed system. It not only integrates the EISs within one business entity (intraorganizational), but also integrates the EISs of different entities across their boundaries (interorganizational). Therefore, interfaces at these boundaries should be explicitly presented. Correspondingly, interoperability and security should be carefully designed for these interfaces. For example, the top level of the proposed Food-IoT solution is a Cooperative Food Cloud (Figure 3-1, **Paper VII**), in which all the organizations in the value chain are connected through web-services. Similarly, the top level of the proposed Health-IoT solution is a Cooperative Health Cloud (Figure 3-2, **Paper VIII**). These top level architectures have represented both the formulation of value chains and the cross-boundary nature of EISs.

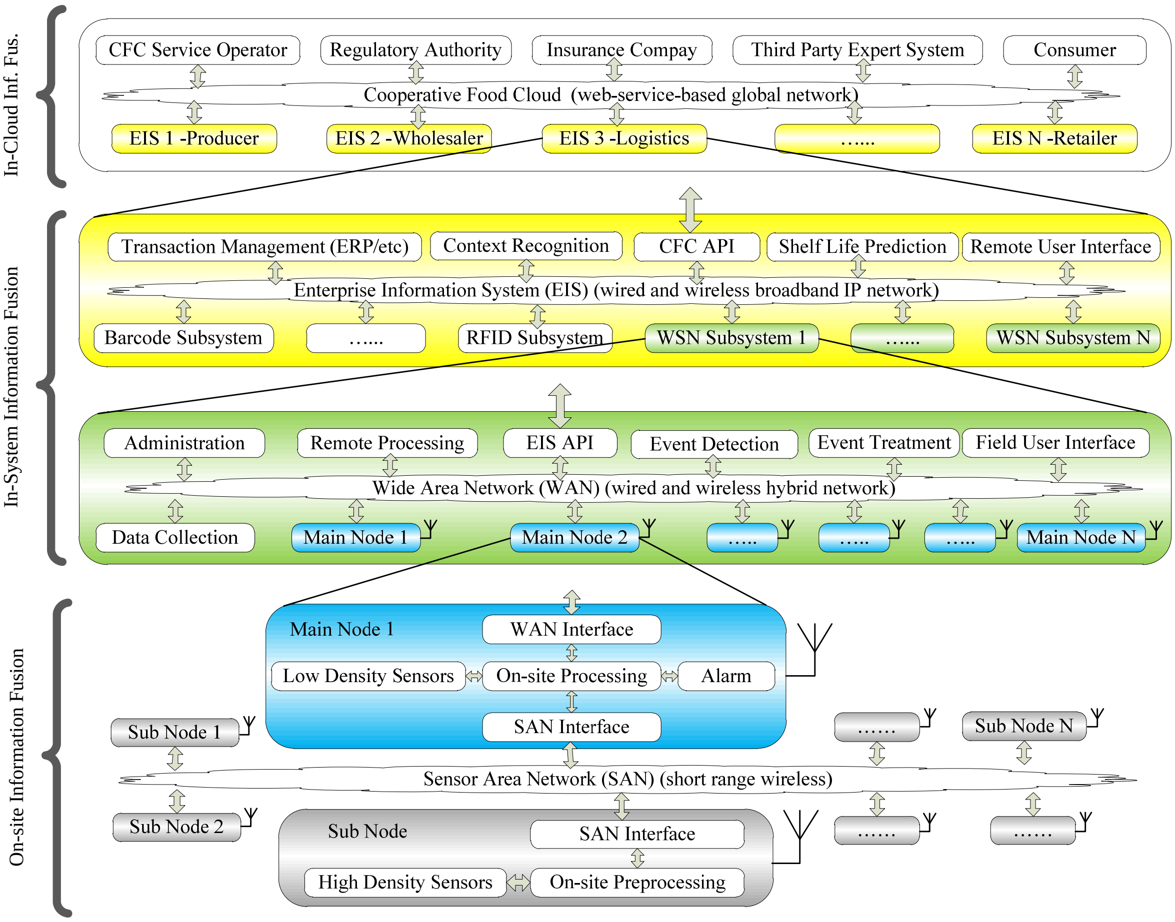

Figure 3-1 A hierarchical EIS architecture of the proposed Food-IoT solution

Secondly, the information integration should be modeled as a cross-layer information fusion. It should be accomplished by a series of data processing at different layers ranging from the sensor node, through gateway and server, and up to the cloud. The timeliness, communication traffic and computational load should be restricted in accordance with hardware capacity of different layer. For example, in the proposed Food-IoT solution, information fusion is implemented at three layers (Figure 3-1): the on-site information fusion running at sensor nodes (e.g. the acceleration data compression and shock alarming), in-system information fusion running at the gateway and server (e.g. the shelf life prediction), and the in-cloud information fusion running in the cloud (e.g. the real-time supply chain re-planning). For another example, in the proposed Helath-IoT, consolidated security mechanisms are applied to the information flows over the entire value chain (**Paper IV**).

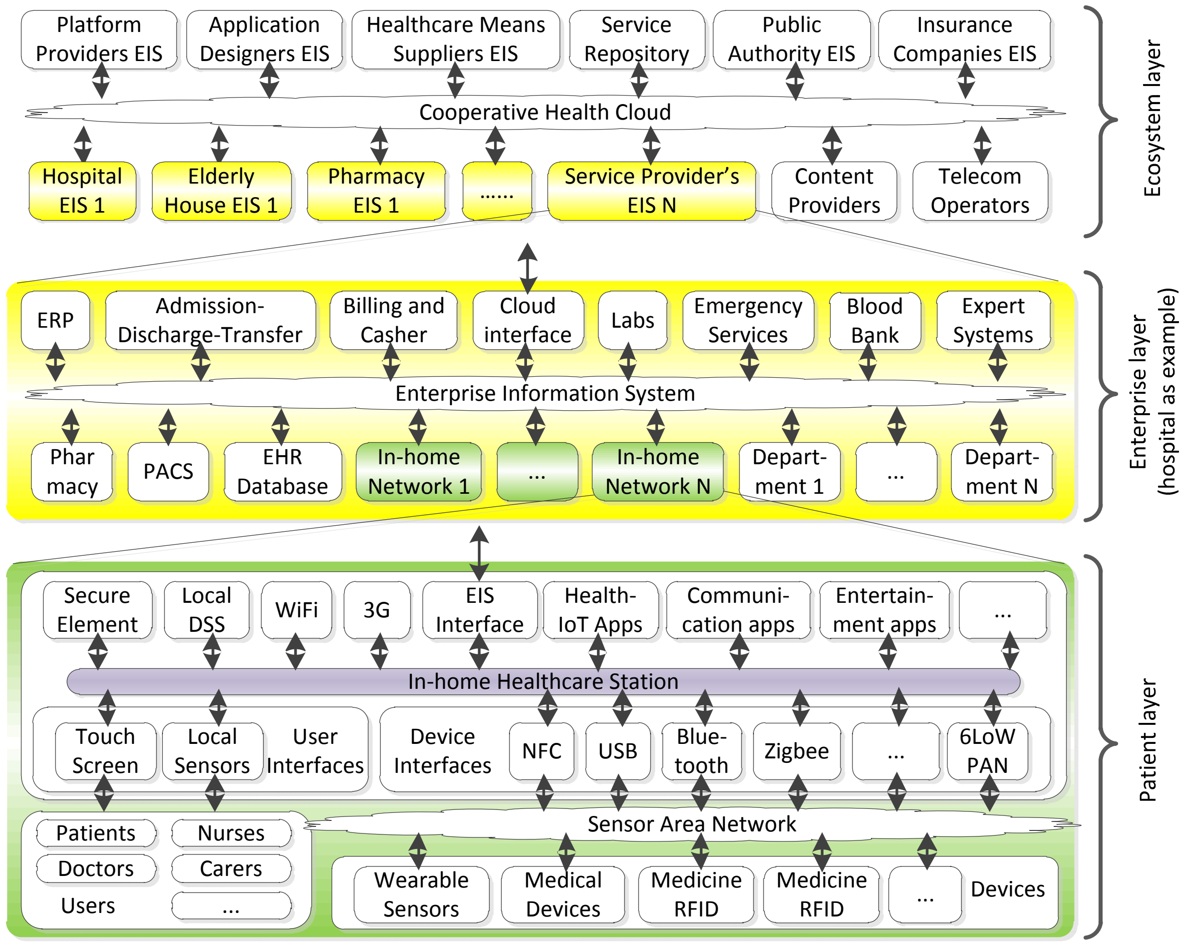

Figure 3-2 A hierarchical EIS architecture of the proposed Health-IoT solution

Thirdly, the system functionality should be modeled as a cluster of services. The basic unit of device and system integration is such service instead of a module of hardware or software. Therefore the service should be well packaged by enclosing a series of necessary hardware and software modules. Additionally, the services can be offered by different business entities in the value chain. So, proper interoperability and security should be specified too. For example, in the proposed Health-IoT solution, an In-Home Healthcare Station (IHHS) is designed as an open platform to integrate different services from different parties (Figure 3-3, **Paper VIII**). The hardware interfaces are merged by a Health Extension based on a standard 3C (consumer, communication, computing) terminal. The software interfaces are merged by the open operation system and standardized Electrical Health Record (EHR) data format. These architectures are important to meet the requirement of SOA when the proposed IHHS terminal is integrated into a real business environment.

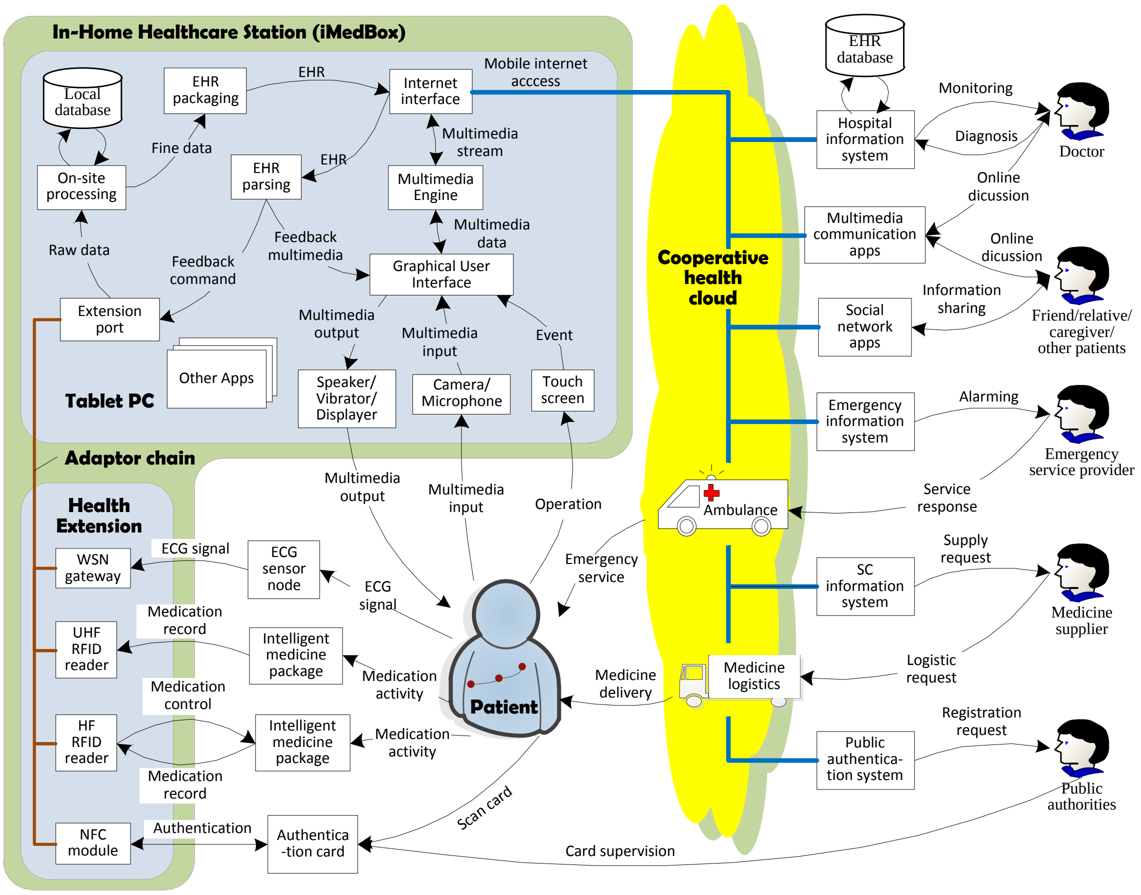

Figure 3-3 Service and device integration through the IHHS of the proposed Health-IoT solution

In short, although we haven’t proposed new techniques tor EIS and IIIE, our work have given concrete examples for the IIIE in practical design of IoT solutions. Additionally, in tradition, the EIS and IIIE methods have more impacts on the design decisions at top layers than those at bottom layers. Our results have confirmed that, the EIS and IIIE design principles can essentially determine the key architectures of bottome layers! So, the experiences gathered here is instructive for both the researcher of EIS and IIIE and the researcher of IoT.

3.3 IoT System for Food Supply Chain

3.3.1 State-of-the-art and Challenges

Many research efforts towards the Food-IoT have been carried out in the recent years. But after an intensive review of literatures, we found that the existing research shows a scattered pattern, and the gap between technology research and business application is one of the primary obstacles towards real business.

On the technology side, some advanced WSN technologies have been demonstrated for farming environmental monitoring, fire detection, farm machinery, pest control, animal tracking, viticulture, precision irrigation, greenhouse, food traceability, precision livestock, supply chain management, cold chain monitoring, etc. (Ruiz-Garcia *et al.*

2009 and 2011, Lee *et al.* 2010). But when we looked into the latest solutions (Huang *et al.* 2006, Kuck 2007, Hsu *et al.* 2008, Abad *et al.* 2009, Carullo *et al.* 2009, Ruiz-Garcia *et al.* 2010, Sallabi *et al.* 2011, Qi *et al.* 2011, Rong *et al.* 2011, Hulstijn *et al.* 2011, Lao *et al.* 2012), we found that, the systems are still in very early stage with low maturity; and although pilot projects have covered many aspects of the FSCs, the solutions are still lack of comprehensive integration. Especially the business aspects like business model, value proposition, and integration with business workflow haven't got sufficient attention in the technical development. Some other studies look more comprehensive from the viewpoint of BTCD, but the technologies that they have investigated are too traditional (typically pure RFID), and the benefits for users are highly limited (Martinez-Sala *et al.* 2009, Jones 2006).

On the business side, many studies have also been carried out on the supply chain behavior, benefit identification, business process representation, business logic modeling, price and cost modeling, performance evaluation, etc. According to our investigation, the existing studies are either inadequate in technology alternatives (mainly RFID rather than the IoT) or too general in applications (general supply chain management rather than specific FSC). Specific explorations on the Food-IoT are far from comprehensive and practical. In general, the huge impact of ICT technologies on the supply chain management (SCM) have been presented (Li 2007 and 2011, Li and Warfield 2011). Real--time collaborative SCM, supply chain integration, and supply chain quality management in the face of complex and fast-changing market conditions will be enabled by the latest IoT technologies (Xu 2011b). It has been proven that there is strong positive relationship between RFID application attributes (equivalent to adoption willingness to some extent) and the level of both IT integration and supply chain integration (Angeles 2010). Furthermore, business benefits of RFID for general SCM have been identified (Tajima 2007, Sarac *et al.* 2010, Ugazio and Pigni 2010, Wamba and Chatfield 2010). Specifically for FSCs, benefits (Cheo *et al.* 2009), process models (Victoria de-la-Fuent and Ros 2010) and pricing models (Zhang and Li 2012) have been studied too. But technology that they considered is mainly the traditional RFID which is only a small subset of key IoT technologies. Moreover, the setbacks of traditional RFID have caused broad debates on the future direction (McWilliams 2006). Although it is hard to give the answer for "*what is the correct path for RFID*", but it has been broadly accepted that "*its adoption hasn't followed the predicted path when it was firstly promoted by Wal-Mart*" (Visich *et al.* 2011). Therefore, more business research on IoT-for-FSC, beyond the RFID-for-SC, is essential to lead the industry to a correct direction.

Additionally, the researchers in agricultural and food engineering area have never stopped their efforts to improve the food quality distributed by complex supply chains. Mechanisms and reasons of food spoilage throughout the FSCs have been identified (German Insurance Association 2002-2011, Jedermann *et al.* 2011, Fellows 2000, Crisosto *et al.* 2008, Martinez-Romero *et al.* 2004, Man and Jones 2000), and shelf life prediction models have been established for a certain group of food products under certain conditions (Dalgaard *et al.* 2002, Jedermann *et al.* 2011, Oms-Oliu *et al.* 2008, Tsironi *et al.* 2011, Palazón et al. 2009). Taking the measures based on these results to reduce the food spoilage is an essential way to resolve the FSC problem.

Given the latest research progresses in IoT technologies, business applications, and agricultural and food engineering, an ideal Food-IoT solution must effectively fuse the latest knowledge of all these disciplines. However this is very challenging due to the lack of comprehensive research framework.

3.3.2 Highlight of Our Work

To resolve the above challenge, we systematically demonstrate the BTCD framework and demonstrate a more comprehensive Food-IoT solution aided by this framework (**Paper VII)**.

Firstly, the whole picture of the modern FSC in the era of IoT is modeled (Figure 3-4). This model is based upon the Value Chain Analysis theory of business research and Business Process Management of EIS research. Then more attractive added-values are created by summarizing and assessing the existing value propositions by quantitative Stakeholder Analysis. Here, the latest results and best practices in business research have been utilized through very clear design logic: *the value creation and distribution*.

Secondly, the sensor portfolio of the wireless sensor devices is derived by thoroughly analyzing the causes of food spoilage. Here, the latest results of agricultural and food engineering are effectively fused through the same design logic as above: *the value creation and distribution*. The sensor portfolio is concrete enough for the electronic engineer to implement the hardware and decide the field deployment of sensor nodes. Moreover, the sensor portfolio can be renewed over time to follow up the progress of sensor technologies.

Thirdly, the information integration architecture is developed fulfilling the requirement of future EIS. The data processing and data mining algorithms are designed to fulfill the concerns of stakeholders at different layers. The latest results of agricultural and food engineering on shelf life prediction are integrated with self-learning capacity. Top level supply chain information and workflow integration is also presented through an example of supply chain re-planning.

Comparing to the existing work, our Food-IoT solution which is developed under the guidance of BTCD has shown more knowledge fusion and better system integrity. In short, this work could be an "instruction manual" for the IoT solution development for FSCs. Under the BTCD framework, developers of ICT, business management, agricultural and food engineering can work together and compound their expertise effectively.

3.4 IoT System for In-Home Healthcare

3.4.1 State-of-the-art and Challenges

Similarly to the Food-IoT, the existing research on Health-IoT are also too scattered (WHO 2011), and the gap between technology development and business application is obstacle towards real business. Effective device and service integration is crucial for the success of Health-IoT solution. As a bridge between the service backend and the patients at home, an In-Home Healthcare Station (IHHS) is needed to realize such service and device integration.

The simplest type of the existing IHHS solutions is pure software apps on a mobile phone or PDA (personal digital assistant). Their functionality and added values are limited by the hardware (Plaza *et al.* 2011), and developers should employ more contextual information, multimedia capabilities, social networks, and even games in the health intervention applications (Klasnja and Pratt 2012). The second type strengthens the software apps by adding external sensors through native interfaces (typically Bluetooth) of the mobile terminal, but the compatible sensors do not include many medical ones; and sensor vendors and apps developers need to work together to facilitate interoperability (Liu *et al.* 2011). The third type, also the most powerful, of solutions customize the IHHS together with biomedical devices, specific communication protocols, and complex application software (Rodrigues *et al.* 2011, De Capua *et al.* 2010, Bsoul *et al.* 2011, Morak *et al.* 2012, Junnila *et al.* 2010, Baek *et al.* 2012, Tartarisco *et al.* 2011, López *et al.*2010, Koutkias *et al.* 2010, Wang *et al.* 2012). These devices measure various vital signs such as ECG, EEG, EMG, SpO_2, glucose, cardiotocography, apnea, heart rate, blood pressure, respiratory rate, posture, etc. (Teng *et al.* 2008). Then the data are transmitted to the IHHS through various wireless body area network (WBAN) techniques (Adibi 2012, Alemdar and Ersoy 2010). The IHHS connects to the service backend through pervasive computing and communication environments (Orwat *et al.* 2008, Delmastro 2012, Istepanaian and Zhang 2012).

These progress has confirmed the possibility of device and service integration through the IHHS. However, the community is demanding a holistic framework to simultaneously address both business issues and technical issues towards the successful integration indeed, and "*to do this, a lot of interdisciplinary work between all stakeholders and the engineers has to be done*" (Ludwig *et al.* 2012). Moreover, the setback of business efforts, e.g. the failure of Google Health, has explicitly shown the challenges to cross the gap between the scattered technologies and holistic business application (Escarrabill *et al.* 2011, Dolan 2011).

Limburg *et al.* (2011) have thoroughly summarized the "*recurring problems*" that the technology development is facing: 1) currently established financial structures slow down innovation; 2) necessary legislations for modernizing health care lag behind; 3) involved parties are reluctant and uptake remains low; 4) technology development focuses too strongly on engineering-driven solutions; 5) technologies are deployed in a fragmented fashion and have poor scalability; 6) the number of stakeholders and dependencies cause complexity; 7) there is a lack of cost-effectiveness studies; 8) research tends to focus on finding clinical evidence in terms of health outcomes, but the impact technology does not rely solely on clinical evidence. These issues can only be resolve by the state-of-the-art business model design. In other words, we should clearly answer "*how to establish a cooperative business ecosystem and deliver enough added values to all stakeholders?*" first when we develop the Health-IoT solution.

3.4.2 Highlight of Our Work

Aided by the BTCD methodology, we propose and demonstrate a more comprehensive IHHS solution towards the Health-IoT, and the methodology itself is refined during this work too (**Paper IV** and **Paper VIII**).

Firstly, the whole picture of Health-IoT is drawn by the convergence of business ecosystems of traditional healthcare and mobile internet. Then a concrete application scenario of IHHS is developed, which is the key element to accomplish the cooperative ecosystem. Here the aforementioned Value Chain Analysis and Stakeholder Analysis approaches are utilized again. Lessons learned from the failure of Google Health are emphasized. For example, the participation of public authority, doctors, and financial sources are enabled by technical measures including the security and authentication schemes, and the service deployment procedure based on apps repository (**Paper IV**).

Secondly, the Device and Service Integration Architectures (DSIAs) and Information System Integration Architectures (ISIAs) of the IHHS are proposed. Here, a series of design principles are specified to fulfill the requirements of the proposed ecosystem, including the reuse of open 3C platform, certification of the Health Extension, interoperability and extendibility, convenient and trusted software distribution, standardized and secured EHR handling, effective service composition, and efficient data fusion. Some of these principles are not optimum from pure technology viewpoint, but they are optimum when the business requirements are prioritized under the BTCD framework. This is a change that we have made (**Paper VIII**).

Thirdly, the proposed IHHS solution is verified by an implemented prototype (the iMedBox) and field trials. Here the above design principles are realized as concrete software and hardware architectures. Although the performances of present hardware and network infrastructure are insufficient to entirely meet our expectation, the feasibility of the proposed architecture is confirmed (**Paper VIII**).

Comparing to the existing work, our IHHS solution which is developed under the guidance of BTCD involves more concern of business requirements and serves better system integrity. To the best of our knowledge, this is the first time that the concept and architecture of the intelligent medicine box are systematically introduced.

4. INCLUDED PAPERS AND CONTRIBUTIONS

4.1 Paper I

Zhibo Pang, Jun Chen, David Sarmiento M., Zhi Zhang, Jie Gao, Qiang Chen, Lirong Zheng, "Mobile and Wide Area Deployable Sensor System for Networked Services", *IEEE Sensors Conference 2009*, pp1396 – 1399, Oct 2009, Christchurch, New Zealand.

Short Summary

To realize the core values of networked sensor services, a wireless sensor system needs to support both mobile wide area deployment and rich functionality. This has been recognized as a enabling challenge of WSN development.

In this paper, we propose a novel wireless sensor system with enhanced mobility, wider deployment, and richer functionality. It is based on a dual-layer dual-directional wireless communication architecture which combines the Wide Area Network and Sensor Area Network natively in the Main Sensor Nodes. Thus the fixed installed gateway and power supply are eliminated and all sensor nodes are mobile and remotely controllable. With optimized power consumption and communication protocols, the battery life can meet the requirement of many practical applications. Hierarchical localization, flexible network access, large local storage, rich sensing function, and on-site data processing are supported too.

As an application example of the proposed architecture, a proof-of-concept prototype is implemented and tested in a fresh food tracking service. The experimental results confirm the feasibility of the proposed architecture.

Contribution

The main contributions in this paper are summarized as follows:

- We propose and demonstrate a wide area deployable WSN system architecture, so-called WAN-SAN coherent architecture, with enhanced mobility and functionality. Based on this architecture, the sensor nodes can be deployed in mobile environment and wider area.
- The implemented prototype shows that, it is possible to realize the proposed architecture with affordable cost and acceptable battery life. These devices have been refined as a research platform and applied in the later solutions for Food-IoT and Health-IoT.

Author's Contribution

The author designed the protocols; implemented the sensor nodes hardware and software; planned the field trial; and wrote the paper.

4.2 Paper II

Jie Gao, **Zhibo Pang,** Qiang Chen, Lirong Zheng, "Interactive Packaging Solutions Based on RFID Technology and Controlled Delamination Material", *The 2010 IEEE International Conference on RFID,* April 2010, pp158-165, Florida, USA.

Short Summary

Interactive packaging can bring people convenient and smart lives, reduce consumption of traditional packaging materials and labor costs. Being integrated in interactive packaging, the Radio Frequency Identification (RFID) and functional material technologies become the most promising enablers.

In this paper, an interactive and intelligent packaging solution integrating RFID and Controlled Delamination Material (CDM) is proposed. Package opening action is electrically controlled by the RFID system. It can add wireless identification, sensing, and acting capacities to ordinary packaging. This will transform the packaging into low-cost and ubiquitous carrier of IoT services in the future. CDM was primarily used in aerospace applications in the past and the conductor/adhesive joint can be easily opened by applying a little electric power on to the material. We measured the electrochemical characteristics of CDM in order to facilitate the system design. A demonstrator is developed and the test results have proven feasibility of the solution and shown the potential of low cost for mass production.

Based on this solution, an interactive pharmaceutical package for pervasive healthcare is further developed. 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.

Contribution

The main contributions in this paper are summarized as follows:

- We propose and demonstrate such interactive and intelligent packaging solution for the first time. The implemented prototype shows that, it is possible to realize the proposed solution by the material and device which is available today.
- We propose and demonstrate an application scenario, the intelligent pharmaceutical packaging, for the proposed intelligent and interactive packaging solution. It can preventively reduce the noncompliance of medication which is a big issue in healthcare. It can enable a promising business opportunity for the IoT.

Author's Contribution

The author designed the communication protocol and measurement circuits; implemented the hardware and software; analyzed test results with the assistance of coauthors; and wrote a part of the paper.

4.3 Paper III

Zhibo Pang, Jun Chen, Zhi Zhang, Qiang Chen, Lirong Zheng, "Global Fresh Food Tracking Service Enabled by Wide Area Wireless Sensor Network", *IEEE Sensors Applications Symposium (SAS-2010),* pp6-9, Feb 2010, Limerick, Ireland.

Short Summary

The damages of fresh fruits and vegetables during the supply chain have caused huge loss of money and serious issue in food safety.

In this paper, we propose a fresh food tracking service based on wireless sensing system. The main components in the system include an operation center, a series of wireless sensor nodes, and web based user interfaces. A set of primary environmental parameters are collected through mobile and remotely controllable wireless sensor nodes, including position, temperature, relative humidity, concentrations of CO2, O2 and ethylene gases and 3-axis acceleration. Real time monitoring, tracking, alarming, close-loop controlling and information sharing are provided as web services. A typical 5-step operation flow of the service is proposed, including user registration, service selection and specification, user login, monitoring and tracking, and service execution. The corresponding functional blocks in the operation center and sensor nodes are presented to accomplish the proposed work flow. The proposed architecture and work flow can simplify the integration of such system into users' enterprise systems and practical business flow.

A prototype system with functioned hardware module, protocol and system software are implemented and tested in field trial.

Contribution

The main contributions in this paper are summarized as follows:

- We propose a fresh food tracking service including the system architecture, service model and work flow.
- The proposed service model is an instructive example for the integration of WSN technology into enterprise systems and business workflow.

Author's Contribution

The author proposed the operational model; implemented the sensor nodes hardware and software; setup the demonstrator; and wrote the paper.

4.4 Paper IV

Zhibo Pang, Qiang Chen; Junzhe Tian, Lirong Zheng, Elena Dubrova. "Ecosystem Analysis in the Design of Open Platform-based In-Home Healthcare Terminals towards the Internet-of-Things". *International Conference on Advanced Communications Technology (ICACT)*. Jan 2013, Pyeongchang, Korea.

Short Summary

In-home healthcare (IHH) services based on the Internet-of-Things (IoT) have big potential in business. To catch the opportunity, a business ecosystem should be established first. Technical solutions should aim for a cooperative ecosystem by addressing the interoperability, security, and system integration. In this paper, we propose an ecosystem-driven design strategy and apply it in the design of IHH terminal.

In particular, a cooperative ecosystem is formulated based on the value chain analysis of traditional healthcare service and mobile internet service. The ecosystem is established on shared infrastructures, so the interoperability of devices from different suppliers is important. By reviewing existing standardization efforts, we propose a set of simplified interfaces between the parties in the ecosystem. In order to achieve the economy of scale, an In-Home Healthcare Station is proposed as the universal platform to support various possible applications. To protect the benefits of all stakeholders, value-centric security schemes are proposed, including the public authority-based authentication, the secure element-based cryptography, and the non-invasive message handover.

The proposed design strategy is applied in the development of an in-home healthcare and medication management terminal (iMedBox). A preliminary version of the iMedBox system is implemented and evaluated by field demonstrations. The positive feedbacks from users confirmed the value of the proposed design strategy. Due to the limitation of resource, the proposed security schemes are not implemented yet, but they are still valuable as the start point of future work.

Contribution

The main contributions in this paper are summarized as follows:

- We propose an ecosystem analysis method and demonstrate it in a concrete design case.
- We identify the stakeholders in the value chains and demonstrate how to involve them into a cooperative ecosystem of the new service.
- We demonstrate how to use the proposed ecosystem-driven method to make decisions on technical architectures (e.g. platform selection, interoperability requirements, etc.).

Author's Contribution

The author proposed the value chain analysis method; accomplished the ecosystem analysis; implemented the prototype with other coauthors; analyzed the results; and wrote the paper.

4.5 Paper V

Zhibo Pang, Qiang Chen, Lirong Zheng. “Content-Extraction-Based Compression of Acceleration Data for Mobile Wireless Sensors”, *IEEE Sensors Conference 2012*, Oct 2012, Taipei, Taiwan.

Short Summary

Real-time monitoring of transport quality based on wireless sensor technology is demanded to measure the vehicle stability and improve transport quality and reduce loss. In such system, 3-axis acceleration sensor is used. The amount of raw data is so huge that effective and efficient compression of the raw data is necessary to make such system usable in practice. However, existing data compression algorithms are unsatisfactory to meet the special requirements of wireless sensor system on performance, complexity, and scalability.

In this paper, a content-extraction based acceleration data compression algorithm for mobile wireless sensors is proposed. It splits the original data into 3 components, Tilt, Shock and Vibration, and then compresses them separately. By making good use of application specific characteristics of the raw data, it has shown significant improvement comparing to existing algorithms. Higher compression ratio, lower complexity and better scalability are achieved simultaneously. With acceptable loss, the data rate of compressed acceleration data may approach the other sensors of the system. This is an essential improvement from the user’s viewpoint since it makes long term and real-time monitoring possible in practice. The algorithm has been proven by a 46-day field test data set.

Although originally proposed for the transport quality monitoring application, the scheme in this paper can be generalized for other applications such as structure/ machine health monitoring, on-board vehicle diagnosis, human/patient activity monitoring, animal tracking, etc. The “content-extraction based compression” is a promising direction of on-site data processing algorithms for wireless sensor applications in the future.

Contribution

The main contributions in this paper are summarized as follows:

- We characterize the acceleration data of the transportation quality monitoring application and analyzed the physical meaning of these characteristics.
- We propose and demonstrate a content-extraction based acceleration data compression scheme for resource-constrained wireless sensors. This scheme has significant improvements in performance, complexity, and scalability.
- The implemented algorithm and field test result shows that, it is possible to realize continuous and long term monitoring of acceleration data by low-cost wireless sensor devices. Many new services will become feasible in practice.

Author's Contribution

The author proposed the compression scheme; implemented the algorithm; measured the performances; analyzed the experimental results; and wrote the paper.

4.6 Paper VI

Zhibo Pang, Kan Yu, Johan Åkerberg, Mikael Gidlund, "An RTOS-based Architecture for Industrial Wireless Sensor Network Stacks with Multi-Processor Support", *IEEE International Conference on Industrial Technology (ICIT2013)*, Feb 2013, Cape Town, South Africa.

Short Summary

The industrial wireless sensor network (IWSN) emphasizes superior reliability, determinism, timeliness, and security towards the industrial applications. The design of industrial wireless sensor network (IWSN) stacks requires the adoption of real time operation system (RTOS). Challenges exist especially in timing integrity and multi-processor support. An optimized architecture is needed, but existing study on this topic is insufficient.

In this paper, we propose an RTOS-based architecture for IWSN stacks with multi-processor support. The communication and information access interfaces between layers are normalized by the so-called normalized inter layer interface (NILI). In a multiprocessor platform, the layers in the stack core are partitioned into multiple parts allocated in different processors. Between every two adjacent parts, a pair of serialization layer is inserted. Correspondingly, the hardware, driver, and abstraction of inter-processor communication (IPC) interface are added. The serialization layer works as a transparent channel in between the two neighbor layers. A series of cross layer information synchronization mechanisms are designed to minimize the traffic overhead between layers. It offers benefits in terms of platform independency, product life cycle, safety and security, system integration complexity, and performance scalability. But it also increases the challenges in timing integrity, memory footprint and CPU load.

A WirelessHART stack is implemented based on the proposed architecture. The workable demonstrator and measured timing performances have proven the feasibility of the proposed architecture in practical product design. Tricks to measure the timing performances are introduced too. Finally, future challenges as well as suggestions to standard improvement are discussed.

Contribution

The main contributions in this paper are summarized as follows:

- We clarify the necessity of RTOS and multiprocessor support in the design of reliable and secure communication of WSN stack.
- We propose and demonstrate an RTOS-based stack architecture with multiprocessor support for reliable and secure communication of WSN. This architecture can increase platform independence and scalability, improve security and safety, simplify system integration and stack construction.

- The implemented prototype for WirelessHART shows that, it is possible to implement such high performance industrial WSN stack on inexpensive commercial chips.
- The experience gathered from this work is also instructive for protocol developers.

Author's Contribution

The author implemented the software of the prototype; established the demonstrator; measured the performance; analyzed the experimental results; and wrote the paper.

4.7 Paper VII

Zhibo Pang, Qiang Chen, Lirong Zheng. "Value creation, Sensor Portfolio and Information Fusion of Internet-of-Things Solutions for Food Supply Chains", *Information Systems Frontiers*, Aug 2012, DOI: 10.1007/s10796-012-9374-9.

Short Summary

The revolution of IoT technologies have brought out great potentials to make today's food supply chain safer, more effective and more sustainable. To catch the opportunities, the system paradigm must be extended from the traditional traceability-centric design to the value-centric design. In this paper, a systematic value-centric business-technology joint design framework is proposed and verified by a concrete solution as well as field trials.

To extend and consolidate the value base, we start from value creation and assessment which evaluates the added-values by a quantitative stakeholder analysis throughout the entire value chain involving consumers, enterprises and public sectors. More attractive "income-centric" added-values such as shelf life prediction, sales premium, precision agriculture, and reduction of assurance cost are highlighted beyond the conventional traceability. To deliver the "income-centric" values to users, the sensor portfolios and information fusions must correspond to the values created above. In this paper, comprehensive sensor portfolios are developed in a systematic way, by exploring causes of food spoilage, comparing available sensing technologies and products, and evaluating the energy and traffic costs. The three-tier information fusion architecture is proposed by mapping all data processing and information delivery functionalities into a global scale "cooperative food cloud". Acceleration data processing, shelf life prediction, and real time supply chain re-planning are introduced as examples of on-site, in-system, and in-cloud information fusion respectively.

Finally, the implemented prototype system and results of field trials are presented. The feasibilities of the proposed design framework and solution have been confirmed. Limitations and future works are discussed too.

Contribution

The main contributions in this paper are summarized as follows:

- We clarify the necessity of the business-technology co-design in the design of IoT solution for food supply chain in order to cross the gap between technological exploration and business application.
- We propose a new design framework based on the business-technology co-design, and demonstrate it in the development of a concrete solution.
- We draw a comprehensive model of the food supply chain powered by the IoT technologies. It gives developers, users and even supervision authorities a whole picture to understand the scenarios and work flows. It can be used as a top level framework for value chain analysis, business planning, system partitioning, EIS integration, etc.
- We identify more added-values of the IoT for food supply chain, and demonstrate how to quantitatively assess these values by stakeholder analysis, and how to realize these values by proper sensor portfolio and information fusion. These
- We identify more added-values of the IoT for food supply chain, and demonstrate how to quantitatively assess these values, and how to realize these values by proper sensor portfolio and information fusion.
- In particular, we investigate the reasons of food damages in food supply chain, and propose a comprehensive sensor portfolio to assess and reduce these damages. We propose the cross-layer architecture for information fusion and a series of algorithms for on-site emergent alarming, shelf-life prediction, and real-time supply chain re-planning.
- The proof-of-concept prototypes and experimental results show that, it is possible to realize the proposed solution and apply it in business practice. The prototypes are instructive guidelines to develop a real product in the future.

Author’s Contribution

The author proposed the methodology and architectures; accomplished the value creation, sensor portfolio, and information fusion algorithms; implemented the hardware and software of the sensor nodes prototype; established the demonstrators; analyzed the experimental results; and wrote the paper.

4.8 Paper VIII

Zhibo Pang, Lirong Zheng, Junzhe Tian, Sharon Kao-Walter, Elena Dubrova , Qiang Chen. “Design of a Terminal Solution for Integration of In-home Healthcare Devices and Services towards the Internet-of-Things”, *Enterprise Information Systems*, DOI:10.1080/17517575.2013.776118, April 2013.

Short Summary

The challenges caused by the aging of population are prompting the modern healthcare to improve efficiency and transform from career-centric to patient-centric. As a promising solution, the Health-IoT (pervasive healthcare service based on the IoT technologies) has promising prospects. However the existing research is rather scattered and lack of interoperability. To realize cross-boundary integration of in-home healthcare devices and services, a comprehensive design framework is needed.

In this paper, a business-technology co-design methodology is proposed and applied to the design of an IHHS (in-home healthcare station) solution. The core of the methodology is the interaction between three key elements: business model, device and service integration architecture, and information system integration architecture. The three elements must be organically integrated and matched. In particular, as the primary task of business model design, a cooperative Health-IoT ecosystem is formulated by deconstruction and reconstruction of traditional healthcare and mobile internet value chains. To accomplish this business ecosystem, the information systems of all stakeholders are integrated in a cooperative health cloud and extended to patients' home through the IHHS. To meet the requirements of business models and information system integration architecture, design principles of the IHHS solution are derived including the reuse of 3C platform, certification of the Health Extension, interoperability and extendibility, convenient and trusted software distribution, standardized and secured EHR handling, effective service composition, efficient data fusion.

Then an IHHS solution, the iMedBox system, is designed based on the propose design framework. It is an intelligent medicine box which can effectively integrate the in-home healthcare devices and services. Detailed device and service integration architecture and hardware and software architecture are presented. Finally the proposed architectures are verified by an implemented prototype. Based on the quantitative analysis of system performances and positive feedback from field trials, feasibilities of the proposed design methodology and solutions are confirmed. Limitations and future works are discussed too.

Contribution

The main contributions in this paper are summarized as follows:

- We propose a business ecosystem model for the new IoT based healthcare services. It gives developers, users and even supervision authorities a whole picture to understand the business interfaces and work flows. It can be used as a top level framework for value chain analysis, business planning, system partitioning, EIS integration, etc.
- We propose the integration architecture to extend the hospital information systems to home, and the integration architecture to integrate in-home healthcare devices and services. These architectures are aligned to the business ecosystem model better, which is helpful to reduce business risk.
- We propose and demonstrate an in-home healthcare station solution based on the proposed architectures. This solution can reduce development cost and time-to-market by utilizing the commercial 3C platfrom, support more third-part devices by rich and extendable interfaces, and integrate third-part services more easily by open platform and standardized data format.
- The proof-of-concept prototypes and experimental results show that, the proposed solution is attractive to users and the architectures can be realized by today's mainstream 3C products.

Author's Contribution

The author proposed the methodology and architectures; implemented the iMedBox hardware and a part of software, implemented the ECG sensor hardware and software; established the demonstrators; analyzed the experimental results; and wrote the paper.

5. CONCLUSIONS

5.1 Thesis Summary

The emerging technology breakthrough of the Internet-of-Things (IoT) is expected to offer promising solutions for food supply chain (FSC) and in-home healthcare (IHH), which may directly contribute to human health and well-being. To reduce the time-to-market and risk of failure, business aspects should be taken into account more than before in the early stage of IoT technology development because the technologies and applications are both immature.

In this thesis, we have investigated the technologies and architectures of the IoT for two applications: food supply chain (the so-called Food-IoT) and in-home healthcare (the so-called Health-IoT). We intend to resolve a series of research problems about the WSN architectures, device architectures and system integration architectures.

The challenges about fundament devices that we have addressed include: the WSN mobility and wide area deployment, efficient data compression in resource-limited wireless sensor devices, reliable communication protocol stack for WSN, and integration of acting capacity to the I2Pack. Correspondingly, the WAN-SAN coherent architecture of WSN, the RTOS-based WSN stack architecture, the content-extraction based data compression scheme, and the CDM-based I2Pack solution are proposed and demonstrated respectively. These solutions have shown satisfactory results at least for the two application cases, and they are suitable for more generic IoT applications to a certain extent.

At the system level, we have addressed the challenges about effective integration of scattered devices and technologies including: the EIS and information integration architectures such as the shelf-life prediction and real-time supply chain re-planning for Food-IoT, and the device and service integration architectures for Health-IoT. Additionally, we have also addressed top level business challenges including: the value chain model and value proposition of Food-IoT, and the cooperative ecosystem model of

Health-IoT. These findings are generic and not dependent on our proprietary technologies and devices.

Being more generic, the so-called Business-Technology Co-Design (BTCD) research approach that we use in this work is an effective approach to resolve the common challenge in IoT research: *the alignment of enabling technology and practical business requirements*. We have demonstrated its effectiveness by design practices. It could be an operable guideline for all IoT research in the future. The *change of mindset* has been happening in our group.

5.2 Main Contributions

The main contributions of this work for the development of Food-IoT and Health-IoT are highlighted in Figure 5-1 and Figure 5-2 respectively. From the developers' point-of-view, a series of questions or challenges should be answered from top to down. In this work, we have tried to answer some of them, and fortunately we have reached some reusable findings for the community.

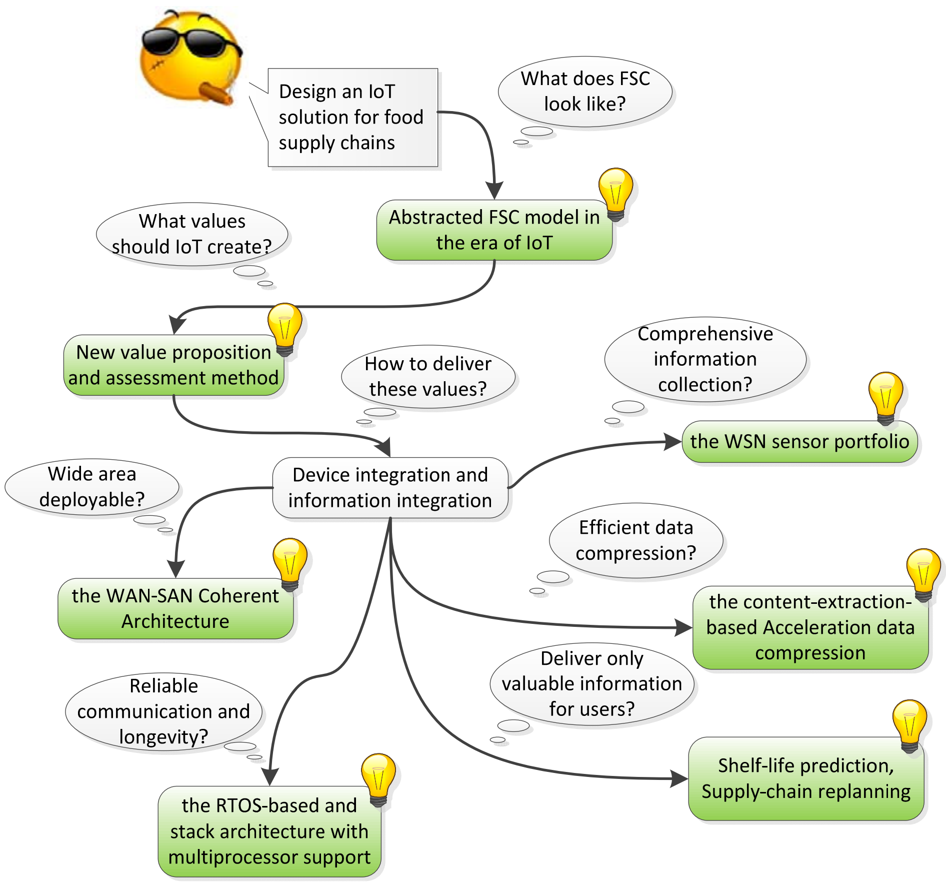

Figure 5-1 Main contributions of this work for the development of Food-IoT

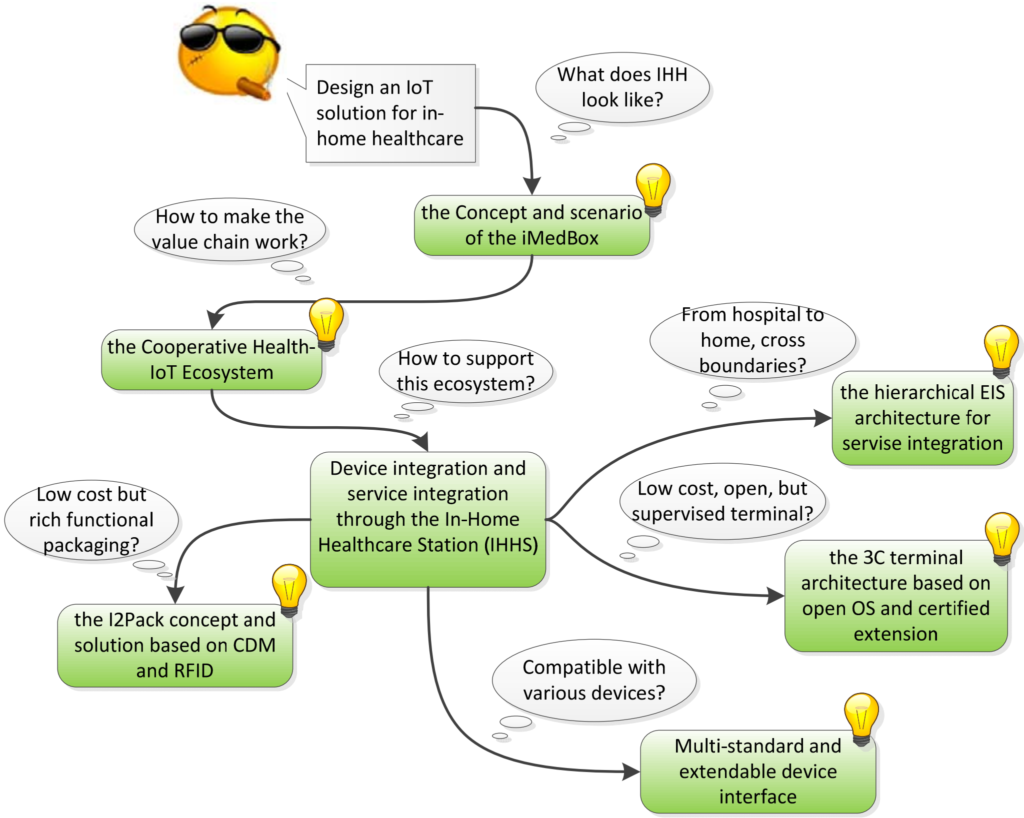

Figure 5-2 Main contributions of this work for the development of Health-IoT

5.3 Future Work

First of all, the enabling devices and technologies will be continuously refined generation-by-generation, just as what has been done before. For example, we will investigate the feasibility to design a passive pharmaceutical packaging by wireless power transmission technology; we will strengthen the mechanical structure of the WSN devices to industrial interference protection level so that they can be deployed in hasher environments; we will optimize the power consumption of the WSN stack by jointly refining the implementation and introducing new mechanisms to the protocol.

The proposed solutions for food supply chain and in-home healthcare will be refined too, and more field trials will be carried out in more real applications. For example, we will investigate the possibility to integrate some on-site diagnosis algorithms (e.g. ECG, daily activity, etc.) to the iMedBox; and we will investigate the possibility to integrate some SOA middleware to the both solutions. At the same time, more applications will hopefully be developed (depending on the development of new partnership) based on the current platform.

Additionally, we will continue investigating the design methodologies and system models. For example, currently the top level models are mapped manually to the technical architectures, it is promising if some model-driven design tools could be used here to automatically “translate” the top level models into engineering usable architectures. For another example, service-oriented modeling of WSN system could be very useful in the planning and optimization of the practical services based on our solutions.

6. REFERENCES

Abad, E., Palacio, F., Nuin, M., González de Zárate, A., Juarros, A., Gómez, J.M., Marco, S. (2009). RFID smart tag for traceability and cold chain monitoring of foods: Demonstration in an intercontinental fresh fish logistic chain. *Journal of Food Engineering,* 93(4), 394–399.

Adibi, S. (2012). Link Technologies and BlackBerry Mobile Health (mHealth) Solutions: A Review. *IEEE Transactions on Information Technology in Biomedicine,* 16(4), 586-597.

Alemdar, H., Ersoy C. (2010). Wireless sensor networks for healthcare: A survey. *Computer Networks,* 54(15), 2688-2710.

Akan, O.B.; Isik, M.T.; Baykal, B.; (2009). Wireless passive sensor networks. *IEEE Communications Magazine,* Vol.47, Iss.8, pp:92–99.

Akerberg, J.; Gidlund, M.; Bjorkman, M. (2011). Future research challenges in wireless sensor and actuator networks targeting industrial automation. *IEEE Int. Con. on Industrial Informatics (INDIN),* 410-415

Akyildiz, I.F. ; Su, W.; Sankarasubramaniam, Y.; Cayirci, E.; (2002). Wireless sensor networks: a survey. *Computer Networks,* 38(2002) 393–422.

Angeles, R. (2010). Moderated Regression: Effects of IT Infrastructure Integration and Supply Chain Process Integration on the Relationships between RFID Adoption Attributes and System Deployment Outcomes. In J.E. Quintela Varajão *et al.* (Eds.): CENTERIS 2010, Part II, CCIS 110, pp. 406–415, 2010. Berlin Heidelberg, Springer-Verlag.

Ashton, K., (2009). I could be wrong, but I'm fairly sure the phrase “Internet of Things” started life as the title of a presentation I made at Procter & Gamble (P&G) in 1999, *RFID Journal,* 22 June 2009.

Atzori, L., Iera, A., Morabito, G. (2010). The Internet of Things: A survey. *Computer Networks*, 54(15), 2787-2805.

Baek, H. J.; Chung, G. S.; Kim, K. K.; Park, K. S. (2012). A Smart Health Monitoring Chair for Nonintrusive Measurement of Biological Signals. *IEEE Transactions on Information Technology in Biomedicine*, 16(1), 150-158.

Brock, D. L., (2001). The Electronic Product Code: A Naming Scheme for Physical Objects. *White Paper of MIT Auto-ID Center*, Jan 2010, MIT-AUTOID-WH-002.

Bsoul, M.; Minn, H.; Tamil, L. (2011). Apnea MedAssist: Real-time Sleep Apnea Monitor Using Single-Lead ECG. *IEEE Transactions on Information Technology in Biomedicine*, 15(3), 416-427.

Carullo, A., Corbellini, S.; Parvis, M., Vallan, A. (2009). A Wireless Sensor Network for Cold-Chain Monitoring. *IEEE Transactions on Instrumentation and Measurement*, 58(5), 1405 – 1411.

Chen, Deji, Nixon, Mark, Mok, Aloysius, (2010). *WirelessHART™: Real-Time Mesh Network for Industrial Automation (1st ed.)*, Springer

Chen SK, Kao T, Chan CT, Huang CN, Chiang CY, Lai CY, Tung TH, Wang PC, (2012). A reliable transmission protocol for ZigBee-based wireless patient monitoring. *IEEE Transactions on Information Technology in Biomedicine.* 2012 Jan;16(1):6-16.

Cheng L., Hailes S., Zhen Cheng, Fu-Yi Fan, Hang D., Yang Yang: (2008). Compressing inertial motion data in wireless sensing systems — An initial experiment, *Int. Summer School and Symp. on Medical Devices and Biosensors*, pp. 293 – 296

Choe,Y. C., Park, J., Chung, M., Moon, J. (2009). Effect of the food traceability system for building trust: Price premium and buying behavior. *Information System Frontiers*, 11:167–179.

Crisosto, C. H., Mitcham Beth, Cantwell Marita (2008). Optimum temperature conditions for producehandlers. In *Central Valley Postharvest Newsletter of University of California*, 17(3), 1-18.

Cypak AB, (2008). The Compliancy Connection: Standard solution for medication monitoring. [on-line] http://www.cypak.com/ [accessed Dec 1, 2012].

Dalgaard, P., Buch, P., Silberg, S. (2002). Seafood Spoilage Predictor—development and distribution of a product specific application software. *International Journal of Food Microbiology*, 73(2-3), 343-349.

De Capua, C.; Meduri, A.; Morello, R. (2010). A Smart ECG Measurement System Based on Web-Service-Oriented Architecture for Telemedicine Applications. *IEEE Transactions on Instrumentation and Measurement*, 59(10), 2530-2538.

Delmastro, F. (2012). Pervasive communications in healthcare. *Computer Communications*, 35(11), 1284-1295.

Dolan, B. (2011). 10 Reasons why Google Health failed. *MobiHealthnews by Chester Street Publishing* Inc, 27 Jun.

Domingo, M. C. (2012). An overview of the Internet of Things for people with disabilities. *Journal of Network and Computer Applications*, 35(2), 584-596.

Duan, L., Xu, L. (2012), Business intelligence for enterprise systems: a survey. IEEE Transactions on Industrial Informatics, published online, Digital Object Identifier: 10.1109/TII.2012.2188804

Edmonds, N.; Stark, D.; Davis, J. (2005). "MASS: modular architecture for sensor systems". *Int. Sym. Information Processing in Sensor Networks (IPSN)*, 393-397.

EIC Laboratories Inc., (2004). The ElectRelease Foil Patch. [on-line] www.eiclabs.com [accessed Dec 1, 2012].

EPCglobal, (2007). "EPC Information Services (EPCIS) v. 1.0 specification 2007", [on-line] www.epcglobalinc.org/standards/epcis [accessed Dec 1, 2012].

Escarrabill, J.; Martí, T.; Torrente, E. (2011). Good morning, Doctor Google. *Revista Portuguesa de Pneumologia (English Edition)*, 17(4), 177-181.

European Commission Information Society (2008). *Internet of Things in 2020: a Roadmap for the Future* [online]. Available from: www.iot-visitthefuture.eu. [Accessed 17 Oct 2012]

European Commission Information Society (2009). *Internet of Things Strategic Research Roadmap 2009* [online]. Available from: www.internet-of-things-research.eu. [Accessed 17 Oct 2012]

Fellows, P. (2000). Food processing technology: principles and practice (2nd ed.). Cambridge, Woodhead Publishing Limited.

Feng, Yi; Hallstedt, J.; Chen, Qiang; Zheng, Li-Rong; Huang, Yiping; (2009). Development and experimental verification of analytical models for printable interdigital capacitor sensors on paperboard, *IEEE Sensors Conference*, 2009, 1034 – 1039.

Ferrari, P.; Flammini, A.; Marioli, D.; Taroni, A.; (2006). IEEE802.11 sensor networking. *IEEE Trans. on Instrumentation and Measurement*, 55(2), 615 – 619.

Gartner Research, (2005). RFID Enables Sensory Network Strategies to Transform Industries. Oct. 2005.

German Insurance Association (2002-2011). Container Handbook. *Marine and Loss Prevention Department of GDV*, www.containerhandbuch.de. Accessed Apr 23, 2012.

Greenstein, Ben; Mar, Christopher, Pesterev, Alex, Kohler, Eddie; Judy, Jack; Estrin, Deborah: (2006). Capturing high-frequency phenomena using a bandwidth-limited sensor network. *Proc. ACM Int'l Conf. Embedded Networked Sensor Systems (SenSys'06)*

Goff-Pronost, M. L., Sicotte, Claude. (2010).The added value of thorough economic evaluation of telemedicine networks. *The European Journal of Health Economics*, 11(1), 45-55.

Gordijn, J.; Akkermans, H. (2001); Designing and evaluating e-business models, IEEE Intelligent Systems, 16(4), 2001, Page(s): 11- 17

Gordijn, Jaap; Akkermans, Hans (2007). Business models for distributed generation in a liberalized market environment. Electric Power Systems Research, Volume 77, Issue 9, July 2007, Pages 1178-1188

Friedewald, Michael; Raabe, Oliver; (2011). Ubiquitous computing: An overview of technology impacts. *Telematics and Informatics*. 28 (2011) 55–65.

He, T.; Ho, W.; Xu, X.F. (2010). A value-oriented model for managing service supply chains. 2010 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2010 , Page(s): 193- 197

Hsu, Y., Chen, A., Wang, C. (2008). A RFID-enabled traceability system for the supply chain of live fish. *In proceedings of IEEE International Conference on Automation and Logistics*, 81-86, doi: 10.1109/ICAL.2008.4636124

Huang, H., Chen, C., Chen, T. (2006). Mobile Diagnosis based on RFID for Food Safety. *In proceedings of IEEE International Conference on Automation Science and Engineering*, 357-362, doi: 10.1109/COASE.2006.326908

Hulstijn, J., Christiaanse, R., Bharos, N., Schmid, F., Wijk, R., *et al.* (2011). Continuous Control Monitoring-Based Regulation: A Case in the Meat Processing Industry.In C. Salinesi and O. Pastor (Eds.): CAiSE 2011 Workshops, LNBIP 83, pp. 238–248. Berlin Heidelberg, Springer-Verlag.

Ikemoto, Y.; Suzuki, S.; Okamoto, H.; Murakami, H.; Xin Lin; Itoh, H.; Asama, H., (2008). Force sensor system for structural health monitoring using passive RFID tags for structural health monitoring. *2nd IEEE Inte. Conf. on Portable Information Devices*, pp.1–6.

iPack VINN Excellence Center, (2010). A General Presentation on Ubiquitous Intelligence in Paper and Packaging. [on-line] http://www.kth.se/en/ict/forskning/centra/ipack/aboutipack/general-presentations-1.54530 [accessed Dec 1, 2012]

Istepanaian, R. S. H.; Zhang, Y.-T., (2012). Guest Editorial Introduction to the Special Section: 4G Health—The Long-Term Evolution of m-Health. *IEEE Transactions on Information Technology in Biomedicine*, 16(1), 1-5.

ITU (2005). *The Internet of Things-Executive Summary* [online]. Available from: www.itu.int/osg/spu/ publications/internetofthings [Accessed 17 Oct 2012].

ITU-T (2008). Ubiquitous Sensor Networks (USN), *ITU-T Technology Watch Briefing Report Series*, No. 4, February 2008.

Jedermann, R., Palafox-Albarran, J., Jabarri, A., Lang, W. (2011). Embedded Intelligent Objects in Food Logistics Technical Limits of Local Decision Making. In M. Hülsmann et al. (eds.), Autonomous Cooperation and Control in Logistics, DOI:10.1007/978-3-642-19469-6_16, Berlin Heidelberg, Springer-Verlag.

Jeffry, S. W.; Higgins, J. E; Gilbert, M. D.; Cogan, S.F.; (2003). Evaluation of Electrically Disbonding Adhesive Propertites for Use as Separation Systems. *44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference*, 7-10 April 2003, Norfolk, Virginia.

Jones, P. (2006). Networked RFID for use in the Food Chain. *In proceedings of IEEE Conference on Emerging Technologies and Factory Automation*, 1119 – 1124, doi: 10.1109/ETFA.2006.355252

José, á. M., Berrone, P., Husillos, F. J., Lado, N. (2007). Reverse logistics, stakeholders' influence, organizational slack, and managers' posture. *Journal of Business Research*, 60 (5), 463-473

Junnila, S.; Kailanto, H.; Merilahti, J.; Vainio, A.-M.; Vehkaoja, A.; Zakrzewski, M.; Hyttinen, J. (2010). Wireless, Multipurpose In-Home Health Monitoring Platform: Two Case Trials. *IEEE Transactions on Information Technology in Biomedicine*, 14(2), 447-455.

Kim, Yunseop; Evans, R.G.; Iversen, W.M.; (2008). Remote Sensing and Control of an Irrigation System Using a Distributed Wireless Sensor Network. *IEEE Trans. on Instrumentation and Measurement*, 57(7), 1379–1387.

Kimura, Naoto; Latif, Shahram; (2005). A Survey on Data Compression in Wireless Sensor Networks. *Proceedings of the International Conference on Information Technology: Coding and Computing (ITCC'05)*, Volume II, 8-13.

Klasnja, P., Pratt, W. (2012). Healthcare in the pocket: Mapping the space of mobile-phone health interventions, *Journal of Biomedical Informatics*, 45(1), 184-198.

Koop, C.E.; Mosher, R.; Kun, L.; Geiling, J.; Grigg, E.; Long, S.; Macedonia, C.; Merrell, R.; Satava, R.; Rosen, J. (2008). Future delivery of health care: Cybercare. *IEEE Engineering in Medicine and Biology Magazine*, 27(6), 29-38.

Koutkias, V.G.; Chouvarda, I.; Triantafyllidis, A.; Malousi, A.; Giaglis, G.D.; Maglaveras, N. (2010). A Personalized Framework for Medication Treatment Management in Chronic Care. *IEEE Transactions on Information Technology in Biomedicine*, 14(2), 464-472.

Kuck, M. (2007). The chill-on project: Novel technologies for a safe and transparent food supply. http://www.chill-on.com. Accessed Apr 23, 2012.

Lambert, Susan (2006). Do We Need a "Real" Taxonomy of e-Business Models? School Of Commerce Research Paper Series: 06-6, ISSN: 1441-3906, Flinders University

Landt J., (2005). The history of RFID. *IEEE Potentials*, 24(4), pp.8-11, Nov.2005

Lao, S.I., Choy, K.L., Ho, G.T.S., Tsim, Y.C., Poon, T.C., Cheng, C.K. (2012). A real-time food safety management system for receiving operations in distribution centers. *Expert Systems with Applications*, 39(3), 2532-2548.

Lee, W.S., Alchanatis, V., Yang, C., Hirafuji,M., Moshou, D., Li, C. (2010). Sensing technologies for precision specialty crop production. *Computers and Electronics in Agriculture*, 74(1), 2-33.

Lee, H.; Özer, Ö; (2007). Unlocking the Value of RFID. *Production and Operations Management*, vol. 16, no. 1, pp. 40–64.

Li, L (2007), Supply chain management: Concepts, techniques, and practices - Enhancing value through collaboration. World Scientific Publishing.

Li, L (2011), Assessing the Relational Benefits of Logistics Services Perceived by Manufacturers in Supply Chain. *International Journal of Production Economics*, 132, 58-67.

Li, L., Warfield, J (2011), Guest editorial: perspectives on quality coordination and assurance in global supply chains. *International Journal of Production Research*, 49(1), 1-4.

Li, S., Xu, L., Wang, X., Wang, J. (2012). Integration of hybrid wireless networks in cloud services oriented enterprise information systems. *Enterprise Information Systems*, 6:2, 165-187.

Li, S., Xu, L., Wang, X. (2013). Compressed Sensing Signal and Data Acquisition in Wireless Sensor Networks and Internet of Things. *IEEE Transactions on Industrial Informatics*, in press DOI: 10.1109/TII.2012.2189222

Limburg, M.; Gemert-Pijnen, J. E.; Nijland, N.; Ossebaard, H. C.; Hendrix1, R.; Seydel, E., (2011). Why Business Modeling is Crucial in the Development of eHealth Technologies. *Journal of Medical Internet Research*, 13(4), e124, doi:10.2196/jmir.1674.

Lin, Tung-Cheng; Chang, Hong-Jer; Huang, Chung-Chien. (2011). An Analysis of Telemedicine in Taiwan: A Business Model Perspective Original. International Journal of Gerontology, Volume 5, Issue 4, December 2011, Pages 189-192

Liu, C., Zhu, Q.; Holroyd, K. A.; Seng E. K., (2011). Status and trends of mobile-health applications for iOS devices: A developer's perspective. *J. Systems and Software*, 84(11), 2022-2033.

Liu, Liran; Jia, Wei (2010). Business model for drug supply chain based on the internet of things. 2010 2nd IEEE International Conference on Network Infrastructure and Digital Content, 2010 , Page(s): 982 - 986

López, G.; Custodio, V.; Moreno, J.I. (2010). LOBIN: E-Textile and Wireless-Sensor-Network-Based Platform for Healthcare Monitoring in Future Hospital Environments. *IEEE Transactions on Information Technology in Biomedicine*, 14(6), 1446-1458.

Ludwig, W.; Wolf, K.; Duwenkamp, C.; Gusew, N.; Hellrung, N.; Marschollek, M.; Wagner, M.; Haux, R., (2012). Health-enabling technologies for the elderly–An overview of services based on a literature review. *Computer Methods and Programs in Biomedicine,* 106(2), 70-78.

Man, C. M. D., Jones, A. A. (2000). *Shelf-life evaluation of foods (2nd Edition)*. New York, NY, Aspen Publishers Inc.

Marcelloni, F., Vecchio, M.: (2008). A Simple Algorithm for Data Compression in Wireless Sensor Networks. *IEEE Communications Letters*, 12(6) 411 – 413.

Martinez-Romero, D., Serrano, M., Carbonell, A., Castillo, S., Riquelme, F., Valero, D. (2004). Mechanical Damage During Fruit Post-Harvest Handling: Technical and Physiological Implications. In R. Dris and S. M. Jain (eds.), Production Practices and Quality Assessment of Food Crops, Vol. 3, “Quality Handling and Evaluation”, pp. 233–252, Netherlands, Kluwer Academic Publishers.

Mayberry, Peter; (2009). Increasing Pharmaceutical Compliance Through Better Packaging. *17th Annual National Symposium on Patient Compliance.*

McWilliams, Gary (2006). Wal-Mart's Radio-Tracked Inventory Hits Static. *Wall Street Journal*. February 15, 2006, page B1.

Mettler, Tobias; Eurich, Markus (2012). A “design-pattern”-based approach for analyzing e-health business models. Health Policy and Technology, 9 May 2012

Michahelles, Florian (ed.) (2011). Business Aspects of the Internet of Things: Seminar of advanced topics. *ETH Zurich*, FS2011.

Miorandi, D.; Sicari, S.; Pellegrini, F. D.; Chlamtac, I. (2012). Internet of things: Vision, applications and research challenges. *Ad Hoc Networks*, 10(7), 1497-1516.

Morak, J.; Kumpusch, H.; Hayn, D.; Modre-Osprian, R.; Schreier, G. (2012). Design and Evaluation of a Telemonitoring Concept Based on NFC-Enabled Mobile Phones and Sensor Devices. *IEEE Transactions on Information Technology in Biomedicine,* 16(1), 17-23.

Morris, Michael; Schindehutte, Minet; Allen, Jeffrey (2005). The entrepreneur's business model: toward a unified perspective. Journal of Business Research, Volume 58, Issue 6, June 2005, Pages 726-735

MTS Medication Technologies, (2012). Single Dose Punch Card Packaging. [on-line] http://www.mts-mt.com/ [accessed Dec 1, 2012].

Mullins, John; Komisar, Randy (2009). Getting to Plan B: Breaking Through to a Better Business Model. Harvard Business Review Press (September 1, 2009)

Munir, S.A.; Biao Ren; Weiwei Jiao; Bin Wang; Dongliang Xie; Man Ma; (2007). Mobile Wireless Sensor Network: Architecture and Enabling Technologies for Ubiquitous Computing, *21st Inte.l Conf. on Advanced Information Networking and Applications Workshops, AINAW '07.* 2(2007) 113–120.

National Information Council (2008). Global Trends 2025: A Transformed World. US Government Printing Office [online]. Available from: www.dni.gov/nic/NIC_2025_project.html. [Accessed 17 Oct 2012]

Oms-Oliu, G., Martínez, R. R. M., Soliva-Fortuny, R., Martín-Belloso, O. (2008). Effect of superatmospheric and low oxygen modified atmospheres on shelf-life extension of fresh-cut melon. *Food Control*, 19(2) 191-199.

Orwat, C.; Graefe, A.; Faulwasser, T. (2008). Towards pervasive computing in health care – A literature review. *BMC Medical Informatics and Decision Making, 8*(26), doi:10.1186/1472-6947-8-26.

Osterwalder, A; Pigneur, Y (2010). Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers (portable version) Switzerland: OSF; 2010. Business Model Generation.

Palazón M. A, Pérez-Conesa, D., Abellán, P., Ros G., Romero, F., Vidal, M. L.(2009). Determination of shelf-life of homogenized apple-based beikost storage at different temperatures using Weibull hazard model. *LWT - Food Science and Technology*, 42 (1), 319-326, doi: 10.1016/j.lwt.2008.03.011

Pang, Zhibo (2010). FreshVision: a food chain visibility service, Business Plan, Aug, 2010. not published.

Pang, Zhibo (2012). Business Model Design for Personal Mobile Healthcare Service: the Methodology and Case Study, MBA Thesis, University of Turku, June 2012.

PaperDisplay, (2012). Paper Display Technology. [on-line] http://www.paperdisplay.se/Technology/tabid/2217/language/en-US/Default.aspx [accessed Dec 1, 2012].

Pardo, D.; Vaz, A.; Gil, S.; Gomez, J.; Ubarretxena, A.; Puente, D.; Morales-Ramos, R.; Garcia-Alonso, A.; Berenguer, R. (2007). Design Criteria for Full Passive Long Range UHF RFID Sensor for Human Body Temperature Monitoring. *IEEE Inte. Conf. on RFID*, 141–148.

Pawar, P.; Jones, V.; Beijnum, B. F. V.; Hermens, H., 2012. A framework for the comparison of mobile patient monitoring systems. *Journal of Biomedical Informatics*, 45(3), 544-556.

PCT International Patent (2007). An electrochemically weakable adhesive composition. *PCT International Patent Publication*, No. WO2007/142600.A1.

Philipose, M.; Smith, J.R.; Jiang, B.; Mamishev, A.; Sumit Roy; Sundara-Rajan, K.; (2005). Battery-free wireless identification and sensing. *IEEE Pervasive Computing*, Vol.4, Iss.1, Jan 2005 pp.37–450

Plaza, I.; Martína, L.; Martinb, S.; Medranoa, C. (2011). Mobile applications in an aging society: Status and trends, *J. Systems and Software*, 84(11), 1977-1988.

Rodrigues, J. J.P.C.; Pereira, O. R.E.; Neves, P. A.C.S. (2011). Biofeedback data visualization for body sensor networks. *Journal of Network and Computer Applications*, 34(1), 151-158.

Roedig, Utz; Rutlidge, Sarah; Brown, James; Scott, Andrew; (2010). “Towards Multiprocessor Sensor Nodes”. *ACM Workshop on Hot Topics in Embedded Networked Sensors (HotEmNets '10)*

Porter, M., E. (1985). *Competitive Advantage: Creating and Sustaining Superior Performance*, Free Press

Porter, M., E. (1996). What is strategy? *Harvard Business Review*, November–December, 61-78.

Porter, M.E. (2008) The Five Competitive Forces That Shape Strategy, Harvard business Review, January 2008.

Qi, L., Zhang, J., Xu, M., Fu, Z., Chen,W., Zhang, X. (2011). Developing WSN-based traceability system for recirculation aquaculture. *Mathematical and Computer Modeling*, 53(11–12), 2162-2172.

Rong, A., Akkerman, R., Grunow, M. (2011). An optimization approach for managing fresh food quality throughout the supply chain. *International Journal of Production Economics,* Volume 131, 421–429.

Ruiz-Garcia, L., Lunadei L., Barreiro, P., Robla, J. I. (2009). A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends. *Sensor,* 2009, 9(6), 4728-4750, doi:10.3390/s90604728

Ruiz-Garcia, L., Steinberger, G., Rothmund, M. (2010). A model and prototype implementation for tracking and tracing agricultural batch products along the food chain. *Food Control*, 21(2), 112-121.

Ruiz-Garcia, L., Lunadei, L. (2011). The role of RFID in agriculture: Applications, limitations and challenges. *Computers and Electronics in Agriculture*, 79(1), 42-50.

Sallabi, F., Fadel, M., Hussein, A., Jaffar, A., & Khatib, H. E. (2011). Design and implementation of an electronic mobile poultry production documentation system. *Computers and Electronics in Agriculture*, 76(1), 28-37.

Sarac, A., Absi, N., Dauzère-Pérès, S. (2010). A literature review on the impact of RFID technologies on supply chain management. *International Journal of Production Economics,* 128 (1), 77-95.

Sheng, Q., Zeadally, S., Luo, Z., Chung, J., Maamar, Z. (2010). Ubiquitous RFID: Where are we? *Information Systems Frontiers,* 12(5), 485-490.

Shrestha, S.; Balachandran, M.; Agarwal, M.; Phoha, V.V.; Varahramyan, K.; (2009). A Chipless RFID Sensor System for Cyber Centric Monitoring Applications. *IEEE Trans. on Microwave Theory and Techniques*, Vol.57 Iss.5 Part 2, May 2009 pp.1303–1309.

Sinderen, M., Almeida, J. P. A. (2011). Empowering enterprises through next-generation enterprise computing. *Enterprise Information Systems,* 5(1), 1-8.

Sollacher, Rudolf; Niedermeier, Christoph; Vicari, Norbert; Osipov, Maxim; (2009). Towards a Service Oriented Architecture for Wireless Sensor Networks in Industrial Applications. *Information Control Problems in Manufacturing*, 13(1).

Song, Jianping; Han, Song; Mok, A.K.; Deji Chen; Lucas, M.; Nixon, M. (2008). WirelessHART: Applying Wireless Technology in Real-Time Industrial Process Control. *IEEE Real-Time and Embedded Technology and Applications Symposium*,377-386

Tajima, M. (2007). Strategic value of RFID in supply chain management. *Journal of Purchasing & Supply Management* 13, 261–273.

Tartarisco, G.; Baldus, G.; Corda, D.; Raso, R.; Arnao, A.; Ferro, M.; Gaggioli, A.; Pioggia, G. (2011). Personal Health System architecture for stress monitoring and support to clinical decisions. *Computer Communications*, 35 (11), 1296-1305.

Teng, X.; Zhang, Y.-T.; Poon, C.C.Y.; Bonato, P. (2008) Wearable Medical Systems for p-Health. *IEEE Reviews in Biomedical Engineering.* Vol 1, 62-74.

Tetu, Y.; Jantunen, I.; Gomez, B.; Robinet, S.; (2009). Mobile-phone-readable 2.45GHz passive digital sensor tag. *IEEE Inte. Conf. on RFID*, pp.88–94.

The Economist (2007). When everything connects: A 14-page special report on the coming wireless revolution. *The Economist*, volume 383, issue 8526, London, April 28, 2007.

Tsironi, T. Gogou, E., Velliou, E., Taoukis, P. S. (2008). Application and validation of the TTI based chill chain management system SMAS (Safety Monitoring and Assurance System) on shelf life optimization of vacuum packed chilled tuna. *International Journal of Food Microbiology*, 128(1), 108-115.

Uckelmann, Dieter; Harrison, Mark; Michahelles, Florian; (2011). Architecting the Internet of Things. Springer-Verlag Berlin Heidelberg.

Ueda, K.; Takenaka, T.; Váncza, J.; Monostori, L. (2009). Value creation and decision-making in sustainable society. *CIRP Annals-Manufacturing Technology*, 58(2) 681-700.

Ugazio, E., Pigni, F. (2010). Measuring RFID Benefits in the Supply Chain. In A. D'Atri and D. Saccà (eds.), Information Systems: People, Organizations, Institutions, and Technologies, Part 8, Pages 469-476, Berlin Heidelberg. Springer Physica-Verlag.

Unander, T.; Nilsson, H.-E.; Oelmann, B.; (2007). Printed touch sensor for interactive packaging and display, *6th Inte.Conf. on Polymers and Adhesives in Microelectronics and Photonics*, pp.12 – 17.

Unander, T.; Nilsson, H.-E.; (2009). Characterization of Printed Moisture Sensors in Packaging Surveillance Applications, *IEEE Sensors Journal*, 9(8), 922–928.

United States Patent, (2003). Electrically disbonding materials. *United States Patent* No.US6620308.B2.

United States Patent, (2008). Electrically disbondable compositions and related methods. *United States Patent Application,* No. US2008/0283415 A1.

Véronneau, S., & Roy, J. 2009. RFID benefits, costs, and possibilities: The economical analysis of RFID deployment in a cruise corporation global service supply chain. *International Journal of Production Economics*, 122(2), 692-702.

Victoria de-la-Fuente, M., Ros, L. (2010). What to Do with Rejected Loads in the Agri-food Chain. In J.E. Quintela Varajão *et al.* (Eds.): CENTERIS 2010, Part I, CCIS 109, pp. 251–260, 2010. Berlin Heidelberg, Springer-Verlag.

Visich, J. K., Pedro M. Reyes, Suhong Li. (2011). Is RFID dead? Definitely not! *DC Velocity Technology Review*. June 27.

Wang, L. ; Xu, L. ; Bi, Z. ; Xu, Y. (2013). Data Filtering for RFID and WSN Integration. *Industrial Informatics, IEEE Transactions on*. in press, DOI: 10.1109/TII.2013.2250510

Wamba, S. F., Chatfield, A. T. (2010). The impact of RFID technology on warehouse process innovation: A pilot project in the TPL industry. *Information Systems Frontiers*, 13(5), 693-706.

Wang, Wen; He, Shitang; (2008). Passive and remote polymer-coated Love wave chemical sensor. *IEEE Ultrasonics Symposium, 2008. IUS 2008.* 1854 -1857.

Wang, You-Chiun; Hsieh, Yao-Yu; Tseng Yu-Chee, (2009). Multiresolution Spatial and Temporal Coding in a Wireless Sensor Network for Long-Term Monitoring Applications. *IEEE Transactions on Computers*, 58(6), 827-838.

Wang, H.; Shi, Y.; Wang Xi. (2012). Development of Medicine Management System for RFID-Based Inteligent Medicine Cabinet. *WAP Conference Series: Education and Social Science Review.* 2012 (1).

World Health Organization (2011). mhealth: New Horizon for Health Through Mobile Technologies. *Global Observatory for e-Health Services*, vol. 3. Geneva, Switzerland: WHO.

Xu, L. (2011a), Enterprise systems: state-of-the-art and future trends. IEEE Transactions on Industrial Informatics, 7(4), 630-640.

Xu, L. (2011b), Information architecture for supply chain quality management. International Journal of Production Research, 49(1), 183.

Xue, Yuyan; Ramamurthy, B.; Burbach, M.; (2010). A two-tier Wireless Sensor Network infrastructure for large-scale real-time groundwater monitoring. *IEEE 35th Conference on Local Computer Networks (LCN),* 874 – 881.

Yick, Jennifer; Mukherjee, Biswanath; Ghosal, Dipak, (2008). Wireless sensor network survey. *Computer Networks*, 52 (2008) 2292–2330.

Yuan, Hao-Chih; Shin, Jonghyun; Qin, Guoxuan; Sun, Lei; Bhattacharya, Pallab; Lagally, Max G.; Celler, George K.; Ma, Zhenqiang; (2009). Flexible photodetectors on plastic substrates by use of printing transferred single-crystal germanium membranes. *Applied Physics Letters*, 94(1) 013102-013102-3.

Zhang, M., Li, P. (2012). RFID Application Strategy in Agri-Food Supply Chain Based on Safety and Benefit Analysis. *Physics Procedia*, Volume 25, 636-642.

Zhang, Ying; Xiao, Hannan; (2009); Bluetooth-Based Sensor Networks for Remotely Monitoring the Physiological Signals of a Patient. *IEEE Trans. on Information Technology in Biomedicine*, 13(6), 1040–1048.

Zheng, Li-Rong; Nejad, M.B.; Zhuo Zou; Mendoza, D.S.; Zhi Zhang; Tenhunen, H.; (2008). Future RFID and Wireless Sensors for Ubiquitous Intelligence. *In Proc. of NORCHIP 2008*, 142–149.

Zhu, Xiuming; Han, Song; Mok, A.; Deji Chen; Nixon, M. (2011). Hardware challenges and their resolution in advancing WirelessHART. *IEEE Int. Con. on Industrial Informatics (INDIN)*,416-421

Ziv, Jacob; Lempel, Abraham: (1977). A Universal Algorithm for Sequential Data Compression. *IEEE Transactions on Information Theory*, 23(3), 337–343.

Zott, Christoph, Amit, Raphael H. and Massa, Lorenzo, (2011). The Business Model: Recent Developments and Future Research (February 7, 2011). *Journal of Management.* DOI: 10.1177/0149206311406265

PART II:
Included Papers

Paper I: Mobile and Wide Area Deployable Sensor System for Networked Services

Zhibo Pang, Jun Chen, David Sarmiento M., Zhi Zhang, Jie Gao, Qiang Chen, Lirong Zheng, *IEEE Sensors Conference 2009,* pp1396 – 1399, Oct 2009, Christchurch, New Zealand.

Paper II: Interactive Packaging Solutions Based on RFID Technology and Controlled Delamination Material

Jie Gao, **Zhibo Pang,** Qiang Chen, Lirong Zheng, *The 2010 IEEE International Conference on RFID,* April 2010, pp158-165, Florida, USA.

Paper III: Global Fresh Food Tracking Service Enabled by Wide Area Wireless Sensor Network

Zhibo Pang, Jun Chen, Zhi Zhang, Qiang Chen, Lirong Zheng, *IEEE Sensors Applications Symposium (SAS-2010),* pp6-9, Feb 2010, Limerick, Ireland.

Paper IV: Ecosystem Analysis in the Design of Open Platform-based In-Home Healthcare Terminals towards the Internet-of-Things

Zhibo Pang, Qiang Chen; Junzhe Tian, Lirong Zheng, Elena Dubrova. *International Conference on Advanced Communications Technology (ICACT)*. Jan 2013, Pyeongchang, Korea.

Paper V: Content-Extraction-Based Compression of Acceleration Data for Mobile Wireless Sensors

Zhibo Pang, Qiang Chen, Lirong Zheng. *IEEE Sensors Conference 2012*, Oct 2012, Taipei, Taiwan.

Paper VI: An RTOS-based Architecture for Industrial Wireless Sensor Network Stacks with Multi-Processor Support

Zhibo Pang, Kan Yu, Johan Åkerberg, Mikael Gidlund, *IEEE International Conference on Industrial Technology (ICIT2013)*, Feb 2013, Cape Town, South Africa.

Paper VII: Value creation, Sensor Portfolio and Information Fusion of Internet-of-Things Solutions for Food Supply Chains

Zhibo Pang, Qiang Chen, Lirong Zheng. *Information Systems Frontiers*, Aug 2012, DOI: 10.1007/s10796-012-9374-9. IF 1.596.

Paper VIII: Design of a Terminal Solution for Integration of In-home Healthcare Devices and Services towards the Internet-of-Things

Zhibo Pang, Lirong Zheng, Junzhe Tian, Sharon Kao-Walter, Elena Dubrova , Qiang Chen. *Enterprise Information Systems*, DOI:10.1080/17517575.2013.776118, April 2013. IF 3.684.