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Integrated ZigBee RFID Sensor Networks for Resource Tracking and Monitoring in Logistics Management

by

Huanjia Yang

A Doctoral Thesis

Submitted in partial fulfillment

Of the requirements for the award of

Doctor of Philosophy

Of

Loughborough University

September 2010

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Abstract

The Radio Frequency Identification (RFID), which includes passive and active systems and is the hottest Auto-ID technology nowadays, and the wireless sensor network (WSN), which is one of the focusing topics on monitoring and control, are two fast-growing technologies that have shown great potential in future logistics management applications. However, an information system for logistics applications is always expected to answer four questions: Who, What, When and Where (4Ws), and neither of the two technologies is able to provide complete information for all of them. WSN aims to provide environment monitoring and control regarded as 'When' and 'What', while RFID focuses on automatic identification of various objects and provides 'Who' (ID). Most people usually think RFID can provide 'Where' at all the time. But what normal passive RFID does is to tell us where an object was the last time it went through a reader, and normal active RFID only tells whether an object is presenting on site. This could sometimes be insufficient for certain applications that require more accurate location awareness, for which a system with real-time localization (RTLS), which is an extended concept of RFID, will be necessary to answer 'Where' constantly. As WSN and various RFID technologies provide information for different but complementary parts of the 4Ws, a hybrid system that gives a complete answer by combining all of them could be promising in future logistics management applications. Unfortunately, in the last decade those technologies have been emerging and developing independently, with little research been done in how they could be integrated.

This thesis aims to develop a framework for the network level architecture design of such hybrid system for on-site resource management applications in logistics centres. The various architectures proposed in this thesis are designed to address different levels of requirements in the hierarchy of needs, from single integration to hybrid system with real-time localization. The contribution of this thesis consists of six parts. Firstly, two new concepts, “Reader as a sensor” and ”Tag as a sensor”, which lead to RAS and TAS architectures respectively, for single integrations of RFID and WSN in various scenarios with existing systems; Secondly, a integrated ZigBee RFID Sensor Network Architecture for hybrid integration; Thirdly, a connectionless inventory tracking architecture (CITA) and its battery consumption model adding location awareness for inventory tracking in Hybrid ZigBee RFID Sensor Networks; Fourthly, a connectionless stochastic reference beacon architecture (COSBA) adding location awareness for high mobility target tracking in Hybrid ZigBee RFID Sensor Networks; Fifthly, improving connectionless stochastic beacon transmission performance with two proposed beacon transmission models, the Fully Stochastic Reference Beacon (FSRB) model and the Time Slot Based Stochastic Reference Beacon (TSSRB) model; Sixthly, case study of the proposed frameworks in Humanitarian Logistics Centres (HLCs).

The research in this thesis is based on ZigBee/IEEE802.15.4, which is currently the most widely used WSN technology. The proposed architectures are demonstrated through hardware implementation and lab tests, as well as mathematic derivation and Matlab simulations for their corresponding performance models. All the tests and simulations of my designs have verified feasibility and features of our designs compared with the traditional systems.

Publications

Journal Publications:

- **Yang, H., Yang, S.**, "RFID sensor network – Network architecture to integrate RFID, sensor and WSN". *Measurement and Control,* volume 40, 56-59, 2007

- **Yang, H., Yang, S.**, "Indoor Localization Systems – Tracking objects and personnel with sensors, wireless network and RFID". *Measurement and Control*, volume 42, 18-23, 2009

- **Yang, H., Yang, S.H.**, "Hybrid RFID Sensor Network for Humanitarian Logistics Centre Management", *Journal of Network and Computer Applications*, in Press, 2010.

- **Wu, W., Yang, H., Yang**, S., "Towards an Autonomous Real-time Tracking System of Near-miss on Construction Sites", *Automation in Construction*, volume 19, 134-141, 2010

Conference Publications:

- **Yang, H., Yao, F., Yang, S.**, "ZigBee Enabled Radio Frequency Identification System", *The Proceedings of the IASTED International Conference on Communication Systems, Networks and Applications (CSNA 2007)*, Beijing, 2007

- **Yang, H., Yang, S.H.**, "Connectionless Indoor Inventory Tracking in ZigBee RFID Sensor Network", *The Proceedings of 35th Annual Conference of the IEEE Industrial Electronics Society (IECON 09)*, Porto, Portugal, 2009

- **Yang, H., Yang, S.H.**, "Mobile Tracking Architecture in ZigBee RFID Sensor Networks", *The Proceedings of the EPSRC Workshop on Human Adaptive Mechatronics (HAM 2010)*, Loughborough, UK, 2010

- **Yang, H., Yang, S.H.**, "RFID Based Automatic Speed Limit Warning System", *The Proceedings of the 8th UKACC International Conference on Control (CONTROL 2010)*, Coventry, UK, 2010

Journal papers under review

- **Yang, H., Yang, S.H.**, "Connectionless Stochastic Reference Beacon Architecture/Model for High Mobility Target Tracking in ZigBee RFID Sensor Network", *submitted to IEEE Sensors Journal*

- **Yang, H., Yang, S.H.**, "Automatic Real-time Speed Limit Warning Based on Radio Frequency Identification", *submitted to Personal and Ubiquitous Computing*

Abbreviations

3G	3rd Generation Mobile Network
4W	Who When Where What
AC	Alternating Current
ALE	Application Level Events
AOA	Angle of Arrive
AP	Access Point
API	Application Programming Interface
ASK	Amplitude-Shift Keying
Auto-ID	Automatic Identification
BER	Bit Error Rate
CCA	Clear Channel Assessment
CITA	Connectionless Inventory Tracking Architecture
COSBA	Connectionless Stochastic Reference Beacon Architecture

CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DNS	Domain Name System
DoD	US Department of Defence
EPC	Electronic Product Code
EPCIS	EPC Information Services
FFD	Full Function Device (IEEE802.15.4)
FSRB	Fully Stochastic Reference Beacon
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphic User Interface
HF	High Frequency
HLC	Humanitarian Logistics Centre
IIVS	In-transit Item Visibility System
IP	Internet Protocol
IR	InfraRed
ISO	International Standards Organization
ISM	Industrial, Scientific, and Medical Frequency Bands
LAN	Local Area Network
LF	Low Frequency

LQI	Link Quality Indicator
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Media Access Control
OC-ALC	Oklahoma City Air Logistics Centre
OCR	Optical character recognition
ONS	Object Name Service
PCB	Printed Circuit Board
RAM	Random-Access Memory
RAS	Reader as a Sensor
RF	Radio Frequency
RFD	Reduced Function Device (IEEE802.15.4)
RFID	Radio Frequency IDentification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTLS	Real Time Location System
SMA cable	SubMiniature version A cable
SMS	Short Message Service
TAS	Tag as a Sensor
TDOA	Time Difference of Arrival
TEDS	Transducer Electronic Data Sheet

TETRA	Trans European Trunked Radio
TOA	Time of Arrival
TSSRB	Time Slotted Stochastic Reference Beacon
UART	Universal Asynchronous Receiver/Transmitter
UHF	Ultra High Frequency
USB	Universal Serial Bus
UWB	Ultra Wide Band
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
ZC	ZigBee Coordinator
ZED	ZigBee End Device
ZR	ZigBee Router

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Chapter 1 Introduction

1.1 Technical Background

1.1.1 Sensors and Wireless Sensor Networks (WSNs)

Wireless sensor network is one of the focusing topics in the realm of computer science and electronic engineering. Smart environments and real-time surveillance are often required in various areas such as building, utilities, industries, home, shipboard, and transportation systems automation. Like any sentient organism, these applications rely first and foremost on sensory data from the real world (Cook and Das, 2004). Variable electronic sensors are the ideal devices to pursue this task. Many types of sensor have been designed for different purposes, some principal measurements used in wireless sensor networks are listed in Table 1-1 as examples.

Table 1-1. Sensor measurements for WSN (Cook and Das, 2004)

Measurand	Transduction Principle
Physical Properties	
Pressure	Piezoresistive, capacitive
Temperature	Thermistor, thermo-mechanical, thermocouple
Humidity	Resistive, capacitive
Flow	Pressure change, thermistor
Motion Properties	
Position	E-mag, E-vision, GPS, contact sensor
Velocity	Doppler, Hall effect, optoelectronic
Angular velocity	Optical encoder
Acceleration	Piezoresistive, piezoelectric, optical fibre
Contact Properties	
Strain	Piezoresistive
Force	Piezoelectric, piezoresistive
Torque	Piezoresistive, optoelectronic
Slip	Dual torque
Vibration	Piezoresistive, piezoelectric, optical fibre, sound, ultrasound
Presence	
Tactile/Contact	Contact switch, capacitive
Proximity	Hall effect, capacitive, magnetic, seismic, acoustic, RF
Distance/Range	E-mag(sonar, radar, lidar), magnetic, tunnelling
Motion	E-mag, IR, acoustic, seismic (vibration)
Biochemical	
Biochemical agents	Biochemical transduction
Identification	
Personal features	Vision
Personal ID	Fingerprints, retinal scan, voice, heat plume, vision analysis

As shown in Figure 1-1, numerous sensor nodes can be implemented at fixed locations either inside the phenomenon or very close to it. They measure the specific environment conditions periodically and send sampling data or alarm mainly in 3 modes:

- Periodically in a predefined time interval;
- Under a specific event, this often happens when the value of a specific measurement reaches a predefined threshold;
- Answering an interrogation.

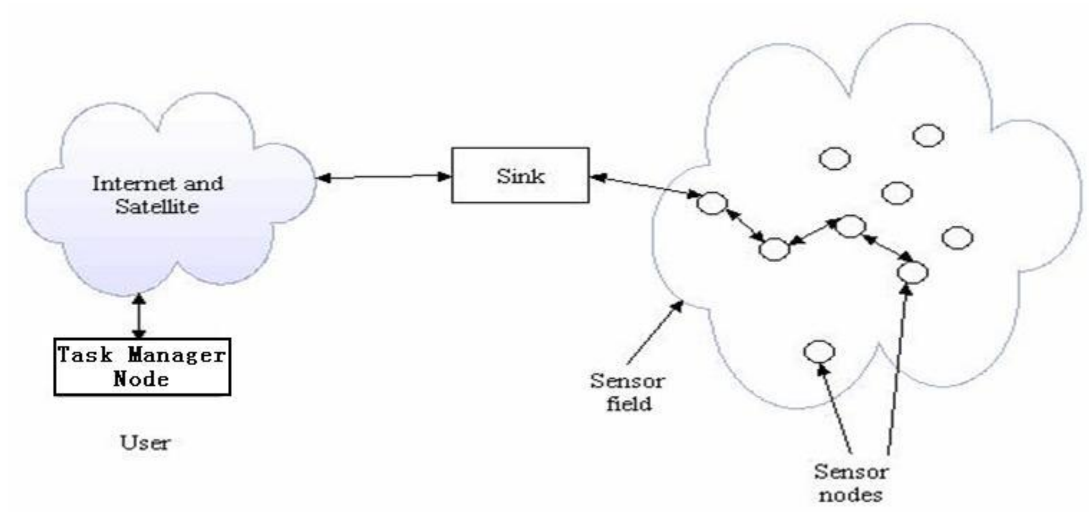


Figure 1-1: Structure of a typical wireless sensor network (Akyildiz et al., 2002)

In order to transfer these data or alarms the sensor nodes are equipped with on-board batteries and radio transmitter systems, via which they can establish an independent wireless network and communicate with each other using a multi-hop communication protocol. The sink node works like a gateway in traditional networks and can be placed anywhere close to the sensor field within the RF range of at least one sensor node. The information collected inside the sensor field will then be sent to the sink node which is responsible for transferring data to the task manager node for application use; this can be done via an external network or a direct cable. In terms of functions and purposes, a wireless sensor network is defined as a group of specialized transducers with a communication infrastructure in order to monitor and record conditions at diverse locations (Yang and Yang, 2007).

The sensor network nodes are usually self-powered either by on-board batteries or by various power gathering approaches from the surroundings, such as solar power, hydropower, wind and vibration (Norman, 2006). Because the resources and the electricity power they can provide are very limited based on the current power converting technologies, the network protocols that can be used to construct a Wireless Sensor Network should be power efficient so that the sensor network nodes can achieve a reasonable lifetime.

While the traditional networks aim to improve service quality and bandwidth efficiency, the chief design objective of WSN is to achieve power efficiency and dynamic network topology, thus the WSN has many unique features, these include: limited communication capacity, limited computation capacity, low and limited power supply, low data rate (compare to traditional ad hoc networks), numerous network nodes, self-organized network protocol, capacity for network self-maintenance and huge real-time data flow. After its first application in military sensing (Melanie et al., 2006), WSN is spreading quickly nowadays into a number of different areas such as the environment monitoring and forecasting, safety control and health monitoring etc.

1.1.2 Radio Frequency Identification (RFID)

The Radio Frequency Identification (RFID) is one of the Auto-ID technologies. Auto-ID is short for automatic identification technology which is a broad term of technologies that enable the machines to identify objects. Instead of having staff identify objects and type their information into a computer manually, the key for Auto-ID technologies is their automatic data capture ability. The aim of these systems is to increase efficiency, reduce data entry errors and free up staffs to perform more value-added functions, such as management or providing customer service. The main Auto-ID technologies include bar codes, smart cards, voice recognition, retinal or fingerprint scans, optical character recognition (OCR) and radio frequency identification.

RFID is a generic term for technologies that use radio waves to automatically identify people or objects (RFID Journal, 2007). Compared to the other Auto-ID technologies the RFID system has its own features: instead of typing or scanning the identification code manually, the RFID systems typically provide us a non-contact data transfer between the tag and the interrogator without the need for obstacle-free, line-of-sight reading; tag information can be rewritable and the tag itself can be recycle and reused; multiple tags can be read simultaneously by a RFID reader, which is known as the batch readability of tags, makes the identification work much more efficient; RFID tags are more reliable than printed barcodes which are easily damaged.

The first RFID application emerged early in 1970s, but it is only in the last decade of the century when the RFID technology started to get the attention from the various industries and spread quickly due to the advances in hardware industry. After having the support from world's largest retailer Wal-Mart (Barlas, 2003) and the US Department of Defense (US DoD, 2004), we can now expect a massive development in the RFID industry. Known as a possible replacement for the barcode technology, RFID could be one of the most promising technologies for future applications in asset tracking, manufacturing, security and access control, payment systems and supply chain management.

The basic components of a typical RFID system include: the transponder or the tag, which is a microchip in which a unique serial code is stored and transmitted when necessary via an antenna attached; the RFID reader, which is used to receive and identify the information sent by tags; the server with savant or middleware, where the readers forward the information to, is a computing device such as a server computer. There are generally 3 types of RFID tags depending on the power source used, which are the active, passive and semi-passive/semi-active tags. Each has its own features and is suitable for certain types of logistics applications, more details regarding differences between various RFID technologies and their corresponding applications are described in Chapter 2.

1.1.3 Real-time Localization Systems (RTLS)

RTLS are the technologies used to track and identify the location of objects in real time using simple, inexpensive nodes (tags) attached to or embedded in objects and devices (readers) that receive the wireless signals from these tags to determine their locations. RTLS typically refers to systems that provide passive or active (automatic) collection of location information. Most people usually think RFID can provide location information all the time. But what normal passive RFID does is to tell us where an object was the last time it went through a reader, and normal active RFID only tells whether an object is on site. Thus the RF based RTLS systems could be deemed as an improved type of RFID technology with extended functionality of real-time localization.

With the growing requirements in mobility of the end user devices, there has been an increased demand of an integrant part of Real-Time Locating System/Service (RTLS) in logistics information systems. The most well known localization service is the Global Positioning System (GPS) using a network of 24 beacon satellites to cover the majority of the earth's surface. It is widely used to track and navigate moving objects outdoors. Its accuracy cannot satisfy most indoor applications and the satellite signal itself is usually unreachable in indoor environments. Thus dedicated systems have to be used for many on-site logistics localization applications. Compared to outdoor applications, the indoor environment is more complex, irregular, unpredictable and inconsistent. Because of this it is very hard for a system to achieve satisfactory performance in all aspects including accuracy, range, power consumption, implementation, cost and maintenance. Most designs have to look for a balance between these parameters. More details about various RTLS technologies and their features are described in Chapter 3.

1.2 Research Problem Description

Logistics management is the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from point-of-origin to point-of-consumption for the purpose of conforming to customer requirements (Lambert and Stock 1993). Logistics involves the integration of information, transportation, inventory, warehousing, material handling, and packaging. Much work has been done to prove that improving the whole supply chain performance relies on improving of the external service quality at each distribution point on the chain, which requires the internal service performance at each distribution point to be improved initially (Conduit and Mavondo, 2001). Thus for the application scenario in this thesis, I focus on the logistics practices of the warehouses and distribution centres in the supply chain.

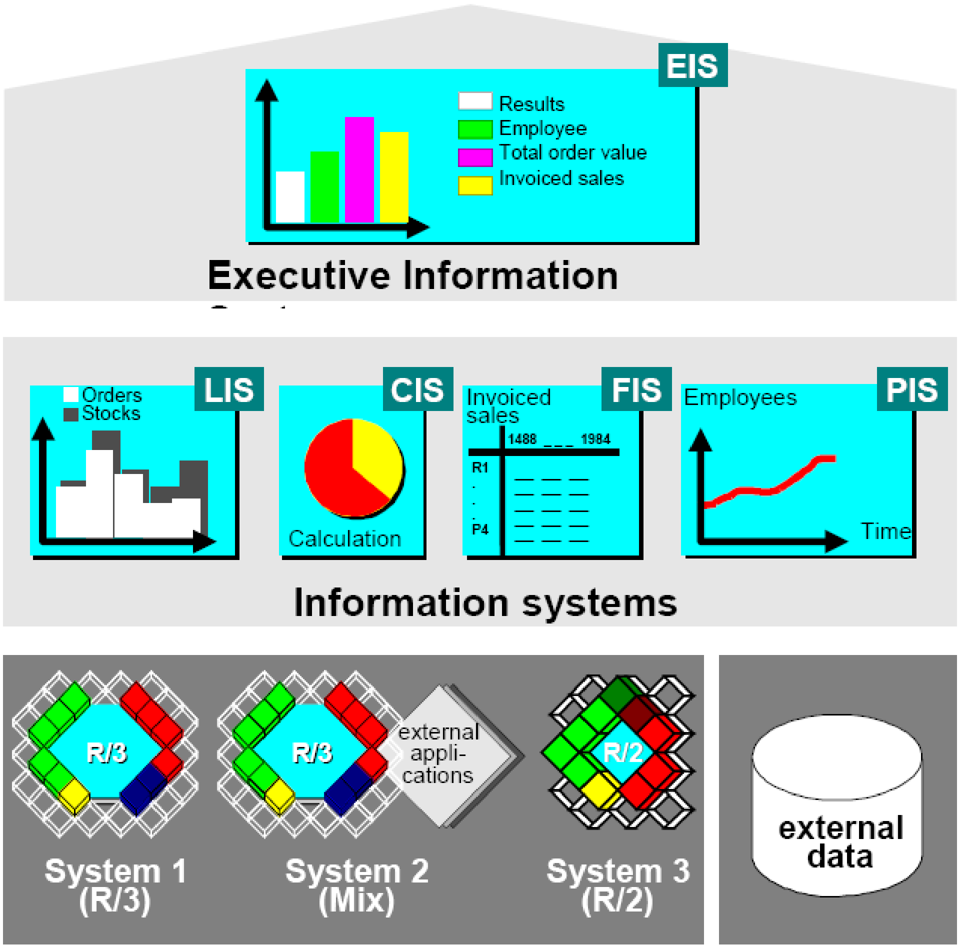


Figure 1-2: General structure of logistics information systems (SAP, 2001)

Today the growing complexity and requirements of logistics applications are making the logistics practices more and more reliant on information systems. There is a lot of research work regarding the various aspects of the information system itself, such as functions/algorithms, components, data structures and interfaces. Most of the information system research is based on the assumption that the required information is already available from various ideal data sources. However, little has been done in how the lower level systems that provide those data sources should be organized to support such information systems. As shown in Figure 1-2, the lower level operative systems under the information systems level provide the upper level Information Systems (IS) with operation data input; they are generally composed of the hybrid data sources and their network, such as sensors, RFID and WSNs. As those technologies have duplicated structures at this level of systems, this thesis investigates the integration and organization of them and focuses on developing a framework of the network level architecture design of a hybrid RFID sensor network in the operative system level to provide an easy-to-implement, cost-effective, robust and complete on-site resource management applications in logistics centres. The system components at the higher level infrastructure, such as data post-processing and localization algorithms, are not concerned in this research.

Sensors, RFID and WSNs

Environmental sensors are the basic data sources for logistics information systems, and the wireless sensor network (WSN), which is one of the focusing topics on monitoring and control, is the most promising technology to connect and organize the sensor nodes. The WSNs together with Radio Frequency Identification (RFID), which includes passive and active systems and is expected to be the most popular Auto-ID technology in the near future, are two fast-growing technologies that have shown great potential in future logistics management applications. However, a hybrid information system for logistics applications is always expected to answer four questions: Who, What, When and Where (4Ws), and neither of the two technologies is able to provide complete information for all of them.

WSNs aim to provide environment monitoring and control regarded as ‘When’ and ‘What’, while RFID focuses on automatic identification of various objects and provides ‘Who’ (ID). Most people usually think RFID can provide ‘Where’ all the time. But what normal passive RFID does is to tell us where an object was the last time it went through a reader, and normal active RFID only tells whether an object is on site. This could sometimes be insufficient for certain applications that require more accurate location awareness. In this case, a system with real-time localization (RTLS), which is an extended concept of RFID, will be necessary to answer ‘Where’ constantly. As WSN and various RFID technologies provide information for different but complementary parts of the 4Ws, a hybrid and integrated system that gives a complete answer by combining all of them could be promising in future logistics management applications. An Integrated RFID Sensor Network is the choice to achieve more efficient resource management systems and supply chains.

Unfortunately, in the last decade those technologies have been emerging and developing independently, with little research being done in how they could be integrated, which is what I investigate in this thesis. The research in this thesis focuses on the network-level architecture designs of a hybrid system that integrates sensors, WSNs and various RFID technologies. The various architectures proposed in this thesis are designed to address different levels of requirements in the hierarchy of needs, which will be introduced in Section 1.5, from single integration of legacy systems to a highly hybrid system with real-time localization.

1.3 Research Challenges

The research in this thesis investigates the development of a framework for the network-level architecture design of hybrid system that integrates sensors, WSNs and various RFID technologies, including the technologies for Real-time Localization System (RTLS) which is considered as a type of more complex and advanced RFID system. Integrating those technologies with WSNs presents a challenge, because WSNs are usually used in special applications where extensive system flexibility is required and because the system is usually resource limited and as such may not have sufficient resources available to implement the same architectures or mechanisms as used in other existing technologies. WSNs are usually low power and low data rate networks with some of its network nodes even relying on very limited on-board battery power. Thus while integrating various new components into the system architecture and designing certain operation mechanisms, issues such as maintaining power efficiency and reducing network traffic load have to be taken into consideration. For example the WSNs may not be able to afford keeping some of the devices always on or having transmission too frequently, and also they may not have the power resource or communication resource to support traditional tracking/localizing mechanisms. In addition, the WSN technologies and standards, such as ZigBee standard as used in this thesis, also introduce various network operation restrictions that could further prevent the architecture and mechanisms being adopted directly from other technologies.

1.4 Research Objectives

The aim of this research is to design, develop, implement and evaluate in complex hybrid logistics applications an integrated RFID Sensor Network, in which various types of RFID systems and the wireless sensor networks can be integrated in a unified architecture. The expected outcome of this effort is to propose a general methodology (framework) for designing RFID Sensor Network systems, which can bring integrated, more valuable and more accurate real-time information for logistics management using a low cost and easy to implement system, and thus increase the efficiency and reduce the cost in managing resources in the supply chain. The aim of this research will be satisfied by the following objectives:

- Investigate relevant literatures to obtain a complete understanding of the topic, and on how Radio Frequency Identification, sensors and Wireless Sensor Networks can be combined in different levels.

- Design a RFID sensor network architecture for integration of existing sensor networks and legacy RFID systems for logistics centre resource management systems.

- Design an integrated and unified RFID sensor network architecture for integration of sensors, WSNs and various RFID technologies for new logistics centre resource management systems.

- Design an improved integrated RFID sensor network architecture for the logistics centre resource management systems with a higher level requirement by adding an integral Real-Time Locating System/Service (RTLS) for inventory tracking.

- Design an improved integrated RFID sensor network architecture for the logistics centre resource management systems with the top level requirement by adding an integrant Real-Time Locating System/Service (RTLS) for high-mobility target tracking.

- Develop hybrid RFID sensor network testing/demonstration systems based on the architectures designed.

1.5 Research Methodology

The first stage of research work, which is the concept development stage, consists of an extensive literature review. As part of the literature review, the related work on how Radio Frequency Identification, sensors and Wireless Sensor Networks can be combined in different levels were investigated and analysed to provide a better and complete understanding of the topic and to assist the design of our integrated architectures. Moreover, a thorough review of the existing indoor RTLS technologies was undertaken. The review allowed the existing knowledge on indoor localization technologies to be applied to WSNs based systems to identify the appropriate methods for indoor WSN localization, to identify the issues and challenges of applying such methods in ZigBee based WSN backbones, and to assist in the development of the research objectives.

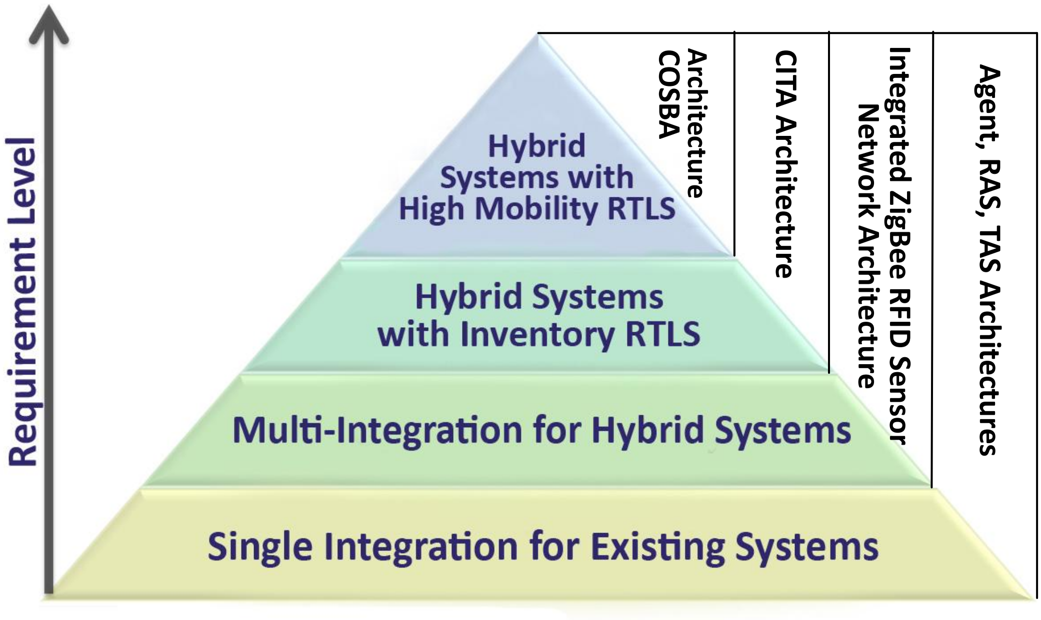


Figure 1-3: Application requirement hierarchy and corresponding architectures

The second stage is the system design stage, in which several system architectures were designed to address different levels of requirements in the hierarchy of needs, from single integration for existing systems to highly integrated architecture for hybrid systems with real-time localization service. The hierarchy of requirements, which is shown in Figure 1-3, is defined by dividing the requirements that I have identified at our review stage into different levels. In order to achieve a unified architecture design framework at the end, the architecture design starts from bottom to top, with each architecture in the research proposed as an improved design over the previous one to address a higher level of needs in the hierarchy of requirements. More specifically, this means each new architecture designed for a higher level of requirements will:

- retain all the features and functionalities of the previous architectures designed for the lower requirement levels;
- add new features or functionalities with the least additional hardware and network cost based on the additional higher level requirements;
- be the optimized solution only for its corresponding level of requirements in the hierarchy of needs;

All the architectures together with their corresponding application requirements in the requirement hierarchy form a framework of RFID Sensor Network architecture design, in which the system engineers can choose the appropriate architecture for their systems based on the scenario and requirements of their specific applications.

The third stage is the validation and evaluation stage, which is actually carried out simultaneously with the second stage. The evaluations of the architecture designs in this research may require the use of both qualitative and quantitative approaches. I have developed a RFID Sensor Network demonstration platform and the technical feasibility of each architecture was validated through hardware realization and actual implementation. The features of the architectures were evaluated in both laboratory environment and warehouse field trials. The validation and evaluation of certain performance benchmarks in our architecture design were accomplished using quantitative approaches such as mathematical justification, computer simulations and experiments figures.

1.6 Contributions of the Research

This thesis aims to develop a framework for the network level architecture design of such hybrid system for on-site resource management applications in logistics centres. The various architectures proposed in this thesis are designed to address different levels of requirements in the hierarchy of needs, from single integration to hybrid system with real-time localization. The contribution of this thesis consists of six parts.

Firstly, two new concepts, “Reader as a sensor” and ”Tag as a sensor”, and their corresponding RAS and TAS architectures for single integrations of RFID and WSN; Secondly, a ZigBee RFID Sensor Network Architecture for hybrid applications; Thirdly, a Connectionless Inventory Tracking Architecture (CITA) and its battery consumption model adding indoor location awareness for inventory tracking in the Integrated ZigBee RFID Sensor Networks; Fourthly, a Connectionless Stochastic Reference Beacon Architecture (COSBA) adding location awareness for high mobility target tracking in the Integrated ZigBee RFID Sensor Networks; Fifthly, improving connectionless stochastic beacon transmission performance with two proposed beacon transmission models, the Fully Stochastic Reference Beacon (FSRB) model and the Time Slotted Stochastic Reference Beacon (TSSRB) model; Sixthly, a case study of the proposed main architecture in Humanitarian Logistics Centres (HLCs). A case study of using the hybrid ZigBee RFID Sensor Network for the real-time tracking of near-miss on construction sites is also available and can be found in our published work (Wu and Yang, 2010) to demonstrate the feasibility of extending our research to a wide range of applications.

1.7 Organization of the Thesis

The structure of this thesis is as follows: Chapter 2 reviews the development of WSN technologies, typical RFID technologies and the current research related to the integration of both RFID and WSN. Chapter 3 provides a thorough review on the existing state of research into the indoor Real-Time Localization System (RTLS) technologies, which I will be aiming to support in the late stage of our research.

Chapter 4 investigates the ZigBee compatibility with all the typical RFID devices, which leads to the design of 3 architectures for single integration into existing systems in different scenarios. Chapter 5 further discusses the features of various single integration architectures, and propose the Integrated ZigBee RFID Sensor Network Architecture for hybrid systems. Chapter 6 introduces a connectionless tracking architecture CITA with tracking mechanism to provide location awareness for the on-site inventory. The key parameters in the tracking mechanism are analyzed with a practical method for choosing the proper values for optimized network performance which is given at the end in a mathematical form. Chapter 7 introduces a connectionless stochastic reference beacon architecture COSBA as an improved design to support high mobility targets localization, which is on the top level of the requirement hierarchy. Additionally, a simulation in Matlab is shown as an evaluation contrasting the proposed architecture against the previous one in terms of network traffic load performance. Chapter 8 investigates in detail the mathematical models of the beacon generating mechanism in the COSBA architecture, focusing on developing the model that can maximize the successful receiving rate of beacon messages at the target nodes. Chapter 9 provides a case study of ZigBee RFID Sensor Networks in Humanitarian Logistics Centres. Chapter 10 concludes the thesis with a summary of the main contributions of the research as well as the areas for future research.

Chapter 2 RFID and Its Integration with Sensors and WSNs

In addition to the brief introduction of RFID in Chapter 1, I here present some more details of the RFID technologies that are essential or helpful for understanding the contents in the rest of this thesis. After that an introduction of IEEE802.15.4 and ZigBee technology is given for the same reason. The state of the art of research related to the integration of RFID, sensors and WSNs is reviewed. I divide the research works into three main categories which are the hardware level integration, logic level integration and the network level integration. The RFID and WSN integrations described in this chapter do not include location tracking technologies. A detailed review of real-time localization technologies will be presented in the following chapter.

2.1 RFID

Radio Frequency Identification is a group of technologies that use radio frequency to automatically transmit target identity. Various types of RFID technologies are designed for different logistics applications. As introduced in Chapter 2, the main differences among those different RFID technologies are the tag power resource and radio communication method between tags and readers. However, the principle architecture of those RFID technologies remains similar. Figure 2-1 shows the typical RFID system architecture which includes three different local layers, which are the tag layer, the reader layer and the local server layer, and a top level enterprise integration layer that can be placed either locally or remotely. The local server layer is sometimes also referred as the interface layer, as it handles the data interchange between top level integration layer and the local hardware layers.

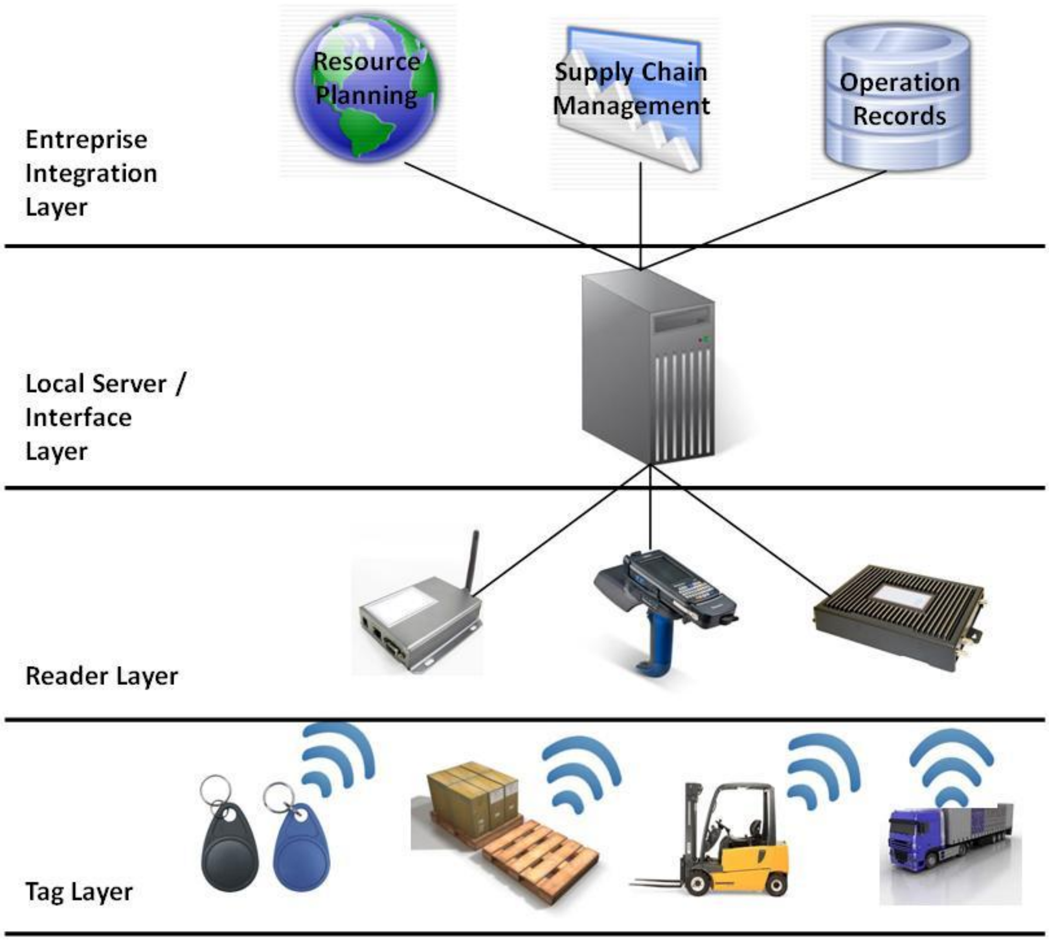


Figure 2-1 Typical RFID system architecture

2.1.1 RFID Tag

The purpose of a RFID tag is to physically store and attach data about an item onto itself. The tags also have the ability to communicate those data so that it can be read out. There are generally 3 types of RFID tags depending on the power source used, which are the active, passive and semi-passive/semi-active tags.

2.1.1.1 Active RFID Tags

The **active tags** have onboard transmitters and a battery as their power resource; they transmit their ID codes through general RF transmitters, thus can have a wide reading range. Active tags usually work on 455 MHz, 2.45 GHz, or 5.8 GHz, and they typically have a read range of 20 meters to 100 meters. Because of their ability of tracking objects over a long distance they are usually used to track large assets, such as containers, vehicles and aircraft.

There are two types of active RFID tags, which are transponders and beacons. Active transponders do not send information spontaneously; they are woken up from sleep mode only when a signal from a reader device is received, then the tag ID is transmitted to the reader. These tags are usually used in checkpoint control systems. The aim of having a tag broadcast its information only when it is within the range of a reader is to conserve battery life. Beacons are used in most Real-Time Locating Systems (RTLS), with which the precise location of an asset can be tracked. Beacons broadcast their tag information periodically, where the pre-set broadcasting interval can be varied from a second to several hours depending on the requirements of different applications. In a RTLS system the tag signal will be received by at least three reader antennas within the tracking area, and its location can then be calculated based on the signal power received at the antennas. Beacons tags are usually used in the outdoor distribution yard and automobile product lines. Both active transponders and beacons can have a read range of up to 100 meters, reading of tags are reliable as they use onboard transmitters to send signal. The cost of an active tag typically ranges from £5 to £30.

2.1.1.2 Passive RFID Tags

The **passive tags** do not have own power resource and onboard RF transmitter, they use inductive/propagation coupling to connect with the reader antenna, which means that the passive tags just simply reflect back the signal emitted by the reader. As a result the passive tags are simple and small and thus are cheaper, which can be 10 to 20 pence, and more reliable under harsh environment conditions, but compared to active tags they can only achieve a much shorter reading range of 0.1 to 9 metres. Tags cannot transmit information without the presence of a reader, and for their communication there is only one way, where the reader inquiries first, then the tags respond.

Frequency Band

As the passive tags, which consists only a microchip and an antenna, are very simple and small, they can be packaged in various ways. They can be put in a plastic card, a key fob, or between a paper and an adhesive layer, which is known as the smart label. Passive tags usually work on 124 kHz, 125 kHz and 135 kHz in LF band, 13.56 MHz in HF band or 860 MHz to 960 MHz in UHF band. The legal frequency bands that RFID can use are not the same in different regions in the world; it has to comply with the frequency regulations in each country.

The operating frequency of an RFID system needs to be chosen depending on its requirement, as radio waves behave differently in different frequency bands. Radio waves at low frequencies are able to penetrate most materials include liquids and can operate well in the presence of metals. As the frequency increases the radio waves begin to behave like light, they become easier to be absorbed by materials and tend to bounce off many object surfaces. Frequencies between 30 KHz and 300 KHz are known as the low Frequencies (LF). The tag-reader data transfer rates are low in this band but they are good in the operating environment containing metals and liquids. Radio waves in High Frequency (HF) band are from 3 MHz to 30 MHz; they still offer fair performance in the presence of metals and liquids, and are used in various applications where they do not interfere with the current equipment. When it comes to Ultra High Frequencies (UHF), which is from 200 MHz to 1 GHz, high data rates between tag and reader can be achieved but the performance in the environment with metals and liquids becomes poor.

However, UHF passive RFID tags are still developing and spreading fast in logistics applications because of some recent mandates of several large enterprises and governmental departments, such as Wal-Mart (Barlas, 2003) and the US Department of Defense (US DoD, 2004). The reasons UHF tags are chosen in the supply chain applications rather than HF and LF tags are the tag cost and the read range. Vendors in the UHF market have offered simple, low cost tags. In the other hand the end users need to read tags from at least 3 meters for RFID to make it useful in a warehouse as there is no way to read a tag on a pallet going through a dock door from less than this distance and also the reader may interfere with the normal operation of forklifts and other equipment at closer distance. LF tags can usually be read from within 0.3 metre and HF tags can be read within 1 metre, while UHF tags can be read from 3 metres to 9 metres.

Coupling

The passive tags do not have on-board battery. They need to gather energy from the reader antenna to power their circuit and should communicate with the reader in a different way called ‘coupling’ as they do not have RF transmitter like the active tags. There are currently four coupling mechanisms, which are backscatter/propagation coupling, inductive coupling, magnetic coupling and capacitive coupling. Magnetic and capacity couplings are close couplings (within 1cm) which are mainly used for smart cards applications (ISO 10536). Inductive coupling is a common type of remote coupling (1cm to 1m) used by the LF and HF band passive tags. An inductively coupled reader uses a coil antenna to generate a magnetic field, which can drive current in the tag’s coil antenna just like a transformer does between its coils. The tag can thus be powered by the current and communicate with the reader. The backscatter coupling is the most popular coupling mechanism used by the UHF EPC tags in supply chain management. A backscatter coupled tag antenna reflects back the RF waves emitted by the reader to send a signal. The tag antenna also conducts some of the energy from the RF power for a small chip, which is able to change the load on tag antenna in order to perform a load-modulated ASK in the backscattered signal. The characteristic of such type of tags is that they reflect the same frequency that the reader used to power and communicate with them, which means the reader and the tags have to take turns to 'talk' in a half-duplex communication mode. The advantage of using backscatter is that the coupling distance can be up to 9 metres, which is known as the long-range coupling/reading.

2.1.1.3 Semi-active tags

Semi-active tags, which are also called semi-passive tags or battery-assisted tags, are also available now in market for specific applications (Power ID, 2003). These semi-active tags contain batteries that are used only to support the embedded memories and sensors. For the communication between reader and tags, the same methods with the passive tags are used, which means the tags generate energy from the reader antenna and reflect a signal back to it. Like the passive tags the communication starts always by the reader's enquiry, and then the tags respond. As the passive tag antennas need to perform two tasks, which are to gather energy to operate the tag and to transmit data, the design of the antennas needs to balance the performance between the two different aspects. Semi-active tags have their own battery for tag operation, thus the antenna design can focus on data transmission. As a result they can be read at even longer distance up to 30 metres, and the performance in the presence of metals and liquids is much better than the passive ones. Semi-active tags do not need time to gather energy and excite the tag chip so faster reading speed can also be another advantage of semi-active tags, which means they can work better to track fast moving objects.

A brief comparison is given in Table 2-1 for the three systems.

Table 2-1. Brief comparison of different RFID tags (Yang and Yang, 2007)

	Passive tag	Semi-active tag	Active tag
Own power for data transmission	No	No	Yes
Own power for chip	No	Yes	Yes
Communication with readers	Backscatter	Backscatter	RF tansmit
Read range	short	medium	long
Tag cost	low	medium	high

2.1.2 Reader

No matter which type of tags is used, they are just storing the data of the item on which they are attached. In real applications data needs to be read out and transferred to a server or a network on demand to be useful. A reader, also called an interrogator, is the device that knows how to communicate with the tags, how to perform the low level events, such as reading from and writing into the tags, and how to send the results of those events to the server or network at a higher level. A reader can be a stationary or a handheld device; the typical components of a RFID reader include antenna, RF transceiver, microcontroller, communication interface, and power supply.

The reader communicates with the RFID tags through its antennas. An antenna could be either an integrated part inside the reader, or a separated part that physically linked to a reader to its antenna port via SMA Cable. A reader should have at least one antenna to perform its task, though two or more antennas may be operated by a single reader. The factor that limits the number of a reader's antennae is the signal loss on the cable that connects it to the reader. Currently the reader can identify the signal from an antenna via a SMA Cable of up to 3 metres.

An RF transceiver is responsible for transmitting reader signal to the surrounding area and receiving tag response via the reader antennas (Lahiri, 2006). The transceiver has two basic parts which are the transmitter and the receiver. The transmitter is used to transmit AC power (semi-active/passive systems only), clock cycle and the interrogation information, while the receiver is used to demodulate the signal sent back from the tags and transfer it to the microcontroller.

The microcontroller is responsible for decoding and error checking the demodulated signal from the RF receiver. It should then process the received tag information and act as a low level-event filter which determines whether an event has been constituted and should be sent to the upper level server/network. The microcontroller should be able to handle the tag protocol as well as the reader protocol.

The communication interfaces of a reader allow it to send event information to the upper level entities, such as a server or a network. Serial interfaces such as RS-232, RS-422, RS-485 and even Universal Serial Bus (USB) interfaces are standard components for most of the reader devices. The advantage of the serial interface is that they are reliable and standardized. However, the data rate is relatively low, the number of devices linked to a single host is limited and dependent on the length of cable used, and the distance between a reader and the computer is restricted to the maximum cable length. Thus more and more readers start to support network interfaces such as Ethernet and even wireless Ethernet or Bluetooth. The network readers are more mobile, flexible and easy to implement especially in the massive deployments.

A Power supply is also an essential part of a reader. Commercial reader products can have some other additional parts, such as an input/output port for an external annunciator, sensor and memory, to enhance the reader performance.

2.1.3 Middleware

The RFID middleware is logically situated between the RFID hardware infrastructures and the real business applications. It usually operates on the server that connects to the RFID readers or the RFID reader network. The middleware directly communicates and controls the reader devices and prepares the event information in standardized format for the business applications at the higher level. The logical architecture and the implementation of the RFID middleware are defined in EPC Application Level Events specification (ALE). Various commercial RFID middleware products compatible to EPC ALE are available in the market. The main tasks for the RFID middleware include:

- Communicating and handling RFID reader devices. As different types of RFID readers may be used in one application, the first task of a middleware is to provide reader interfaces to eliminate the confusion of various reader APIs and avoid duplicated development for each reader type, so that a uniformed abstract interface can be provided for applications.

- Providing a middle level event filter. Multiple read cycles are required in almost all RFID management events due to limited reading accuracy. As the detailed read cycle level results contain high-volume data and are not interesting and meaningful to the user applications, the middleware should process the raw data received from the reader devices and provide the applications with more concise and comprehensive results at event level.

- Providing standard application level API. Event level information is send via a standardized interface in the way of a service to the higher level applications. Interfaces in C/C++, JAVA, .NET or Web service are the typical APIs which make the information provided more semantic and simplify the development of business applications.

- Providing data storage. Middleware may also contain a backend database to store the tag information, but this is optional as tag information can also be store at the application level.

2.1.4 RFID Protocols

Tag protocols

The RFID tag protocols describe the general conformance requirements of RF tag and reader devices, they also define the air interface and the RF data protocol used for communication between the reader systems and the RF transponders. The data storage format in the tags, the anti-collision procedures and the security and privacy features for the tags are also concerned.

Table 2-2. EPC tag classes (Jackson, 2004)

<table>
<tr><th>EPC Class</th><th>Definition</th><th>Programming ability</th></tr>
<tr><td>Gen 1-Class 0</td><td>"Read Only" passive tags</td><td>Programmed as part of the semiconductor manufacturing process</td></tr>
<tr><td>Gen1-Class0+</td><td>"Write-Once, Read-Many" version of EPC Class 0</td><td>Programmed by customer then locked</td></tr>
<tr><td>Gen 1-Class 1</td><td>"Write-Once, Read-Many" passive tags</td><td>Programmed by customer then locked</td></tr>
<tr><td>Gen 2-Class 1</td><td>"Write-Once, Read-Many" passive tags. UHF Gen2 protocol ratified by EPCglobal on Dec. 16, 2004</td><td>Programmed by customer then locked</td></tr>
<tr><td>Class 2</td><td>Rewritable passive tags</td><td rowspan="3">Can be reprogrammed many times</td></tr>
<tr><td>Class 3</td><td>Semi-passive tags</td></tr>
<tr><td>Class 4</td><td>Active tags</td></tr>
<tr><td>Class 5</td><td>Readers</td><td>N/A</td></tr>
</table>

The EPCglobal tag specification classifies the RFID tags into 6 classes from the simplest class 0 passive read-only tag to the most complex class 5 active tags which have the ability of powering and reading other tags. The classification is shown in Table 2-2. However, the specification defines only the air interfaces for UHF class 0 and class 1 tags. ISO 18000 family is another suit of standards concerning the RFID tag air interfaces. The ISO standards are more complete in frequency band coverage as they specified the air interfaces for RFID tags in all frequency bands and in most EPC classes. Details of ISO standards can be found in Section 2.1.5 RFID standards.

Reader protocols

The RFID Reader protocols are used to define the data exchange between the host computer/controller and the reader device. Typical reader protocols describe the format of messages exchanged between the host and the reader, specify how the host could discover, address, configure and control the reader device to write and read from the RFID tags. Each RFID manufacturer has its own reader protocol. Those protocols are all similar, but not similar enough to make them be able to interoperate. EPCglobal has recently published a reader protocol standard which describes itself in three layers: reader layer, messaging layer and transport layer (EPCglobal, 2006). The reader layer is the heart of the reader protocol, which specifies not only the content and abstract syntax of messages exchanged between the reader and host, but also the operations that Readers perform and what they mean. The messaging layer specifies how messages defined in the Reader Layer are formatted, framed, transformed, and carried on a specific network transport. The transport layer corresponds to the networking facilities provided by the reader OS.

2.1.5 RFID Standards

There are mainly two competitive RFID standards in the world; they are the ISO RFID standards and EPCglobal standards.

2.1.5.1 ISO RFID Standards

ISO has been working on RFID standards for decades and has published a number of RFID related standards. They can be divided in two parts: the general standards and the application standards. The general standards provide basic models and architectures to which the application standards specify the details and supplements depend on various applications.

General standards

ISO 15961 and ISO 15962 specify the data protocol used to exchange information in radio-frequency identification (RFID) system for item management, each of them focuses on one particular interface. ISO 15961 addresses the information interface with the application system while ISO 15962 deals with the processing of data and its presentation to the RF tag, and the initial processing of data captured from the RF tag. ISO 15963 describes numbering systems available for the identification of RF tags.

The ISO 18000 standard family is a set of proposed RFID specifications for item management that could be ratified as standards during 2004. The family includes different specifications that cover all popular frequencies like 135 KHz, 13.56 MHz, 860-930 MHz and 2.45GHz. The standards deal only with the air interface protocols between the reader device and tags, but not the data structure.

- 18000-1: Generic parameters for air interface communication for globally accepted frequencies
- 18000-2: Parameters for Air Interface Communication below 135 KHz (LF)
- 18000-3: Parameters for Air Interface Communication at 13.56 MHz (HF)
- 18000-4: Parameters for Air Interface Communication at 2.45 GHz (UHF)
- 18000-5: Parameters for Air Interface Communication at 5.8 GHz (Microwave)
- 18000-6: Parameters for Air Interface Communication at 860/930 MHz (UHF)
- 18000-7: Parameters for Air Interface Communication at 433.92 MHz (DoD)

ISO 18046 and ISO 18047 are test method standards. ISO 18046 provides test method guidelines for performance characteristics of radio frequency identification (RFID) devices (tags and interrogation equipment) for item management, and specifies the general requirements and test requirements for tag and interrogator performance which are applicable to the selection of the devices for an application. 18047 defines the RFID device conformance test methods, in which the different Part 1 to 7 provide test methods for conformance with the frequencies in 18000 1 to 7 respectively.

Application standards for supply chain management

Based on the ISO general standards which deal with data encoding and interface protocols, the ISO application standards define the application constrains, tag dimension, tag position, data content and format and frequency used for various applications. The ISO RFID standards for supply chain management include:

• ISO 17358 - Application Requirements, including Hierarchical Data Mapping
• ISO 17363 - Supply chain applications of RFID -- Freight containers
• ISO 17364 - Supply chain applications of RFID -- Returnable Transport Items
• ISO 17365 - Supply chain applications of RFID -- Transport Units
• ISO 17366 - Supply chain applications of RFID -- Product Packaging
• ISO 17367 - Supply chain applications of RFID -- Product Tagging (DoD)
• ISO 10374.2 - RFID Freight Container Identification
• ISO 14816 - Road transport and traffic telematics, Automatic vehicle and equipment identification -- Numbering and data structure

The structure of the ISO RFID standards family located in the different tracking levels of logistics units can be described in Table 2-3:

Table 2-3. Structure of ISO RFID standard family

ISO Standard	Tracking level
ISO 14816	Movement Vehicle (Cargo Plane, Ship, train and truck)
ISO 10374 ISO 18185 ISO 14816 ISO 17363	Container level
ISO 17364	Pallets level
ISO 17365	Transport unit level
ISO 17366	Package level
ISO 17367	Item level

2.1.5.2 EPCglobal Standards

EPC is the abbreviation for Electronic Product Code proposed by the Auto-ID centre at MIT, who has been driving towards development of a standard specification for item level tagging in the consumer goods industry. This has led to a new group called EPCglobal, a not-for-profit joint venture set up by the Uniform Code Council and EAN International, the bar code standards body in Europe. EPCglobal is an umbrella organization overseeing local chapters that will work with companies to encourage the adoption of EPC technologies. It issues EPC codes to companies that subscribe to its service.

ISO has created many RFID standards which deal with both the air-interface protocol and applications for RFID. But EPC not deals only with how tags and readers communicate, but also wants to create network standards to govern how EPC data is shared among companies and other organizations. The EPCglobal standard architecture, which is known as the EPC network, is shown in Figure 2-2. Besides tag data format, air interface for reader-tag communication and reader protocols for the communication between readers and applications, the EPC network also provides EPCIS and ONS services in their architecture.

EPCIS (the Electronic Product Code Information Service) is a specification for a standard interface for accessing EPC-related information. It provides a standard interface for the supply-chain partners and enables them to share and exchange information efficiently. The result is that all involved partners can use the same interface to exchange information, no matter what database type they are using for storing that data. This simplified the integration process between the supply chain partners.

The Object Name Service (ONS) works in a similar way to the Domain Name System (DNS) in the Internet. When a reader device reads an RFID tag, the Electronic

Product Code is passed to middleware, which, in turn, goes to an ONS on a local network or the Internet to find where information on the product is stored. ONS points the middleware to a server where a file about that product is stored. The middleware retrieves the file (after proper authentication), and the information about the product in the file can be forwarded to a company's inventory or supply chain applications.

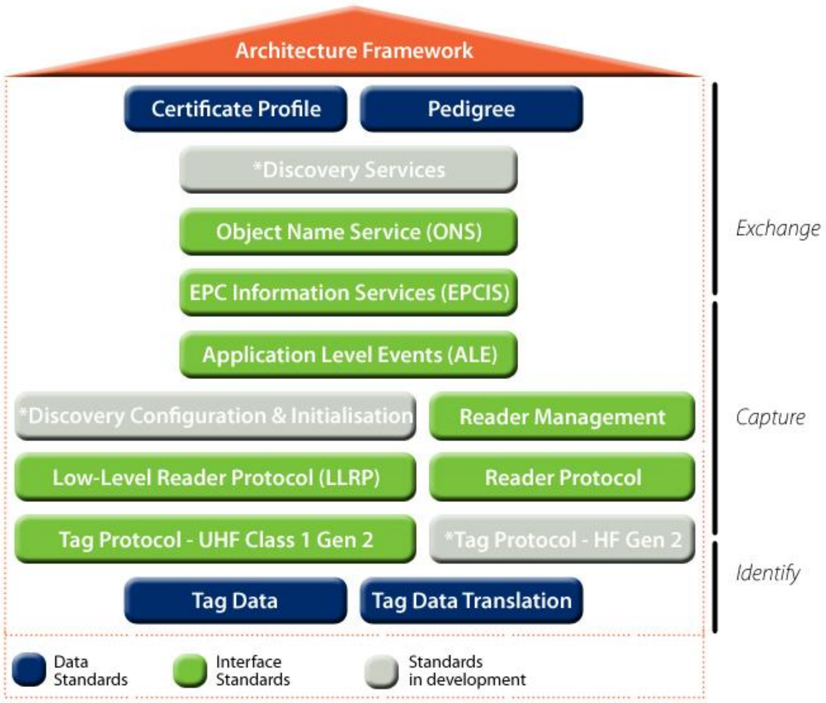


Figure 2-2: EPC standards overview (Thiesse and Michahelles, 2006)

Currently, the two largest drivers for RFID today, which are Wal-Mart and the US Department of Defense (DoD), have different views in choosing standards for their mandates. Wal-Mart has decided to use the EPC standard, while the DoD wants to use the EPC for general purpose applications and use the ISO 18000-7 for air interface (US DoD, 2007). Although the EPC standard also includes air interface specifications, they are not interoperable with the ISO 18000 standards. In 2006 ISO has accepted the EPCglobal Class I Gen2 tag specification to be the ISO 18000-6C standard, which started to unify the air interface standards from the most important UHF passive tags.

2.2 WSN and ZigBee/IEEE802.15.4

2.2.1 Low-Rate Wireless Personal Area Network (LR-WPAN)

In the past decade, the need for low cost, low data rate and battery powered network applications has encouraged further research into the development of the Low-Rate Wireless Personal Area Network (LR-WPAN). WSNs are usually considered to be one of the forms of the LR-WPAN. For the general local wireless networks, the most widely researched and used standards include Bluetooth and WiFi.

Bluetooth is one of the most wide adopted LR-WPAN standards in practice. It defines a wireless, frequency hopping communication standard the forms short-range ad-hoc networks. It has been very popular on mobile phones, headsets, PDAs, laptops, and in-car systems to support the short range plug-and-play applications such as transferring pictures, music, files and GPS data. However, Bluetooth technology targets the short term plug-and-play applications and thus is not designed to be a power efficient standard, with the devices running Bluetooth protocol consuming a considerable amount of energy. As a result, it is not able to support most of the WSN applications that requires real-time and long-term monitoring. Moreover, a Bluetooth network has a very limited number of nodes, with only a maximum of one master node and seven slave nodes supported in one network it is far from enough for most WSN applications.

The WiFi standard is widely used in both private houses and commercial buildings for providing wireless computer network access for personal computing devices such as laptops, PDAs, and smart phones. Similar to the problem of Bluetooth for WSN applications, WiFi technology also suffers limited connectivity and high device power consumption. Furthermore, WiFi is not a pure wireless network as the network backbone, which consists of a number of WiFi APs (Access Points), is actually a wired network. As a result, WiFi technology is not, in its current form, appropriate for

WSN applications.

Due to the drawbacks of Bluetooth and WiFi technologies, the IEEE (Institute of Electrical and Electronic Engineers) proposed IEEE 802.15.4 as a new LR-WPAN standard for WSNs, aiming to overcome the problems associated with the existing standards. After its initial release, it has had problems in network configuration for large scale wireless mesh networks. This results in the formation of the ZigBee Alliance from a consortium of semiconductor manufactures and technology provider around the world. The IEEE 802.15.4 standard defines the Physical and Medium Access Control (MAC) layers. The ZigBee standard adds a Network layer and an Application framework layer in order to enhance the functionality and ease of implementation.

2.2.2 IEEE 802.15.4 and ZigBee

The IEEE 802.15.4 standard defines the Physical and MAC layers for LR-WPANs. The Physical layer is responsible for characterising the Physical attributes and behaviours of LR-WPAN nodes. This includes turning hardware operation states, selecting RF channel, estimating the RF link quality (LQI), receiver energy detection, and clear channel assessment (CCA) for CSMA/CA operation in MAC layer. The RF communication at the Physical layer is supported in three licence-free ISM (Industrial, Scientific, and Medical) frequency bands including 2.4 GHz with 16 channels and a 250 kbps data rate, 902 to 928 MHz with 10 channels and a 40 kbps data rate and, 868 to 870 MHz with 1 channel and a 20 kbps data rate. The IEEE 802.15.4 standard supports a 64-bit long address and a 16-bit short address, theoretically resulting in a single network being able to support a maximum of 2^{16} nodes.

The MAC layer of IEEE 802.15.4 standard defines the basic transmission structure. It defines two types of devices, Full Function Devices (FFDs), and Reduced Function

Devices (RFDs). FFD incorporate all the MAC layer functions, including the ability to connect to any node in range and forward messages. This enables a FFD to act either as a network coordinator or as a common node. There is one and only one network coordinator in each IEEE802.15.4 network; it is responsible for sending beacons to the whole network for synchronisation, communication, and network join services. As a result of the absence of network layer in IEEE802.15.4 network, no routing service is supported and only the network coordinator forwards messages. The other common node FFDs can communicate only with their one-hop neighbours. This limits an IEEE802.15.4 network's topology to star or peer-to-peer network only. The RFDs have access to only limited MAC layer functions. They usually have on-board sensor and actuators for monitoring their respective environments. Once the RFD is ready to transmit sensed information, it may communicate with only one FFD. All devices on the LR-WPAN compete for access to the channel using a standard anti-collision protocol of Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA).

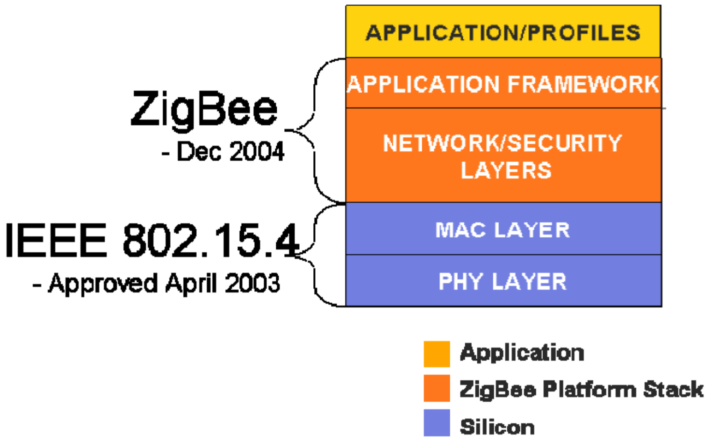


Figure 2-3 Network layers of IEEE802.15.4 and ZigBee

The ZigBee standard is implemented on top of the IEEE 802.15.4 Physical and MAC layers. Two more layers which are the Network and Application framework layers are added. The objective of the addition is to enhance the network organization ability and standardise the upper layers of the protocol stack.

The Network layer defines three device types, end device, router, and coordinator, that map on to the FFD and RFD specified by the IEEE 802.15.4 standard. ZigBee coordinators are FFDs and are responsible for managing the whole network. ZigBee routers are FFDs capable of providing message routing services; they are able to communicate with the end devices connecting to themselves and all the other routers. ZigBee end devices can be either RFDs or FFDs; they provide only the simple functions; they are usually equipped with onboard sensors and actuators and can only report to their own parent nodes which could be either a router or a coordinator. By introducing network router nodes, which enables the network layer to provide routing service and multi-hop communications, more complex topologies such as tree and mesh topologies are supported as depicted in Figure 2-3. In addition, the network layer also provides security service and more advanced management of nodes joining and leaving the network.

ZigBee is suitable for communication applications that require reliable and low data rate transmission within a relatively short range. The applications such as toy control, plant control, and home automation control all belong to this kind. ZigBee promises at most 250kbps data rate which is enough for simple control (normally 40kbps can be accepted by most home automation, environment monitoring and other similar applications (Tynheim, 2002)). Another key feature of the ZigBee standard is its powerful and simple network ability. The ZigBee can organize a network that can theoretically manage 65,535 network devices. The ZigBee stack can be used to route messages reliably and provide strong in-built security measures (Whittaker, 2005). Unlike other network communication technologies, ZigBee is a very low-power requirement technology. Two AAA batteries can support ZigBee device working for years (Kinney, 2003). Compared with WiFi and Bluetooth, ZigBee has many unique advantages in the low-data rate market.

As an innovative technology, ZigBee can be adopted to work in associate with many traditional applications. For example, currently garage doors are often controlled by infrared, which means users must send out the signal when they are in front of the door. Using ZigBee, when the user is within the range of ZigBee network (normally the peer-to-peer communication range of ZigBee is 100m outdoor) he/she can give out the signal to open the garage door and time is saved. ZigBee technology can help products network and improve remote management ability. In the information society, it is very interesting and considerable for manufacturers to engage the development of products based on ZigBee.

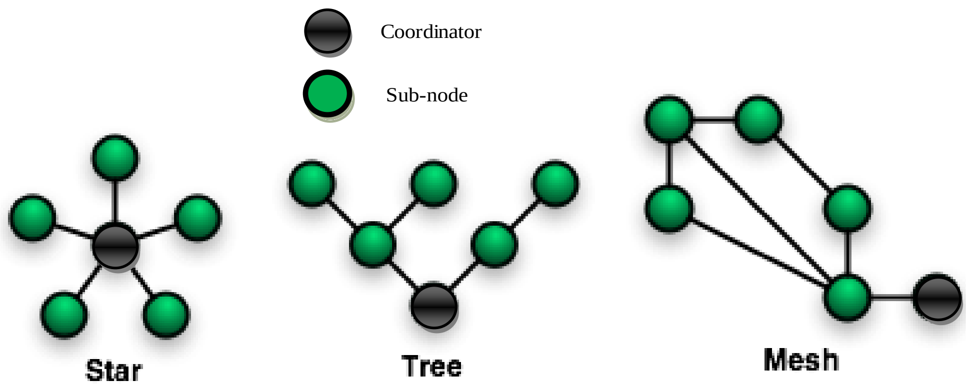


Figure 2-4: Network topologies: (a) Star, (b) Tree and (c) Mesh

Because the communication components are supported by IEEE 802.15.4, ZigBee can provide excellent peer-to-peer communication. The upper layer-network layer defined by the ZigBee specification gives ZigBee the ability to extend the range of the network. There are two basic and one advanced network topologies supported: star, tree and mesh. Star topology, as shown in Figure 2-4(a), is the simplest one. Each device communicates with a central device called the coordinator. The coordinator is responsible for receiving messages directly from sub-devices or relaying messages from one sub-device to another sub-device. The drawback is that if the coordinator fails, the whole network will fail. The tree topology, as shown in Figure 2-4(b), is like a reverse tree. The bottom node is the coordinator. Each node will have a parent node used to join the network. If one node wants to communicate with another node, it must first send the message to their common ancestor node and this ancestor node will relay the message to the destination node. The advantages of the tree topology are that it is easy to extend the network and the rule to route is easy to achieve. The drawbacks are more delay will be introduced if the range of the network is large. And those nodes, which have many sub-nodes, are the fatal nodes that will cause the same problem in star topology. In virtue of the network layer, ZigBee can support a mesh topology which is shown in Figure 2-4(c). Each node is equivalent in the network except the coordinator, which is still responsible for building and maintaining the network. Each node has the ability to relay messages according to the network layer and it is faster than in tree and star topologies, especially if the network covers a large area.

Our research in this thesis will be based on ZigBee technology, as it is currently the most standardised, accepted and widely used wireless sensor network standard in the world. More features of using ZigBee technology with RFID will be discussed in Chapter 4.

2.3 Related Work in Combining RFID with Sensors and WSNs

Generally, the RFID-enabled sensor networks can be used in the supply chain management to monitor two types of goods during their transportation and storage:
- Goods that are sensitive to environmental changes. These goods usually require specific environmental conditions during transportation and storage, for example temperature, humidity and vibration etc;
- Perishable goods and foodstuffs, such as fruits and vegetables, which have quality and value changes while moving in the supply chain.

Sensor-enabled RFID networks can also be used in production line management. Tagging some core component/assembly and recording their specifications would lead to quicker repairs or better maintenance. Tags should be writable, active and integrated with special sensors to meet the needs of feedback status (temperature, pressure, humidity, etc) of the object tagged (Lu et al., 2006). Such a network can also be responsible for the monitoring of manufacturing processes, tracking tagged components and the status of a product. Therefore, people can ensure that automated processes are kept synchronized and product quality is under control throughout the manufacturing processes (Collins, 2006).

Care of the elderly at home and patients' healthcare at hospitals are other possible applications for sensor enabled RFID systems (Consolvo, 2004). People will be able to use these systems to monitors patients' medication intake, to track patient position in real time and monitor their health condition (Ho et al., 2005).

There are also research and applications for RFID sensor networks in mass server maintenance, fire safety networks and real time location system. Most of these efforts are intended to identify objects or persons and also to determine their states as well.

There are a number of research avenues concerning the combination of the RFID system and the sensors or sensor networks. I classify those into three levels:

- Hardware level integration of RFID and sensors, which includes combining RFID transponders and sensor nodes by embedding them onto one board and combining sensors with RFID reader devices where sensors work with RFID reader devices to improve system performance or to enable new system functions;
- Logic Level Integration of RFID and sensor networks, where RFID networks are connected with either sensor devices or sensor networks to perform collaborated tasks, but the border between the two different networks is still clear at this level.
- Network Level Integration of RFID into Wireless Sensor Networks (WSNs), which studies how RFID networks and wireless sensor networks cooperate and work together at the network level; the border between the two networks starts to become blurred.

2.3.1 Hardware Level Integration - RFID and Sensors

2.3.1.1 RFID Sensor Tags/Nodes

The first stage for a RFID system to work with sensors is to embed simple sensors into the RFID transponders. Various types of sensors have been placed onto the RFID transponder boards to achieve the sensing capability for specific applications.

Active RFID sensor tag

Many active and semi-active / semi-passive tags have incorporated sensors into their design, allowing them to take sensor readings and transmit them to a reader at a later time (Consolvo, 2004). They are functionally less than sensor network nodes because they do not have the capacity to communicate with one another through a self-organized network, but they are functionally more than a simple RFID transponder. In this way, RFID is combined with the sensor technology. Special readers are required in these types of systems so that sensing information can be read at the same time while reading the unique ID from the RFID sensor tags. The hardware level integrations do not involve any concept of wireless sensor networks.

Passive RFID sensor tag

In (Nambi and Nyalamadugu, 2003) researchers tried to give passive RFID tags sensing ability by equipping them with a microcontroller and a temperature sensor. In their experiments the tags worked on 13.56 MHz in HF band, thus used inductive coupling to communicate with the reader and gathered energy from it to power the microcontroller and the sensor. The microcontroller then sent the sensing information to the reader via the communication channel between the tag and the reader by Amplitude Modulation. Although the authors were trying developing a microwave tag at 5.8 GHz with more types of sensors, it remains illustrative and the experiment they have done remains in HF band which is not a popular frequency band for logistics applications.

In (Philipose et al., 2005) researchers from Intel proposed another approach of integrating passive RFID tag and sensors. In their prototype two passive tags were attached to each object as well as an experimental sensor using mercury switches. A mercury switch is a switch whose purpose is to allow or interrupt the flow of electric current depending on the switch's physical direction or acceleration. A mercury switch consists of a sealed glass tube containing two unconnected electrodes on one end of the tube and a small amount of liquid mercury inside. As long as the liquid metal remains on the opposite end of the tube, the electrodes remain disconnected and the switch state is open. Once the tube is moved past a certain angle or is subject to acceleration parallel to the tube's direction, the mercury will pool between the two electrodes and a connection is made resulting in switch state changes to closed. Once the liquid mercury has returned to the other end of the tube the electrical current stops immediately and the switch state return to open. The mercury switch could be used as a tilt, rotation or acceleration sensor. In Philipose's prototype each passive tag is connected to a mercury switch which is used as a tilt and acceleration sensor, two tags and their switches are placed anti-parallel to one another. When the acceleration is positive the first switch open and the reader read the first tag ID; under negative acceleration, the second tag returns its ID. The purpose of the design is to detect the moving state of the items in use, the RFID tag antenna of the items in their rest position will be disconnected by the mercury switch so that they will not report to reader. The limitation of this work is that it is not a generalized design which means it focuses only on a certain type of sensor, the mercury switch, and is only suitable for specific applications. Since the design requires a passive RFID tag to present each state of the sensor reading, it is not practical for most of the environmental sensors with constant reading range used in logistics management applications.

In the recent years a UK company has announced the first commercial passive RFID sensor tag in the world (Collins, 2007). It works only under 13.56MHz HF band, which limits its reading range to up to 2 metres; and the cost is about 5 GBP per tag. Both the tag cost and its frequency band limit its application to only some special scenarios with a small deployment and reading scale.

Although these types of the RFID sensor tags have illustrated an important improvement in the RFID technology, their integration remains at the hardware level which means they are simply aiding limited functionalities to certain hardware components and do not involve any concept of sensor networks. Most of this work still has the problems of high tag cost, limited working frequency band and compatibility with international standards. None of the practical designs can work in UHF band with a reasonable tag cost which means they are not capable of being applied to the massive scale deployment in supply chain management applications, which is the biggest market of passive RFID technology.

RFID sensor nodes

A ZigBee end device with the following features can be defined as an RFID sensor node:

- With on board power resource such as the battery;
- With standard identity stored in the device;
- With standard wireless communication ability and is able to transmit its standard identity either to another sensor node or to a reader/gateway device;

The RFID sensor nodes are not necessarily attached with the real sensor devices if focusing on the node ability of handling wireless sensor network protocols and the ability of storing and transmitting its own standard identity.

IEEE 1451 standard family is the closest standard for RFID sensor nodes, which defines the identity, interface and data format of connecting smart transducers to networks (National Instruments, 2007). It is a planned set of standards for smart sensors that will make it easier and cheaper to deploy a wide variety of sensors.

- IEEE 1451.0 - This portion of the standard defines the structure of the TEDS (Transducer Electronic Data Sheets) the interface between .1 and .X, message exchange protocols and the command set for the transducers.
- IEEE 1451.1 - Specifies collecting and distributing information over a conventional IP network.
- IEEE 1451.2 - Wired transducer interface – 12 wire bus working on a revision which will put IEEE 1451 on RS- 232, RS-485 and USB.
- IEEE 1451.3 - This is the information to make multi-drop IEEE 1451 sensors work within a network.
- IEEE 1451.4 - This portion of the standard specifies the requirements for TEDS (Transducer Electronic Data Sheets). This is software only.
- IEEE 1451.5 - This section of the standard specifies information that will enable 1451 compliant sensors and devices to communicate wirelessly, eliminating the monetary and time costs of installing cables to acquisition points. The IEEE is currently working on three different standards, 802.11, Bluetooth and ZigBee.
- IEEE 1451.6 - This is the information required for the CAN (consolidated auto network) bus.

Currently, IEEE 1451.1 and IEEE 1451.4 have been published; IEEE 1451.3 has been approved and is awaiting publication and the IEEE 1451.2 is awaiting revision. The Transducer Electronic Data Sheet (TEDS) defined in the standard enables the self description of individual sensors and IEEE 1451.5 established the wireless interfaces and protocols for them to cooperate with microcontrollers. The problem of IEEE 1451 is that the sensor identity remains at the sensor type level, which means two sensors of the same type from the same manufacturer will have the same TEDS. This is similar to the current barcode identity system, thus adaptations have to be made before it can be used for RFID sensor nodes.

2.3.1.2 RFID Reader

Sensors can be also combined with RFID readers to improve their performance. There are two main purposes of using sensors on a reader device, one is to monitor the surrounding environmental conditions for the requirements of the tagged items, and the other is to control the reader itself based on some external event detected by the sensor. An example of the latter is to use motion sensors together with the RFID readers at a warehouse door, which is shown in Figure 2-5 (Mesarina, 2005). While a pallet is moving through the door the motion sensor will activate the readers to read the tags on the passing objects. This could make the reading more reliable and avoid unexpected readings when an asset is passing in front of the door within the reader's reading range but not entering the warehouse.

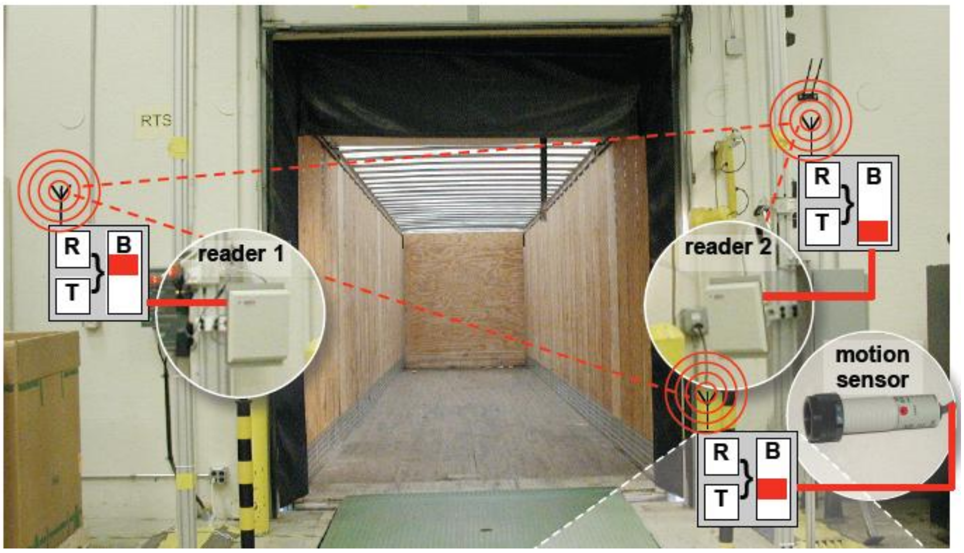


Figure 2-5: Readers with motion sensor (Mesarina, 2005)

Currently, some sensor nodes are now using RFID readers as part of their sensing capabilities. An example of a RFID reader designed to mate directly with the sensor nodes is the SkyeRead Mini M1 made by SkyeTek, which could read directly from the Crossbow Mica2Dot sensor motes (Ho et al., 2005; Crossbow Inc., 2006). The upper layers in this case will still remain as the typical RFID network architecture.

The idea of adding sensors to RFID tags and to RFID readers can both be considered as hardware integration. Such integration does not change the architecture of the RFID network which limits the flexibility of the system, and its implementation completely relies on hardware manufacturers. In this case I am also looking to integrate these two technologies at the logic level or network level, where the hardware integration of them is not essential.

2.3.2 Logic Level Integration – RFID and Sensor Networks

While integrating the two different technologies' network architecture, the idea to connect them directly to a single server and integrate them by software applications is quite straightforward. Bravo and Hervás have carried out an experiment in which sensor and RFID systems are integrated to support the visualization service in clinical sessions (Bravo et al., 2006). Two RFID readers and several sensors are connected directly to a computer which acts as the server. The readers are placed on the door and near the display screen in the session room; the former is used to offer services implicit in this technology such as location, access, presence, inventory, routing phone calls, etc., the latter is placed near the display screen so that the system could identify the doctor or nurse who is approaching the screen and that appropriate information prepared for his/her presentation could be displayed. The on-screen display could be changed depending on the presenter's hand actions which are caught by the sensors placed below the display. The system in this work is not really a RFID sensor network. It's easily integrated in very small and simple scenarios such as within an office or a meeting room, but using direct connections for larger applications, such as supply chains or manufacturing lines, will limit the scale of the scenario, and require a large number of interfaces on the server.

To solve the problem of limited server interface number Liu's inventory management system (Liu, 2007) uses the field bus to connect sensors and RFID readers to a central server. In the system, RFID technology is used to identify staff, freight and vehicles, while the sensors are responsible for providing information on environmental conditions such as temperature and humidity. All the readers and sensors are considered as information collectors and are connected to a local server via standard field bus. This system is closer to a RFID sensor network; though no sensor network concepts are involved in the architecture.

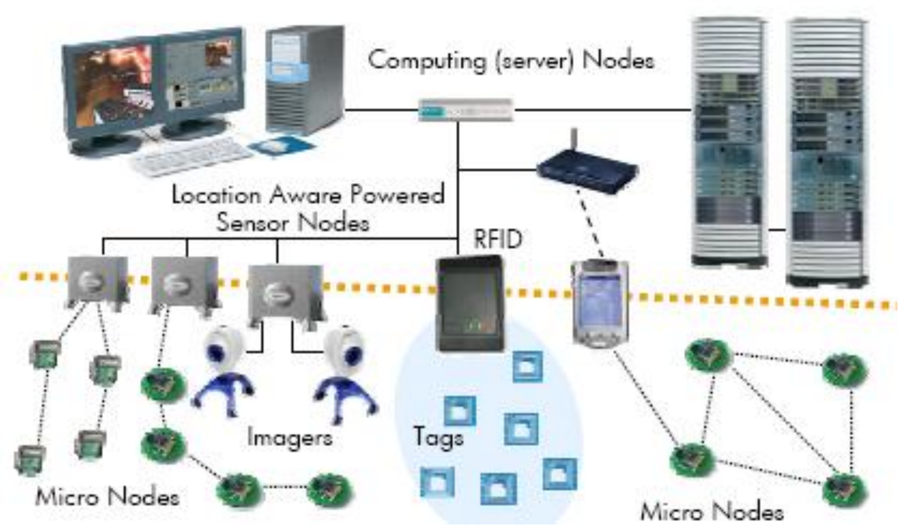


Figure 2-6: HP's sentient overlay network (Pradhan, 2005)

As shown in Figure 2-6, an example that starts to involve both RFID and sensor network concepts is the Sentient Overlay Network in HP Lab (Pradhan, 2005). This architecture design inserts hierarchy of diverse ad-hoc wired and wireless network structures and computing nodes that are capable of processing and filtering both sensor and RFID data. The RFID network and the sensor networks are working separately in their standard mode. RFID readers and sensor network gateways are assumed to be wired and powered, and are compatible with the IP-based network standards. The upper layer communication between the ad-hoc networks and the server nodes is based on standard wired IP networks and a wireless LAN, which depends on the specific requirements. Comparing to previous work, this work is the first to consider the presence of both RFID and sensor networks in one architecture. It tries to organize all the different types of components into a standard computer network, aiming at designing system architecture to integrate HP's existing products and provide sensing and RFID solutions for large enterprises with well established IT infrastructure.

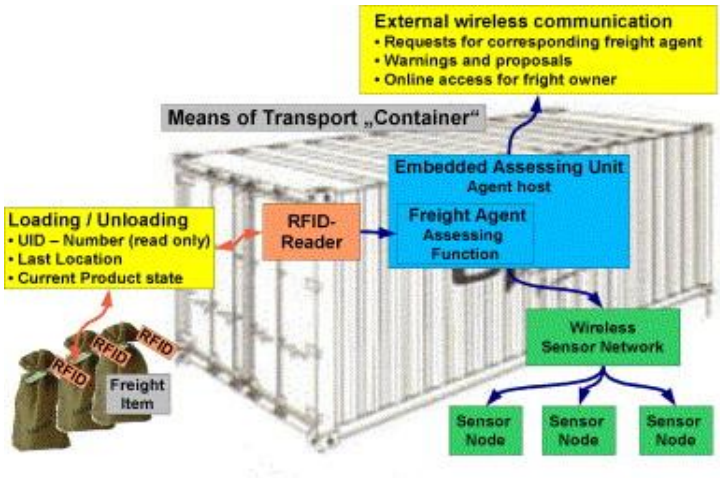


Figure 2-7: Jedermann’s sensor system prototype (Jedermann et al., 2006)

Jedermann’s sensor system prototype for fruit logistics (Jedermann et al., 2006) could be a more specialized example trying to bring together just RFID and wireless sensor networks in a small operation scenario - all inside a container. In his prototype, which is shown in Figure 2-7, standard fruit containers are equipped with RFID readers to read the unique ID number of every freight item as well as their transport information stored on their RFID labels. In order to monitor the fruit states, sensor networks are implemented in the containers to measure temperature, humidity and ethylene production rate. The RFID networks and the sensor networks in the prototype all report to a freight agent, which could send out warnings and recommendations through the external network, such as a WLAN of a cargo ship. This research is the closest work to our research subjects. However, the whole system is designed to operate only in a container, which is a very small scenario with limited scale of implementation. It is similar to the “Agent network” architecture that will be proposed in Chapter 4, and a further discussion including such architecture will be shown in Chapter 5 that such design may encounter problems when the implementation scale extends.

Sometimes the agent device and the central node/coordinator of the wireless sensor network can be integrated in a single device but this does not affect the essence of the logical system architecture. An example of such architecture can be found in Chen and Duan’s design (Chen and Duan, 2007) for an in-transit visibility system (IIVS). The purpose of their system is to achieve the real-time surveillance of the valuable or dangerous materials during their transportation by vehicles such as on a cargo. Each transportation vehicle is equipped with a local server, which acts as the agent device as well as the central node of the wireless sensor network inside the vehicle. Passive UHF RFID reader and GPS receiver are also implemented on the vehicles, they communicate with the local server by serial connections. Collecting all the on-vehicle information, the local server then reports to the control centre via a GPRS network and Internet. Again such architecture works only for a small scale implementation as an in-vehicle system, which is similar to Jedermann’s scenario of a container.

2.3.3 Network Level Integration – RFID into WSNs

Englund and Wallin’s work (Englund and Wallin, 2004) has a special structure. They gave the passive RFID readers radio frequency ability, and used a network protocol that is very similar to the wireless sensor network protocols to provide multi-hop data transfer ability. Their work expanded the reading range limit of the short range RFID system, and at the same time implemented the ability of reading RFID tags from distances that are well beyond the range of ordinary RFID readers. But neither sensor nor active RFID has been involved in the work.

Mason, Shaw and Welsby have introduced a similar work in their paper (Mason et al., 2006); they managed to have a RFID reader communicate with a MICA2 mote, which is a sensor network development product of Crossbow Technology, Inc. In their experiment two MICA2 motes are implemented, one is attached to a LF passive RFID reader, the other one is connected to a computer. Communication between the reader and the computer via MICA2 motes was then established successfully. However, there is no further experiment with more motes involved, and neither sensor nor active RFID has been involved in the work.

An example application that might be considered as related research is the work from UC Berkley (Ferguson, 2007). They are constructing a mesh network in a hospital or a warehouse. In the network they implement only 2-3 access points, which is similar to the combined gateway devices in our architecture. The access point will then lead to an interrogator and then to the server devices. Numerous nodes with ID, which can be considered as RFID sensor nodes, will then come in and form a mesh network topology. These RFID sensor nodes start to communicate and report their nearest range, measuring the distance from one node to the next. The researchers are now investigating algorithms through which the location of every node could be calculated. This work does not contain the concept of RFID integration, and it is still in concept stage far from mature.

2.4 Discussion

In this chapter a literature review is provided to investigate how RFID, sensors and WSNs can be combined. The existing systems and experiments have been categorized in three levels, which are the hardware, logic and network level, depending on the different architectures that have been used to integrate RFID, sensors and WSN for various applications. Each of them has its own features and is suitable for specific application. Comparison and discussion of these methods will be discussed in Chapter 5. In this thesis I will mainly focus on network-level integration for our architecture design, as the network-level architectures requires less hardware integration, fewer compatibility issues among devices from different manufacturers and highly integrated functionalities.

Chapter 3 Indoor Localization with Sensor, Wireless Networks and RFID

Advances in ubiquitous mobile computing and the rapid spread of information systems have fostered a growing interest in indoor location-aware or location-based technologies. Before looking to integrate localisation functions with RFID and ZigBee WSN technology in the later part of this thesis, the primary technologies used in indoor localization systems are introduced in this chapter, by classifying them in three categories: Non-RF technologies, Active-RF technologies and Passive-RF technologies. Both commercialised products and research prototypes in all categories are involved in our discussion. The Passive-RF technologies are further divided into "Mobile tag" and "Mobile reader" systems. It is expected that such classification can cover most of the indoor localization systems. Features of these systems are briefly compared at the end of this chapter. From this review we expect to learn two main points: firstly, the suitable location tracking solutions for ZigBee based RFID Sensor networks; Secondly, what are the possible localization algorithms/mechanisms I will be looking to support in our future architecture designs, and what hardware and network services they will require to operate properly.

3.1 Introduction

An information system is always expected to provide answers to four types of questions: Who, What, When and Where. Information such as ID, time and incident descriptions can be useless if it is not associated with a physical location. With the growing requirements in mobility of the end devices, a Real-Time Locating System/Service (RTLS) has become an integral part of many information systems. The most well known localization service is the Global Positioning System (GPS) using a network of 24 beacon satellites to cover the majority of the earth's surface. It is widely used to track and navigate only moving objects outdoors. Its accuracy cannot satisfy most indoor applications and the satellite signal itself is usually unreachable in indoor environment. Thus dedicated systems have to be used for on-site localization. Compared to outdoor applications, the indoor environment is more complex, irregular, unpredictable and inconsistent. Because of this it is very hard for a system to achieve satisfactory performance in all the aspects including accuracy, range, power consumption, implementation, cost and maintenance. Most designs have to look for a balance between these parameters.

Many new technologies have emerged in the past decade to achieve accurate and reliable tracking of objects within buildings, the performance of indoor localization has improved significantly. Different systems have been designed for various applications. The application scale varies from tracking thousands of objects and personnel in industry and public applications to navigating a single vacuum cleaner in a home automation system. The current research in indoor localization technology can be classified in three categories: Non-RF technology, Active-RF technology and Passive-RF technology. The Passive-RF technologies can be further divided into "Mobile tag" and "Mobile reader" systems. The definitions of the different categories are given below:

- Non-RF technologies. The group of localization technologies that do not use radio frequency as ranging or communication media between the mobile devices and the fixed reference devices.

- Active-RF technologies. The group of localization technologies that use radio frequency as communication and ranging media between the mobile devices and the reference devices, and that both the mobile devices and the fixed reference devices are powered either by on board batteries or by mains power supply.
- Passive-RF technologies. The group of localization technologies that use radio frequency as communication and ranging media between the mobile devices and the reference devices, and that either the mobile devices or the fixed reference devices work in passive mode without the support of on board batteries and mains power supply. The Passive-RF technologies are usually based on passive RFID technologies and can be further divided into "Mobile tag" and "Mobile reader" systems.
  - "Mobile tag". The group of Passive-RF technologies with all mobile devices operating in passive mode;
  - "Mobile reader" systems. The group of Passive-RF technologies with all fixed reference devices operating in passive mode.

For the remaining of this chapter I will introduce and discuss the primary technologies based on the above classification.

3.2 Non-RF Technology

As most of the current indoor tracking systems today use radio frequency I group all other technologies together as non-RF technologies and discuss them here. Such technologies include inertial, video image processing, infrared (IR) and ultrasound.

Inertial localization is the tracking approach with the simplest system architecture. As no network or even reference points are needed, the mobile objects operate a 'stand alone' system which uses self-contained sensors to measure its own movement, such as the variables of moving distance, orientation of movement, acceleration and velocity etc. Based on this sensing information the system is able to estimate the current position of the device relative to its starting point. If the starting point can be specified on a pre-learnt map the system will be able to generate the absolute location of the mobile object on it. An example of the inertial system can be found in the work (Collin et al., 2003). Such systems suffer poor localization accuracy especially in long term observations due to drift and error accumulation.

Video image processing is another technology with relatively simple system architecture. Video systems usually do not require the mobile objects to carry any additional devices. Current technologies can determine numbers, human faces and even body motions from video clips (Cai et al., 1995). Object or human localization can be done using such systems, but line of sight requirement, a large amount of computer processing and imperfect identification error rate prevent the technology from being adopted in commercial applications.

Infrared (IR) is one of the most common approaches in Non-RF system. In such system mobile objects are equipped with infrared emitters to transmit their ID information via modulated infrared light. Receivers are deployed in the environment to cover the area that the mobile objects can reach. When the infrared light is received by a particular receiver, the location of the mobile object can be determined within a predefined area around the receiver. The Active Badge developed by AT&T is one example application adopting this technology (Want et al., 1992). The disadvantages of infrared systems include requiring line-of-sight connection between emitter and receivers, short range signal transmission and low localization accuracy.

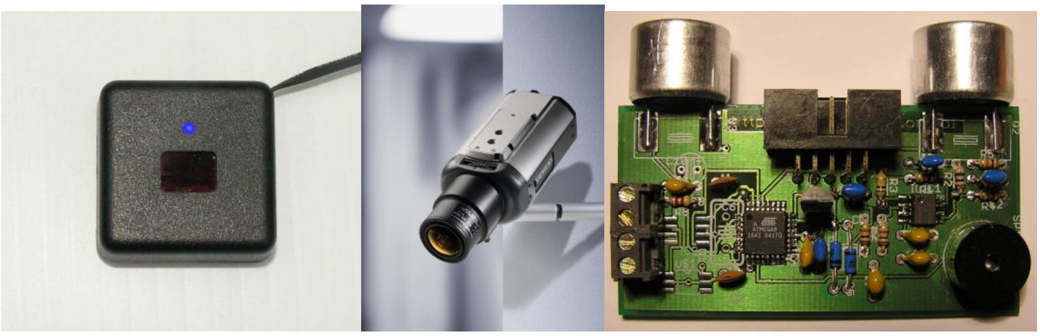


Figure 3-1: IR sensor (left), video camera and ultrasound node

Ultrasound is the most popular technology used in Non-RF systems. Its main advantage is that it is able to provide very high localization accuracy. This is because the speed of ultrasound is relatively slow which consequently gives the system more opportunity to perform range measurement calculations. The MIT Cricket system is a primary example of the use of ultrasound in an indoor environment tracking with a granularity of a few feet (Priyantha et al., 2000). But like the infrared systems, line-of-sight requirement between emitters and receivers is a disadvantage of ultrasound positioning. It also requires a complicated and costly system infrastructure.

Non-RF technologies all have unresolved weakness such as low localization accuracy, short operating range and the need for line of sight connection. Those problems have prevented the growing of Non-RF technologies and most of the interest nowadays has been turned towards RF-based technologies.

3.3 Active-RF Technology

Due to the unsolvable problems that the Non-RF technologies encountered, more and more indoor localization systems are using RF based technologies for range measurement. Radio frequency does not require strict line of sight path for transmission. This makes the site survey and system implementation much easier. In addition, some of the radio frequency based wireless data networks are already in use in many buildings; they can therefore be upgraded to support the localization applications with little or no hardware change.

Most of the research in RF based indoor localization uses Active-RF systems. Much work has been done in system design, locating algorithms and implementation of such systems. But the basic approaches of these systems are similar: to deploy base stations in the environment and to calculate location based on the base station signals received by the mobile nodes carrying on mobile objects. It is noted that for Active-RF systems there are three main features which identify each project: its range measurement approach, position estimation algorithm and network standard.

Range measurement

The first feature is the way in which the range is measured between the mobile nodes and the base stations. The range measured by the mobile nodes can be absolute distance, relative distance, relative direction or even just RF connectivity. RF connectivity does not require any additional function in the data network hardware. Each mobile node will be considered to be "connected" to those base stations it can hear. The Angle of Arrive (AOA) technique can compute the relative direction of a signal source to a base station by using directional antennas. The Time of Arrival (TOA) and Time Difference of Arrival (TDOA) techniques calculate the absolute distances between a mobile node and the base stations, simply by multiplying the speed of light with the RF travel time in the air. These techniques require very accurate device clock and network synchronization, as a small clock drift can lead to a very large distance measurement error (about 30cm per ns drift). This increases the hardware cost of TOA and TDOA based systems. Received Signal Strength (RSS) and Bit Error Rate (BER) are two parameters that are both related to the distance. They can be used to describe the relative distances between a mobile node and base stations. RSS and BER techniques do not have very strict requirements for hardware and can easily be supported by low level processors.

Localization algorithms

The second feature is the design of algorithms to estimate the mobile node location based on the distance, direction or connectivity of data gathered. If the AOA information of a mobile node is gathered from multiple base stations then its position can be calculated by the intersection point of the lines coming out of the base stations towards the mobile node’s direction. For 2-D localization, a node’s AOA data from 2 base stations can be enough to locate it. If we obtain just the connectivity information of a node to the base stations, we can use the Centroid algorithm. This simply calculates the average position of all the base stations that the node can hear. When absolute distance or relative distance data is gathered, there are several algorithms we can choose from. The proximity algorithm locates the node within the RF range of the closest base station to it. Systems using the triangulation algorithm will draw a circle around each base station based on the distance measurements from the node, each circle represents a possible area for the node position, and the intersection of all these circles is the node location. The problem of all the above algorithms is that they have not considered the multipath effect in RF transmission. Radio waves can be reflected by walls, floors and obstacles before arriving at the receiver’s antenna; even if the radio waves can penetrate these objects it attenuates faster in them then in the air. This means the signals that arrive at a receiver’s antenna may not represent the relative distance or the source direction accurately. Actually, they are very unlikely to be correct in an indoor environment. It would not be unusual for a base station in the next room receives higher signal strength than the base station in the same room as the mobile node. The best approach to deal with multipath affect is the RF Fingerprinting algorithm. It is an algorithm widely used in current commercial indoor RTLS systems. This algorithm requires the system to be trained before normal operation. Samples of the RSS, TOA or BER data from all the base stations are performed at each point within the environment. The list of sampling results from all base stations at a same position is considered to be the fingerprint of this particular position. During normal operation the fingerprint information of a mobile node is sampled regularly and is compared to the fingerprints database the system has previously learnt to determine the node’s current location. This algorithm significantly improved the indoor localization accuracy of Active RF systems.

Network standards

The last feature is the RF network standards in which the sensors and localization algorithms are implemented. The choice depends on cost, accuracy, range, data transmission capacity and existing network infrastructures on site etc. Options include WiFi, Bluetooth, Active RFID, Ultra wideband (UWB), Wireless Sensor Network (WSN). The advantage of WiFi is that such network infrastructure exists in many buildings, and localisation technology can usually be adopted without any hardware modification. Most of the WiFi localization systems are using TOA (Ciurana et al., 2006) or RSSI (Bahl and Padmanabhan, 2000) measurements and fingerprinting algorithm with an accuracy of 2 to 5 metres depending on site survey. Bluetooth Systems usually use RSS or BER and Triangulation with an accuracy of around 10 metres. SpotON (Hightower et al., 2000) and LANDMARC (Lionel et al., 2003) are two main indoor localization systems using active RFID technology. Both systems use active tags as mobile nodes and estimate the target node position by analyze the inter-tag RSS information. These systems are still in prototype development and their actual accuracies are hard to compare. UWB has recently become a new means of indoor localization. It uses TDOA and Triangulation for position estimation. UWB base stations can send a very short beacon pulse which offers increased immunity to multipath cancellation due to the ability to discriminate between direct and time-orthogonal reflected waves (Fontana, 2004). This enables UWB technology to overcome the multipath problem that appears in the other RF technologies. An accuracy of 15cm for indoor environment has been achieved in commercialised product (Ubisense UWB, 2009). MERIT (Lee et al., 2006) is a primary localization system using WSN. The researchers use RSS between nodes and base stations and estimate the node position at room level using the Proximity algorithm. They put RF reflectors beside the base stations to ensure the base station within the same room with the mobile node will receive the best RSS. In their experiments a 98.9% accuracy was achieved.

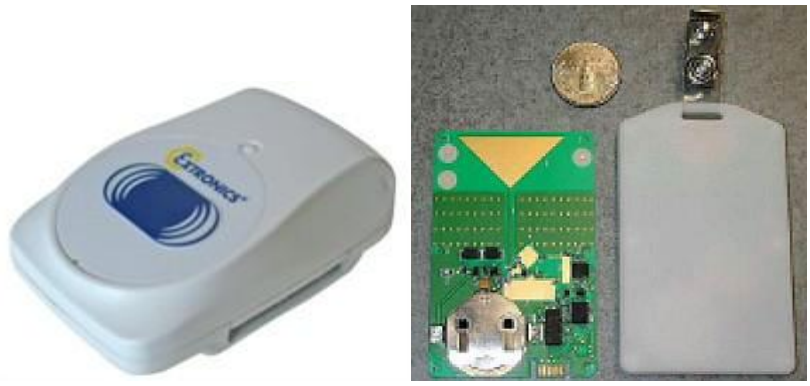


Figure 3-2: A WiFi RTLS tag (left) and a UWB tag (right)

WiFi localisation may be the most popular technology used in current commercialised indoor localisation systems, not only because it is a mature technology providing acceptable accuracy and hardware cost for most applications, but also because the 802.11 standard used by WiFi is dominating most of the indoor wireless local area data network solutions. This means that the customers may not need to purchase a whole set of localization system infrastructure if it is already in their buildings. Despite of the large market share of WiFi localization, WSN and UWB based systems still have great potential in taking its place. WSN system features even lower hardware and maintenance cost than WiFi. Much work has been done in adopting WSNs in building security and fire safety applications; this is likely to happen in the near future and will make WSN a competitive technology for indoor localization. UWB has been proved to be the most accurate RF indoor localization technology as it does not have the multipath problem that the other RF systems encounter. The barrier for adopting UWB in commercialized systems is the cost, lack of standard and national RF regulations. Because UWB may act as noise in other RF systems working in licensed RF bands, it is still forbidden in some countries. Efforts are being made in both the business and academic research communities to overcome these problems and if successful, it is likely that UWB will replace WiFi in applications in which the accurate location of objects is of primary importance irrespective of system costs.

3.4 Passive-RF System

Active-RF systems have complicated system infrastructures and relatively high cost in hardware and maintenance. They are usually adopted in large scale applications such as the tracking of patients inside a hospital (Burnell, 2008) or tracking vehicles and machines within industrial plants and warehouses (Ibach et al., 2005). For some smaller applications like home automation or assisting the visually impaired, Passive-RF systems which have much simpler designs and implementation are preferable.

In Passive-RF systems either the node attached to the target object or the reference nodes implemented in the environment are simple passive circuits which do not need access to mains power or battery. These passive nodes act as attached reference points and do not work until an associated reading device is present nearby. Passive Radio Frequency Identification is the most commonly used technology for Passive-RF systems. The passive tags, or backscatters, are first designed to replace the barcode used for object identification. With no power resource and RF transmitter, they use inductive/propagation coupling to connect with the tag reader's antenna. This means that the passive tags just simply reflect back the signal emitted by the reader. These passive tags are simple, cheap and have a read range from 0.1cm to 10m depending on the frequency band used.

3.4.1 Mobile Tags

For some applications, the accuracy of tracking is only required at room level or building sector level. For such applications, RFID readers can be installed at the access points of each room or between different sectors of the building. Objects or persons to be tracked are equipped with passive RFID tags. By monitoring the information presented by the tag at each access point it has responded to, the system is able to determine its location within a specific room or a building sector. Such systems are easy to implement and maintain, but suffer a lack of real-time access to the objects position. Many people think RFID can provide real-time location information of the tags, but actually all it can provide is the location of a tag when it last passed a reader device (Ferguson, 2007). Thus the object locations in the systems using access points are not based on instant tag query, but on presumptions made from the limited log of readings.

If an application requires more accuracy or if instant access to the tracking nodes is preferred, dense reader deployment will be necessary in order to make sure tagged objects are always within the range of at least one reader antenna. “Smart Shelf” is an example of dense reader deployment designed for a supermarket environment (Healthcare-Packaging, 2007). Reader antennas are mounted on each layer in every shelf to give full radio coverage to all the goods on display. Such system can provide real-time location of all the merchandise at item level. After integrating the smart shelf with the store inventory management systems, it can also alert store personnel to refill particular merchandise or retrieve the out of date goods by continuously monitoring the number of them on the shelf and their product information. Leading supermarkets in the world such as Wal-mart, Tesco and Metro are all testing the smart shelf technology and are expecting a massive implementation of it in the near future.

Figure 3-3: Smart shelves for books (left) and pharmaceuticals (right)

When passive RFID technology was first introduced, the standard infrastructure of its design was to have the reader devices mounted at fixed positions, and the tags attached to the mobile targets. Reader devices were designed to provide the upper layer server with the tags' information each time they presented themselves within the range of its antenna. The "access point" and the "smart shelf" applications are based on this infrastructure which can be described as the "Mobile tag" infrastructure. Although in the "smart shelf" system instant query to each item is possible, it is based on the fact that the position of the tracked objects (merchandise displayed on shelf) are relatively fixed and only within a particular sector of the building – the shelf. This has actually limited the ability of RFID to undertake real-time localization tasks. In specific applications when objects are mobile and need to be tracked in real-time, an even denser deployment of passive RFID readers is unavoidable to ensure the coverage of every minute area inside a building. In most cases the cost of the passive RFID readers makes such dense deployment impractical. On the other hand, passive RFID tags are originally proposed to be attached to massive moving objects, so they are designed to have very low cost which makes it feasible for large scale deployment with acceptable costs. This leads to another infrastructure for passive RFID localization technology, the "Mobile reader" infrastructure. In such systems passive RFID reader device are attached to the target objects, while a large number of passive tags are deployed in the environment to act as location marks. The location of an object is calculated based on the tags detected at any instant by the reader located on the object.

3.4.2 Mobile Readers

A typical "Mobile reader" system is based on the passive RFID-assisted localization. These systems focus on using passive RFID technology to calibrate their current localization approaches, which means the localization and navigation tasks are not solely based on passive RFID but use a combination of two or more different technologies. Tsukiyama has deployed passive RFID tags on the wall inside a building. A robot equipped with a reader device can use the tags as landmarks to help guide itself from one point to another using ultrasonic rangefinders (Tsukiyama, 2005). Another researcher, Kulyukin, attached passive RFID tags to various objects and made a robot guide for the visually impaired inside a building. This robot uses ultrasonic sensors (Kulyukin et al., 2004) or laser sensors (Kulyukin et al., 2005) to guide the robot and uses the RFID tags as landmarks. In the work (Miller et al., 2006), researchers developed a system for first responder's localization using inertial sensors and the dead-reckoning approach. Based on the system they studied, they proposed an option to implement passive RFID tags on the wall and floor inside buildings to assist the dead reckoning based navigation system and improve its performance. The researchers declared that they achieved enhanced accuracy of their inertial tracking systems by adding the assistance of passive RFID tags. In the work (Yang et al., 2006), researchers used a similar dead reckoning method calibrated by passive RFID tag array on the ground to locate and guide a robot in an indoor environment. They proposed a hexagon tag array and analyzed the uncertainty of the calibrating system. These RFID-assisted localization systems combine different technologies to perform tracking. Passive RFID technology is usually used only for calibration purpose, thus the accuracy of the systems vary and mainly depend on the main approaches they use.

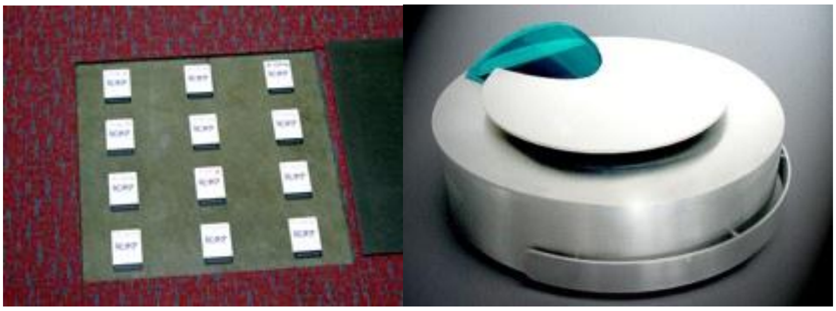


Figure 3-4: Passive RFID tags deployed under carpet (left), Vorwerk's smart vacuum cleaner with built-in RFID reader (right)

Another type of "Mobile reader" systems is the passive RFID-based localization. For those systems the localization is completely based on a passive RFID system. In the work (Hahnel et al., 2004), researchers built a mobile robot localization system by deploying passive RFID tags on the wall inside an office building, and equipped tracked personnel with a two-antenna RFID reader. They studied the RFID reader antennas and established a sensor measurement likelihood model which describes the likelihood of detecting an RFID tag given its location relative to one of the antennas. With the antenna sensor model, a human motion model and a previous learnt site map, Monte Carlo localization was applied to estimate the movement of persons in the environment. The experimental results have shown a localization error of 2 to 3 metres after the system has been initialized and became stable. The system was further improved in the work (Schneegans et al., 2007) using a RFID snapshot method. In this method they treated the list of detected tags along with the number of detections over a short measurement cycle as a feature vector, which they called a "snapshot", of each particular position in the environment. The system first needs to learn the snapshots at known positions in a training phase. Snapshots gathered by the reader during normal localization operations will be compared to the snapshots table established in training to estimate the movement of tracked robot or personnel. Such an idea is quite similar to the RF fingerprinting approach using by WiFi indoor tracking systems introduced earlier in this chapter. The researchers demonstrated their system providing similar accuracy, but with less computation overheads and faster converging outputs comparing with the system in (Hahnel et al., 2004). The most systematic research of the moving-reader systems is found in Bohn's works (Bohn and Mattern, 2004; Bohn, 2006, 2008). They proposed a Super-distributed RFID Tag Infrastructure in which they investigated different aspects of the system from tag distribution patterns to the design of dedicated middleware. Passive RFID tags are no longer deployed randomly in the environment, but in predefined grids under the floor. They proved that by regulating the tag distribution patterns the tracking algorithm can be simplified and the localization error can become predictable and controllable. Further research in such RFID grids has been done in the work (Koch et al., 2007) by evaluating various passive RFID technologies. In the work (Willis et al., 2005), researchers tried to add more environment information in the tags in the grid besides their ID and coordinates. The information written in each tag depends on its location, for example, tags in a traffic pattern leading to a door may contain door location, type of handle and opening directions. They argued that using the information in the tags the mobile node can perform stand-alone self-localization, making the system more flexible while protecting the user privacy. All of the above systems calculate current target position based on the data from a reader indicating which tags are currently presenting within the reader antennae at the moment. Localization algorithms are simply the calculation of the geometric centre of the tags detected. A commercialized prototype of the super-distributed RFID infrastructure called “Smart Floor” (Vorwerk, 2005) has been developed by German carpet and vacuum cleaner company Vorwerk, guiding their robot vacuum cleaners to perform cleaning work or transporting goods and persons as shown in Figure 4. In the recent work (Gueaieb and Miah, 2007), the researchers proposed an approach to estimate the angle between the mobile target orientation and the direction of a particular tag relative to it. Their mobile target is equipped with a passive reader with one transmitting antenna in the middle and two receiving antennas at both sides; the reader is designed to be capable of computing the phase information of the signals received. When the reader reads a particular tag the signal reflected back from the tag is received by both receiving antennas. By comparing the phase difference of the two receiving signals the relative direction of the tag can be estimated. Although the researchers in that project were using this technique for navigation of the mobile target, it has the potential to enable target self localization by estimating the relative direction of multiple tags using an approach similar to the AOA algorithm used in the active RF systems.

The idea of the “Mobile reader” infrastructure is mainly studied and applied in robot and vehicle localization and navigation. This is because the current passive RFID reader devices are relatively large in size; they also have relatively high power consumption and need to be supported by large capacity battery which makes further contribution to the size and weight of the final packaging; the last and the most important fact is that the passive RFID reader have quite strict requirement in antenna and tag orientation while performing reading operations, it is easier to fix the antenna position and orientation on a robot than on a person whose pose and motion are much more complicated and unpredictable. However, with the advance in hardware design we can expect the RFID reader devices to become smaller and more power efficient in the next few years. Thus it is likely that in the near future, the devices will become so small that solutions such as putting reader and antennas under the shoes will become possible.

The Passive-RF systems introduced in this section, especially the passive RFID-based systems, have relatively simple system infrastructure and are easy to implement. In “Mobile tag” systems the mobile nodes attached to tracked objects are low cost passive tags, which are currently the only acceptable option for applications requiring one-time disposable use of the nodes, such as shelf monitoring in supermarket and post tracking. Even for the general localization applications the “Mobile reader” systems are competitive. The reference nodes deployed over the environment are simple, cheap passive tags which do not need mains power or battery to be driven; this makes the cost of the systems lower and their maintenance easier than the Active-RF systems. The simple hardware design of these tags also means they are robust and are able to last for a long time in the environment which drives the system maintenance cost even lower. In addition, the mobile nodes use a stand-alone on-board self-localization algorithm without any communication to a network or a server, cutting down the need for additional hardware and protecting end users’ privacy. The whole system can also be considered being off when no nodes are to be tracked, because if there is no mobile node/reader device in operation then there is no active device within the system. Those features of “mobile reader” Passive-RF systems make them preferable for some specific small-scale applications with a very limited number of mobile nodes to be tracked and discontinuous tracking operation. Examples of such applications include home service robots, such as a robot vacuum cleaner, and auto-assistant for the visually impaired. In these scenarios the tracked personnel or machines are limited in number and only need to be guided occasionally or during a specific period of time. The adoption of Active-RF systems in these cases will be inefficient and costly and the user will need to keep a system/network infrastructure working all the time. Last but not least, passive tags have stronger resistance to tough environmental conditions and can be expected to provide assistant information to the first responders' applications during emergency incidences. A brief comparison of the main indoor tracking systems on market is shown in Table 3-1.

Table 3-1. Comparison of main indoor tracking systems in the market

	Infrared	Ultrasound	WiFi	UWB	Mobile reader
Frequency Band	About 10^{14}Hz	> 20KHz	2.4GHz, 802.11a 5GHz	3.1-10.6 GHz	125KHz, 13.56 MHz, 868MHz, 2.4GHz
Range	Room	Room	< 100m	< 50m	0.1m-10m
Accuracy	0.3 m	0.1 m	2-5 m	0.15 m	0.2 m
Hardware Cost	Low	Medium	Medium	High	Medium
Beacon Always ON	Yes	Yes	Yes	Yes	No
Line of Sight	Yes	Yes	No	No	No
Power consumption	Low	Low	High	Low	High
Emit Orientation	No	Yes	No	No	Yes

3.6 Discussion

In this chapter the primary technologies used in indoor localization systems are introduced. Both commercialized products and research prototypes were discussed. The technologies are classified in three categories: Non-RF technologies, Active-RF technologies and Passive-RF technologies. The Passive-RF technologies are further divided into "Mobile tag" and "Mobile reader" systems. Features of these systems were also compared. The trend of the proportion of RF-based indoor localization technology is still upwards. It is hard to compare the various RF-based systems which all have their own advantages and are suitable for specific applications. Although WiFi localization systems are currently the most widely implemented indoor tracking systems, the "Mobile reader" Passive-RF technologies and UWB in Active-RF technologies have the potential to achieve solutions with better performance and will attract more interest in both enterprise and academics in the near future. As for the ZigBee-based WSN systems in logistics applications, there are several points we could learn from this review:

Firstly, RF based tracking technologies have shown great advantages over the non-RF ones. For logistics applications there will usually be goods and equipment moving and being placed within most parts of the operation area, the requirement of having line-of-sight connection between reference device and mobile device in non-RF technologies makes them impractical. Thus using RF as localization media is our choice for ZigBee-based hybrid systems.

Secondly, comparing to Active RF technologies, passive RF technologies show significant weakness for logistics applications. As systems for such applications usually operate in a large-scale area, with a relatively large number of mobile nodes to be tracked, both the passive RFID based 'mobile reader' and 'mobile tag' systems will have very high hardware cost and high energy consumption. It is neither flexible, nor cost-efficient to cover the whole operation area with either passive RFID readers or passive RFID tags. Thus the Active RF technology is the best option.

Thirdly, however, directly adopting the existing active RF systems, such as WiFi and UWB, is not a good choice for ZigBee-based systems, as a considerable amount of additional hardware device and network structure will be added. As ZigBee devices already have the RF transmission capability, I will investigate how to develop the network architectures based on those existing ZigBee devices. Using RSS is the most popular range measuring method in the wireless sensor networks, because there is no additional hardware integration and implementation required.

Fourthly, another significance of this review is that it does give us a clear idea of the operation procedure of those active RF technologies' localization algorithms, which I will be looking to support in our network architectures. This enables us to gain the knowledge of what network-level services these algorithms require for them to operate properly, which is essential for the validity of our future architecture designs.

Chapter 4 ZigBee Enabled RFID – Architectures for Single Integration of Legacy Systems

As described in Chapter 1, our investigation of the integration of RFID and WSN starts from the bottom of the requirement hierarchy which is the single integration of legacy systems. In this Chapter I will discuss the possible implementation of the ZigBee technology into the RFID systems, which will lead to the architectures for the integration of RFID and ZigBee-based WSNs upon a single type legacy system. After discussing the ZigBee compatibility of the devices and communication links in the typical RFID system, I will present three architectures for integrating RFID and ZigBee-based WSNs. They are the Agent network architecture for integrating WSN with existing networked RFID systems, the RAS architecture for integrating existing WSN systems with both the passive/semi-passive RFID and the active RFID, and the TAS architecture for integrating existing WSN systems with active RFID only. This is followed by the benefits of having such architectures compared to the current wireless technologies used in RFID products. Demonstration systems of both network-level integration architectures, the RAS and TAS architectures, on ZigBee based hardware platform are shown in the last part of this chapter to validate the designs.

4.1 Implementation of ZigBee in RFID

According to the features of the different RFID technologies and the device layers of general RFID system architecture discussed in Chapter 2, it is possible for the ZigBee technology to be implemented on most of the RFID devices.

A RFID server is generally a high computing ability device such as a PC or a Laptop in order to run the complex systems such as RFID savant software; external power source and large memory are also essential for these devices, thus there will not be any difficulty for the RFID server to work with the ZigBee technology.

All ***RFID readers*** are equipped with relatively large memory and a microprocessor. Although RFID reader devices do not always have an external power source, most of the passive RFID readers, normally with an operating current of 100 to 300 mA, have far higher energy consumption than ZigBee devices and are usually supported by external power. Some of the active readers may be powered by onboard batteries, but as they have a similar or higher power consumption level than the ZigBee devices they can still support a ZigBee module and achieve a reasonable battery life.

The components of an active ***RFID tag*** include a battery that operates the active tag, an on-board processor, small memory chip and RF transmitter. This is very similar to the components of an end device in ZigBee. Though the memory of current tags is usually not enough for a ZigBee protocol stack, it can still be implemented subject to a memory upgrade or, which is the simplest way, to have a ZigBee end device act as an active tag with the program properly developed inside. The cost of an active ZigBee tag may be slightly increased in this case. The passive and semi-passive RFID tags do not have a self-powered RF transceiver, thus there is so far no way for ZigBee to work on them.

Table 4-1. ZigBee compatibility of RFID devices

Communication between	Server	Reader	Tag
Active RFID	√	√	√
Semi-passive RFID	√	√	×
Passive RFID	√	√	×

The compatibility of ZigBee and the RFID devices are summarised in Table 4-1. The ZigBee technology can now work in the reader layer and server layer of passive and semi-passive RFID systems, and in all device layers of active RFID systems. Thus it is possible for ZigBee to handle the following data communications:

- Between a reader and a server
- Between two readers
- Between a reader and an active RFID tag
- Between two active RFID tags
- Between RFID system and the devices of another external or combined system.

In a specific application ZigBee can be chosen to control one or more of these data links. Different functions and features can be achieved when different combinations of data links are chosen. In the following discussion I will first choose to use ZigBee in the highest device level (server) in the RFID architecture, and then extend its usage layer by layer to reach the devices in the bottom level (tags).

Server-reader communication

Most of the current RFID systems in the market use a serial port, such as RS-232, and USB ports to link a single or a small number of readers to the server in small-scale applications. A serial port needs particular cables to wire all the readers to the server, and the number of reader device that can be connected is limited to up to 127 including the bus devices. When a large number of readers needs to be connected in a more complex scenario, Ethernet or WIFI technologies are often chosen. Firstly we let ZigBee work only for the communication between the Savant server and the readers, which means the other data links will be like a traditional RFID system. No reader-to-reader communication is available in this case. It is essential to have the server-reader ZigBee data links first for the implementation of ZigBee between and within the reader layer and the server layer. The network topology is like a typical hierarchical star network, where the server is at the top of the network as the root node. All the readers are connected directly to the server via ZigBee-enabled wireless channels. The tags, no matter active or passive, are read by readers and can be considered as the sub-nodes of the reader that read from them. The role of the server in this ZigBee network is the coordinator, and the readers will act as the ZigBee end nodes.

Based on the above discussion, for all active, passive and semi-passive RFID systems, the server device and the reader devices are always compatible for ZigBee implementation, thus the ZigBee-enabled server-reader communication is possible for all types of RFID systems.

Reader-reader communication

We now extend ZigBee implementation into the reader-reader communication. This should be based on the established server-reader ZigBee links and could be optional in specific applications. There is no reader-reader communication in existing products. But having such an option will bring us new features for the RFID system. The network topology is a hybrid mesh network. The server and all the readers construct a ZigBee mesh network, in which the server will act as the coordinator and the readers will be the ZigBee routers. Particular ZigBee routers may also be implemented at a proper place to help the routing in specific area depending on the application needs. The tags are still traditional ones and are considered to form the sub star networks with the reader that read them. Like the server-reader communication, the ZigBee enabled reader-reader communication is also possible for all type of RFID system.

Reader-tag communication

As only the active tags are compatible with ZigBee, the implementation of ZigBee between reader layer and tag layer is only possible for active RFID systems. The readers work as the ZigBee routers and the active tags will act as the ZigBee end nodes, while the server works always as the network coordinator. A hybrid mesh network architecture remains in this extension of ZigBee usage.

Tag-tag communication

To have a tag-tag communication may not have been much considered by the RFID manufacturers. But ZigBee can achieve this by simply allowing the communication between two end nodes, that is, in the active RFID systems, to have two active tags exchanging data.

Communication with other ZigBee devices

The communication with other ZigBee-enabled systems or individual devices can be easily achieved. This will usually be a wireless sensor network. We can simply add ZigBee sensor nodes into the ZigBee RFID structure and only slight changes should be necessary in the application layer protocol before they can be accepted by the network and communicate with the server and other ZigBee RFID devices. These will usually be implemented in the RFID reader layer and also in the tag layer for active systems. The network topology is still a hybrid mesh as we only add new types of device in each layer.

4.2 Agent Network Architecture

Based on the discussions on the compatibility of ZigBee technology and various RFID components, we could now discuss integration architectures for various scenarios in logistics applications with certain existing system structures. Researchers in this area have always assumed that their target systems are to be implemented in an empty site with no existing system structures that have already been deployed. However, this is not always the case. Actually, it is likely that a logistics centre has had certain level of RFID or WSN systems that are already implemented and are operating. In the remainder of this chapter I will discuss various ways to achieve combined system architecture based on different existing system structures.

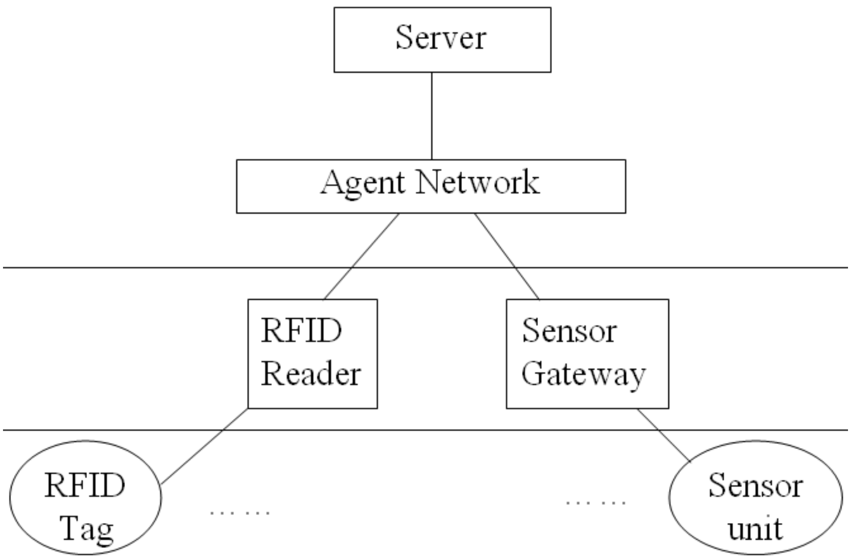


Figure 4-1: Agent network architecture

The first scenario is that a RFID system and a separate WSN system are available or already deployed. The most common way to make a RFID system and a sensor network work together for a particular application is to implement the "agent network" architecture. As shown in Figure 4-1, the RFID network and the sensor network work in the same layer, but not directly connected to each other. To make them work corporately an agent network is added as a backbone here to link the central server and the two networks together. The structure and protocol used by the agent network can be any of the existing network standards, such as the IEEE 802.11 family and IEEE 802.15 family for a wireless network, or standards for a wired network depending on specific application.

There are two ways to connect the RFID reader devices and the sensor network gateway devices to the agent network: either should the devices themselves have the interfaces compatible with these standards so that they can have the ability to construct a data network, or a network agent device, which can be connected to one or several readers and sensor gateway devices, will pursue the task of constructing the agent network backbone.

The “Agent Network” architecture is also suitable for the type of scenario where a RFID network is already deployed and a WSN system becomes desirable. RFID system usually cover only the site access points rather than covering the whole site area that may be required to be monitored by wireless sensor. Because WSNs are easy to be implemented, deploying a full WSN system and making use of the “Agent Network” architecture is the easiest and fastest way to achieve a joint operational system in this case.

4.3 RAS Architecture

Another possible scenario is that a WSN-based system is already in place when a certain type of RFID technology becomes desirable. In this case, in order to achieve the combined architecture for RFID systems and the sensor networks, our approach is to extend the conception of a ‘sensor’.

Generally speaking, a sensor is a device that responds to the stimulus of a particular type of environmental condition or pursues a specific physical measurement. In this combined structure of “Reader as a sensor” (RAS), the concept of the sensor is extended to involve the RFID reader as a sensor device. What a reader device ‘sense’ is the appearance, the approaching or the passing of a RFID transponder/tag within its reading range. In this case, the RFID readers and the sensor nodes of the wireless sensor networks are considered to be with similar functionalities and are in the same layer of the system architecture. The sensor network gateway device, such as a ZigBee coordinator or any predefined sink node, will also act as the gateway device between the RFID readers and the central server/network. All information generated by the readers will be sent to the central server via the sensor network gateway device. The architecture is shown in Figure 4-2.

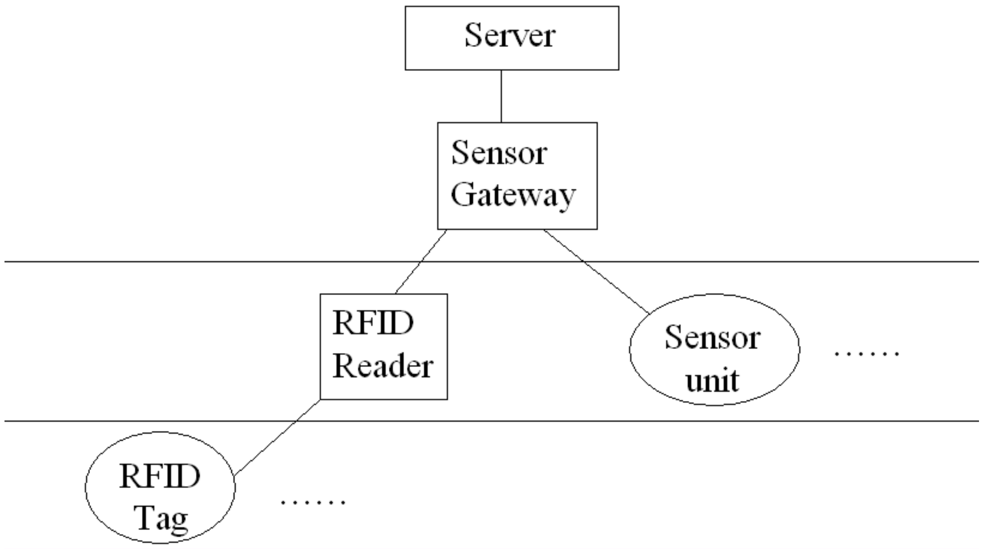


Figure 4-2: RAS architecture

Although various interfaces and protocols such as RS-232, RJ-45 or WiFi are capable of bridging the RFID readers and the sensor network gateway devices, the Wireless Sensor Networks technology used by the wireless sensor nodes like ZigBee technology is preferred to make the reader devices purely integrated into the network system like real WSN nodes.

4.4 TAS Architecture

In Section 4.1 I have stated that the active RFID tags are able to handle the ZigBee technology protocol stack. Actually, an active RFID tag is very similar, if not the same, as a ZigBee end device. The basic components that construct an active RFID tag, which are power resource, microcontroller and RF transmitter, are almost all the basic components of a ZigBee end device which just has additional sensors/actuators. As a result, a ZigBee end device actually has the potential of acting as an active RFID tag, with its parent nodes acting as active RFID readers. As a result of this, I have the "Tag as a sensor" (TAS) architecture for the scenarios where a WSN system is already in place, and an active RFID system is expected to be integrated.

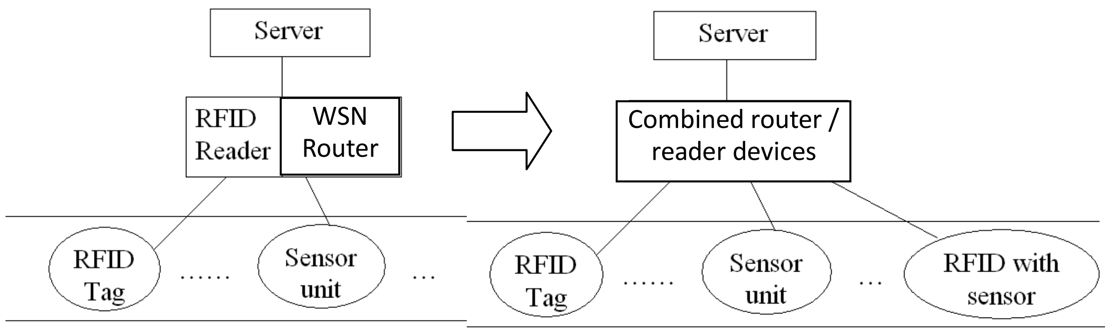


Figure 4-3: TAS architecture

In the 'Tag as a sensor' (TAS) architecture, which is shown in Figure 4-3, the 'sensor' concept is extended to treat the RFID transponder/tag devices as a sensor. What a transponder device 'sense' is the unique identification code stored in the tag's memory. When a tagged asset or person goes within the reading range of the reader device, the tag senses the identification code of the asset or the person and transmits the identification code to the reader device. In this case the RFID tags and the ZigBee end devices are considered to be in one layer of the architecture. The reader devices and ZigBee network routers, which lead to combined router/reader devices, are in another layer. The server together with the network coordinator/sink node is at the top level of the architecture. The server, the combined reader/router devices, the general sensor nodes and the RFID sensor tags/nodes communicate with each other in a unified ZigBee network. When we are using only RFID sensor nodes in the network, as they work in a very similar way to the typical sensor network nodes, the combined reader/router devices could actually be achieved by using the sensor network routers with slight software level modification.

4.5 Features of ZigBee Enabled RFID

ZigBee is a wireless network technology concerned mostly with the architecture and the data transport inside the network. It allows wireless communication among all the devices within its network. With the implementation of ZigBee technology in the traditional RFID system, the server, the RFID readers and even the active tags can construct a wireless network with a hybrid mesh architecture. The network level integrations, which include the RAS and TAS architectures, have started to show some of the unique features of integrating ZigBee with RFID technologies. The advantages of using ZigBee technology in RFID systems include:

Lower power consumption. ZigBee is designed for low data rate and power-efficient communication. With a low data rate RF transmission, a relatively simple network protocol stack and the ability to sleep during idle, a ZigBee device can work for years with only normal AAA size batteries depending on the actual application requirements. Taking into consideration that the data transmission speed of ZigBee (20 ~250 kbps) is sufficient for transferring RFID information, the devices in the reader layer can be supported by an internal battery and have a reasonable lifetime. For example the handheld readers may benefit from ZigBee implementation as the current products are using WiFi and Bluetooth with power consumptions far more than that of ZigBee (Kinney, 2003). The active RFID tags can also benefit from such a feature to have an even longer battery lifetime.

Multi-hop reading. One of the most important features of ZigBee is its multi-hop routing protocol based on a mesh network topology. ZigBee can thus allow multi-hop communication between a reader and the server device, this means that the readers are not required to be placed near the server and could be installed anywhere within the transmission range of at least one other ZigBee reader device or a ZigBee router. The whole system can operate correctly as long as the server can connect with at least one ZigBee reader or router device, and at least one multi-hop path can be found between each reader and the server. The self-organizing and self-healing routing protocol supported by ZigBee guarantees a new path to be generated automatically to maintain the data communication when one of devices in the path between two devices is down; this makes the data communication even more robust.

Working with other ZigBee devices. ZigBee provides the possibility for a RFID system to communicate or even to combine with a wireless sensor network. A RFID sensor network can be used in many different logistics applications such as to monitor the required environmental conditions during the transportation and storage of the perishable goods and foodstuffs and the goods that are sensitive to environmental changes. Sensor nodes can be added directly into the ZigBee RFID systems subject to slight changes in the application layer protocol, which makes the combination of the two systems simple and reliable under a unified standard and architecture.

Large number of devices. While the application becomes more complex and the application scale becomes larger in some scenarios, a large number of tags or even readers may be required. To link them all together we need the network standard to be capable of massive device management. The current wireless technologies struggle for large-scale applications. The Bluetooth master device can connect with only 7 active devices and the 802.11 standards allow a connection with up to 32 devices for each access point (AP). The situation will turn even worse when sensor nodes are added. ZigBee has the potential to address such an issue. Each ZigBee reader/router device is capable of interconnecting with up to 255 active devices and each of these devices can connect to a further 255 devices. In theory, this extends the system capacity to up to 65536 nodes.

Wireless network architecture. ZigBee provides us a purely wireless infrastructure for the network backbone. With the support of ZigBee a cable-free RFID system can be established with increased flexibility. The system implementation is simplified as the readers can be implemented at any place required by the application. The cost of system implementation can thus be reduced. One may argue that the WiFi and Bluetooth technologies can provide a similar structure and most of the features, but actually this is not the case. Current Bluetooth-enabled RFID readers can communicate with the server via an IEEE 802.15.1 connection. A pairing process is required each time before operating and the connection has a very limited RF range, which is up to 10m at the moment. This makes it difficult for Bluetooth to satisfy a wide range of applications. WIFI-based RFID systems are using either the IEEE 802.11 connections between server and readers, or use the WiFi tags for real-time locating (RTLS) applications. When server and readers construct a WLAN, which is called a reader WLAN, data communication is possible. However, the power consumption of WIFI can be a problem for battery-assisted devices such as handheld readers and active tags. On the other hand, wired WIFI access points (AP) are usually essential in a reader WLAN and are essential in a WIFI RTLS system as they act as the readers; this draws the system backbone back to a wired architecture and increases the difficulty and cost of the system implementation.

Active RFID standard. ISO 18000-7 may be the only general RFID standard established particularly for active RFID, but actually one could find that a pair of different 433MHz ISO tags can hardly work with each other. One manufacturer’s active RFID tags do not necessarily work with any other manufacturer’s RFID readers, even at the same frequency. With the crossbreeding caused by licensing, one manufacturer can comply with the ISO standard, yet not be interoperable with another product that conforms to that same standard (Wood, 2007). So simply adherence to the ISO 18000-7 standard protocol does not ensure true interoperability, which should be the original goal of having the standard. ZigBee is the same communications technology based on the IEEE 802.15.4 protocol in 2.4 GHz frequency to everyone. So by using ZigBee nodes, regardless of which manufacturer the tags are produced by, hardware from different systems can be expected to work together when required. This can be very useful in logistics applications where products from different suppliers do not necessarily carry tags from a same manufacturer.

4.6 Demonstration System

4.6.1 ZigBee Enabled WSN with Passive RFID – RAS Architecture

This demonstration is used to test the feasibility of using ZigBee technology for RFID system. One ZigBee device is set as the command device, which is used to receive messages from a remote reader. We suppose one ZigBee device integrated with temperature and humidity sensors as a RFID reader. Three ZigBee devices are set as routers deployed between the coordinator and the remote reader. Figure 4-4 shows the deployment of this experiment. When the ZigBee reader reads a signal from a tag, it will send out the tag information to the ZigBee coordinator immediately. Then the information will be displayed on the screen to the users. According to our test, the minimum interval time for sending out tag ID can be 5ms (200 packets/second).

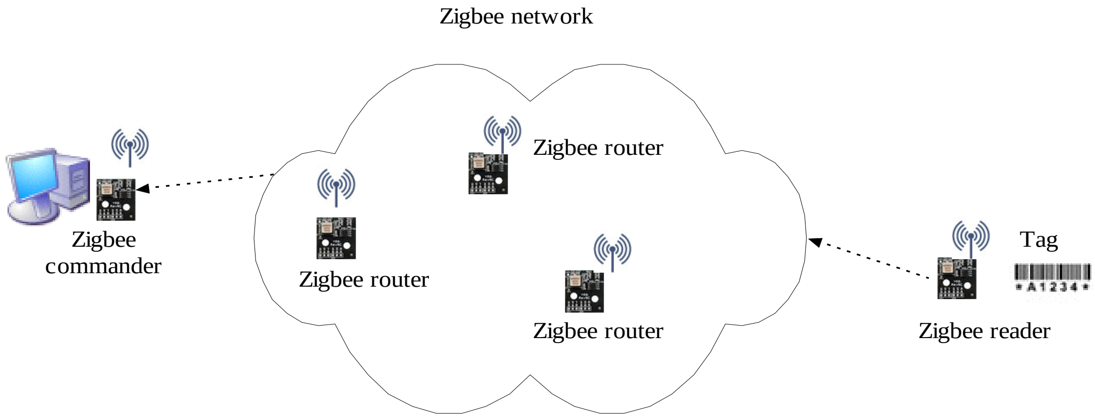


Figure 4-4: Deployment of the ZigBee/RFID experiment

When the system starts, the commander (coordinator) and three routers are shown on the screen. The responsibility of the coordinator is to create the ZigBee network. After those three routers join the ZigBee network created by the coordinator, they will be ready for relaying messages from the ZigBee reader to the coordinator. Figure 4-5 shows the user interface of initialization.

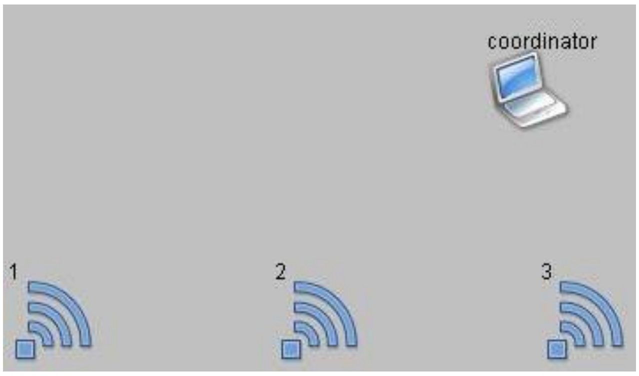


Figure 4-5: Initialization, nodes 1, 2, 3 represent the routers.

After initialization, the ZigBee reader will join the ZigBee network through one of those routers and start to work. When it detects some tags, it will immediately send out the tag information and the sensor readings through those routers to the coordinator. The coordinator will display the received message on the screen. Figure 4-6, in which Node 4 is the ZigBee reader, shows the displaying interface and gives the explanation of detail of node 4.

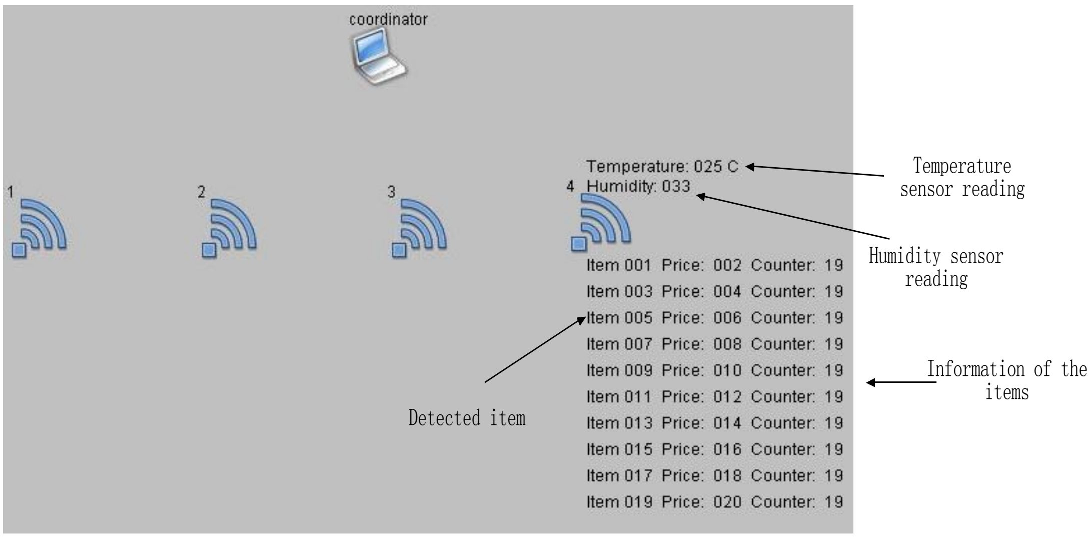


Figure 4-6: Displaying information received from the reader

If some items have been removed, the display will keep update and show the current status. Figure 4-7 shows the status of items when last five items have been removed.

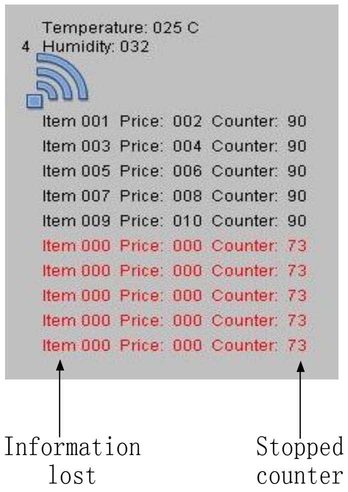


Figure 4-7: Reading information after removing some items

4.6.2 ZigBee Enabled WSN with Active RFID – TAS Architecture

In the second experiment, I tried to make the tag as an end device associated with the temperature and humidity sensor. When this tag reaches in the range of a ZigBee reader, it will send its own information and temperature and humidity values sensed around itself to the coordinator via the routers. Figure 4-8 shows the deployment of the active RFID mode based on ZigBee.

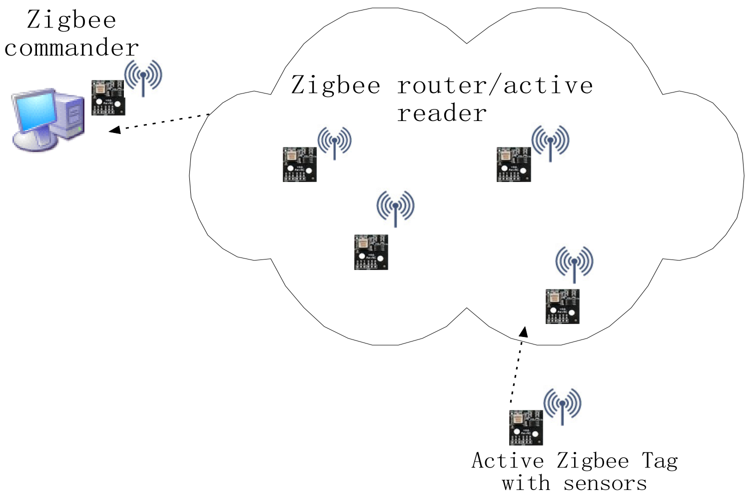


Figure 4-8: Active mode of RFID/ZigBee network

After the ZigBee coordinator and four ZigBee routers create the network, the whole network is ready for receiving the active ZigBee tag's information. Figure 4-9 shows the interface of the display when an active ZigBee tag is within the range of the network.

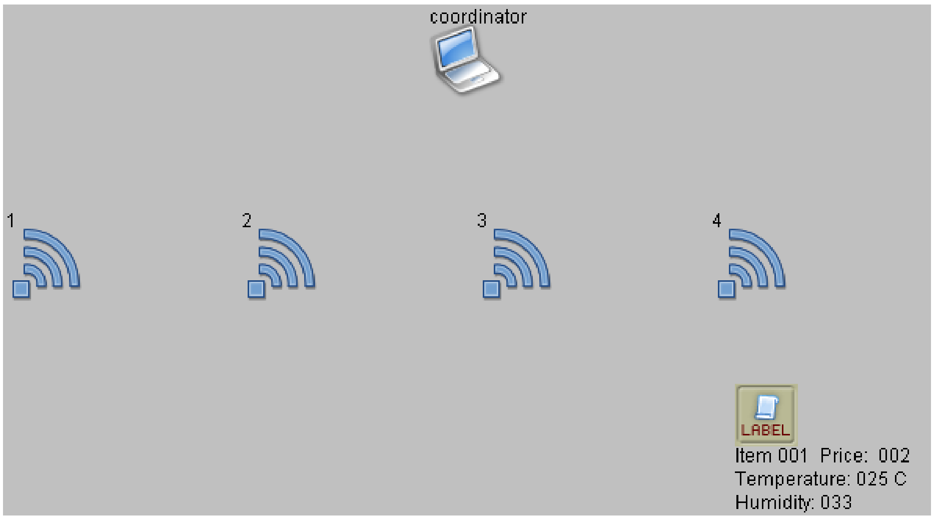


Figure 4-9: Interface of the demo for active ZigBee tag

The experiment illustrates the combination of the ZigBee and RFID technology. Using the network capability of ZigBee, the effective range of RFID can be extended. According to our test, the minimum interval time for sending out tag ID can be 5ms (200 packets/second). The demonstration systems show that the general RFID system tasks can be performed correctly using ZigBee devices in my architectures. This proved the feasibility of our designs in this chapter.

4.7 Discussion

In this chapter I have discussed the possible implementation of the ZigBee technology into the RFID systems. After discussing the ZigBee compatibility of the devices and communication links in the typical RFID system, I presented three architectures for integrating RFID into ZigBee based WSNs. They are the Agent network architecture for integrating WSN with existing networked RFID systems, the RAS architecture for integrating existing WSN systems with both the passive/semi-passive RFID and the active RFID, and the TAS architecture for integrating existing WSN systems with active RFID only. This is followed by the benefits of having such architectures compared with the current wireless technologies used in RFID products. Demonstration systems of the network-level integration architectures, the RAS and TAS architectures, on ZigBee-based hardware platform are shown in the last part of the chapter to validate the designs. In the next chapter I will compare and analyze the advantages of various architectures, which lead to a unified integrated architecture for multi-type integration of various RFID technologies and ZigBee-based WSNs in a logistics centre.

Chapter 5 Integrated ZigBee RFID Sensor Network Architecture

In Chapter 2 I classified the integration of RFID, sensor and wireless sensor networks into three levels: the hardware-level integration, the logic-level integration and the network-level integration. In Chapter 4 I also proposed architectures in logic level and network-level for integrating various RFID with ZigBee enabled wireless sensor networks depending on different scenarios. In this chapter I will discuss the design of integrated RFID sensor networks when no existing RFID or WSN system is deployed within a hybrid application scenario that requires multi-type system integration. I will first discuss the features of different integrations and architectures introduced in Chapters 2 and 4. A hybrid, unified and modularized RFID sensor network architecture is then proposed. A demonstration system is presented at the end of the chapter to validate our design.

5.1 Features of Existing Architectures

5.1.1 Hardware Level

5.1.1.1 Passive RFID Sensor Tags

There are two power supply options after attaching a sensor device on a passive RFID tag, which were described in Section 2.3.1.1. One is to equip the tag with additional battery to power the sensor and peripheral circuit, the other is to use ambient power scavenging (Roundy et al., 2004). Adding a battery on a tag changes the passive tag to a semi-active or even an active one, this will refer to the active RFID sensor tags which will be discussed later in this chapter in Section 5.1.1.2. Ambient power scavenging means gathering energy from the surroundings, for example from the RFID reader antenna. Such type of passive or semi-active RFID tags use inductive/propagation coupling to communicate with readers. Not only the reader devices for passive or semi-active RFID should be implemented in particular fixed positions, but also the requirements for antenna direction and angle are very critical. This has reduced the flexibility of the system. Large directional antennas are also required and at the same time the antenna RF power increases significantly when trying to have a longer reading range. These constraints could lead to high cost and health hazard caused by radio radiation. As a result, sensors have rarely been placed on those passive RFID transponders. In summary, passive RFID sensor tags are tested only in small and special systems due to three main reasons:

- Passive RFID tags do not have their own power resource. They use inductive coupling (LF & HF tags) or propagation coupling (UHF tags) with the reader antenna to gather energy for powering the chips in the tag and reflecting signals back to the reader. Though the current antenna technologies can support a passive RFID tag working in most frequency bands, they can hardly derive enough power resource to activate a sensor, especially in the UHF band, which is the main frequency band used by passive tags in logistics applications.

- The sensor in a passive tag can monitor its environment only when a reader interrogates the tag. This means: firstly, this limits the tag's application, as they cannot be used in the event driven system; secondly, close presence of the reader device in the scenario is required for passive sensor tags to be activated. However, for most of the physical conditions measured in logistics applications, such as temperature and humidity, this means that the reader itself can monitor the physical conditions that the passive sensor tags are trying to capture, which makes the passive sensor tags even less useful.
- High cost is still limiting their usage in massive applications. Passive tags are used for mass implementation in logistics applications mainly because of their low tag cost. Adding sensors will significantly increase the cost of each tag which is very unlikely to be acceptable for massive applications.

From the above discussion we can conclude that with current technologies, embedding passive RFID tags and sensor devices on a 'passive RFID sensor tag' is relatively impractical and not cost effective, though simple passive RFID tags are still indispensable in massive supply chain and manufacturing applications, especially when tracking the relatively low-value objects or consumable goods where the tags are very unlikely to be recycled.

5.1.1.2 RFID Sensor Nodes and Active RFID Sensor Tags

Comparing to embedding sensors in passive RFID tags, integrating sensors with active RFID tags is more feasible and relatively easier. Active tags are seldom used in massive supply chain applications as they have a higher cost and a limited battery life. But they still have a place in the scenarios where cost is not the primary concern and where the tasks are hard to be pursued by passive tags. However, systems with traditional active RFID sensor tags do not have the positive features of the systems using networked ZigBee RFID sensor nodes, which are organized in a self-organized network with multi-hop and power-efficient communication. The RFID sensor network using RFID sensor nodes could benefit from many features from wireless sensor networks, which is much more flexible and powerful compared with the traditional RFID system structure. In supply chain and manufacturing applications some large objects, such as vehicles and fixed machines, are difficult to be tracked by passive tags and need to be monitored in real time, the RFID sensor nodes could be a better option instead of using traditional active RFID tags.

5.1.2 Logic and Network Level

For the three architectures that were proposed in Chapter 4, I will illustrate their implementations in the fruit container scenario. This makes the different architectures easier to understand and to be compared by putting them into the same application. The fruit container application is chosen as it is a simple but typical and an integrated scenario that can represent all the aspects concerned in the logistics applications.

5.1.2.1 Agent Network Architecture

A system prototype for the agent network architecture given by Jedermann et al. (2006) has been introduced in Chapter 2. The advantage of the agent network architecture is that people can use typical RFID devices and sensor network devices to construct a cooperative RFID sensor network without requiring customized special hardware devices. This is a simple and cost-effective way, especially for companies who wish to develop a RFID sensor network based on their existing but separated RFID networks and sensor networks.

5.1.2.2 RAS Architecture

If we try to apply the 'Reader as a sensor' (RAS) architecture to the same fruit container application, the prototype can be described by Figure 5-1. ZigBee sensor network is implemented in the container to monitor the environment conditions during the transport; while the RFID reader in each container is given a RF transmitter and works as one of the sensor nodes. The reader uses a wireless sensor network protocol to communicate with the other sensor nodes deployed in the container. The ID information gathered by the reader is transmitted in the same way as the sensing information in the WSN and reaches the external network or server via the sensor network gateway device. The network scale can be increased when more containers arrive in the same place, with only one gateway device required. All information is processed at the central server and can be used for further higher-level integrations afterwards.

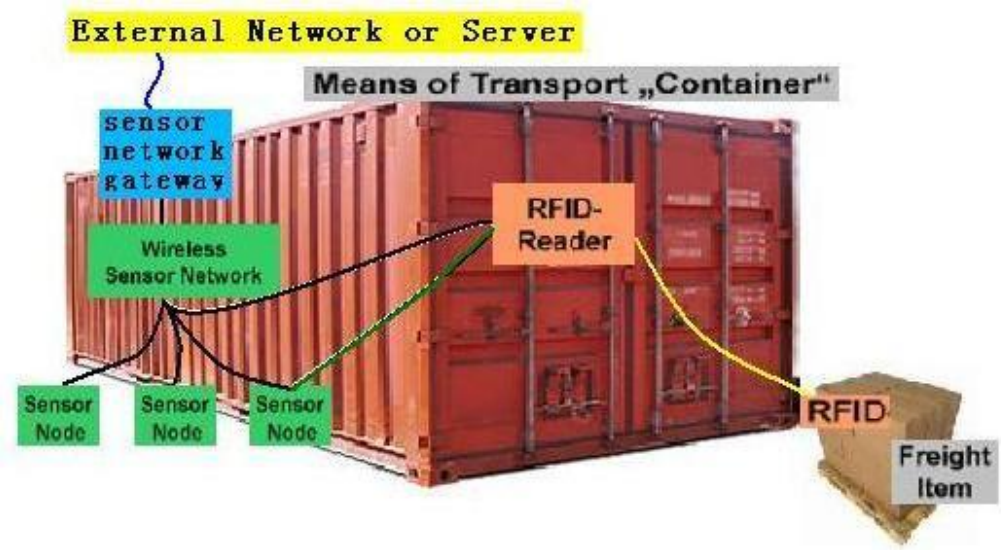


Figure 5-1: RAS architecture prototype

The RAS architecture presents a more integrated network for RFID and sensor networks. As ZigBee wireless sensor network technology is implemented not only on the individual sensor nodes, but also on the reader devices, such architecture can provide us with further advantages:

- Firstly, we can make the whole architecture more integrated by using a unified network protocol between every two RFID system local level layers described in Figure 2-1, therefore design and development of the system could be simplified.
- Secondly, ZigBee WSN technology allows multi-hop communication between RFID readers and the sensor network gateway device. This means that the readers are not required to be placed near the gateway, and could be installed anywhere within the transmission range of any sensor node.
- Thirdly, ZigBee WSN technology supports a self-organizing and self-healing in network topology, which make the data communication more reliable.
- Fourthly, ZigBee WSN technology is a low-speed and power-efficient communication standard, as the data transmission speed (20 ~250 kbps) is sufficient for RFID information, reader devices can benefit from the power-efficient feature of the WSN protocol as some of them may be battery driven.

The RAS architecture can integrate both active and passive RFID networks as the reading procedure and the communication between the tags and readers is very similar to the typical RFID systems. However, the related work that intend to use such architecture remain in the passive RFID area. This is because in the scenarios where active RFID tags are necessary, the tasks of the active tags can be pursued by the RFID sensor nodes in the following TAS architecture which has even more features than the traditional active RFID system.

5.1.2.3 TAS Architecture

An example of the implementation of ‘Tag as a sensor’ (TAS) architecture for the fruit container application is shown in Figure 5-2. The freight is tagged by active RFID sensor nodes in the box or pallet level. Active RFID sensor nodes should be used in order to support on-board sensors and the ZigBee technology. Individual sensor nodes can also be implemented in the containers as a supplement. These active RFID sensor nodes and normal sensor nodes from all containers can establish a ZigBee wireless sensor network. The ID together with corresponding sensing information from the tags can be sent to the sensor network gateway device using ZigBee communication. In this case, the tags can be considered as being 'read' by the gateway device which also functions as the active tag/sensor nodes reader. The difference with a traditional active RFID system is that in our prototype only one gateway-reader device is needed and it is not necessary for the gateway-reader device to have a read range that covers all freight area, because information can be transmitted using the multi-hop routing protocol of ZigBee technology.

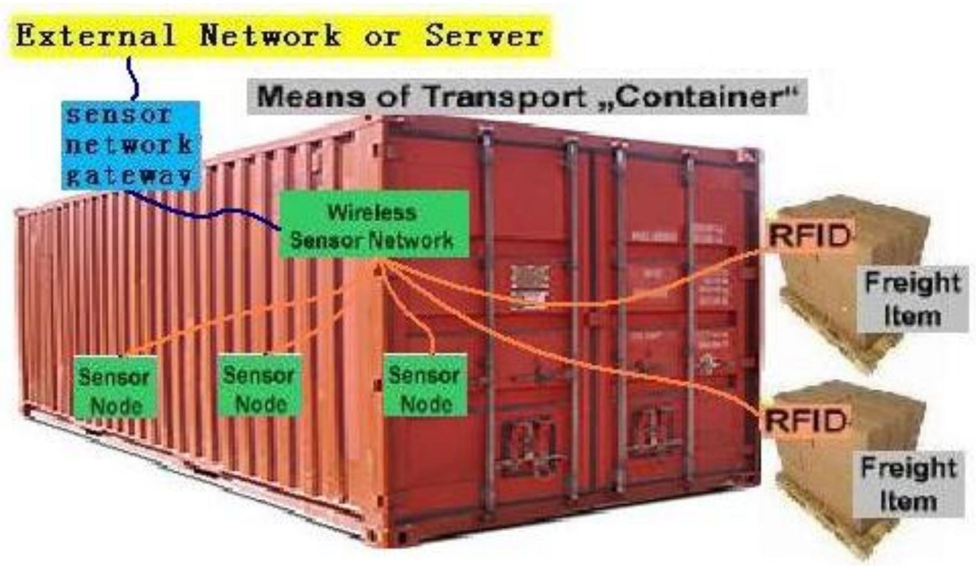


Figure 5-2: TAS architecture prototype

As shown in Figure 5-2, one of the significant features of TAS architecture is a unified and simplified structure, where the RFID sensor nodes discussed in Sections 2.3.1.1 and 5.1.1.2 could be easily integrated into the system. Systems with such architecture are suitable for the operation of active RFID systems to track the large or valuable objects during their transportation. The other features of this architecture when using RFID sensor nodes include:

- A reliable and power-efficient communication brought to the tags/nodes by the ZigBee sensor network protocol. Power efficiency is more important in this case as active tags have a limited power resources;
- The possibility for server and reader devices to interrogate a tag as long as it is in the covered by area of the whole sensor network. This feature enables a real-time tag/node state interrogation function with a further real-time localization function to become possible.

5.2 Integrated RFID Sensor Network System Architecture

Based on the discussion in Section 5.1, each integration approach has its own features and is suitable for particular applications. Passive tags are practical in massive implementations for cheap and non-recycled goods in logistics applications. The RAS architecture is the most suitable solution for integrating passive systems into ZigBee sensor networks; on the other hand active RFID sensor nodes are better than active tags in many ways, and perform better in the TAS architecture. Individual sensor nodes without a specific identification or the tag reading functions can work in all the architectures at an appropriate layer. Comparing to the two network level integration architectures, the 'Agent network architecture' is the most suitable prototype for enterprises who want to combine their existing RFID system with sensor networks. However, if a brand new system is being constructed, the RAS and TAS architectures are better as we can profit from a unified WSN network architecture, which has features such as a much more reliable network backbone, power-efficient data transmission protocol and unified network architecture and standard. The TAS prototype does not require any particular reader device, thus it can be cost-effective for the small and medium applications. For the large applications the RAS prototype could be the better choice as the passive systems will be adopted when tag cost becomes more critical.

Based on the above discussion, in a large and complex scenario that all the related systems, including active RFID, passive RFID and sensors, are required, each of those architectures could thus be suitable for different parts of the whole application. Even some smaller applications may still require more than one of these approaches for different parts. But choosing different system architectures for different parts of application separately will increase the system complexity, bringing more difficulties and cost to system integration and management. In this case a unified and integrated RFID sensor network architecture is required.

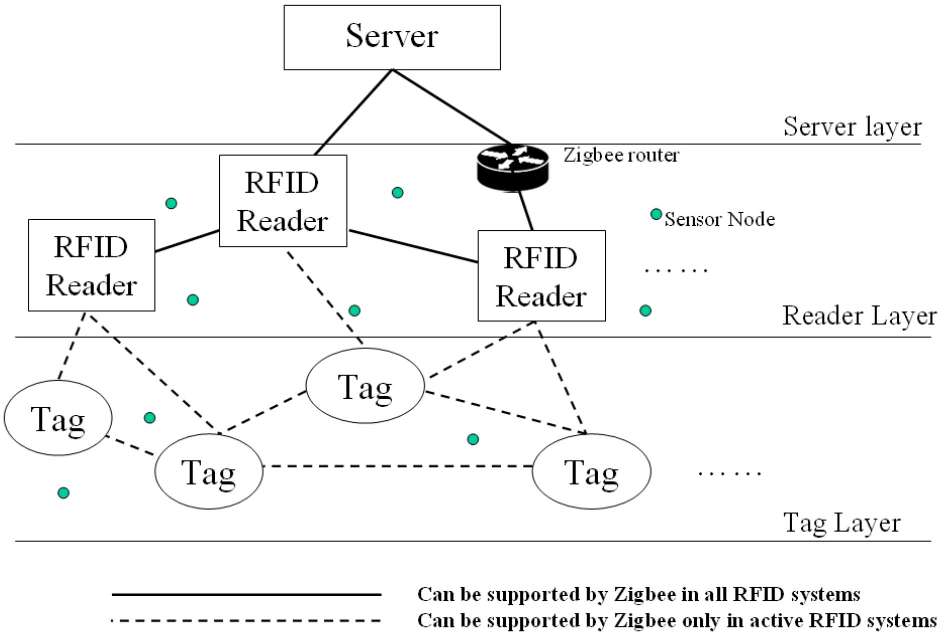


Figure 5-3: Integrated hybrid sensor network system architecture

Our RFID sensor network architecture for such hybrid applications is presented in Figure 5-3, where the small round circles represent ordinary wireless sensor nodes, the solid lines represents the connections that can be supported by ZigBee in all RFID systems and the dotted line represents the connections that can be supported by ZigBee only in active RFID systems. The relative positions of the three local layers, which are the tag layer, reader layer and server layer, in the typical RFID system structure described in Section 2.1 are also presented in the figure.

In this integrated architecture all communications inside the network are supported by ZigBee technology except the communication between passive RFID tags and their readers. Some ZigBee routers will be modified to be able to read the wireless sensor nodes with ID like the active RFID system. Readers deployed outside the server's direct radio range, no matter whether they are passive or combined router/reader devices, can benefit from the sensor network protocol to communicate with the server through the other reader and router devices using multi-hop routing protocol. Although traditional active RFID can also be involved if their reader can be made to be compatible with the ZigBee technology, the ZigBee based RFID sensor nodes are recommended to undertake the identification for large valuable objects in place of the traditional active RFID tags. These RFID sensor nodes can be read by the modified ZigBee routers or even the server/coordinator device directly depending on applications. Individual wireless sensor nodes without ID function can be implemented in the scenario as supplement to monitor the environment, which is the typical task for the original pure Wireless Sensor Networks. This integrated architecture for hybrid RFID sensor network is actually a combination of the different network-level architectures using the wireless sensor network protocol. Thus it can benefit from the features of all different architectures discussed in Section 5.1. Due to the flexibility of the sensor network architecture, modularisation design can be carried out for developing such types of systems. Sensor nodes, combined router/reader devices acting as virtual active RFID systems, ZigBee enabled traditional passive and active RFID reader devices can be made into system-compatible, plug and play modules. This can simplify the design and implementation of the final system for each different application.

5.3 Demonstration System

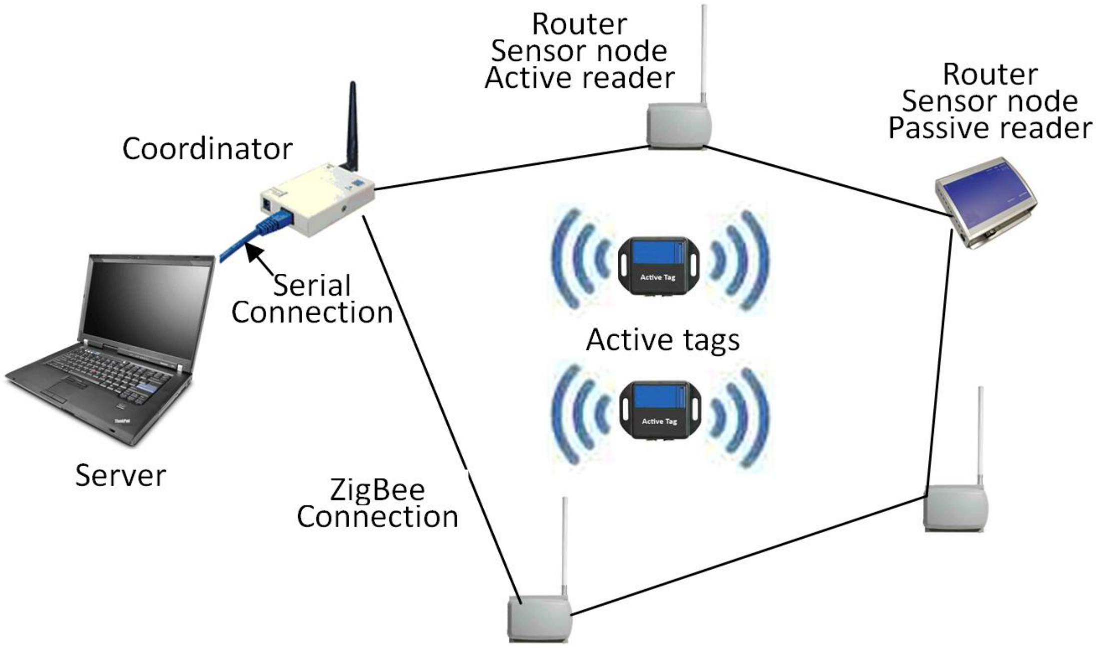


Figure 5-4: Demonstration system layout

I built a complete integrated demonstration system to show the feasibility of our hybrid architecture design. The components and structure of the demonstration system are shown in Figure 5-4. The demonstration system consists of one computer server, one ZigBee coordinator, three environmental sensor nodes which also function as active RFID readers, two active ZigBee RFID sensor tags and one ZigBee-enabled passive RFID reader. All devices are linked together within one self-organized ZigBee wireless sensor network. Active RFID tags report to the active RFID reader nodes periodically, and both the active RFID readers and the passive RFID readers report the ID information to the coordinator periodically. The sensor nodes also report the environmental information to the coordinator periodically. All the reporting intervals can be set and reconfigured separately. The ZigBee coordinator device is connected to the computer server via a serial connection, and all the information is displayed on the server screen by a demonstration interface that shows an imaginary scenario of a general production workshop or warehouse.

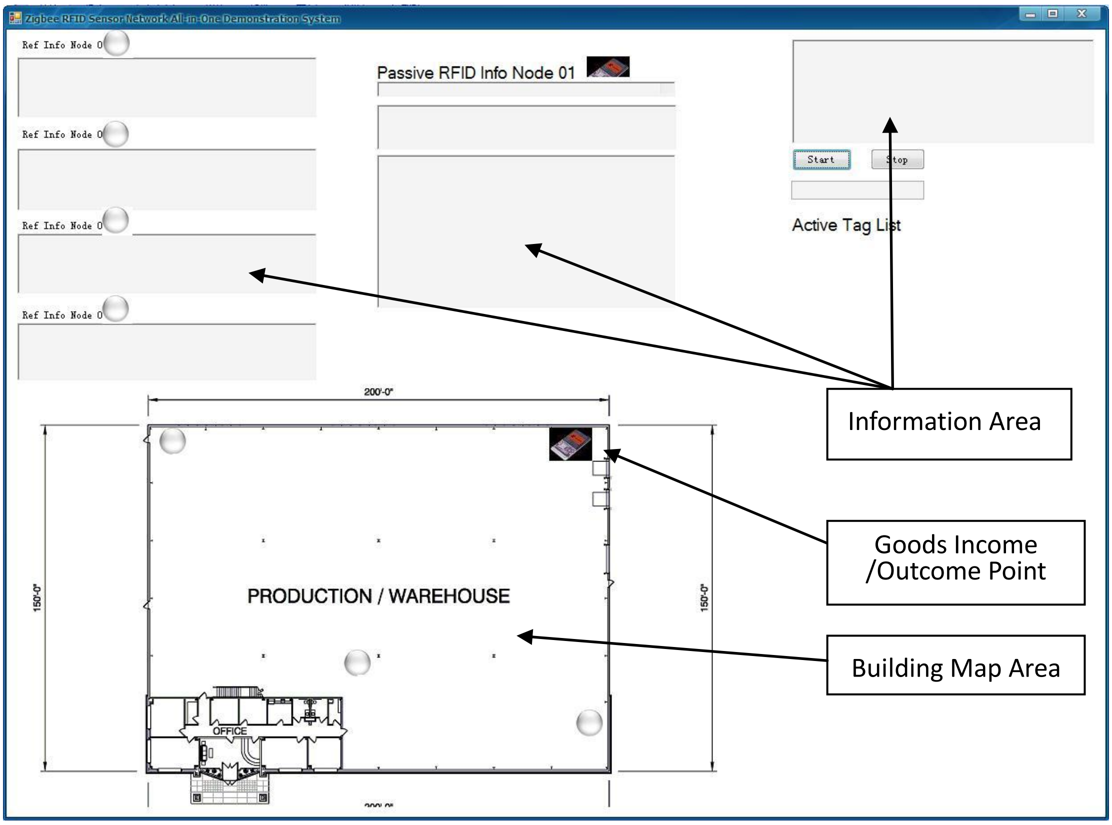


Figure 5-5: Demonstration system interface

Figure 5-5 is the demonstration interface on the server computer. The structure of the demonstration system and its deployment is shown in the building map area of the interface. The ZigBee coordinator together with the server computer is considered to be located in the control room within the office area. Environmental sensor nodes, which also act as active RFID reader devices, are deployed at the environmental monitoring points; they also need to cover the production/warehouse operation area for the active RFID function to work properly. A ZigBee-enabled passive RFID reader is deployed at the illustrated goods inward/outward point. The ID information and the environmental information will be displayed in the information area of the interface. The deployment of the system was proved to be simple and fast. As most of the devices in the system use on board battery as power resource, their deployment is simply placing and turning on. With the self organizing of the wireless sensor network backbone, the communication links are established instantly and the data is reported back quickly.

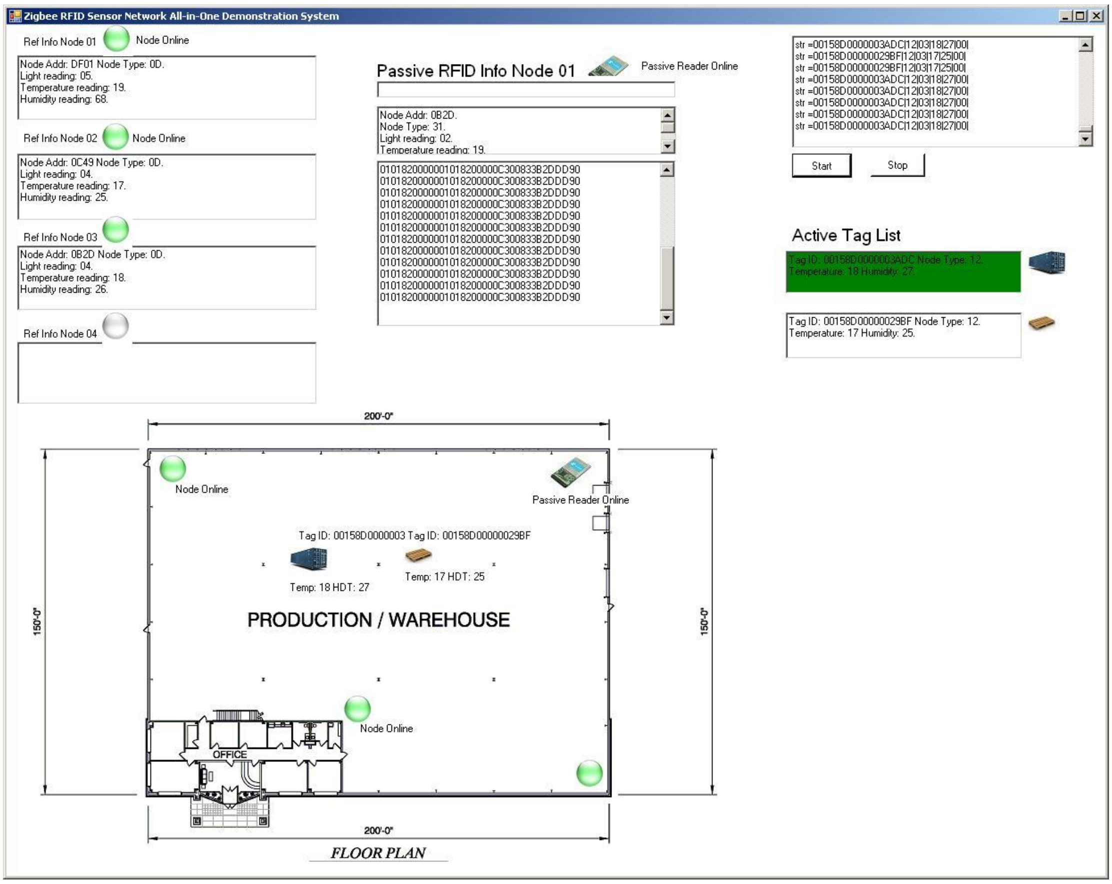


Figure 5-6: Demonstration system interface while the system in operation

In order to start the demonstration system, what we need to do is simply switching on the coordinator first, connecting to the coordinator from the server and turning on the sensor nodes and various readers. Passive tags do not need to be operated and active tags can be activated at any time.

Figure 5-6 shows the server interface while the whole system is in full operation. The dark icons in both the information display area and the building map area indicate that the nodes they represented are active online, and are reporting environmental sensor data as well as active RFID information regularly. The environmental sensor data from each node is displayed under the node name tags located in the top left of the screen. Two active ZigBee RFID tags, which could represent a container or a pallet, are within the site and have been read by the active reader nodes; their icon with ID and on-board sensor data are displayed in both building map area and information area of the interface. The bright passive reader icon indicates that the ZigBee enabled passive RFID is active online. In our demonstration the passive reader interrogates its scanning area regularly and reports to the coordinator. The passive tag IDs read by the passive reader are displayed in the corresponding information area located in the top middle of the interface. As a demonstration system, the information box that was updated most recently is turned green/dark. A debug window in the top right corner of the interface shows all the communication on the coordinator. The demonstration system starts and works perfectly, proving the feasibility and features of our architecture design.

5.4 Discussion

In this chapter the comparison of the existing architectures used to combine RFID, sensors and WSN in different levels are discussed. Those designs are usually developed for very small and simple scenarios or even for demonstration only. Each of them has its own features and is suitable for particular scenarios. As in large and complex applications each of these integrations or architectures could be suitable only for different parts of the whole scenario. In this case, I presented and discussed an integrated RFID sensor network architecture for hybrid applications. It presents a unified and flexible system structure for multi-system integrations in logistics applications with hybrid inventory types. A demonstration system of the architecture is developed on ZigBee based hardware platform to validate the design.

Chapter 6 Connectionless Inventory Tracking Architecture - CITA

In Chapter 5, an integrated ZigBee RFID sensor network architecture was designed as an 'all-in-one' system solution, which integrates sensors, WSNs and both active and passive RFID systems for logistics centres' resource management. However, such architecture aims to support only ID and environmental sensing functions and has to be further developed to satisfy the applications with a higher requirement level when location awareness is considered to be useful. In this chapter I investigate a reliable mobile tracking architecture for ZigBee RFID sensor networks, which targets the requirement level at a higher level, in which real-time location awareness of inventory/goods is required. A Connectionless Inventory Tracking Architecture, the CITA architecture, based on ZigBee RFID sensor network is proposed for inventory management applications. Such an architecture features a consistent network structure, low energy consumption and no accumulated error for localization algorithms with the least additional cost and hardware required on top of the existing integrated ZigBee RFID sensor network systems. A simple demonstration system is also developed to illustrate the feasibility of our design.

6.1 Current Prototypes for ZigBee-based Tracking

One of the main tasks of the ZigBee RFID sensor network is inventory tracking. Various solutions have been proposed by researchers for ZigBee-based mobile tracking. Blumenthal et al. (2007) proposed a ZigBee indoor tracking system in which all the reference nodes as well as the mobile target nodes are ZigBee router devices. This ensured a fully-connected network in which the mobile node can communicate with all the reference points nearby in order to satisfy the centroid localization algorithm adopted. The prototype proposed by Alhmiedat and Yang (2008a) used a similar but improved network architecture by modifying the localization algorithm with a triangle algorithm and weighted LQI model. Such systems require dense router deployment and the whole network is a full router network. But in most cases, this is not practical for real applications. Typical ZigBee networks have only a small number of router devices in the network while most of the task nodes are end devices so that they can be kept in sleeping mode most of the time to save battery life.

Alhmiedat and Yang (2008b) proposed an improved system model in which the fixed reference points can either be a router or an end device. Mobile nodes are still ZigBee routers. Using a proposed re-connection phase the mobile router can gain access to all the nearby fixed nodes. The mechanism in the re-connection phase is actually to force the network to re-organize and the authors argued that there is a chance that the nearby fixed end devices may change their parent node to the mobile router. The problem with such a system is that the network is under reorganization all of the time and, from our experiments with ZigBee hardware, this procedure consumes a significant amount of power on the end devices. Furthermore, the system performance is very likely to decrease rapidly when the number of mobile nodes in the same area increases, because when one mobile node is measuring the RF strength by communicating with the reference nodes within the area, it will fully occupy all the end device reference nodes, making them unable to talk to any other mobile nodes in the same area. Another important issue is that as all the mobile nodes in such a system are ZigBee routers the system's network topology becomes inconsistent. This effect will be discussed in the following section.

A further improved model based on the work of Alhmiedat and Yang (2008b) is an attempt to overcome the reference nodes occupying problem. The method proposed is when the first mobile node is being tracked and occupies some of the end device reference nodes within the area; the other mobile nodes will consider the tracked mobile node as a reference node when looking for reference triangulation. As soon as it find its own reference triangulation and is tracked, the other mobile nodes will also consider it as a reference point. While this method seems to allow multiple mobile nodes in the same area to be tracked simultaneously, its network structure is still inconsistent and it brings a new problem of accumulated localization error. Using a mobile node as a reference point will result in its localization error being partly accumulated into the error of the second mobile node's location calculation.

6.2 CITA Architecture

6.2.1 Concept of Design

ZigBee routers participate in packet relaying within the network which means they not only need to conduct much more frequent RF transmission but also need to be active all the time. Both of these significantly cut down the battery life and make the use of ZigBee routers as mobile nodes impractical in real applications. According to our experiment, a ZigBee router with two AAA size batteries can work for only up to 24 hours before the battery is dead. On the other hand, ZigBee End Devices (ZED) are based on IEEE802.15.4 RFD (Reduced Function Device); that means they have a simpler structure, cheaper cost and less energy consumption because of their simple role in the network. They do not take part in the network routing mechanism and can thus be put into sleep mode while idle. Using the same set of two AAA batteries the measurement and calculation on our hardware suggest that with a 0.5 second RF active time and 3 minute sleep time a ZED can expect a battery life up to a year, which can be further extended to 2 years if the application can allow either a longer sleep time or a larger battery such as two high-capacity AA cells. This enables the mobile node to have a much more reasonable battery life, thus making ZEDs more suitable to be used as the RFID sensor tags on pallets and trays.

Another reason to favour ZED as mobile nodes is that the mobility of routers causes extreme routing overhead because their movement causes continuous changing of the logical topology in the network backbone and results in the mesh network constantly being reorganized (Sun et al., 2007). The movement of a router also results in all the ZEDs coupled with it being disconnected and having to search and join the network again and again, which is a very power consuming operation. The movement of router devices in a ZigBee network causes heavier traffic, inconsistent network topology and larger energy consumption not only by itself but also by all the end devices.

On the other hand, ZEDs are also preferred to be used as the fixed terminal nodes for two reasons. Firstly, they are more power efficient and could stand longer during possible power loss time in HLCs. Secondly, increasing router numbers results in more hierarchies in network topology, according to the work of Liang et al. (2006) the more hierarchy a ZigBee network has, the more complexity it has with a concomitant lowering of efficiency in mobility support.

But using ZED as mobile nodes is not a simple adoption. Tagging the freight pallets with ZEDs leads to a problem with the network connection/link number restriction. This is the reason why current ZigBee-based tracking prototypes use routers as mobile nodes. The network link number of a ZED is limited by ZigBee specification to only 1 up-bound connection to its parent node, which must be a ZigBee router (ZR). This means if a mobile target is tagged with ZED it can only have one connection at the same time while a typical localization algorithm requires at least three. To overcome this problem our connectionless architecture is proposed.

6.2.2 Connectionless Tracking Architecture

People naturally think that if a mobile node needs to be tracked it has to be connected to at least three reference nodes with known positions to satisfy the existing localization algorithms. This is the approach that all the existing systems take. But actually it can be enough for the mobile nodes to simply "listen" to the reference nodes instead of having to "connect" with them, which means they do not have to be network linked with the ability for 2-way data transmission. For network standards such as ZigBee, WiFi, Bluetooth etc, the reason why two nodes need to be network linked is that they need to have a guaranteed direct data transmission. A tracked mobile node does not need to send data to the fixed reference nodes; and while RF power strength is measured by the receiver, it does not need to receive any data except for the identity of the reference nodes. Based on this idea, a connectionless tracking architecture at the network level is proposed for the ZigBee RFID Sensor Network inventory management system, as shown in Figure 6-1.

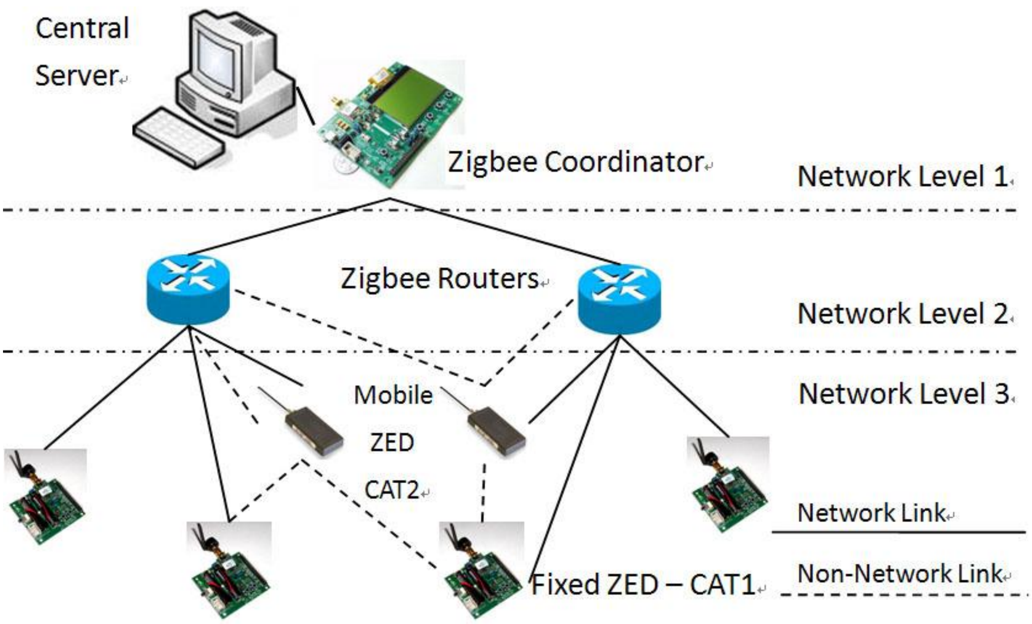


Figure 6-1: Connectionless tracking architecture

Network level 1: A ZigBee coordinator together with the local server at the top level of the architecture is responsible for establishing and initialization of the indoor

ZigBee network. The coordinator also acts as the sink node of the ZigBee network. It is connected directly to the central server via a cable link, such as RS-232 or USB serial interfaces using which, the central server is able to retrieve all the information gathered from the network nodes.

Network level 2: At the mid-level ZigBee router devices are responsible for data relaying and ensuring the full RF coverage of the network within the building. ZigBee is a multi-hop network in which information from a terminal node goes through a virtual path before reaching the destination nodes/server. The path is constructed by a chain of several routers which pass the information packages along from the previous node to the next one. In the ZigBee specification, the routers are required to have access to a main power resource so that they can remain active; these router devices can provide a full network coverage as long as we have at least one router reachable, or in other words within its RF range, anywhere in the building. Instead of the much denser router deployment requirement in the traditional ZigBee tracking systems, this minimum requirement for network coverage is enough for the implementation of our system architecture. The detail will be further discussed in the "tracking CAT2 mobile nodes" part later in this section

Network level 3: At the lowest level there are ZEDs for data collection. These ZEDs are divided into two categories. The first category (CAT1) includes those fixed data nodes responsible for gathering information at specific locations. ZEDs carrying temperature, humidity or chemical sensors deployed at various environmental control points in the warehouse fall into this category. The other category (CAT2) includes the mobile ZEDs located on pallets or trays. The CAT1 ZEDs also act as reference nodes in the connectionless tracking system; while the other ZEDs in CAT2 make use of them as well as the routers as reference points for their localization. Dedicated reference devices may also be used in cases where a CAT2 mobile node cannot cover within the RF range of at least 3 reference nodes. The dedicated reference device can be either a ZigBee router or a CAT1 node. CAT2 nodes also carry a passive RFID tag to be used during the goods receiving and shipping procedure for easy association and dissociation between the node and the goods on the pallet to which it is attached. We also need to consider ZigBee-enabled RFID passive readers and determine their category: A reader device installed at a fixed position is defined as a CAT1 node, otherwise if it is a mobile reader carried by staff or a forklift, it will be considered as a CAT2 node.

Data communication: The data communication of the inventory management system is handled completely by the ZigBee standard. Primary data communications that occur in the system are regular information reports from all the level 3 nodes to the coordinator/server, the data stream from the ZigBee enabled passive RFID readers at various access points to the server and the data inquiries started by the server to one or some of the network nodes. These data communications are typical point-to-point network data transmissions that can be managed by the standard network protocols used by ZigBee.

Tracking CAT2 mobile nodes: The connectionless tracking mechanism of our ZigBee RFID Sensor network can be described as follows: the CAT2 mobile nodes are typical ZigBee end devices equipped with a RF listener module whose function is to analyze the packets it can hear within the channel of the ZigBee network. From each packet the RF listener module retrieves and provides the CAT2 node processor with the ID of the reference node which sent the packet, the RF power strength and error check result. The error check result indicates whether there were collisions or significant interference during the packet transmission. A negative error check result will invalidate the reading of the source ID, which may have been incorrectly transmitted, and its RF power strength reading, which may be incorrect due to collision or interference. If the check is passed then the source ID and RF strength reading are accepted as a reference pair, which will then be sent via the ZigBee network to the server to update the database. A localization algorithm on the server could then locate the CAT2 nodes based on the reference information pairs in the database, while the inventory tracking system then tracks goods in the warehouse by finding the corresponding inventory associated with the CAT2 node ID in the inventory database. Most of the existing localization algorithms require at least three reference points for a mobile node to be located with a satisfactory accuracy. Using the CITA architecture, the minimum implementation requirement of is to ensure that at any place in the building/site, a CAT2 mobile nodes should be within the RF range of at least three reference nodes, of which only one node is required to be a router providing network access. This has significantly lowered the implementation requirements. Dedicated CAT1 reference nodes can be deployed where necessary to help meet this requirement.

6.3 Deployment of CITA Network Architecture

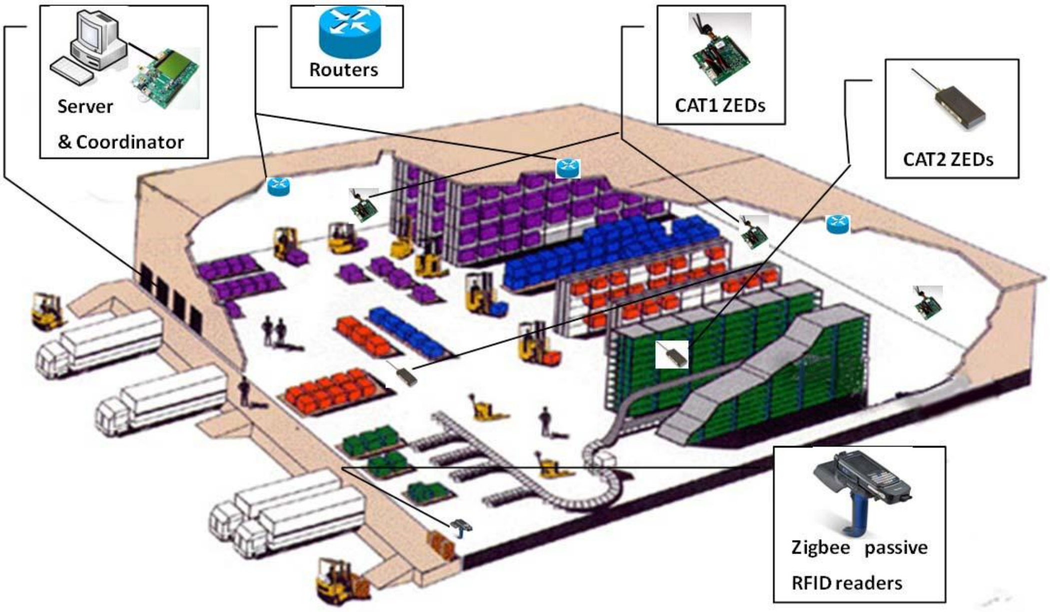


Figure 6-2: ZigBee based CITA architecture implementation

An illustration of the network implementation of a ZigBee-enabled RFID sensor network with CITA architecture is shown in Figure 6-2. The central server together with the ZigBee network coordinator at network level 1 can be installed in the warehouse office. The coordinator is responsible for the establishment of the ZigBee network, and acts as the network sink node from which the server will retrieve all the information collected by the network devices. The central server is expected to run the database service and exchange information with user applications on demand, thus it should be at least a dedicated PC-level device with a mains power resource. As the ZigBee coordinator is physically connected with the server via a serial interface, it can easily obtain main power supply and thus always be kept active.

- ZigBee routers at network level 2 will then be deployed in the site. We configure the ZigBee network as a mesh network to enable better mobility support (Sun et al., 2007), thus the deployment criteria for the router devices are: The ZigBee coordinator must connect to at least one router;
- Each router must be able to connect to at least one other router that is reachable by the ZigBee coordinator device through a multi-hop path.

To achieve a proper router deployment the procedure is similar to drawing a topological graph, in which the nodes are ZigBee routers and two nodes are considered to be linked if the routers they represent are within each other's RF range. The deployment procedure can be simply described as:

- Deploy the router devices from near the coordinator, and then extend the network coverage by deploying more routers until the whole building/site is fully covered;
- For each new router deployed, make sure it can either connect directly to the coordinator device, or it can connect to at least one router that is already deployed.

ZigBee routers should be supported by mains power and always be kept active to guarantee the network connectivity (ZigBee Alliance, 2004). They can be deployed at locations where it is convenient for a mains power connection as long as the deployment procedure above can be satisfied. In addition, they can carry an on-board battery for working in the emergency situations, such as when the logistics centre encounters a temporary power lost. According to our experience ZigBee routers can work for several days powered only by AAA batteries.

With a full ZigBee network coverage deployed, the end devices at level 3 can then be deployed. CAT1 nodes are fixed data nodes being responsible for gathering information at specific locations. Their deployment will be based on the warehouse management regulations, which have no influence on the network architecture. CAT1 nodes carrying temperature sensors which are deployed at various warehouse temperature control points provide one possible example.

CAT2 nodes are deployed on the standard pallets or trays. These nodes also carry passive RFID tag so that they can be easily and accurately associated or dissociated with the inventory they are carrying by the ZigBee enabled passive RFID readers.

Since the routers and the CAT1 nodes have fixed position after deployment, they will be used as reference points for tracking CAT2 nodes. To ensure the operation of the system's tracking mechanism, dedicated CAT1 reference nodes can also be deployed to positions where a CAT2 node cannot be within the RF range of at least three reference nodes.

6.4 Implementation of General Functions

Typical inventory management systems usually have a logical structure with three virtual components: the data collection network, the central database service and the user application. A ZigBee RFID sensor network is part of the data collection network. The central database service is responsible for storage, maintenance and responding to inquiries of the data gathered by the data collection network. User applications are the customized software normally with graphical user interfaces (GUI) for the management staff, who are not normally professionals in technology or informatics. Various logics for management functions, such as layout management, location reservation, consolation, pick-to-clear etc., concerns only the data exchange between the database service and the user application; these high level functions do not require instant action and will not affect the architecture of the data collection network where our RFID sensor network is located. In my research I focus on the data collection network of the whole system. Generally speaking, the functions of the data collection network can be summarized as: updating the inventory and environmental information in the central server database either on demand or on a regular basis, which can be based on a predefined time interval, the occurrence of certain event triggers or the mix of the two. Three primary low-level functions related to the data collection network are identified with discussion on how they can be supported by our architecture.

Inventory inbound and outbound

The inventory inbound procedure is assisted mainly by ZigBee passive RFID readers installed at the warehouse receiving area (CAT1 readers) or carried by staff or forklift (CAT2 readers). The purpose of this procedure is to identify the incoming goods, and allocate a CAT2 device to the goods' pallet or tray. Passive RFID tags are carried by the CAT2 nodes attached to the pallets and trays. They will be recognized and recorded when detected by the passive RFID reader. If the incoming goods have passive tags in the package, they can easily be associated with the CAT2 node allocated to them through the reader. The working procedure of the ZigBee RFID sensor network can be formulated in 3 steps:

i). ZigBee-enabled passive RFID reader notifies the central server to initialize a goods inbound procedure;

ii). After receiving confirmation the reader identifies the goods and the CAT2 node from their passive tags and sends their id to the server through the ZigBee network;

iii). The server receives this information and updates its database by associating the goods with the CAT2 node.

In the situation where incoming goods do not have pre-attached passive RFID tag the warehouse staff will be responsible for providing the server with goods information using the input interface on the ZigBee-enabled passive RFID reader (Yang et al., 2007). Outbound/shipment of goods has a very similar procedure for the ZigBee RFID sensor network to follow. The only difference is that in step 2 the server will dissociate the goods with the CAT2 node instead of associating with them.

Regular environment and inventory report

Inventory information is updated regularly to provide a relatively constant view of the goods' location and condition. CAT1 nodes are required to report to the server periodically in a predefined time interval t. Their communication with the server will result in information packets exchanging between these CAT1 and their parent nodes as well as between the routers nodes themselves. CAT2 nodes analyze the communication within their RF range for a period of t_l, identify the sender of all packets it "heard" and the RF strength during their reception to generate reference information pairs. These pairs are then sent to the server via the network and are stored in the server database for localization. The CAT2 nodes will then switch to sleep mode and repeat this procedure periodically with a predefined time interval T. The parameters t, t_l, T will be discussed in Section 6.5.

Inventory inquiry and picking

Inventory inquiry does not necessarily cause an action to be carried out within the RFID sensor network, as all the inventory and environment information in the server database is refreshed regularly and thus can be considered to be up-to-date. Actually the ZigBee standard does not support remote network wake-up. It is difficult to activate an end device in the deep sleep mode until it reaches the end of the preselected sleep time interval and is woken up by its own on-board events. Thus enquiries from user applications can be well served by the server database service and will not involve the data collection network. The picking procedure is assisted by the ZigBee-enabled mobile passive RFID readers carried by staff or forklifts (readers in

CAT2). The picking procedure can be described as:

i). ZigBee-enabled passive RFID reader notifies the central server to request permission to initialize a picking procedure;

ii). After receiving confirmation from the server the reader will then identify the picked goods and the CAT2 node on its original pallet by their passive tags and send their id to the server through the ZigBee network;

iii). The server receives this information and updates its database by dissociating the picked goods and the CAT2 node on original pallet;

iv). the reader then identifies the CAT2 node on the new pallet/tray for picked goods from its passive tag and sends id to the server;

v). The server updates its database by associating the picked goods with the CAT2 node on new pallet/tray.

6.5 CITA Operation Parameters *t, T* and t_l

The power resource used at network level 2 and level 3 nodes are different. CAT2 nodes at level 3 are powered by on-board batteries and thus need to have a power efficient operation strategy. We use the same definitions given in Section 6.4for *t*, *T and* t_l. Our recommendation for the value of the length of channel listening period is $t_l \in (t, 2t]$. A t_l in this range should be long enough for the CAT2 node to correctly receive packets from all the reference nodes covering it. In the remainder of our discussion we set $t_l = 2t$ unless otherwise noted.

The selection of the value of *T* and *t* is discussed together as they are related to each other. After a battery is chosen and the battery capacity fixed, the power consumption of a node depends on its average working current. For ZigBee end devices like the CAT1 and CAT2 nodes, the result is also related to the length of active time and sleep time. There are two situations possible in the real applications that result in two different strategies to determine t and T.

6.5.1 Situation 1 - Fixed Nodes with Main Power

The first situation is that all the fixed end device reference nodes use main power. In this case we are only concerned about the battery life of CAT2 nodes, which can be expressed in Equation (6.1): B_{CAT2} represents the CAT2 nodes' battery life in hour, $E_{battery}$ is the capacity of the battery set carried on board in mAh, I_{ZED} is the average working current of CAT2 nodes in mA.

$$B_{CAT2} = \frac{E_{battery}}{I_{ZED}} \times \frac{T}{t_l} = \frac{E_{battery}}{I_{ZED}} \times \frac{T}{2t} \tag{6.1}$$

From Equation (6.1), as $E_{battery}$ and I_{ZED} are decided by hardware design, they can be considered as constants in our discussion. Thus the battery life B_{CAT2} could be extended by simply increasing the ratio between T and t. Based on this result value of T and t can be selected by taking into consideration of the system specifications in practice. For example, in a final system design $E_{battery}$ and I_{ZED} have been fixed by hardware design, and the management regulations require a battery life of $B_{\min CAT2}$, maximum updating interval for environment monitoring at $t_{\max}$ and minimum inventory tracking updating interval at $T_{\max}$. To satisfy the system specifications we can use $t_{\max}$ and Equation (6.2) to calculate a corresponding $T_{t\_\max}$, and then with $T_{\max}$ and Equation (6.3) we get a corresponding $t_{T\_\max}$:

$$T_{t\_\max} = \frac{2t_{\max} \times I_{ZED} \times B_{CAT2}}{E_{battery}} \tag{6.2}$$

$$t_{T\_\min} = \frac{E_{battery}}{I_{ZED}} \times \frac{T_{\max}}{2B_{CAT2}} \tag{6.3}$$

The value of T and t could then be decided by one of the following two rules that are actually equivalent:

i) if $T_{t\_max} > T_{max}$ then select $T = T_{max}$, $t = t_{T\_max}$, otherwise set $T = T_{t\_max}$, $t = t_{max}$;

ii). Or if $t_{T\_max} > t_{max}$, then select $T = T_{t\_max}$, $t = t_{max}$, otherwise set $T = T_{max}$, $t = t_{T\_max}$.

6.5.2 Situation 2 - Fixed Nodes with Batteries

The second situation is that all the end devices, which include both CAT1 and CAT2 nodes, are battery powered. In this situation we are concerned not only about the mobile CAT2 nodes, but also about the CAT1 reference nodes' battery life. This can be expressed in Equation (6.4), in which B_{CAT1} represents the CAT1 nodes' battery life in hour and a new parameter τ represents the active time of CAT1 reference nodes in each updating period t .

$$B_{CAT1} = \frac{E_{battery}}{I_{ZED}} \times \frac{t}{\tau} \qquad (6.4)$$

In this situation we consider the concept of network battery life, which is defined as the time when the first out-of-battery node appears in the network. In the system we have:

$$B_{network} = \min(B_{CAT1}, B_{CAT2}) \qquad (6.5).$$

To find the rule for achieving maximum value of $B_{network}$, first normalise T and t into expressions of τ . As for CAT1 nodes the communication time $\tau << t < T$, let:

$$T = a\tau, t = b\tau \qquad (6.6)$$

Equations (6.1) and (6.4) are normalised as:

$$B_{CAT1} = b \times \frac{E_{battery}}{I_{ZED}}, B_{CAT2} = \frac{a}{2b} \times \frac{E_{battery}}{I_{ZED}} \qquad (6.7)$$

Equation (6.7) shows that when $T = a\tau$ is fixed, changing the coefficient b of CAT1, the data updating interval, will affect the battery life of both CAT1 and CAT2 nodes, but in an opposite direction. With inverse proportion between B_{CAT1} and B_{CAT2}, $B_{network}$ will reach its maximum value if and only if the following condition is satisfied:

$$B_{CAT1} = B_{CAT2} \tag{6.8}$$

Substitute Equation (6.7) into Equation (6.8), we have:

$$b \times \frac{E_{battery}}{I_{ZED}} = \frac{a}{2b} \times \frac{E_{battery}}{I_{ZED}} \Rightarrow a = 2b^2 \tag{6.9}$$

This suggests that for a selected coefficient a (or b), $B_{network}$ reaches its maximum value if and only if b (or a) satisfies Equation (6.9). Substitute Equation (6.9) back into Equation (6.6), we get the ratio between T and t for achieving maximum $B_{network}$.

$$\left.\begin{array}{r} t = b\tau \\ T = a\tau = 2b^2\tau \end{array}\right\} \Rightarrow \frac{T}{t} = 2b \tag{6.10}$$

Equation (6.10) can be used for selecting the proper value for T and t to achieve the maximum network battery life in real applications.

6.6 Demonstration System

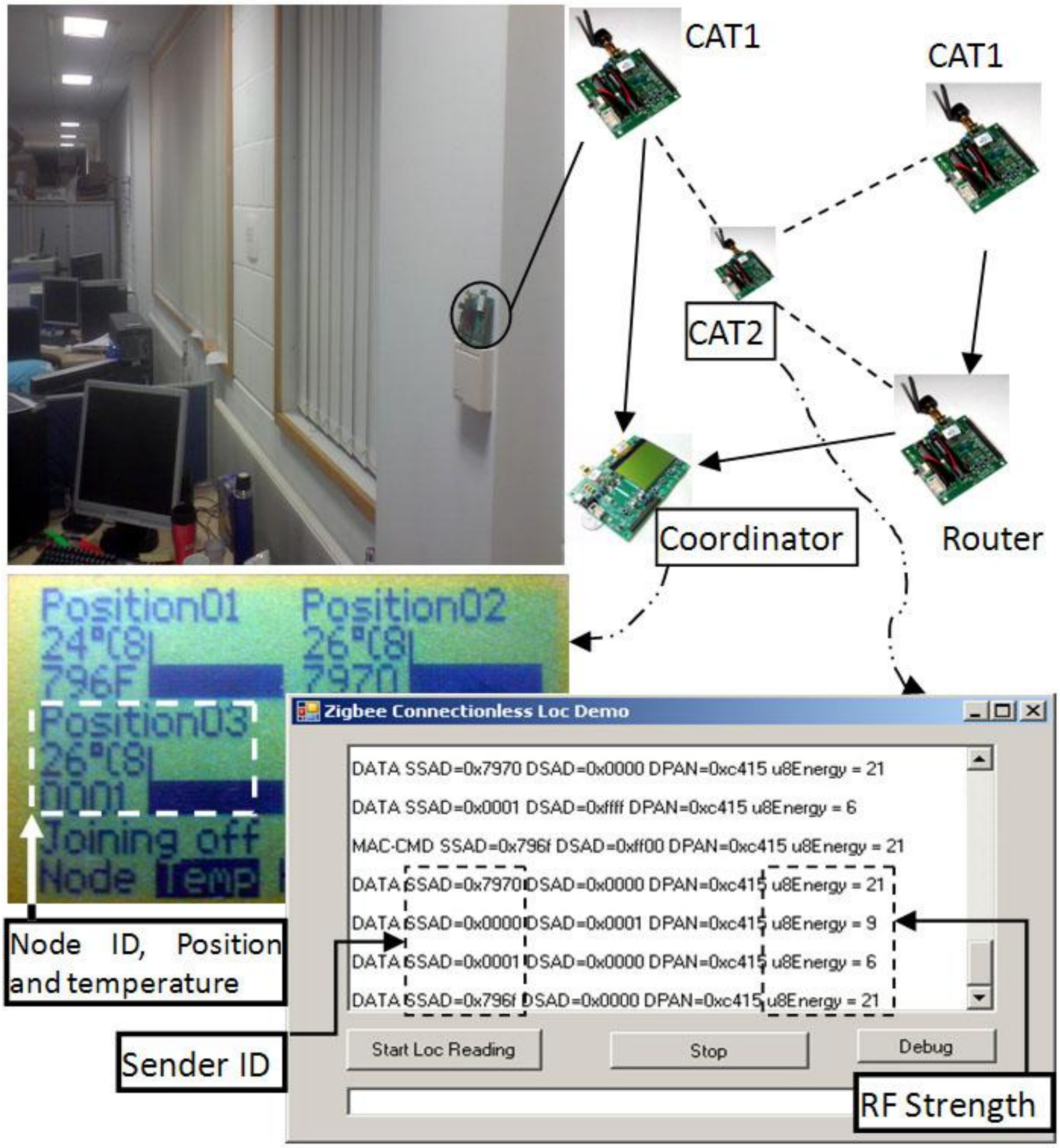


Figure 6-3: ZigBee connectionless tracking demonstration system

I developed a simple demonstration system using the Jennic JN5139 ZigBee sensor network development kit. As shown in Figure 6-3, One module was set as the coordinator, which was used to receive messages from the remote nodes. Three more modules integrated with temperature and humidity sensors were deployed at fixed positions in our laboratory which is an open environment. These three fixed nodes consisted of one router and two ZEDs. They are considered as the environmental control points in a warehouse. A third ZED was designed and programmed to be able to listen to the RF traffic and act as an end device in the network. No additional hardware is required to perform this function as all the nodes in a ZigBee network are all actually listening to the channel their network is using. All the packets in the channel are demodulated at the physical layer regardless of whether the packet is for the node or not. It is at the MAC layer where the packets with a destination other than the particular node are filtered. This third ZED node was considered as one of the mobile nodes on a pallet.

Figure 6-3 shows the system deployment of this experiment. The coordinator establishes the network, followed by the joining of the fixed router and the end devices, which make the network a typical ZigBee monitoring system. The fixed nodes exchange the environment information with the coordinator and this information is displayed on the screen of the coordinator's monitor. The mobile end device successfully retrieved from this data traffic the ID of the fixed nodes and the RF signal strength at its current position; this information could then be used by proper localization algorithms such as a triangle algorithm developed in our research group (Tariq and Yang, 2008a). The network topology is maintained with only one normal end device joined per mobile target. This demonstration system shows the feasibility of our architecture and its hardware realization.

6.7 Discussion

The connectionless tracking architecture CITA for ZigBee RFID sensor network allows mobile node to carry ZigBee end devices that can be supported by simpler, cheaper and power efficient hardware comparing to the router devices used in the existing ZigBee tracking systems (Sun et al., 2007). This enables the mobile node to have a much reasonable battery life subjects to the value chosen for T and t.

The existing ZigBee-based tracking systems requires either a dense router implementation and routers as mobile nodes that leads to higher cost, less flexibility and more complicated network structure, or suffer accumulated localization error due to using mobile nodes as part of the reference points. The CITA architecture proposed in this chapter does not require dense router deployment. Instead, it uses ZEDs as mobile nodes and is mainly based on the existing structure and hardware of the ZigBee RFID sensor network without affecting its implementation and performance. The data collection network could thus support warehouse inventory tracking with the least additional hardware and cost while at the same time avoiding accumulated localization error.

Challenges still exist in future research. Even though the current CITA architecture is designed for inventory tracking applications, it is not perfect for tracking high mobility targets, which requires a much higher location updating rate. It can efficiently carry out the tracking of inventory that stays at a fixed position for most of the time and does not move together. A higher updating rate can be achieved in theory by simply setting smaller value for T and t, but considering the nodes in network level 3 (includes CAT1 and CAT2) of the CITA architecture are all battery assisted it is very unlikely to be practical to use a value that is small enough for tracking high mobility targets because this will significantly reduce the battery life of both the mobile nodes and the battery-assisted reference nodes. This will be further discussed in the next chapter, in which I will also show that when the CITA architecture is used for high mobility tracking, the network traffic load within the network backbone will increase rapidly, sometimes even beyond the capability of typical ZigBee devices. As a result, the tracking of forklift and personnel will require more hardware and more complicated mechanisms.

Chapter 7 High-Mobility Node Tracking Architecture – COSBA

ZigBee is one of the most exciting wireless sensor network (WSN) technologies for monitoring and control. In Chapter 5, an integrated ZigBee RFID sensor network was designed as an ‘all-in-one’ system for logistics centres’ resource management. A connectionless tracking architecture based on a ZigBee RFID sensor network was then designed in Chapter 6 for location awareness of general inventory required by higher-level logistics centre management applications. At the top of the requirement level there is one more function to be added, which is the location awareness of the staff and moving vehicle/equipment, which I refer to as high mobility mobile targets. The connectionless tracking architecture CITA in Chapter 6 aims to support the location tracking service of the general inventory that does not move frequently. Such architecture suffers power and network traffic issues when applied to high-mobility mobile target tracking. In this chapter I investigate an architecture that can support the tracking of high mobility mobile targets. A connectionless stochastic reference beacon architecture (COSBA) based on a ZigBee RFID sensor network is proposed as an improved design for tracking both inventory and mobile targets. With only a small amount of additional hardware required, the COSBA architecture not only inherits the previous connectionless inventory tracking system’s features, but also has longer battery life, lower network traffic level and more importantly implements the system’s capability of mobile target tracking. A simulation in Matlab is presented to show the improvement of the new architecture compared to the connectionless inventory tracking architecture in terms of network traffic load. The implementation of such an architecture is also discussed with a demonstration system presented at the end of the chapter.

7.1 High Mobility Targets in CITA Architecture

As an attempt to improve the current systems, I have proposed in Chapter 6 a connectionless tracking architecture. This allows the use of ZigBee end devices (ZEDs) as mobile target node, and introduces the concept of "RF listener" for mobile node without any established network link with the reference nodes. The environmental monitoring nodes also act as reference nodes, the information messages sent back to the server by those nodes are also heard by the mobile nodes and used as reference messages to measure the receiving signal strength (RSS) between the mobile and reference nodes. This design provided a solution for warehouse inventory tracking with the least hardware requirement, reasonable mobile node battery life and at the same time provided the server localization algorithms with accurate data by avoiding the accumulated localization errors. The disadvantage of this design is that the fixed nodes must generate enough network traffic in order to ensure a mobile node can monitor enough fixed reference nodes in each active period. Thus such architecture requires that the sensor nodes periodically report to a central server. The interval of two adjacent reports is fixed and is not only a compromise between the application requirements and hardware battery life, but also a compromise between the battery life of the fixed and mobile nodes, which has been proved to be in an inverse relationship. I have concluded that the information report interval of the fixed nodes should be much shorter than the mobile node location updating interval. This was designed for the inventory tracking applications in which stock information is updated infrequently about every 10-20 minutes or even longer, and both the tagging and fixed nodes' battery life are to be maximised. For mobile target tracking, which requires that localization has to be updated more frequently, about every 2-3 seconds, the previous designed model results in fixed nodes, which sends messages with a much shorter interval, sending report tens or even hundreds times per second. This is not desirable, because the fixed nodes will quickly exhaust their batteries. It will also cause a high traffic load within the network that would result in traffic congestion. To overcome those issues I propose an improved architecture called the COnnectionless Stochastic reference Beacon Architecture (COSBA), which enables the tracking of high -mobility targets in our ZigBee RFID Sensor Networks, while at the same time maintaining normal network traffic loads and long device battery life. The word "Stochastic" here means that a reference node sends beacon messages in a stochastic process rather than a periodical process throughout the timeline.

7.2 Connectionless Stochastic Reference Beacon Architecture – COSBA

7.2.1 Concept of Design

7.2.1.1 Battery Life

Our interviews with engineers from relevant companies, suggest that in the real applications of mobile tracking, battery life of fixed nodes is of greater concern to the users than the battery life of mobile nodes. In the inventory tracking architecture, our discussions were based on the principle that both the mobile nodes and the fixed nodes work with on-board batteries that cannot be replaced or recharged frequently. But in mobile target tracking, the mobile nodes are either carried by vehicles/machines, where they can easily gain access to the on-board batteries that are usually more than sufficient for any ZigBee hardware, or carried by staff, where they can be recharged on a daily basis. The battery life of the fixed reporting/reference nodes is what the engineers and users are actually interested in, because these batteries cannot be recharged on a daily basis and are not expected to be replaced frequently. This is the biggest difference between the applications of inventory tracking and mobile target tracking. Thus our design for the mobile target tracking architecture need only try to prolong the battery life of the fixed reference nodes. Without the need for compromising between the battery life of fixed nodes and mobile nodes, we let the mobile nodes stay on and listen to the RF channel all the time. In this case the fixed nodes can send their report/reference messages only at the rate that is equal to or very close to the localization updating rate required.

7.2.1.2 Network Traffic

The previous connectionless architecture design is not applicable for mobile target tracking also because in such applications it will cause high traffic load within the network, which leads to congestion. Environment monitoring nodes that report to central server nodes too frequently can also cause serious congestion within the network backbone, as ZigBee is a low data rate standard. Enabling all the fixed nodes to report to central servers at a high updating rate is not practical. This will prevent the more important information from arriving at the server in time, or even totally bring down the network service. High network traffic loads will also reduce the node battery life in the network backbone when, in certain circumstances, they lose mains power support. Therefore the expected mobile target tracking architecture must reduce the network traffic. By having the mobile nodes listen to the channel all the time, the sending rate of environment information is reduced. But in applications, the required updating rate for environment monitoring reporting is usually much smaller than the rate required for mobile target tracking. So using monitoring reporting messages for such types of localization means that most of the network traffic caused by environment reporting is wasted, because the central server is not interested in such frequent environment information updating. For example, monitoring information may need to be reported every 10 minutes, but at the same time, the localization process may need an updating interval of 2 seconds. To satisfy the localization process each fixed node has to report to the central server every 2 seconds, though most of these messages are of no interest to the application itself. Network loads and hardware battery life are largely wasted in such a frequent reporting mechanism. To solve such problem, in our new design for mobile target tracking, I will prevent the messages sent for localization purpose from propagating within the network. This is achieved by letting the fixed nodes send short beacon type messages rather than monitoring reports for the mobile nodes to analyze. The short beacon messages are enough for mobile nodes to determine the RSSI of the sender nodes, but will be marked as not eligible for propagating within the network. To avoid interference between data transmission and beacon broadcast, the main network and the short beacon message mechanism will need to work on different IEEE 802.15.4 channels.

7.2.1.3 Connectionless Beacon

For a beacon network, the common network standards usually require a central coordinator device to broadcast a timing frame periodically to start a beacon interval, and all beacon nodes receive and follow such frames for accurate synchronization so that they could then be lined up for transmission in a beacon interval without conflict (Francomme et al., 2007; Burda et al., 2007). In the IEEE 802.15.4 network standard, the only way of achieving this is through the guaranteed time slot (GTS) mechanism in a beacon-enabled mode. In this method of network organization each beacon node needs to listen to the channel constantly for a timing frame and to synchronize with each other. There has to be a central coordinator device that covers the whole operation area and broadcast the beacon timing frames. Those synchronizing activities consume a considerable amount of energy on the beacon nodes, which is even higher than the power consumption on actual beacon sending activities. According to the hardware datasheet for the Jennic JN series ZigBee wireless sensor node, the RF receiver is an independent circuit with greater power consumption than the RF transmitter. Furthermore, the RF receiver has to be powered on during the whole operation cycle because the node itself cannot anticipate when the next frame will arrive, whereas the RF transmitter needs only to be turned on during actual frame transmissions, which are actually very short periods. According to the datasheet of the Jennic sensor nodes I used, not only does the RF receiver work for a much longer time than the transmitters during operations, but they also have larger power consumption per unit time than the transmitters (Jennic Ltd., 2009). Thus, reducing receiving time is more efficient than reducing transmitting time in prolonging the nodes' battery life. For beacon nodes the RF receivers exist only because they need to be synchronized in order to avoid collisions with adjacent beacon nodes. But actually, it is not a disaster to have collisions so long as the collision occurrence probability is below an acceptable threshold, which should be given by real application specifications, and performance of the localization process is not noticeably affected. In this case, I consider the synchronizing function of the beacon nodes to be unnecessary and the role of a receiver is redundant. So in my design I only need the beacon nodes to transmit reference messages without any responsibility for listening. According to the power consumption calculation of the Jennic JN5139 application notes, which states that the device operating current is the same for both RF receiving and transmitting, this should be able to prolong the nodes battery life depending on the application. For example, a device with a 5:1 idle-transmission time ratio should be able to prolong its battery life by 5 times. The beacon messages are sent randomly through the time line and the collision probability can be controlled by adjusted the average beacon transmitting rate.

7.2.2 COSBA Architecture

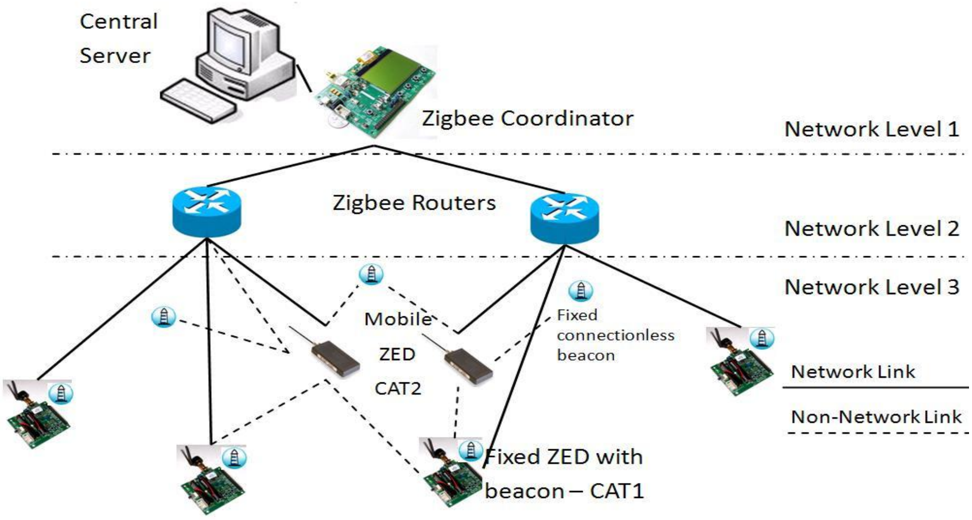


Figure 7-1: Network architecture of COSBA

Taking into consideration all of the discussions in Section 7.2.1, I propose the connectionless beacon architecture for mobile target tracking in ZigBee RFID Sensor Network. The network architecture is illustrated in Figure 7-1. The central server, network routers and environmental monitoring nodes remain the same as for the CITA architecture. I add battery powered beacon nodes at reference points to assist the system localization process. The mobile target nodes listen to the messages sent periodically by the reference beacons and generate their RSSI information for localization purposes. The reference beacons operate in a different ZigBee/IEEE802.15.4 channel to that used by the main data network in order to avoid unexpected collisions.

<u>Network level 1 and Network level 2:</u> The devices, such as the server, ZigBee coordinator and ZigBee routers, as well as their data communication in network levels 1 and 2 are exactly the same with the CITA architecture which I have described in Section 6.3.2.

<u>Network level 3</u>: The primary differences between the CITA architecture and the

COSBA architecture are presented in network level 3, at this level there are ZEDs for data collection. In Chapter 6 I classified these ZEDs in two categories, which are the CAT1 and CAT2 nodes. I have also discussed in Chapter 6 the advantage of using ZEDs as mobile nodes, which means cheaper and more power-efficient hardware, more stable network topology and less network routing overhead (Liang et al., 2006; Sun et al., 2007). The difference of the COSBA architecture in comparison to the CITA architecture is that the CAT1 ZEDs will carry additional hardware for performing the connectionless stochastic beacon function in order to act as reference nodes. The dedicated reference beacon nodes are deployed in network level 3 instead of the redundant ZEDs used in the CITA architecture for localization purposes only. The other CAT2 ZEDs make use of both the CAT1 nodes and the dedicated reference beacon nodes as the reference nodes for their localization.

Tracking mobile nodes: The connectionless tracking mechanism of our ZigBee RFID Sensor network can be described as follows: the CAT2 mobile nodes are typical ZigBee end devices equipped with a RF listener module whose function is to analyze the beacon packets it can hear on the beacon channel used. From each packet it hears, the RF listener module retrieves and provides the CAT2 node processor with the ID of the reference beacon node that sent the packet, the RF power strength and the error check result. Failure of the check code indicates that there were collisions or significant interference during the packet transmission, this will invalidate the reading of the source ID, which may have been incorrectly transmitted, and its RF power strength reading, which may be incorrect due to collision or interference. If the check is passed, then the source ID and RF strength reading is accepted as a reference pair. The mobile nodes analyse the beacon channel for a predefined period R, then summarise the reference pairs it received in the last receiving period and send them via the main ZigBee data network to the server to update the database. A proper localization algorithm on the server will locate the CAT2 nodes based on the reference information pairs in the database. Most of the current localization algorithms require at least three reference points for a mobile node to be located with satisfied accuracy, so the minimum deployment requirement of the connectionless tracking architecture is to ensure that at any place in the building/site, a CAT2 mobile nodes should be within RF range of at least three reference beacon nodes only one of which nodes is required to be a router providing network access. Dedicated reference beacon nodes can be deployed where necessary to help meet this requirement. Normally the more reference beacons reachable by a mobile node, the higher the accuracy that can be achieved.

7.3 Deployment of the COSBA Network Architecture

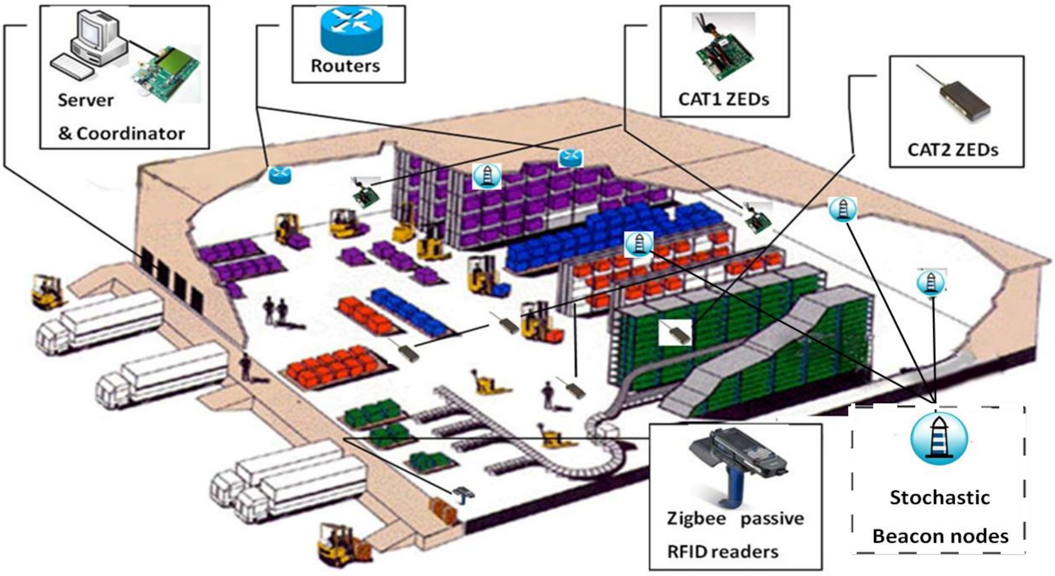


Figure 7-2: ZigBee based COSBA architecture deployment

A diagram of the network implementation of a ZigBee enabled RFID sensor network with COSBA architecture is shown in Figure 7-2. The deployment of server, ZigBee coordinator and ZigBee routers at network levels 1 and 2 is very similar to the CITA architecture. The primary deployment criterion is to provide full ZigBee network coverage within the logistics centre. After that the end devices at level 3 can then be deployed. CAT1 nodes are fixed data nodes responsible for gathering information at specific locations. Their deployment will be based on the warehouse management specifications. Since the CAT1 nodes have fixed positions after deployment, they can also be used as reference points for tracking CAT2 nodes. Thus CAT1 nodes can carry out beacon sending function as well as data monitoring tasks. Dedicated beacon nodes are then deployed to provide the area with full beacon coverage. To ensure the operation of the system's tracking mechanism, full beacon coverage usually means that a mobile node should be able to receive the beacon signal from at least three reference nodes at any position in the operation area. This number can be larger and normally the more reference nodes reachable, the higher the accuracy and reliability that can be achieved.

The tracked targets carry CAT2 nodes. They are divided in two operation modes: mobile mode and inventory mode. Nodes that are defined to be in mobile mode are carried by mobile targets, such as staff, equipment and forklift. They listen to the beacon channel constantly in order to determine the received signal strength from each beacon node it can hear. The beacon information is summarized at the end of each receiving slot and sent periodically to the server via the ZigBee data network channel. The beacon information-updating interval is chosen according to the requirements of each particular application. Nodes that are in inventory mode, are carried by tracked freights, such as on standard pallets or trays, and require a much longer tracking update interval. These nodes monitor the beacon channel until they have gathered enough beacon information to be sent back to server via data network channel. They then go into sleep mode to save their battery power until the next information update time point. The information-updating interval is chosen according to the requirements of each particular application. These nodes also carries passive RFID tags so that they can be easily and accurately associated or dissociated with the inventory they are carrying by the ZigBee-enabled passive RFID readers.

7.4 Network Traffic Load of the COSBA Architecture

I conducted simulations in the Matlab environment to analyze and compare the network traffic load of the CITA architecture and COSBA architectures under various circumstances. The results are shown for three different scales of network deployment, which have a topology of 3x3, 4x4 and 5x5 fixed nodes respectively. The network topologies used in the simulations are shown in Figure 7-3. The number of mobile targets is set to 10 nodes in all simulations, and application requirement for maximum environment information update interval is set to 5 seconds. I generated the curves showing the change in traffic load at the receive point of the coordinator/sink node, that has the heaviest traffic load in the network, while the required localization update interval varies in a certain range. The network configuration and nodes' locations do not have influence on the simulation as I studied only the traffic load at the sink node, which is the destination of all transmissions.

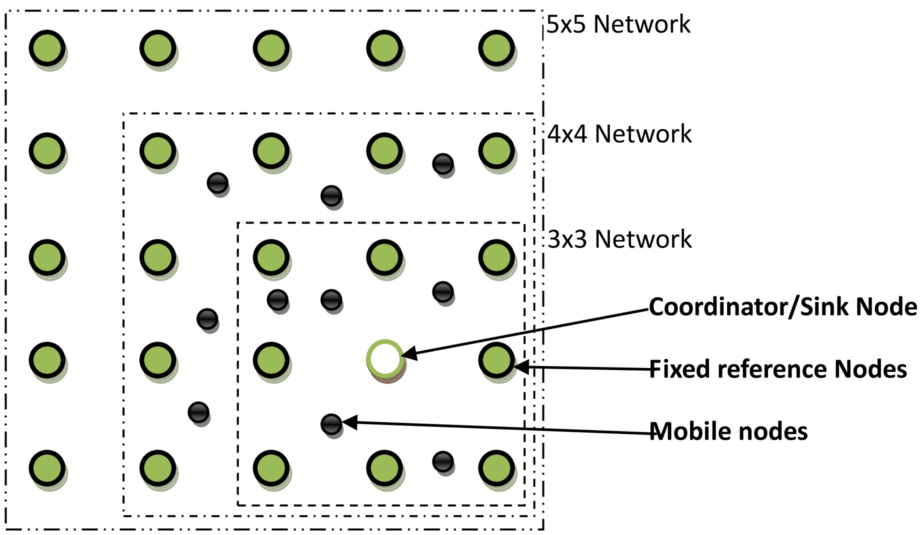


Figure 7-3: Network topologies of the simulations

Figure 7-4 shows the traffic load in packets/second at the sink node in both CITA and COSBA architectures with the required localization update interval varies from infinitely small to 20 minutes. The sink node traffic load of the CITA architecture is always higher than that of the COSBA architecture. At a localization updating interval of 5 minutes (300s) to 20 minutes (1200s), which is the typical localization updating interval range of various inventory tracking applications, the COSBA architecture has quite low traffic load at the sink node, while the CITA architecture shows a relatively higher but still acceptable traffic load performance. Both architectures demonstrate good performance stability while the updating interval decreases from 20 minutes to 5 minutes, though the CITA architecture's traffic load does rise slightly. As for the network scale, a larger number of network nodes cause more increase in traffic load to the CITA architecture than to the COSBA architecture, but the performance is still acceptable for inventory tracking.

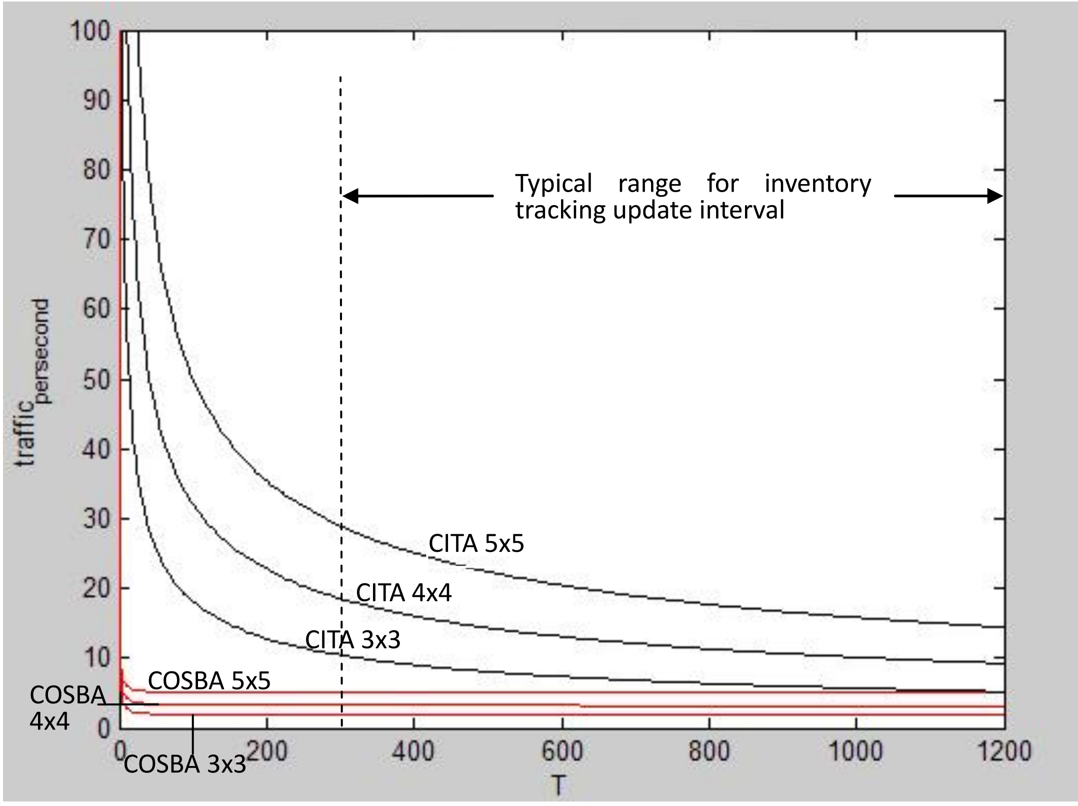


Figure 7-4: Traffic load at sink node in CITA and COSBA with localization update interval varies from infinitely small to 20 minutes

Taking into consideration that the CITA architecture requires less additional hardware and implementation work, it has shown good performance in network traffic load and performance stability. The performance of the COSBA architecture is better than the

CITA architecture in the typical location update range of inventory tracking applications. Although the difference is obvious, it is achieved at an additional cost. Thus the CITA architecture still has its place in inventory tracking applications, for which it was originally design to operate. However, for high-mobility target tracking applications the results are not showing the same trend.

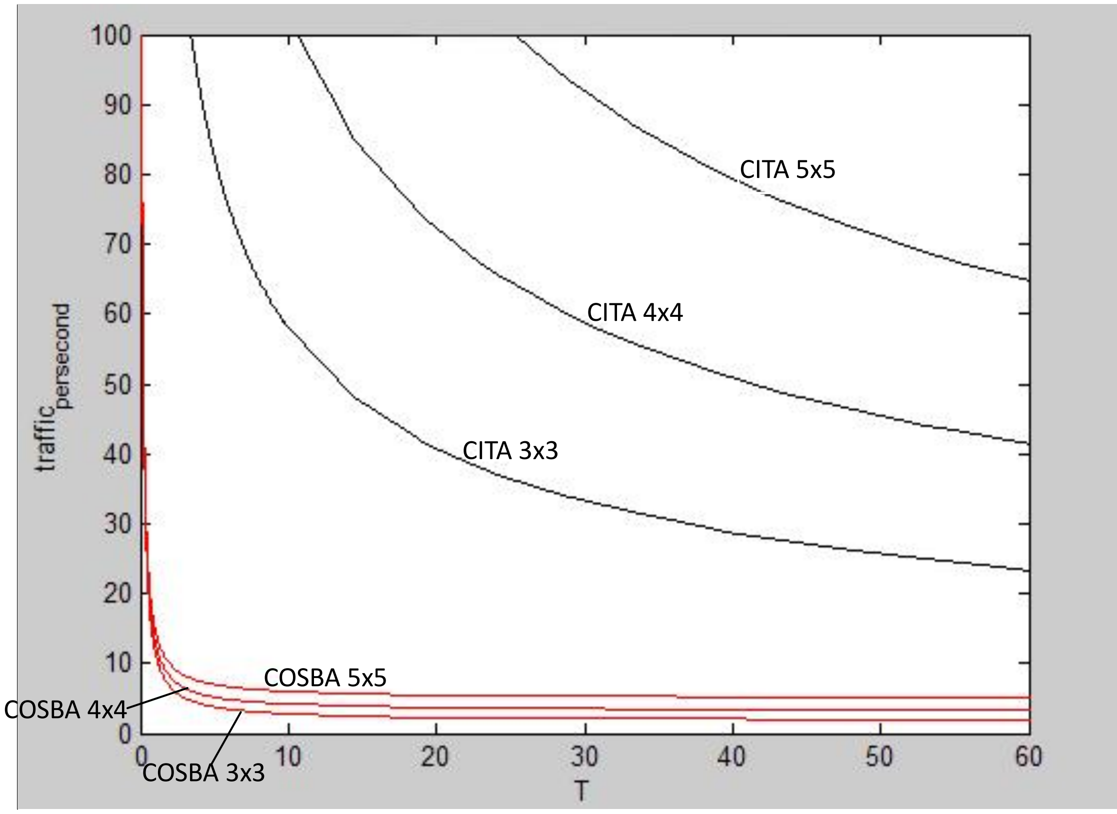


Figure 7-5: Traffic load at sink node in CITA and COSBA with localization update interval varies from infinitely small to1 minutes

Figure 7-5 shows the traffic load in packets/second at the sink node in both the CITA and COSBA architectures with the required localization update interval varying from infinitely small to 1 minute (60s). The typical high-mobility target tracking applications usually have a localization update interval range of 2 second up to 30 seconds. While the interval varies in this range, the CITA architecture shows an extremely high traffic load that increases rapidly when the update interval decreases. A the same time, the COSBA architecture has shown a very good and stable performance with only slight increase in traffic load until the interval decreases beyond the normal requirement range of high-mobility target tracking applications. As for the influence of network scale in this range, the COSBA architecture only has slight increase in traffic while the CITA architecture has been extremely sensitive to the increase of network nodes. The traffic load of CITA rises dramatically when the number of network node increases. In our experience with deploying and operating ZigBee based WSN, the maximum packet processing rate I have ever achieved on a single ZigBee Full Function Device (FFD) node has never gone over 200 packets per second. At a scale of 5x5 the CITA traffic load has already gone beyond the processing capability of the coordinator/sink node.

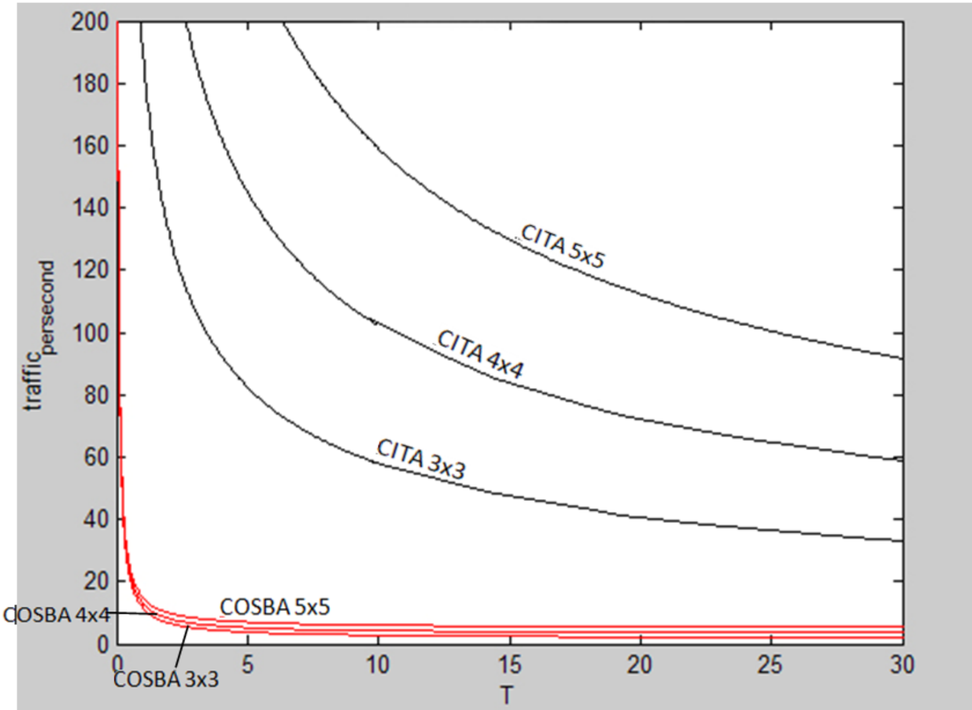


Figure 7-6: Traffic load up to 200 p/s with localization update interval varies from infinitely small to 30 seconds

In summary, the CITA architecture shows its place in the general inventory applications in which it is designed to operate, but is not able to support the high-mobility target tracking applications due to suffering extreme network traffic load when the network scale increases or the tracking updating interval decreases in the typical range of high mobility target tracking. The COSBA architecture, on the other hand, shows much better and stable performance and is not excessively sensitive to the change of network scale within the typical range of tracking updating interval for high-mobility target tracking applications.

7.5 Demonstration System

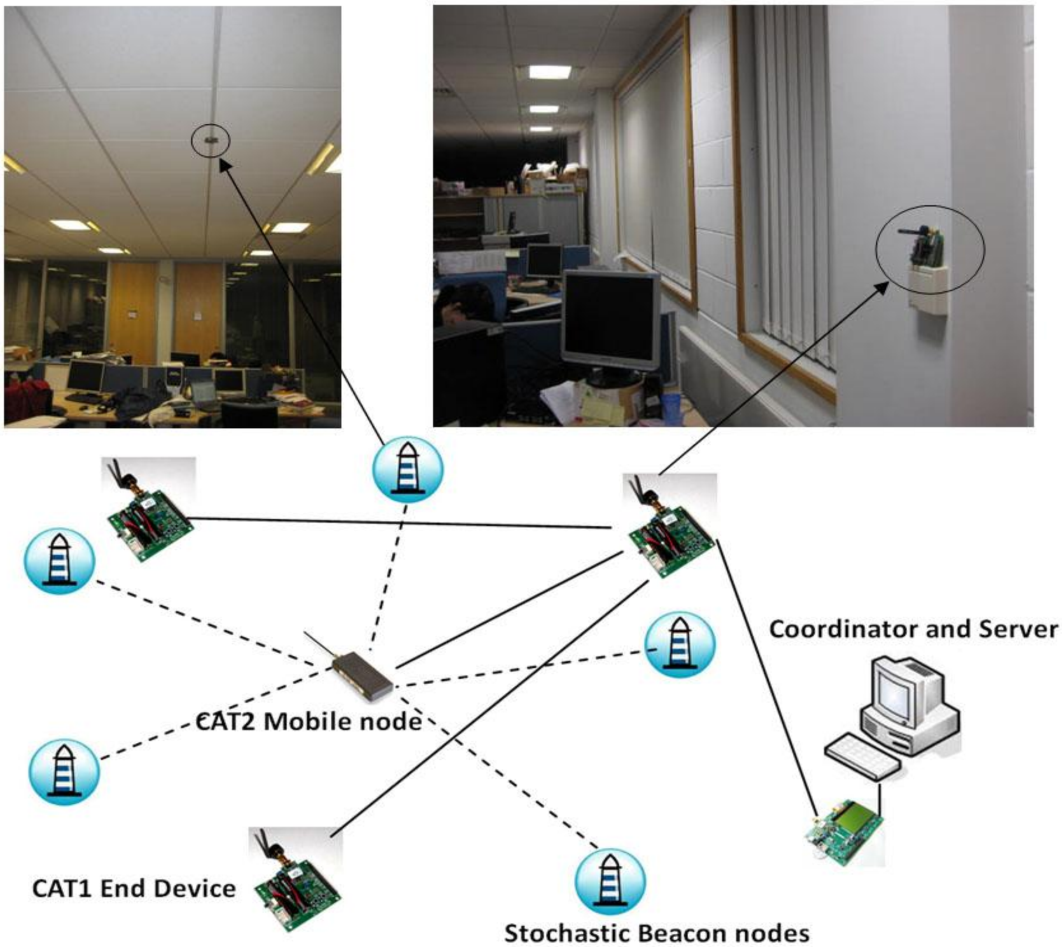


Figure 7-7: Structure of demonstration system

The demonstration system was developed using the Jennic JN5139 development kit. Our system structure is shown in Figure 7-7. One module is set as the coordinator, which is used to receive messages from the remote nodes. Three more modules integrated with temperature and humidity sensors are deployed at fixed positions in an open environment within our laboratory. Among these three fixed nodes there is one router and two end devices. They are used as illustrations of the environmental control points in a warehouse.

Five modules were programmed as the connectionless beacon devices. Instead of using the standard ZigBee stack, I programmed them based on the production test API provided by Jennic, which allows full and accurate control of the device's sleep/wake up and frame sending activities that are performed at the lower network layers. The devices send reference messages at a predefined average beacon interval *T*.

The last end device was designed and programmed to be able to listen to the beacon channel and act as an end device in the ZigBee data network. This node will be considered as one of the mobile nodes carried by mobile targets.

Figure 7-7 shows the system deployment for this experiment. The coordinator establishes the network on IEEE802.15.4 channel 14, followed by the connection of the router and end devices and making it a typical ZigBee monitoring system. The fixed nodes exchange environment information with the coordinator where the information is displayed on the screen. The beacon nodes send out reference messages, which occupy the beacon channel for approximately 1 to 2 ms, at an average rate of 0.5 transmissions / second on IEEE802.15.4 channel 18. The mobile end device successfully retrieves from these messages the ID of the fixed beacon nodes and their RSSI at its current position; this information is then sent to the server via the ZigBee network and could then be used by proper localization algorithms such as a triangle algorithm developed in our research group (Tariq and Yang, 2008a). The network topology is maintained with only one normal end device joined per mobile target. By adjusting the average rate of sending beacon messages I can achieve on the receiver an acceptable beacon-receiving rate, which assures that the tracking performance is not noticeably affected by collisions.

According to the Jennic hardware power consumption document (Jennic Ltd., 2007), the battery life of a JN5139 working as dedicated beacon, as in our demonstration system, is estimated as follows: Procedure for the device to wake up from RAM held mode needs 13.43ms at 9mA working current; sending a short beacon message should then take less than 1ms with 44mA working current; assuming another 5ms operation which is a comfortable length for the device to calculate the next beacon interval and go back to sleep, the current drawn is again 5mA. The current drawn during the sleep period is 0.025mA with RAM held, and the sleep period in our demonstration was 2 seconds in average. Thus the average current drawn of the device, denoted by *I*, is given as:

$$I = (9\times 13.43 + 44\times 1 + 9\times 5 + 0.025\times 2000) \div (13.43 + 1 + 5 + 2000)$$
$$= 259.87 / 2019.43 \approx 129\mu A$$

With two 1250mAh battery, battery life B is estimated as:

$$B = 1250 / 0.129 = 9714\_hours \approx 406 \text{ days.}$$

This is a very reasonable battery life taking into consideration that the national regulation requires that those electronic devices must be checked and serviced once a year. And as I am using a ZigBee sensor network development board, which is a more complicated and power hungry device than needed, the battery life can be further extended by having specially designed hardware for the dedicated beacon devices with simplified and streamlined components. Thus the performance of this demonstration system illustrated the feasibility of our architecture and its hardware realization.

7.6 Discussion

In this chapter I proposed a connectionless Stochastic Reference Beacon Architecture (COSBA) for mobile target tracking in ZigBee RFID sensor networks. Comparing to the traditional ZigBee based tracking system, the features of our design include:

i). It allows mobile nodes to use ZigBee end devices that can be supported by simpler, cheaper and power efficient hardware compared to the router devices used in current ZigBee tracking systems, and does not have performance decrease when multiple mobile targets are present in the same area;

ii). Current ZigBee-based tracking systems requires either a dense router implementation that leads to higher cost, less flexibility and a more complicated network structure, or suffer accumulated localization error due to using mobile nodes as reference points. The connectionless stochastic reference beacon architecture does not require dense router deployment. Instead, it is mainly based on the existing ZigBee RFID sensor network hardware and does not affect the network structure, implementation and performance. The data collection network could thus support warehouse inventory tracking with minimal additional hardware and cost while at the same time avoiding the accumulated localization error;

iii). Comparing to our previously designed connectionless inventory tracking architecture CITA, the COSBA architecture not only inherits the previous connectionless inventory tracking system's features such as consistent network structure and no accumulated error, but also has longer hardware battery life, lower network traffic level and enables the tracking of targets with higher mobility while at the same time maintaining support for normal inventory tracking with the least additional devices, which are the dedicated beacons that are very simple and low-cost devices with reasonable battery life and simple deployment.

Chapter 8 Beacon Generating Algorithms for COSBA Architecture

In order to maximize the successful receiving rate for beacon messages, the key pointsof the COSBA architecture is to design a proper reference beacon message generating model that produces the minimum beacon collision probability and the maximum beacon receiving success probability. In this chapter I will investigate two models for this purpose. Such mechanism and the two models are unique designs. Their mathematical analyses differ to the performance analysis used in Ethernet or CSMA as in my mechanism I have a constant packet rate and have no collision detection and performance adjustment. Before going into the discussion of various algorithms, I summarize and give the following assumptions and constraints that will be applied in the remainder of this chapter:

- Beacon nodes do not have receivers and do not have any synchronization; they work in a stand-alone mode and regularly send reference beacon messages.
- The sending time of each message is calculated by the beacon node using a built-in algorithm.
- For the sake of simplicity in manufacturing and implementation, all beacon nodes are designed to be the same, which means they have identical hardware, message sending time algorithm and algorithm parameters, and operates in the same

frequency channel chosen from the channel list defined in the IEEE 802.15.4 standard.

- A time slotted receiving mode is used in all of our designs. This means that the time line is divided into predefined time slots of length R. A mobile target node will monitor the wireless channel used by the reference beacon nodes within each time slot and summarize the beacon messages it received. It will then repeat the monitoring process in the next time slot.

8.1 Fully Stochastic Reference Beacon Model (FSRB)

The most straightforward method is to let each reference node send its beacon messages randomly throughout the time line, with a predefined sending probability P at any observation moment. Because all the nodes are identical, they have the same probability of sending. This model can be briefly described as follows: at any specific moment, each node has a probability P of sending a beacon message. For such a model, under the most extreme situation when $P=1$, which means each node will definitely send a message, conflict will occur among the messages sent by all the nodes located within the antenna RF range of a target node receiver. However, as P becomes smaller the probability of beacon message conflict decreases. In this case we could expect a certain threshold for P that is small enough for the conflict probability to reduce to an acceptable level, but not so small as to make the sending interval too long for the application. I call this the Fully Stochastic Reference Beacon (FSRB) model. When the value of the time domain is continuous, the definition of the fully stochastic reference beacon model's sending process turns into differential form, which can be described as: each reference node sends a beacon message with probability Pdt in any infinitesimal time interval dt. In this section I will discuss the sending and receiving performance of such a model.

8.1.1 Beacon Sending Process of FSRB Model

First I discuss the mathematical model of the beacon sending process in a real-time localization system using fully stochastic reference beacons.

Taking the definition of fully stochastic reference beacon in the continuous time domain, from any observation start time $t_{start} = 0$, the probability for a node to send the next beacon message in the period of $[t, t+dt]$, denoted as $P(t)$, is given as:

$$P(t) = P\{\overline{X}(0,t)\} \times P\{X(t, t+dt)\}$$

where $P\{\overline{X}(0,t)\}$ means the probability of no beacon sending before t and $P\{X(t, t+dt)\}$ means the probability of a beacon sending occurrence in $[t, t+dt]$.

Suppose that $[0,t]$ is divided into n intervals with length t/n, as n becomes large, the probability of a reference node sending a beacon message in any one of these intervals becomes $P \cdot t/n$. Thus the probability of no beacon message being sent in $[0,t]$ means no message sending in all of these small intervals, which can be given as,

$$P\{\overline{X}(0,t)\} = \lim_{n \to \infty}(1 - P \cdot \frac{t}{n})^n = e^{-Pt}$$

As $P\{X(t, t+dt)\} = P$, we have.

$$P(t) = P\{\overline{X}(0,t)\} \times P\{X(t, t+dt)\} = P \cdot e^{-Pt} \tag{8.1}$$

This means for each reference beacon node, the interval between two adjacent message sending follows the exponential distribution.

The stochastic beacon sending process of each beacon node with the length of the intervals between two adjacent beacon sendings being an exponential distribution $P(t) = P \cdot e^{-Pt}$, in which $P > 0$, is actually a ***Poisson process*** with an intensity of P

(Nelson, 1995). The mathematical expectation of the length of the sending intervals is $E[P(t)] = 1/P$, which represents the average length of the sending cycle in the process. The properties of the Poisson process will facilitate our discussion in the remainder of this chapter. For the convenience of our discussion, I define the sending process on each reference node as a Poisson process with a sending rate $1/T$, in which $T > 0$ is the average beacon sending period. As a Poisson process can be uniquely defined by the probability distribution of the sending intervals, our FSRB model can now be described as: A reference node calculates a waiting time, denoted by t_s, following the exponential distribution $\varphi(t) = \frac{1}{T} e^{-\frac{1}{T} \cdot t}$ after each beacon sending, and sends the next beacon after a time interval of t_s; it then calculates a new value for the waiting time t_s based on the same random distribution $\varphi(t)$, and the process continues by repeating this procedure. This is also how our hardware devices in the demonstration system perform the sending process in reality. Such method enables the reference beacon nodes to go to sleep mode between the sending of two beacon messages. Further details will be given in Chapter 9. For the system to have a unified hardware design and a stable message transmission rate, all reference beacon nodes are considered to be identical and are using the same random distribution function $\varphi(t)$ with exactly the same parameters.

8.1.2 Sending Performance of FSRB Model

We now calculate the probability expectation of a beacon message being sent successfully. As all beacon messages have the same fixed length, let l be the time length required for sending each beacon message through the wireless channel. The channel is occupied during the period of a beacon message sending. During this period, the occurrence of another beacon message sending from any one of the nodes located within a target node's antenna RF range will result in the invalidation of both beacon messages. Thus the condition for a beacon message sent by one of the nodes at time t_s to be successful is that no beacon message is sent by any other nodes in the same RF range within the period $[t_s - l, t_s + l]$. Let N be the number of reference beacon nodes that a target node's receiver can hear at each position. The probability for a beacon message sent by one of the N nodes to be successful, denoted by $P_{success}$, is a conditional probability given as:

$$P_{success} = P\{[\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)] \mid [X_1(t_s)]\}$$

Where $X_1(t_s)$ represents the event of one of the N nodes sending a beacon message at t_s and $\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)$ represents the event of no beacon message sending from any other *N-1* nodes in the period of $[t_s - l, t_s + l]$.

The poisson processes are additive, thus the combined stochastic process of beacon sendings from the other $N-1$ reference nodes is a Poisson process with an intensity of $(N-1)/T$ and sending interval distribution of $\varphi_{N-1}(t) = \frac{N-1}{T} \cdot e^{-\frac{N-1}{T}t}, T > 0$. Poisson process is memoryless, which means waiting time before the occurrence of the next beacon message sending is independent of the observation's start time. This means that the event $\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)$ does not relate to t_s, so the two events $\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)$ and $X_1(t_s)$ are independent of each other. Thus we can have:

$$P_{success} = P\{[\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)] \mid [X_1(t_s)]\} = P\{\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)\}$$

As the event of no beacon message sending from the other N-1 nodes in the period of $[t_s - l, t_s + l]$ is equivalent to the event of sending interval length larger than *2l*, we

can have:
$$P_{succ} = P\{\bigcap_{i=2}^{N} \overline{X_i}(t_s - l, t_s + l)\}$$
$$= P\{\bigcap_{i=2}^{N} \overline{X_i}(0, 2l)\}$$
$$= 1 - \int_0^{2l} \varphi_{N-1}(t)dt = e^{-(\frac{N-1}{T})\cdot 2l} \qquad (8.2)$$

where $P\{\bigcap_{i=2}^{N} \overline{X_i}(0, 2l)\}$ means the probability of no beacon sending from the other *N-1* nodes in a time interval of *2l*. It shows that $P_{success}$ is not related to the observation time, thus it is a determined value when *N*, *T* and *l* are fixed. Figure 8-1 shows the variation of $P_{success}$ while the average beacon sending period *T* varies in *(0,3.5)* with number of beacon nodes within the target node's RF range *N=5* and the beacon message's channel occupation time *l=0.02 second.* According to our reviews in Chapter 3, a number of 5 reference nodes is enough but not excessive to support all the existing indoor localization algorithms. As $P_{success}$ will be even higher when *N<5*, our models will be able to support all RTLS algorithms as long as it achieves satisfactory performance for *N=5*.

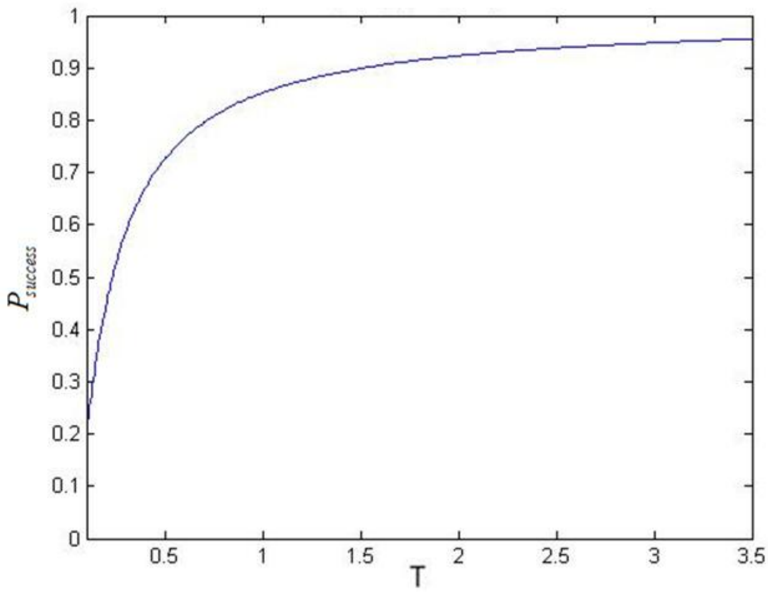


Figure 8-1: FSRB Probability of successful sending with *N=5, l=0.02* and *T=[0,3.5]*

8.1.3 Receiving Performance of FSRB Model

As I use a time-slotted receiving mode, the criterion for a successful receiving is that at least one beacon message is correctly received within a time slot. The probability expectation of successful receiving from a specific reference beacon node in each time slot, represented by P_R, is given as:

$$P_R = P\{Y_{k>0}(R)\} = 1 - P\{Y_{k=0}(R)\}$$

Where $P\{Y_{k>0}(R)\}$ represents the probability of at least one beacon message being received correctly in a receiving time slot, $P\{Y_{k=0}(R)\}$ represents the probability of all beacon messages sent in a receiving time slot being failed. The probability $P\{Y_{k=0}(R)\}$ can be calculated as follows:

$$P\{Y_{k=0}(R)\} = \sum_{k=0}^{\infty}\{P[X_k(R)] \times P[Y_0(X_k, R)]\}$$

Where $P[X_k(R)]$ represents the probability of k beacon messages being sent in a time slot, $P[Y_0(X_k, R)]$ represents the probability of none of those k beacon messages being received correctly.

In a Poisson process with an intensity of $1/T$, the probability of k events in a time interval length of R is given by:

$$P[X_k(R)] = \frac{(R/T)^k}{k!} e^{-R/T}, R > 0, \quad k = 0,1,2,...$$

As $P[Y_0(X_k, R)]$ can be given as $(1 - P_{success})^k$, we have:

$$P\{Y_{k=0}(R)\} = \sum_{k=0}^{\infty}[P[X_k(R)] \cdot (1 - P_{success})^k]$$

$$= \sum_{k=0}^{\infty}[\frac{(R/T)^k}{k!} e^{-R/T} \cdot (1 - P_{success})^k], R > 0, \quad k = 0,1,2,...$$

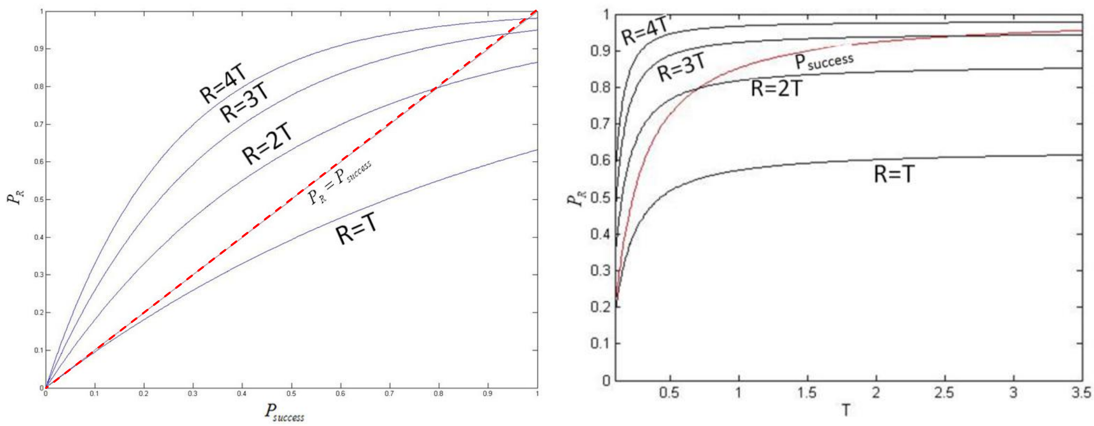
Since the summation of the series $\sum_{k=0}^{\infty}\frac{x^k}{k!}$ has a limit of e^x, we have:

$$P\{Y_{k=0}(R)\} = e^{-R/T} \cdot e^{(R/T)(1-P_{success})} = e^{-(\frac{R}{T}\cdot P_{success})}$$

Hence P_R, which is the probability expectation of successful receiving from a specific reference beacon node in each time slot, can now be given as:

$$P_R = 1 - P\{Y_{k=0}(R)\} = 1 - e^{-(\frac{R}{T}\cdot P_{success})} \tag{8.3}$$

As I have previously proved that $P_{success}$ depends only on *N*, *T* and *l*, the result in Equation (8.3) shows that when the sending parameters *N*, *T* and *l* are fixed, the probability expectation of successfully receiving at least one beacon message from a specific reference node in each time slot P_R is related only to the length R of the receiving slots regardless of where the slots' start time are in the process. This means that a mobile receiver can have the same receiving performance, which is given in Equation (8.3), from all reference nodes regardless of what time each of the devices is turned on.



(a) (b)

Figure 8-2 (a). FSRB Probability of successful receiving related to that of successful sending; (b). FSRB Probability of successful receiving with *N=5, l=0.02* and *T=[0,3.5]*

Figure 8-2(a) shows how P_R is related to the sending success rate $P_{success}$. In comparison to the dotted line of $P_R = P_{success}$, the results show that P_R is always lower than $P_{success}$ when $R = T$; The performance improves when R is increased, but P_R always falls below $P_{success}$ before reaching $R = 4T$, which is a relatively large receiving slot to be used in practice. Figure 8-2(b) shows the changes of P_R when the average sending period increases from 0.1 to 3.5. While T increases, the receiving performance P_R rapidly improves until T reaches 0.5, then shows a moderate increase before T reaches 1 and a very slight improvement after T is larger than 1s ($T/l>50$). Comparing to the curve of $P_{success}$, when $P_{success}$ has a large value that is at least over 0.8, the receiving probability P_R can only exceed the sending success probability $P_{success}$ when $R/T>=4$. The total number of reference nodes that can be heard by a mobile node is set to $N=5$ in all simulations. The reason is that according to our reviews in Chapter 3, a number of 5 reference nodes should be enough but not excessive to support almost all the existing indoor localization algorithms.

8.2 Time Slot Based Stochastic Reference Beacon Model (TSSRB)

8.2.1 Beacon Sending Process of TSSRB Model

In real applications the usability specifications usually define the localization updating rate, which results in a maximum receiving time slot length R_{MAX}. But on the other hand, we want the average beacon sending period to be as long as possible to save the energy on the beacon reference nodes. In this case, we expect that a beacon sending model could provide us with satisfied receiving performance while keeping the ratio of R/T as low as possible. In Section 8.1 I discussed the FSRB architecture. The results of its performance analysis show a lowered receiving probability P_R in each receiving time slot compared to the sending success probability $P_{success}$. The results also suggest a slow improvement of P_R when R/T is increased. The reason for those results is that the FSRB model's beacon interval is a random variable defined on domain $[0,+\infty)$. This means that although the beacon nodes send their message with an average sending rate, the beacon messages' sending times are distributed unevenly on the timeline. Having a certain level of randomness in the beacon message sending process does decrease the beacon conflict probability. However, the randomness level in FSRB model seems to be too high for the mobile nodes to achieve a regular successful receiving rate. For example, several beacon messages may be sent from a reference node in one receiving slot, while in the next receiving slot there may be no message sending at all. Since we need only one beacon message to be successful in each receiving slot, all the other beacon messages sent in the same receiving slot are wasted no matter whether they are sent successfully or not. Consequently, to improve the beacon receiving performance, we need an improved beacon message sending model in which the sending times should be distributed more evenly in the receiving time slots, while at the same time a certain level of randomness in sending times needs to be maintained to avoid conflicts.

In order to achieve this design objective I add further constraint to the sending model to make the message sending more evenly distributed on the time line. This constraint is to divide the beacon sending time line into a slotted pattern. The sending time line of each reference node is divided into time slots with fixed length T, in which it only sends one beacon message. A reference node generates a sending time t_s within each sending time slot following a random distribution $f(t)$. I call this model the Time Slot based Stochastic Reference Beacon (TSSRB) model. For the system to have a unified hardware design and stable message-transmitting rate, all reference beacon nodes are considered to be identical and are using the same random distribution function $f(t)$ with exactly the same parameters. In this case, the performance of the FSSRB model is related only to the random distribution $f(t)$ used by the reference nodes to calculate each of their sending time t_s.

8.2.2 Random Distribution *f(t)* and Sending Performance of TSSRB Model

First I discuss the beacon message sending performance of the TSSRB model. $f(t)$ is a random distribution within each time slot and thus its probability density function can be given as:

$$P[t_s = t] = \begin{cases} f(t) & t \in (0,T) \\ 0 & t \notin (0,T) \end{cases}$$

A beacon message sent at time t_s will fail if it conflicts with a beacon message sent by another reference node. Taking into consideration that all beacon messages have the same fixed length, let l be the channel occupying time of each beacon message. The condition for such a beacon message to be sent successfully is that no other beacon message is sent within the period $[t_s - l, t_s + l]$. Let N be the number of beacon nodes a mobile receiver can hear, the probability for a beacon node to send a message successfully at t_s, denoted by $P_{success}(t_s)$, is given as:

$$P_{success}(t_s) = \int_{t_s - l}^{t_s + l} [1 - f(t)]^{N-1} dt$$

The mathematical expectation for a beacon node to send a message successfully within each time slot, denoted by $E(P_{success})$, is given as:

$$E(P_{success}) = E[P_{success}(t_s)] = \int_0^T f(t_s)\{\int_{t_s - l}^{t_s + l} [1 - f(t)]^{N-1} dt\} dt_s \tag{8.4}$$

To maximizes $E(P_{success})$, we need to adopt the principle of maximum entropy. The entropy of a random variable is a concept in information theory that measures the uncertainty of a random variable in probability distributions. As all nodes are considered to be identical, they are using exactly the same probability distribution $f(t)$ to calculate the sending time t_s in each time slot. Thus the problem can be considered to be finding the distribution $f(t)$ on $t \in (0,T)$, from which any two calculation outcomes should have the least probability of coming together. Or in other words, it means that the distribution $f(t)$ should contain the least trend/constraint that could make it favour any specific values or sub-domains within its field of definition; otherwise its outcomes will have a higher probability of falling into the set of values or sub-domains that it favours, and thus have a higher probability expectation of conflict with each other.

According to the principle of maximum entropy, the probability distribution of a stochastic variable with the least constraint, or with the highest randomness, is the one with the maximum entropy under given constraints. This holds for both discrete and continuous distributions (Lisman and Van Zuylen, 2008). In our problem the entropy of $f(t)$ is given as:

$$H(t) = -\int_0^T f(t)\ln f(t)dt$$

The use of the natural logarithm here is for convenience in algebra. As $f(t)$ is a random distribution defined in the domain $(0,T)$, we need to maximize $H(t)$ subject to the constraint:

$$\int_0^T f(t)dt = 1$$

By applying the method of Lagrange multipliers, we set λ as a constant multiplier. Thus a $f(t)$ with the maximum entropy must satisfy:

$$-\frac{\partial}{\partial f}(f\ln f) + \lambda\frac{\partial}{\partial f}(f) = 0 \;\;\Rightarrow\;\; -1 - \ln f(t) + \lambda = 0 \;\;\Rightarrow\;\; f(t) = e^{\lambda - 1}$$

As λ is a constant, the result shows that the maximum entropy is achieved by the uniform probability density distribution on $(0,T)$, which can be given as:

$$f(t) = \begin{cases} 1/T & t \in (0,T) \\ 0 & t \notin (0,T) \end{cases}$$

The mathematical expectation of a beacon message being sent successfully can thus be given by:

$$E(P_{success}) = \int_0^T f(t_s)\{\int_{t_s-l}^{t_s+l} [1-f(t)]^{N-1} dt\} dt_s \quad = \left(\frac{T-2l}{T}\right)^{N-1} \tag{8.5}$$

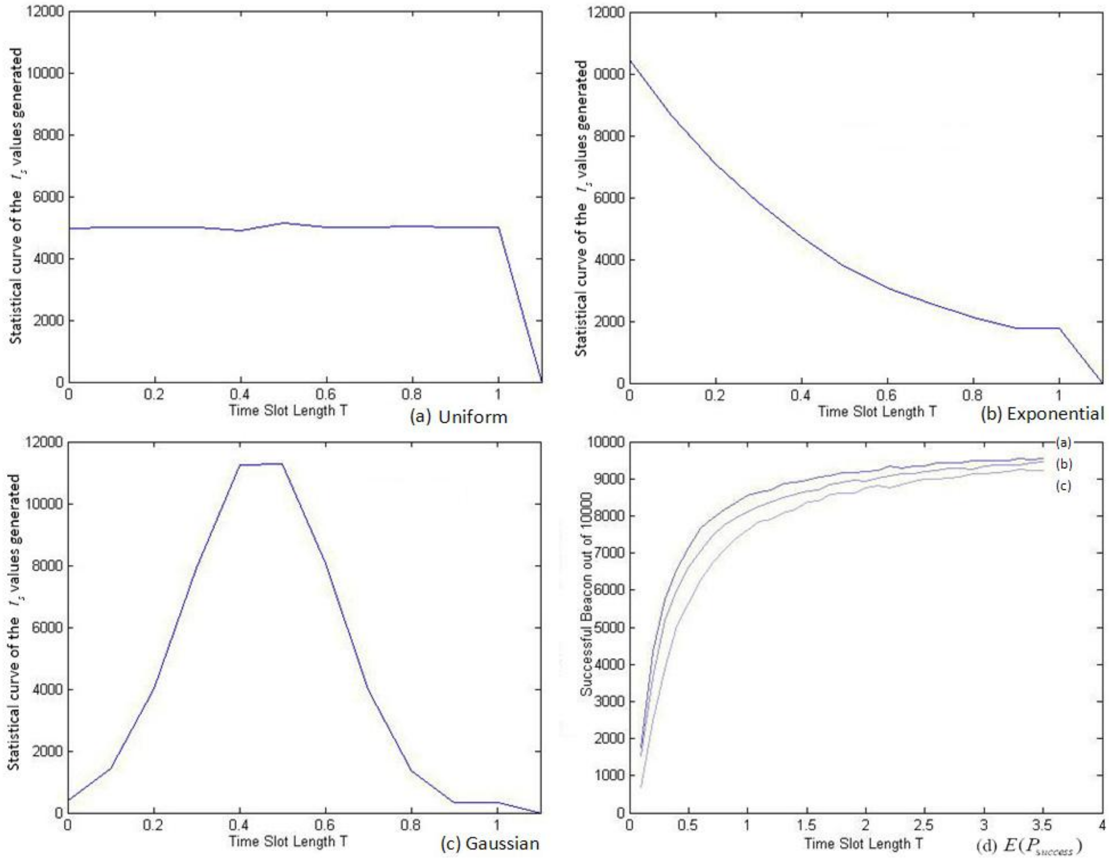


Figure 8-3: Simulation results of various t_s distributions and their probability of successful sending

I conducted a series of simulations based on the Matlab environment. The results I obtained match closely with the predicted outcome given by our derivations. In the simulation I set the total number of beacon nodes within receiver RF range $N = 5$ and the channel occupying time of sending each beacon message $l = 0.02$. I ran the simulations for a period of 10^4 time slots using a uniform distribution as well as two other distributions to provide comparison data. Figure 8-3(a) shows the actual distribution of t_s calculated with a uniform distribution, Figure 8-3(b) and 8-3(c) shows the actual distribution of t_s calculated with an exponential distribution and a Gaussian distribution respectively. The methods used to generate non-uniform random variants can be found in the work of Press et al. (2002). Figure 8-3(d) gives the curves showing the average number of successful beacon messages over 10^4 time slots for all the three distributions when the sending time slot length T increases from 0.1 to 3.5. It shows that the uniform distribution achieves the highest success rate, and that its absolute value closely matches the result predicted by Equation (8.5).

8.2.3 Receiving Performance of TSSRB Model

A time-slotted receiving mode is used by the mobile nodes in our design. The criterion for a successful receiving is that at least one beacon message is correctly received within a time slot. I will prove that in the TSSRB model, the probability expectation of successfully receiving at least one beacon message from a specific reference node in each time slot, represented by $E(P_R)$, is related to the length of monitoring of the time slot R and the start time of the receiving time slot t_R. This means the $E(P_R)$ is time-correlated and results in a certain level of inconsistence in beacon receiving performance among the mobile receivers.

8.2.3.1 TSSRB Receiving Performance When R=T

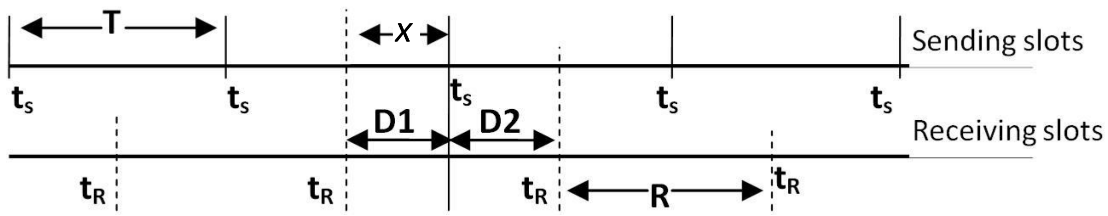


Figure 8-4: TSSRB Sending and receiving slots when $R \leqslant T$

Figure 8-4 shows the situation where $R \leqslant T$ and the receiving slot with a start time t_R has an offset of x before the start time of a message sending time slot. The probability expectation of successfully receiving at least one beacon message from a specific reference node in each time slot, denoted by $E(P_R, R \leq T)$, can be calculated as follow:

$$E(P_R, R \leq T) = E(P_{success})P\{X(D1)\}P\{\overline{X}(D2)\} + E(P_{success})P\{\overline{X}(D1)\}P\{X(D2)\}$$
$$+P\{X(D1)\}P\{X(D2)\}P\{Y_{k>0}[X(D1), X(D2)]\}$$

where $P\{X(D1)\}$ and $P\{X(D2)\}$ represent the probability of a beacon message being sent within the period D1 and D2 respectively, $P\{\overline{X}(D1)\}$ and $P\{\overline{X}(D2)\}$ represent the probability of no beacon message being sent within the period D1 and D2 respectively. $P\{Y_{k>0}[X(D1), X(D2)]\}$ represents the probability of at least one beacon message being received correctly in the receiving time slot R when there were beacon messages being sent in both the time periods D1 and D2. In practical it is not useful to monitor the channel for a period shorter than the sending time slot T, thus I discuss only the situations when $R = T$.

For $R = T$, we have:

$$\begin{cases} P\{X(D1)\} = P\{\overline{X}(D2)\} = x / T \\ P\{\overline{X}(D1)\} = P\{X(D2)\} = (T - x) / T \\ P\{Y_{k>0}[X(D1), X(D2)]\} = \{1 - [1 - E(P_{success})]^2\} \end{cases}$$

Thus we have:

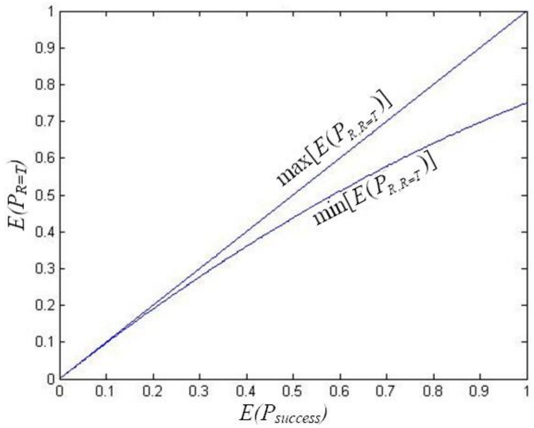
$$E(P_R, R = T) = \frac{x}{T} \cdot \frac{x}{T} \cdot E(P_{success}) + \frac{T-x}{T} \cdot \frac{T-x}{T} \cdot E(P_{success}) + \frac{x}{T} \cdot \frac{T-x}{T}[2E(P_{success}) - E^2(P_{success})]$$

Where $E(P_R, R = T)$ is the probability expectation of successfully receiving at least one beacon message from a specific reference node in each time slot when $R=T$. Expanding and simplifying the above equation we have:

$$E(P_R, R=T) = E(P_{success}) + [(\frac{x}{T})^2 - \frac{x}{T}] \cdot E^2(P_{success}) \tag{8.6}$$

From Figure 8-4 we have $\frac{x}{T} \in [0,1)$, considering $E(P_{success})$ as a constant and applying derivation we can obtain the maximum and minimum $E(P_R, R=T)$ that is related to the offset x:

$$\begin{cases} \max[E(P_R, R=T)] = E(P_{success}) & , \quad x=0 \\ \min[E(P_R, R=T)] = E(P_{success}) - E^2(P_{success})/4, & x/T = 1/2 \end{cases} \tag{8.7}$$



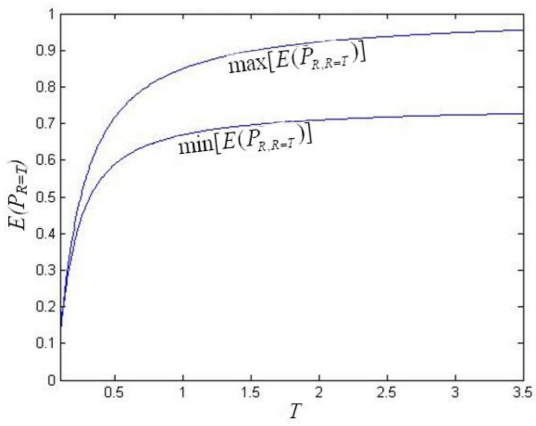


Figure 8-5a: Relationship between $E(P_R,R=T)$ and $E(P_{success})$ when $x/T=1/2$ in TSSRB

Figure 8-5b: Change of $E(P_R,R=T)$ with $N=5$, $l=0.002$ and $T=[0,3.5]$ in TSSRB

Based on the Equations (8.5) and (8.7), Figure 8-5a shows the relationship between $E(P_R, R=T)$ and $E(P_{success})$ when $x/T=1/2$. Figure 8-5b shows the change of $E(P_R, R=T)$ when the sending time slot length T increases from 0.1 to 3.5. The value of $E(P_R, R=T)$ varies within the area bordered by the curves of $\max[E(P_R, R=T)$ and $\min[E(P_R, R=T)]$ given in Equation (8.7).

8.2.3.2 TSSRB Receiving Performance When R=nT

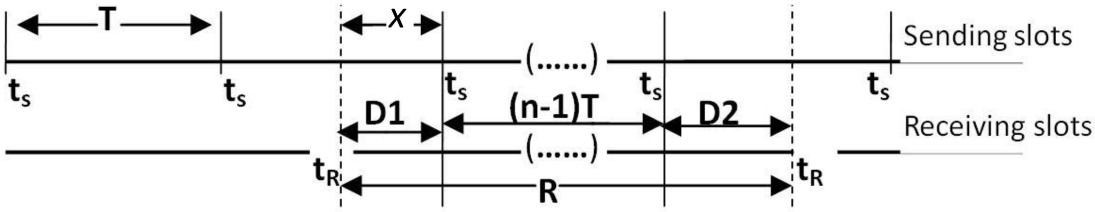


Figure 8-6: TSSRB Sending and receiving slots when *R=nT*

Now I extend the discussion of beacon message receiving performance to $R = nT$, where $n = 1, 2, 3....$ Figure 8-6 shows the situation when the mobile node's receiver monitors the beacon channel with a receiving time slot length of *R* that is an integral multiple of T to increase the chance of correctly receiving the beacon message. According to the principle of probability expectation, the $E(P_R, R = nT)$ can be calculated as follow:

$$E(P_R, R = nT) = 1 - P^{n-1}\{Y_{k=0}(T)\} \times P\{Y_{k=0}(D1, D2)\}$$

where $P\{Y_{k=0}(T)\}$ represents the probability of no beacon message being correctly received within a full sending time slot of *T*, $P\{Y_{k=0}(D1, D2)\}$ represents the probability of no beacon message being correctly received within the two offset periods D1 and D2. The receiving probability in the two offsets D1 and D2 is actually the same with the situation *R=T*, thus the probability expectation of successfully receiving at least one beacon message in the two offsets periods D1 and D2 is the same with $E(P_R, R = T)$ given in Equation (8.6).

Also because:

$$P\{Y_{k=0}(T)\} = 1 - P\{Y_{k>0}(T)\} = 1 - E(P_{success}),$$

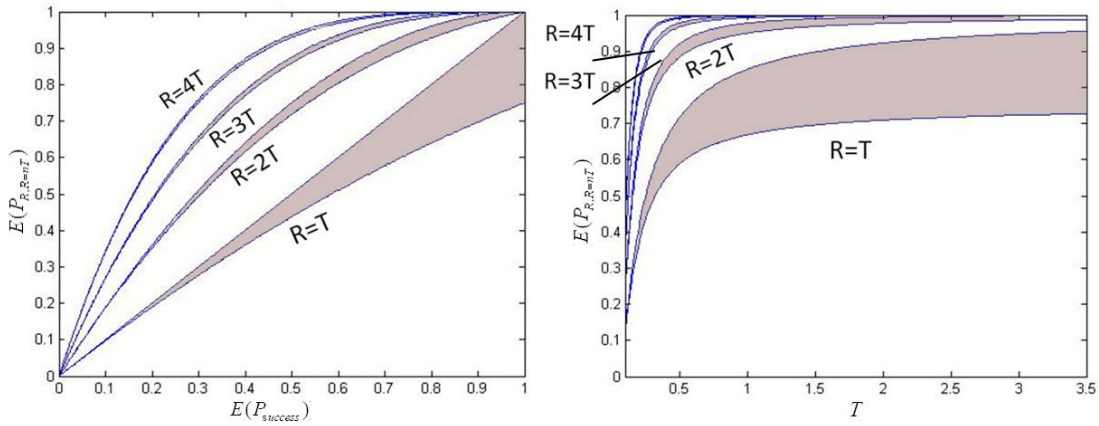
we have:

$$E(P_R, R=nT) = 1 - P^{n-1}\{Y_{k=0}(T)\} \times P\{Y_{k=0}(D1, D2)\} = 1 - [1 - E(P_{success})]^{n-1} \times [1 - E(P_R, R=T)]$$

$$= 1 - \{[1 - E(P_{success})]^{n-1} \cdot [1 - E(P_{success}) + [(\frac{x}{T})^2 - \frac{x}{T}] \cdot E^2(P_{success})]\}$$

Considering $E(P_{success})$ as a constant, we obtain similar results of $E(P_R)$ for $R=nT$, $n = 1, 2, 3...$:

$$\begin{cases} \max[E(P_R, R=nT)] = 1 - [1 - E(P_{success})]^n & x/T = 0 \\ \min[E(P_R, R=nT)] = 1 - \{[1 - E(P_{success})]^{n-1} \cdot [1 - E(P_{success}) + E^2(P_{success})/4]\} & x/T = 1/2 \end{cases} \quad (8.8)$$



(a) (b)

Figure 8-7: (a) TSSRB Probability of successful receiving related to probability of successful sending; (b) TSSRB Probability of successful receiving with N=5, l=0.02 and T=[0,3.5]

The results based on the Equation (8.8) are shown in Figure 8-7. It can be concluded that in the TSSRB model, the probability expectation of successfully receiving at least one beacon message from a specific reference node in each time slot $E(P_R)$ is not a determined value even when *T, l, f(t)* and *R* are fixed. It depends on the start time of the receiving time slots t_R, or in other words the offset x between the start of the sending and receiving time slot, and reaches its minimum when receiving slot starts at the mid-point of a sending slot. This means the $E(P_R)$ is time-correlated, and since the parameter t_R or the offset x is not user controllable, the receiving performance will thus vary between the maximum and minimum borders of $E(P_R)$ given by Equation (8.7).

8.3 Comparison of FSRB and TSSRB Models

I will compare the two models' performance when they have the same average sending rate, as this leads to the same energy consumption in long-term operation.

8.3.1 Influence of Asynchronous on FSRB and TSSRB Models

As all beacon nodes are non-networked and are not synchronized, not only can we not guarantee that the receiving time slot starts at the same time as the sending slots, but also the sending time slots on different beacon nodes are not guaranteed to start together at the same time. Indeed, it is highly unlikely that any two reference nodes would start their sending slots at the same time. This asynchrony of the beacon nodes does not have any influence to the performance of FSRB model in which the sending process is not time correlated. However, such asynchrony may result in a performance variance in receiving beacon messages from different reference nodes.

8.3.1.1 Influence of Asynchrony on Expectation of Sending Success Rate

For a pair of reference nodes in the same RF field, consider the situation where the slot start times of node B is later than that of node A with an time offset of y. The equivalent description is that the slot start times of node A is earlier than that of node B with an offset of y. The expectation of node A's sending success rate is:

$$E(P_{success\_Async}) = \int_0^y f(t_s)\{\int_{t_s-l}^{t_s+l}[1-f(t)]^{N-1}dt\}dt_s + \int_y^T f(t_s)\{\int_{t_s-l}^{t_s+l}[1-f(t)]^{N-1}dt\}dt_s$$

When $f(t)$ has uniform distribution, we have:

$$E(P_{success\_Async}) = \int_0^T f(t_s)\{\int_{t_s-l}^{t_s+l}[1-f(t)]^{N-1}dt\}dt_s = E(P_{success})$$

This suggests that the asynchrony of time slot does not affect the message sending performance. I conducted a number of simulations in Matlab and discovered that the sending performance results of synchronous and asynchronous time slot matched each other.

8.3.1.2 Influence of Asynchrony on Expectation of Receiving Success Rate

Since the reference nodes' sending slot are not starting together, for each mobile node, their receiving slot could start with different offset with respect to each reference node. In this case the receiving performance from different reference nodes varies between the maximum and minimum values given by Equation (8.8).

8.3.2 Comparison of Sending Performance

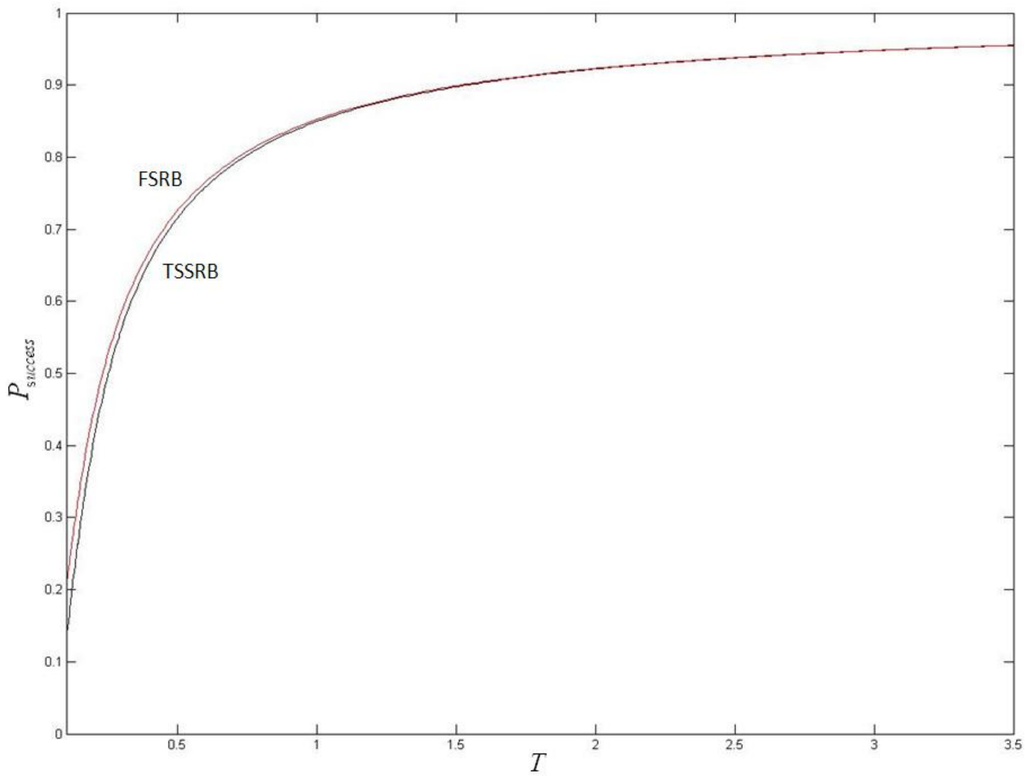


Figure 8-8: Comparison of probability of successful sending

Figure 8-8 shows the changing of sending success rate $P_{success}$ while the average sending period increases in both time-slotted and fully stochastic beacon systems. The number of reference node within a same RF area is set at $N = 5$, the time length of sending a beacon message is set at $l = 0.02s$. The result shows very small difference in the sending performance of both beacon systems. The fully stochastic reference beacon system has a slightly higher sending success rate at low performance levels, but the time-slotted beacon system catches up quickly as T increases. At high performance levels, which are more important since this is the area in which the final system should be designed to work, there is no difference between the two systems.

8.3.3 Comparison of Receiving Performance

No matter how good the sending performance can be made, it is the receiving performance that is most significant in the real applications. Figure 8-9 shows a comparison of the FSRB model and the TSSRB model when the receiving time slot length increases from $R = T$ to $R = 4T$. As I have discussed previously in Sections 8.1 and 8.2, the receiving performance of FSRB model is consistent and always appears as a single line, while the receiving performance of TSSRB model varies within an area bordered by the maximum and minimum receiving probability given in Equation (8.8).

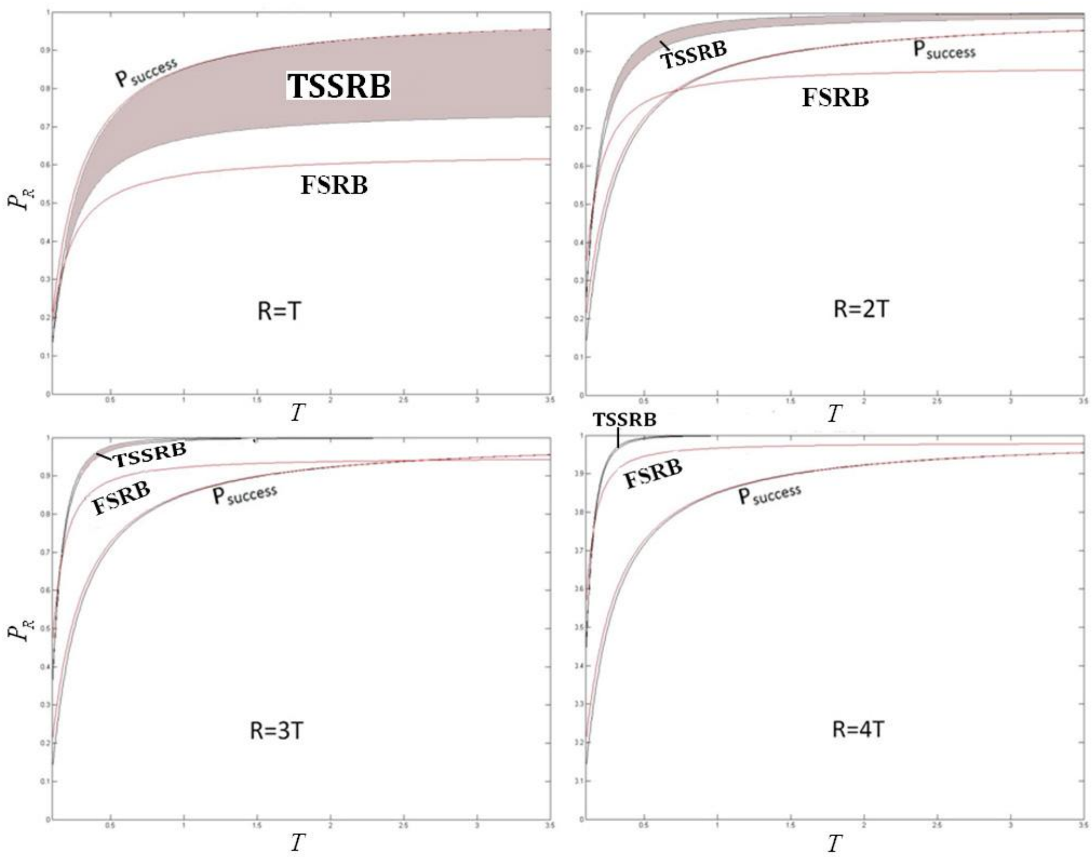


Figure 8-9: Comparison of probability of successful receiving

According to the results in Figure 8-9, when $R = T$, the TSSRB model performance varies considerably, and is always lower than the sending success probability $P_{success}$. However, even the receiving performance at the lowest border is higher than the receiving performance of the FSRB model, which is steady and consistent but too low. When the receiving time slot is increased to $R = 2T$, both models' receiving performance increases but the FSRB model performance is still lower than its corresponding sending success probability while the TSSRB model shows a dramatic improvement in both its receiving performance and consistency. The receiving performance of the TSSRB model at *R=2T* is already above the corresponding sending success rate $P_{success}$ and moves very close to 1, and at the same time the variation area of its performance narrows significantly. While the performance of the FSRB model still increases slowly when the receiving time slot is increased to *R=3T* and *R=4T*, the TSSRB model's performance improves significantly. At high performance levels, which I have mentioned to be the most important part, the receiving performance of the TSSRB model approaches 100% and the inconsistency becomes so insignificant that it can be neglected.

From these results in Figure 8-9 it can be concluded that the TSSRB model outperforms the FSRB model regardless of receiving time slot lengths. By slightly increasing the receiving slot length the TSSRB model's successful beacon receiving probability can quickly approach 100% and the inconsistency in performance quickly becomes insignificant. The reason why the TSSRB model is so sensitive to the increase in the receiving slot length is:

- Firstly, when R increases the receiving time slot starts to overlap more and more full sending slots; unlike the FSRB model, a reference node in the TSSRB model must send a beacon message within each of the sending time slots and thus the probability of receiving at least one beacon message is rapidly increased;
- Secondly, the inconsistency in performance of the time slotted beacon is caused by the two offsets at the beginning and the end of a receiving time slot; when $R = T$ this is the most significant factor; but as R increases, the increasing number of full sending time slots in the middle of a receiving slot quickly becomes the main factor that influences the receiving performance and the effect of the two offsets becomes less and less significant.

8.4 Conclusion

In the final system design the TSSRB model is recommended. From our theoretical deductions and the simulation results, when N=5, which would well fulfill the requirements for the indoor RF localization algorithms, the choice of $R = 3T$ and $T = 100l$ appears to be a sweet point between tracking performance and beacon battery life. However, the exact value of those parameters should be determined using our performance equations given in Sections 8.2 and 8.3 based on the usability specifications of the actual application. Usually the maximum localization updating rate of T seconds and the minimum localization failure probability of P will be specified in such specifications and the objective is thus to choose the right parameters to achieve the longest battery life for the beacon nodes subject to the application specifications being fulfilled.

Chapter 9 Integrated ZigBee RFID Sensor Network for Humanitarian Logistics Centre (HLC) Management – A Case Study

Various information technologies have been designed to assist with the resource management of distribution centres in a typical supply chain. But the humanitarian distribution centre has its own characteristics including hybrid freight types (food, medicine and general living goods, as well as a need to track rescue equipment, vehicles and on-site staff), destabilised operating circumstances and swift response to emergencies etc. None of the existing technologies can satisfy all of these diverse needs and the adoption of several different technologies may lead to higher cost, slower implementation and more complex integration. In this chapter I study the implementation of our integrated ZigBee RFID sensor network system architecture for the resource information management system in humanitarian logistics centres (HLCs) as a case study. The aim of the study is to provide a complete, simple easy-to-implement and flexible solution based on our final architecture framework involving all the functions in our requirement pyramid for distribution centres in the humanitarian supply chain and provides the ability to monitor all of their resources, including freight, rescue equipment, vehicles and people, as well as the local environment.

Our findings and contributions in the study are as follows. Compared to the old systems, the system using the integrated RFID sensor network architecture is able to provide complete information for logistics centre resource management while the cost, complexity and time required for such a system implementation were significantly reduced as a result of the simple and flexible network architecture. In addition, the system can easily and quickly be removed and re-implemented in the event of a possible emergency relocation of the centre. The system development and evaluation have shown the feasibility and value of this approach. The work has demonstrated the completeness of information that the system can provide, as well as the flexibility of such a low-cost but complete system which can lead to significant improvements in the overall performance of the humanitarian supply chain.

9.1 Introduction

Humanitarian aid is defined as material or logistical assistance provided for humanitarian purposes, typically in response to humanitarian crises. The primary objective of humanitarian aid is to save lives, alleviate suffering and maintain human dignity. Humanitarian logistics is a broad term that covers operations concerning supply chain strategies, processes, and technologies that will help make humanitarian aid more effective. There are two main streams of humanitarian logistics: continuous aid work and disaster relief. The term disaster relief includes emergency responses to sudden catastrophes such as natural disasters (earthquakes, hurricanes, floods, fires, volcano eruptions, etc.) as well as man-made disasters such as terrorist attacks and nuclear accidents (Kovacs and Spens, 2007). Famine relief is also categorized as one type of disaster relief (Long, 1997).

Logistics has always been considered as an important factor in humanitarian aid operations, in which logistics efforts account for 80 percent of the disaster relief effort (Trunick, 2005). An interest in humanitarian logistics has increased rapidly inside academic circles as well as with external practitioners over the past few years. The combined budgets of the ten top aid agencies around the world exceeded 14 billion dollars in 2004 (Thomas and Kopczak, 2005), while the 100 major relief agencies in 1995 managed only over 1 million each (Long and Wood, 1995). This industry will continue to expand as a five-fold increase in both natural and man-made disasters is expected in the next 50 years (Blanco and Goentzel, 2006).

Both natural and man-made disasters which have occurred in the past few decades have alerted the world community to the importance of being able to build an efficient and agile humanitarian supply chain (Oloruntoba and Gray, 2006). Current research focuses mainly on planning humanitarian logistics at a macro level (Kovacs and Spens, 2007; Özdamar et al., 2004; Tomaszewski et al., 2006; Van Wassenhove, 2006). In the general field of logistics management research, much work has been done to prove that improving the whole supply chain performance relies on improving the external service quality at each distribution point on the chain, which requires the internal service performance at each distribution point to be improved initially (Conduit and Mavondo, 2001). This is similar to the case in humanitarian logistics. Thomas (2003) suggests that the speed of response for major humanitarian programmes depends on the ability of logisticians to procure, transport and receive supplies at the site of a humanitarian effort, such as the humanitarian logistics centres (HLCs) which are the most important sites where both freight and information flows are congregated, relayed or distributed.

This means one of the most important aspects of the whole problem can be considered as the need to improve the HLC's on-site performance. Because efficiency and correct decision-making are based on situation awareness, an appropriate on-site information infrastructure is important for a humanitarian logistics centre to achieve high internal and external service performance. Systems such as a typical RFID system and information networks have been implemented in some of the logistics centres in the general supply chain, but the fast emergency response features of humanitarian logistics prevent them from being adopted directly into humanitarian logistics centres.

Thus the aim of this chapter is to study the integrated ZigBee RFID sensor network in the HLCs as an information infrastructure to help increase the efficiency of each humanitarian distribution point/centre by providing higher freight and resource visibility and state monitoring ability for internal process management; thereby reducing the possibility for the occurrence of bottlenecks in the humanitarian supply chain.

Our research began with a user requirement analysis based on both literature reviews, which explored existing studies carried out by other researchers, together with interviews with emergency personnel. After this user requirement analysis was completed, current emerging technologies – RFID and sensor devices were identified as applicable for logistic management. An information infrastructure for HLC based on our previous research was then presented and a method for a general implementation of such an infrastructure was developed. A demonstration system was built using our hardware development kits and was validated in a laboratory environment. A field trial was then carried out at a standard 4200 m^2 warehouse with a self-contained two story office in an industry estate near Loughborough.The demonstration system and the field trial validate the proposed infrastructure and demonstrate the potential to emergency personnel and services for the consideration of a possible real application. The findings of the field trial are summarized and discussed at the end of this chapter.

9.2 User Requirements of Information Infrastructure for HLC Management

The transport and delivery of emergency aid goods and materials is the main task of the humanitarian supply chain. Consequently, the initial transportation of such commodities is the very first thing on the scene that needs to be managed. To correctly and efficiently monitor the flow of commodities, information on the goods inside the logistics centre, such as type, amount, position and state, should be recorded and updated in real-time. Food and medicine are key goods in the humanitarian supply chain; these types of goods require specific environmental conditions during storage and transport, which means information on environment monitoring is also necessary. Other freight includes large and valuable specialised rescue equipment (Özdamar et al., 2004) as well as forklifts, plant and vehicles which should also be tracked for management and safety considerations. As disaster management involves working inside a disaster-affected area, which may not even be the original region or even the country of origin of the staff, security issues cannot be ignored. Possible harsh environments may present another hazard to workers in the centre. Our interviews with emergency personnel also emphasised that the most important issue in any emergency scene is knowing what emergency personnel and equipment are on the scene, where they are, and whether or not they are safe. Tracking the position of staff members can help protect their safety and provide early warning of security problems or accidents. Thus location tracking of both equipment and people is equally important in humanitarian aid actions in an unknown environment.

A humanitarian logistics centre may not be the first warehouse to require an information infrastructure for identifying goods or monitoring environment conditions, but many distinctive features of emergency aid prevent such a centre from directly adopting any existing systems for general logistics centres. Humanitarian supply chains have been characterised as being unpredictable, turbulent and requiring flexibility (Oloruntoba and Gray, 2006). The distribution centres in such a chain should have a fast response to emergency actions, which means that they may need to be established, modified, moved and re-established in a limited time frame. This certainly requires that the supporting information system must be flexible, simple and fast to implement.

An emergency logistics centre may start operating in the affected area shortly after the natural or man-made disaster occurred, which means the after-effects of the disaster may still exist; examples include the after shocks of earthquakes or human attacks. Thus the information supporting system should have a robust infrastructure so that a certain level of such after-effects will not lead to functional failures.

On the other hand, international humanitarian operations are sometimes hindered by administrative and logistical bottlenecks caused by poor infrastructure in the aid-receiving region (Van Wassenhove and Samii, 2003). For example, humanitarian logistics may operate in a destabilised infrastructure such as the lack or non-continuous supply of electricity (Cassidy, 2003). The occurrence of the disaster in the area may also cause failure of any existing logistics and communication facilities such as GSM mobile networks. Thus the proposed system should be based on a stand-alone platform which does not rely on existing infrastructures to operate.

Further, as the centre may be located in or near the disaster-affected area, the safety of the staff and the equipment may be another issue that a humanitarian distribution centre should consider. The main real-time tracking systems available today cannot provide satisfactory performance for such on-site tracking tasks; the Global Positioning System (GPS) is not capable of tracking objects indoors, while a mobile network-based system relies on local base stations which may have failed during the disaster. Any WiFi-based tracking system is power consuming and its implementation is time consuming.

In summary, distribution centres in the humanitarian supply chain have the following requirements for their information support systems:

- Tag and identify various types of freight, tracking them in the logistics process;
- Monitor specific storage conditions of some goods, thereby maintaining their quality;
- Tag and identify equipment such as specialised rescue equipment, vehicles, plant and medical equipment, tracking them for both logistics and safety purposes;
- Tag and identify staff and officers working and living in the centre, tracking them for both management and safety purposes;
- Have a simple but reliable network architecture and devices that do not depend on any local facilities which cannot be assured in a disaster area;
- Have an easy and fast implementation process to perform fast responses to emergency actions.

9.3 Current Technologies – RFID and Sensor Devices in Logistics

There is a great deal of existing literature concerning logistic centre management using RFID or sensors, but a very few consider HLC and emergency resource management, and none which demonstrate how to integrate, implement and maintain these technologies in a HLC in emergency situations.

Currently, RFID is one of the exciting technologies in logistics applications. Research has shown that by using RFID, a logistics centre can track the status of material and vehicles throughout the supply chain in logistics centres and increase delivery reliability in terms of correct materials orders and timely deliveries (Hamzeh, 2007).

Thus, more and more logistics centres are implementing or planning to implement various RFID systems to help improve the performance. For example, RFID has been employed at Shanghai Port Logistics Centre in replacement of IC cards when container trucks enter operation zones (Shu et al., 2007). A RFID-based real-time parts tracking system is also helping US military aircraft spend more time in the air and less on the ground at the Oklahoma City Air Logistics Centre (OC-ALC), where RFID has contributed to a reduction of service times for aircraft by over 50% (Domino Printing Sciences Plc., 2008). The Spanish supermarket chain Mercadona has installed RFID-tagged pallets within the dry, fresh and frozen goods areas of its logistics centre near Madrid (Food Quality News, 2005), while Wal-mart in the US and Metro in Europe are trying to popularise passive RFID tags on all their goods. These practices, in general logistics centres, all concentrate on the adoption of a dedicated type of RFID technology to track a single type of target, such as the containers for port logistics centre, aircraft parts for air logistics centre and pallets for supermarkets' logistics centres. Even more examples of RFID in general logistics centres can be listed. Most of them are very simple application of RFID technology and have a very similar and typical RFID system architecture, which is achieved by implementing the RFID readers and connecting the readers directly to a central server either via a direct cable link or via a cable network link. Although these practices have demonstrated the value of RFID technology in helping logisticians to improve the performance of logistics centres, their system architecture cannot be adopted directly by HLCs because a single type of RFID technology is not capable of tagging and tracking a HLC's hybrid freight type (food, medicine and general living goods as well as rescue equipment, vehicles and on-site staff) while the adoption of several such systems leads to high cost, slow implementation and complex integration. For example, passive RFID is practical only used for a massive implementation of cheap, non-recycled and non water or metal based goods whilst the active RFID can perform the task for objects that are either too large to be tracked closely (e.g. containers or rescue equipment) or too far away from the reader when tracked remotely on a real-time basis (e.g. vehicles, on-site staff). To adopt all these technologies the traditional system architecture will result in having individual reader devices from all required RFID types at each reading point. Each of these readers will also need individual cable or network links to the server, which results in high cost and slow implementation due to the duplicated network implementation. These limitations of traditional system network architecture cannot satisfy the hybrid freight tracking, low cost and swift response to emergency incidents required by HLC resource management systems.

On the other hand, sensors are also implemented in some logistics centres for various other purposes. In the Sydney Port Intermodal Logistics Centre at Enfield, sensors cooperate with time switches and timer delays for controlling the comfort heating and cooling and switching on and off of lights in order to optimise building performance and system control strategies (Sydney Ports Corporation, 2005). At the Berlin Inner-City Logistics Centre, a container tracking system has been tested in which temperature, pressure and humidity sensors are used to monitor the freight status, as well as the use of movement/acceleration and shock sensors for security purposes. These sensors are connected with the microcontroller in the container which communicates with a central server via GSM/SMS. The Inner-City Logistics Centre announced that the system enhanced the economic efficiency of the intermodal freight transport and obtained positive impacts for the environment (Reitemann and Lauer, 2005). These practices have shown the value of sensor devices in logistics centre management to monitor the condition and state of some particular freight with special needs. But the network architecture they used for integrating sensor devices into the resource management system are not directly adoptable for HLCs because they either require a direct cable link to server or rely on existing communication facilities in the area (GSM/SMS) which might not be practical nor reliable in HLC scenarios.

All the work listed above tried to implement either a sensor device or a single type of RFID device in general logistics centres for tracking goods, monitoring freight status and improving economic efficiency. But humanitarian logistics centres have their own features and requirements, such as tracking multi-type targets and easy/fast implementation for swift response, which make these existing systems' architecture either inappropriate or inadequate for HLC applications. The passive RFID tagging system has come to an international standard and is spreading quickly throughout the world; passive tags are durable, cheap and are the ideal and practical system to be used for freight tracking purposes. But the features of passive RFID tags also limit their use: the limitation of their reading range means they are not suitable for tracking large equipment and vehicles; their poor performance when tagging water or metal based materials prevents them from tracking human beings, of which 60 to 70 percent of body weight is made up by water, and most pieces of large equipment, which are generally made of metal. Active RFID plays a major part in human, equipment and vehicle tracking, but their tag cost makes them impractical for general freight tagging, and their operating principles are completely different from the passive systems, which means readers in active and passive RFID systems will not read tags from the other's system. In HLC resource management both types of RFID technologies are necessary for the tracking of a hybrid type of freight as well as the equipment and on-site staff for security reasons. Existing technology will require two different systems to be implemented to fulfil the tracking tasks in our scenario. On the other hand environmental monitoring is required by HLC to ensure the quality of certain types of freight, such as medicine and food, which requires sensor devices to be attached to the freight. This may add another structure to the system. Adoption of the traditional systems of all the technologies required above and simply integrating in software/management coordination means implementation of two or three different systems (sensors, active RFID and passive RFID) with similar communication architecture. An example is the Sentient Overlay Network in HP Lab, which inserts a hierarchy of diverse ad-hoc wired and wireless network structures and computing nodes that are capable of processing and filtering both sensor and RFID data (Pradhan, 2005). The RFID network and the sensor networks are working completely in their standard mode. RFID readers and sensor network gateways are assumed to be wired and powered and compatible with the IP-based network standards. The upper layer communication between the ad-hoc networks and the server nodes is based on standard wired IP networks and wireless LAN, which depends on the specific requirements. Such network structure is too complicated to be adopted by HLC due to its high cost, complexity of deployment and the needs of highly professional technicians for both deployment and maintenance purpose. An improved prototype from (Jedermann et al., 2006) is a RFID and sensor system for fruit logistics using an agent network architecture. In his prototype standard fruit containers are equipped with RFID readers to read the unique ID number of every freight item as well as their transport information stored on their RFID labels. In order to monitor the fruit state, sensor networks are implemented in the containers to measure temperature, humidity and ethylene production rate. The RFID networks and the sensor networks in the prototype all report to a freight agent, which could send out warnings and recommendations through the external network, such as a WLAN of a cargo ship. This prototype provides a more light-weight and simpler structure for small scale applications, but the agent network structure makes the system unsuitable for extended scenarios. Having the RFID systems linked directly to the agent device and the sensor network working independently, the system will grow into a structure which is basically very similar to the adoption of several traditional systems. These duplicated implementations bring high cost in hardware and reduce the flexibility for emergency response. Thus a system with a new architecture is required which should provide integrated functions on a lightweight platform to suit the special needs of HLCs. One of the main objectives in this study is to design a unified information infrastructure which can seamlessly accommodate wireless sensors, active tags, and passive tags.

9.4 Integrated ZigBee RFID Sensor Network for HLC Management

9.4.1 Information System Infrastructure for HLC Management

Based on the previous discussion of HLC information infrastructure and current technical practices, the requirement for the design of a new system architecture for HLC resource management system is raised. This study aims to study the solution by implementing the integrated ZigBee RFID Sensor Network as a unified information infrastructure which can seamlessly accommodate wireless sensors, active tags, and passive tags.

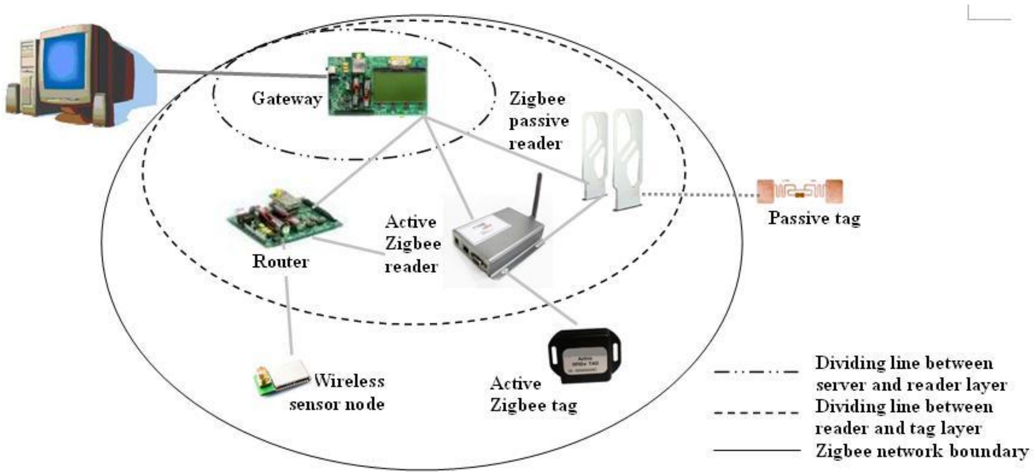


Figure 9-1: Integrated hybrid RFID sensor network system architecture

Out of our work in previous chapters we can construct an integrated hybrid RFID sensor network system architecture as shown in Figure 9-1, the all-in-one system solution for HLC management. ZigBee, a Wireless Sensor Network (WSN) standard based on IEEE 802.15.4, is used as the main communication protocol to connect almost all the system components. It is a wireless technology maintained by the ZigBee Alliance and features a cost-effective, low-power and multi-hop wireless communication in a self-organized mesh network for monitoring and control networks. In this integrated architecture all communications inside the network are expected to be supported by ZigBee, except for the communication between passive RFID tags and their readers. Some WSN routers will be modified to become virtual active readers, which are able to read the wireless sensor nodes with ID like an active RFID system. Remote readers, no matter whether they are passive or virtual active readers, can use the sensor network protocol to connect with the server through the other readers and router devices using multi-hop communication. Although traditional Active RFID can also be involved if their reader can be made to be compatible with the WSN network protocols, wireless sensor nodes are recommended to undertake the identification of large, valuable objects in place of traditional active RFID tags to simplify the architecture. The modified sensor network routers or even the server can read these RFID sensor nodes directly, depending on the application. Dedicated wireless sensor nodes without an ID function can be implemented in the scenario as an additional device to monitor the environment, which is a typical task for the pure Wireless Sensor Networks. Due to the flexibility of the sensor network architecture, modularisation design can be carried out for developing such types of systems. Sensor nodes, active and passive RFID readers can be made into system-compatible, plug-and-play modules. This can simplify the design and implementation of the final system for each different logistics centre. The compatibility of various RFID devices to WSN network and the feasibility of using WSN protocol to performance active RFID service have been demonstrated in our previous work (Yang et al., 2007; Yang and Yang, 2007). Our recent work also demonstrated the capability of such architecture to be further extended for a real-time tracking service (Yang and Yang, 2009a, 2009b).

9.4.2 System Implementation in HLCs

Figure 9-2 describes how the proposed integrated hybrid RFID sensor network architecture can be implemented in a humanitarian distribution centre.

Because of the poor performance of standard passive RFID tags when they work with materials containing metal and water, active tags are recommended for tracking vehicles, engineering plant, large special rescue equipment and people in the scenario. ZigBee end devices are modified to act as active RFID tags; they can be manufactured in various package shapes for different purposes. For tracking the staff and officers in the centre the tag can be made as wrist strip or badge or be integrated in other personal devices such as watches and mobile phones. The package of the active tags for vehicles and equipment could come with a belt or screw holes to help fit them to the vehicle chassis or equipment frame.

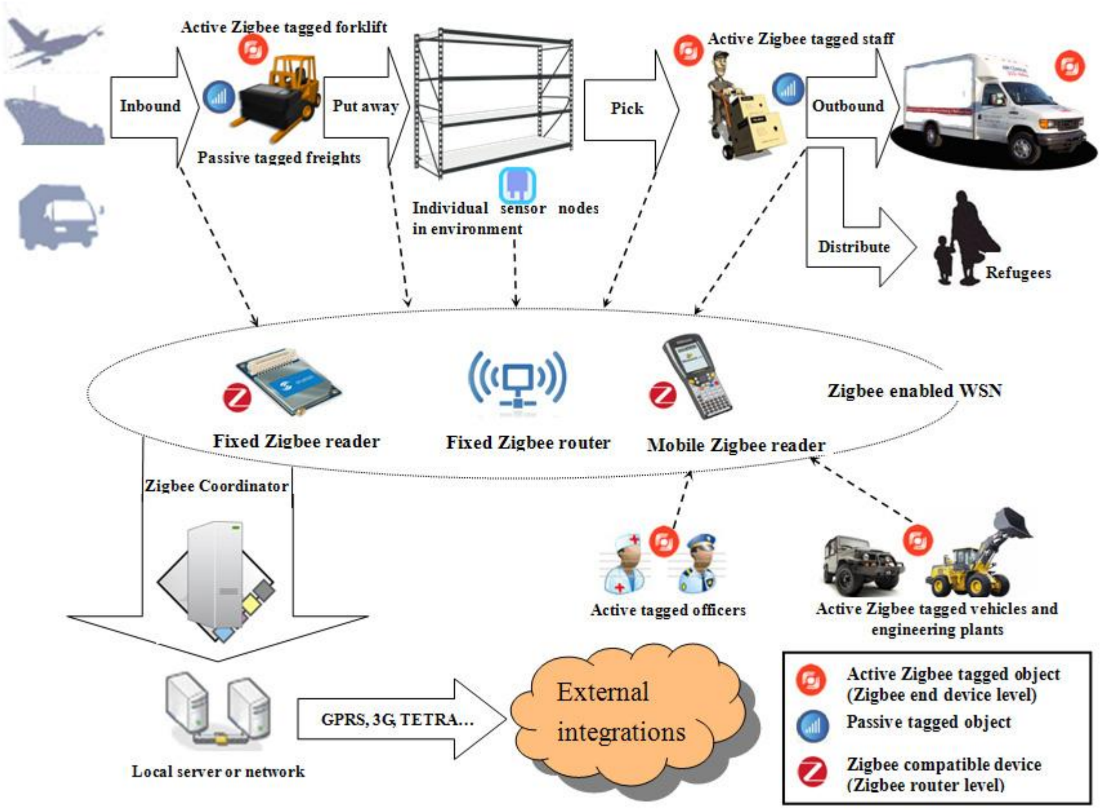


Figure 9-2: ZigBee enabled RFID sensor network in humanitarian logistics centre

Those active ZigBee tags communicate with the active ZigBee readers modified from typical ZigBee routers. These reader/router devices should be implemented over the entire scenario to ensure coverage throughout the centre. The density of the readers depends on the security level or the accuracy of tracking required. Generally speaking, this can be divided into three levels: site level, sector level and room level. A site level accuracy means the information required for the tracked object is just whether it is on-site or not; this requires only a basic amount of readers to ensure network coverage. This accuracy level can be easily satisfied as long as the tag can communicate with at least one reader/router device when it is in the centre. If a sector level accuracy is chosen then each tag should be able to find multiple reader/router devices in the centre. By indicating the reader which has the best Receiving Signal Strength Indicator (RSSI) with the tag, the position of the tracked object can be limited to within a rough area near a specific reader. In certain circumstances when room level or even metre level accuracy is necessary, the tag should be able to obtain the RSSI or TDOA (Time Difference of Arrival) indicator from no less than three reader/router devices whenever it is in the distribution centre, thereby requiring the highest reader density.

The freight going through the centre is expected to be tracked by typical passive RFID tags. Traditional passive RFID readers are integrated with the ZigBee routers/readers to be able to read both traditional passive tags and active ZigBee tags. These hybrid ZigBee readers should be installed at all access points where logistics actions are carried out.

To increase the flexibility of the system, both the ZigBee active reader and the passive hybrid reader can also be designed as handheld devices with rechargeable batteries for temporary operations where fixed readers are not useable.

Dedicated wireless sensor nodes can also be implemented in the scenario where certain environmental conditions need to be monitored. For example food, water and medicines should be stored under certain temperature conditions; while humidity in fruit storage may be crucial (Jedermann et al., 2006). Some dedicated ZigBee routers may also be implemented to help establish and maintain a ZigBee WSN backbone with passive and active ZigBee readers. The local server or network can connect to the ZigBee coordinator or any programmed sink node in the WSN to retrieve information, which could be processed locally for decision support or could be sent over to a remote command centre via other WAN network such as GPRS, 3G or TETRA etc. All the nodes/devices can be designed to be battery assisted, which means they will use an external power supply in general situations, but can switch to battery during possible electricity supply outages caused by either man-made accidents or the after affects of the disaster.

9.5 Demonstration System and Field Trial

9.5.1 Demonstration System structure

The structure of the hardware demonstration system is presented in Figure 9-3. The ZigBee network is constructed using a Jennic JN5139 development kit (Jennic Ltd., 2006). A ZigBee coordinator (ZC) establishes the ZigBee network first; several ZigBee routers (ZR) could then join the network. The active ZigBee tags and readers, passive ZigBee readers and individual sensor nodes could then join the network on a plug-and-play basis.

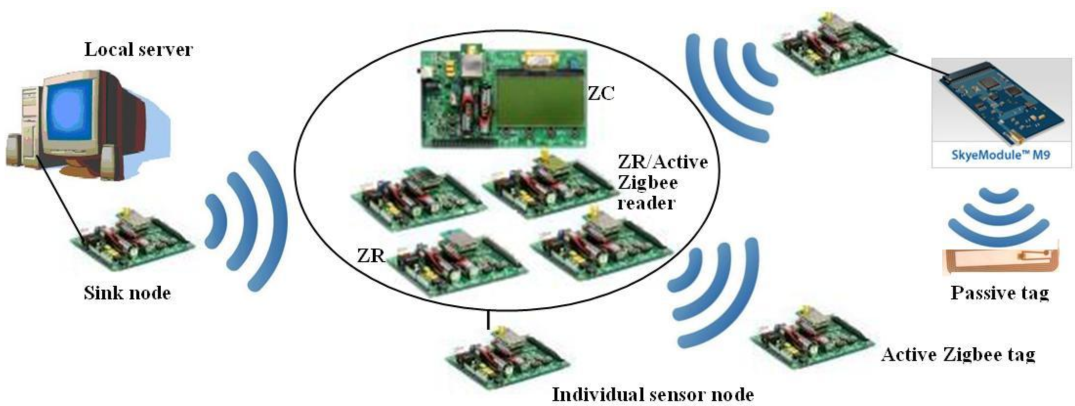


Figure 9-3: Structure of the ZigBee RFID sensor network demo system

9.5.1.1 Active ZigBee Tag

These are the ZigBee-enabled active RFID tags modified from ZigBee end devices (ZED). The ZEDs are the simplest nodes in the ZigBee network; they are usually battery based and contain just the basic functionality to communicate with only their parent nodes, which may be a ZigBee router or a ZigBee coordinator. The ZEDs are concerned with routing tasks in the network and packets sent from other devices in the network cannot be relayed via such devices. This allows the ZEDs to use the sleep mode when there is no data to transfer and thereby to achieve a longer battery life. Less memory space is required for ZEDs thus the cost of manufacture is even lower than the routers or coordinator. These features of ZEDs make them suitable for working as an active RFID tag. In our demo system the Jennic JN5139 ZigBee module and its development board, which are shown Figure 9-4, were used to develop the active ZigBee tags. A unique identification code is stored in the ZED memory and program has been written for it to enable transmission of the ID code to an active ZigBee reader device when necessary.

Figure 9-4: Jennic JN5139 ZigBee module and development board

Active ZigBee tags can work in both beacon enabled and non-beacon enabled modes.

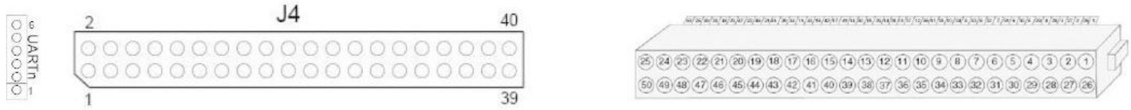
In non-beacon enabled mode the tags send ID information to a reader device only answer to an interrogation. When they are not interrogated by a reader device the tags can go to ZED sleep mode to save energy. If beacon mode is enabled in the network then the tags are synchronized to the coordinator of the ZigBee network and transmit ID information periodically, they can sleep in the predefined time slot between beacons; this also lowers their duty cycle and extends their battery life.

9.5.1.2 Active ZigBee Reader

These are the ZigBee-enabled active RFID readers modified from ZigBee router (ZR). Besides performing the routing task, these devices are also programmed to communicate with the active ZigBee tags and carry out the basic RFID functions such as reading and writing tag information. According to the ZigBee specification the ZRs in the network do not go to sleep mode as they are supposed to be ready for relaying incoming packets, so a mains power supply is recommended for ZR. In our demo system the Jennic JN5139 ZigBee module and its development board are also used to develop active ZigBee readers.

9.5.1.3 Passive Tag and ZigBee Reader

The passive tags are the typical EPC GEN2 UHF passive RFID tags and the passive ZigBee reader is designed by integrating UHF EPC reader module with either a ZigBee end device or a ZigBee router, depending on whether a routing function is necessary. In our demo system a Skyetek DKM9 UHF passive RFID reader module (Skyetek Inc., 2006) is chosen to be integrated with a ZigBee router using a Jennic JN5139 module and its development board. The DKM9 UHF RFID reader module is connected to the UART0 pins through a self-made PCB board. The pin mapping of the JN5139 development board and the DKM9 reader module, and their connection are shown in Figure 9-5. With this design the DKM9 reader module is able to transmit the tag information through the ZigBee network constructed by JN5139 chips.



PinJ9/J4	JN5139
N1/38,40	GND
N4 / 8	UART receive
N5 / 7	UART transmit

Pin	DKM9
14	RxD/UART receive
15	TxD/UART transmit
25-27/49	GND

Figure 9-5: Pin mapping and connections of JN5139 and DKM9

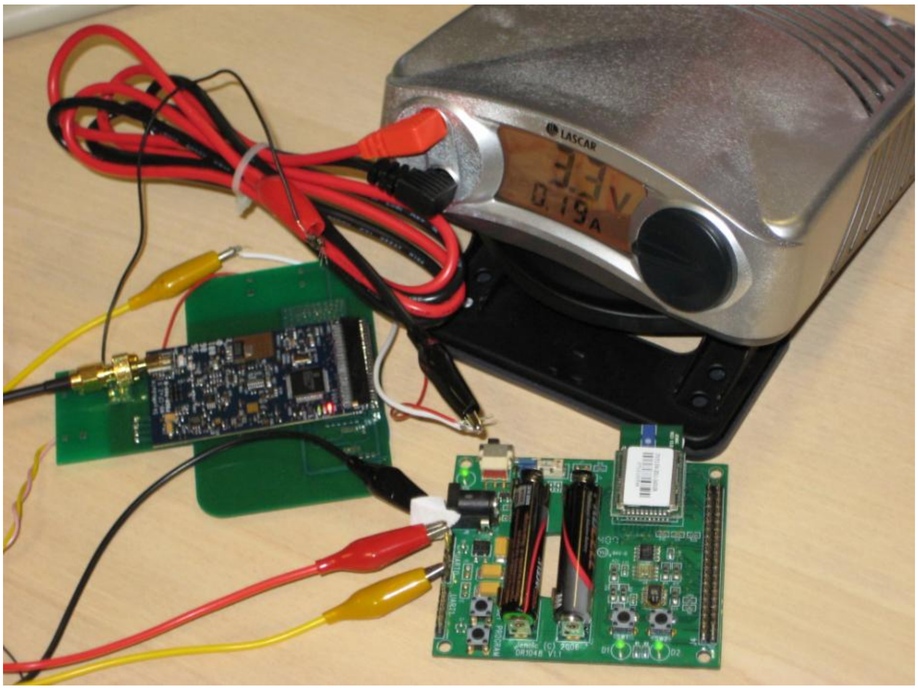


Figure 9-6: Integration of passive RFID reader and ZigBee router

9.5.1.4 Dedicated Sensor Nodes

The ZigBee modules are programmed to be typical wireless sensor network nodes, the running of these nodes is not affected by RFID reader devices and functions being introduced into the network. With the sensors provided on the development board of the JN5139-EK010, we are able to monitor the temperature, light and the humidity of the environment around a specific sensor node.

9.5.1.5 Local Server Connection

Equipped with a USB-R232 3.3V converter, the local server computer is connected to the UART0 pins of a JN5139 ZigBee module via the development board connectors. Through the module, which acts as the sink node of the network, the local server is able to access the ZigBee network and retrieve the information it requires.

9.5.1.6 Interfaces between Sensor Node Devices and Various RFID Devices

The Integrated ZigBee RFID Sensor Network architecture works on a ZigBee-based network backbone in which both passive and active RFID are integrated. This avoids the cost and time needed for the deployment of a separate RFID-based network in the same scenario. The interface for interactions between sensor node and various RFID devices are as follows:

The active RFID function is performed by modified ZigBee end devices which naturally are part of the ZigBee network. As a ZigBee end device already has all the hardware required to perform the functionality of an active RFID tag, this integration could be considered as having a virtual interface between the active RFID program and ZigBee network stack on the sensor node board, there is no hardware interface required for this integration.

For the passive RFID function I integrated the passive RFID reader with a ZigBee end device, this integration is achieved by hardware integration. Those two hardware boards are both embedded modules and are connected via a standard 4-wire UART interface. I then developed for the Jennic sensor boards a passive RFID reader driver program which enables the ZigBee end device to interrogate and control the reader device through the UART interface. Data from the reader could then go through the end device to the central server via the ZigBee network.

All those hybrid data are transmitted through a unified ZigBee network to the server for them to be recognized by the middleware/interface on the server. I designed a protocol defining the data format that should be followed by all the network nodes when they transmit data to the server. The protocol defines several control areas in the packet payload, two control information describes the property of the data transmitted, so that the server could identify from which node the data came, what the data is about and whether this node is performing an active RFID tag function, is integrated with a passive RFID reader or is just a normal environmental monitoring nodes. This protocol has successfully integrated the data from various types ZigBee RFID Sensor Network node at the server part and could be deemed as another virtual interface.

9.5.2 Embedded Software Design

9.5.2.1 ZigBee Coordinator

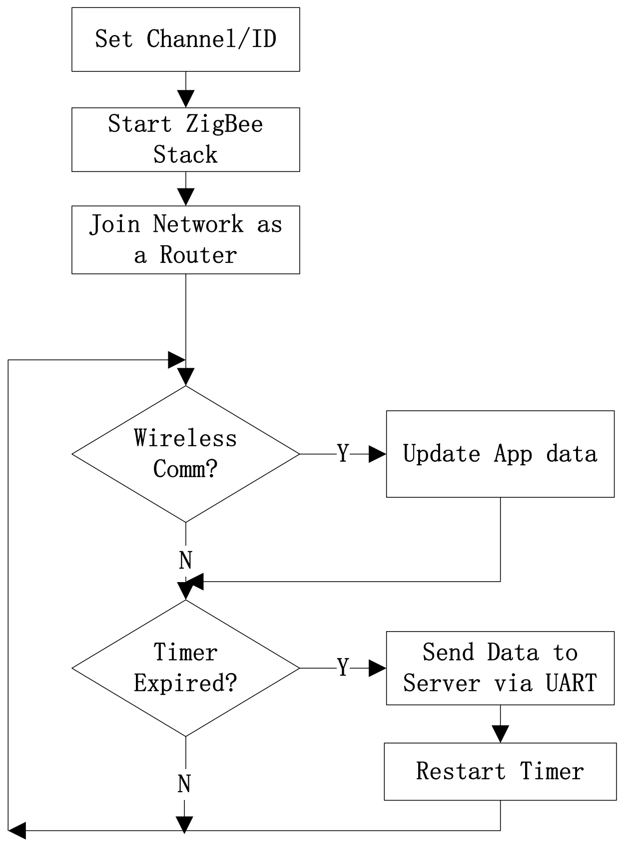


Figure 9-7: Flowchart of the coordinator / sink node

The coordinator is the main component of the Zigbee network. Its responsibility is creating the network, allocating network identification and operating channel and managing the requests from other network devices for joining the network. In our demonstration system the coordinator is also used as the network sink node. It is connected with the central server by a serial connection. As shown in the flowchart of the coordinator in Figure 9-7, the operating channel and network identification are set first. After that, only the network devices that operate on the same wireless channel with the correct network identification can join the network. The coordinator then initializes and starts the Zigbee stack. After that the ZigBee network is created and ready for qualified devices to join.

A timer that controls the rate of reporting data to the server is started before the coordinator device enters an infinite loop, in which it keeps processing two activities:

- Wireless Communication: When the coordinator receives incoming data packet, it will update the application data, such as the network device list, tag list and sensor data.

- Reporting to server: If the timer is expired the coordinator will report the latest application data to the server via UART.

9.5.2.2 ZigBee Router

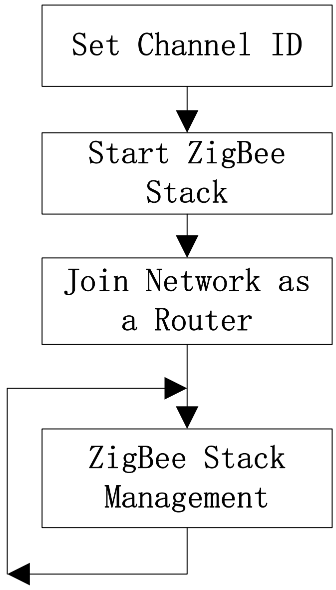


Figure 9-8: Flowchart of the router nodes

The operation of the router nodes is described in Figure 9-8.

- Set Channel/ID: In order to join the correct ZigBee network, the operating channel and network identification need to be set first.

- Start ZigBee Stack: Start the Zigbee stack and run the device as a router.

- Join Network as a Router: After starting the ZigBee stack, a router will be accepted by the coordinator and will be allocated a network address.

- Stack Management: After the device joins the network, the ZigBee stack will fully take charge and the device operates as a router in the network. The routing operation will be handled automatically by the stack.

9.5.2.3 Dedicated Sensor Node

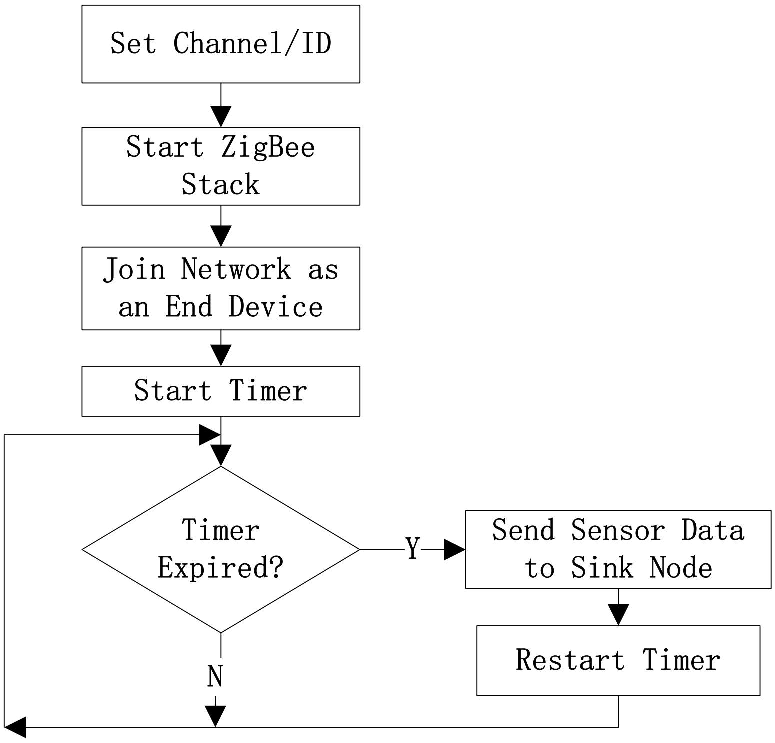


Figure 9-9: Flowchart of the dedicated sensor nodes

The flowchart of the dedicated sensor nodes is shown in Figure 9-9. After starting its ZigBee stack with the correct operating channel and network identification, a dedicated sensor node joins the network as an end device. It will be allocated a network address by its parent node, which is usually the nearest router device. It manages a timer which controls the rate of reporting sensor data to the sink node. If the coordinator / sink node is not the direct parent node of the sensor node, the sensor data may be relayed by ZigBee routers or other network devices that operate as a router in the network. The timer has to be restarted each time after the sending of sensor data for the device to trigger the next sending operation.

9.5.2.4 Active ZigBee Tag

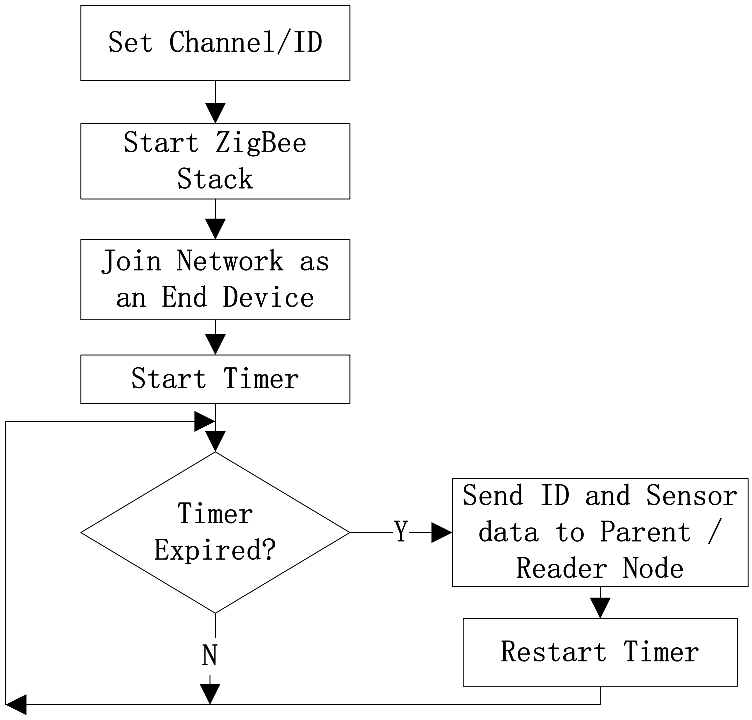


Figure 9-10: Flowchart of the active ZigBee tags

The flow chart of the active ZigBee tags is shown in Figure 9-10. Its initialization, which is very similar to the initialization of dedicated sensor node, is the typical start up procedure of a ZigBee end device. After starting its ZigBee stack with operating channel and network identification being set correctly, an active ZigBee tag joins the network as an end device. It manages a timer which controls the rate of reporting its ID and sensor data to its parent node. The timer has to be restarted each time after the data sending for the device to trigger the next sending operation.

9.5.2.5 Active ZigBee Reader

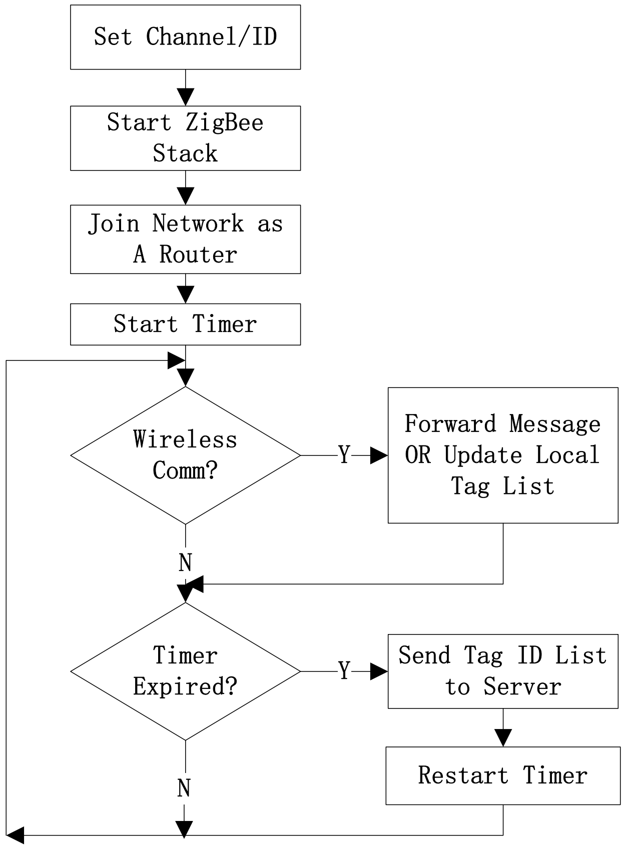


Figure 9-11: Flowchart of the active ZigBee reader nodes

An active ZigBee reader device has a similar initializing procedure, which is shown in Figure 9-11, with the ZigBee routers. After starting its ZigBee stack with operating channel and network identification being set correctly, an active ZigBee reader node joins the network as a router device. While handling routing operations in the network, it also collects the ID and sensor data from its direct child nodes that act as active tags. A timer is managed to control the rate of reporting the collected active tag data to the sink node.

9.5.2.6 Passive ZigBee Reader Node

The operation of the passive ZigBee reader node is described in Figure 9-12. A passive reader node is the most complicated device in all the system. It initializes and joins the network as an end device. Two timers, which are a reading timer and a reporting timer, are managed by the device to control the rate of passive tag reading and reporting reading results back to server respectively. Different to the active tags that reports ID to their parent node, the passive ZigBee reader node reports the tag ID list directly back to the sink node. The data may be relayed by its parent node if the passive reader node is not directly connected to the sink node, but the relaying is just an automatic process and the parent node will not maintain a copy of the information in the way that the active reader nodes do.

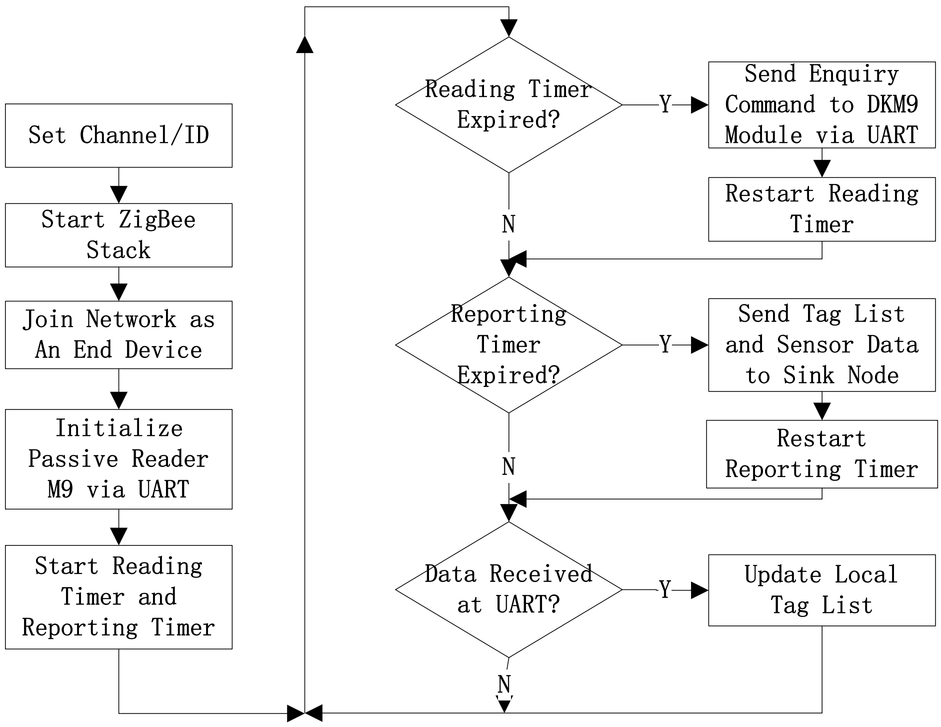


Figure 9-12: Flowchart of the passive ZigBee reader nodes

9.5.3 Field Trial

The demonstration system based on the integrated RFID sensor network architecture is fully working in a laboratory environment. The features of the proposed system architecture over the traditional systems are mainly focused on the integration of all the useful systems into a low cost, fast-to-implement, robust and unified system architecture, which will be of great benefit to the HLCs that require swift emergency response. The features such as self organizing, self healing and network recovery are the technical aspects that supports those features and are usually only evaluated by telling whether they exist or not exist in a system, so in the research of this chapter I have considered that a field trial in a typical environment (e.g. a real warehouse) is the best way to prove/demonstrate the system's features. The system has been evaluated using a standard 4200 m^2 warehouse in a local business park where field-trials were carried out. The warehouse comes with self-contained two storey offices and is located in an industrial estate close to Loughborough. The freight type is medicine and medical equipments placed on ground pallets. The warehouse is considered as the main site of a humanitarian logistics centre in which three researchers first acted as system engineers trying to carry out the deployment of a resource management system into the warehouse to evaluate the complexity of system implementation. The evaluation focuses on the time required to deploy all fixed devices of the system and to correctly configure the whole system architecture into full-working order. Two ZigBee compatible passive RFID readers are planned to be deployed at the warehouse access point. One local server with a ZigBee coordinator device, three ZigBee routers and eight active ZigBee readers were also to be deployed. The implementation of passive RFID tag and active ZigBee tags are not involved in the implementation evaluation as they are not part of the initial implementation.

The evaluation was initiated by setting up the server in the warehouse office and connecting it with the ZigBee coordinator, which automatically establishes the ZigBee network for the system. The researchers then deployed the three ZigBee routers to extend the system network range to provide a full coverage in the warehouse. The first two routers were simply deployed by plugging into existing electric outlets at or close to the planned positions. The third required a power extension lead from the nearest outlet to enable it be deployed at a satisfactory position. Once a router was positioned it was turned on and automatically joined the system network. The eight ZigBee virtual active readers were then deployed. Three of them also required power extension leads to be positioned at planned places. Like the routers they were turned on automatically after deployment and join the ZigBee network. Two ZigBee compatible passive RFID readers were deployed finally at the warehouse access points by attaching them at the appropriate position at one side of the entrance and plugging into an electric outlet. All devices automatically joined the ZigBee network and appeared on the server screen. The implementation was completed by giving some simple configuration to each point in the server program. The whole implementation took the three researchers three hours to complete.

To compare with the implementation of system based on a traditional system architecture the researchers then tried to simulate the deployment of a similar system using cable network links. As well as all the reader device deployments, which were required in a traditional system, the researchers needed to implement one local area network (LAN) router and three switches instead of the three ZigBee routers to link all devices into a LAN network. Based on the already positioned reader devices it took the researchers three more hours to complete about quarter of the cabling and router/switch configurations. We estimated as least one more day would be required to complete the whole wired network implementation.

The researchers did a quick test to demonstrate the performance of the previously implemented ZigBee/RFID sensor network based system. Passive RFID tags were attached to several freight cartons which were then put onto a pallet with an active ZigBee tag. There are temperature and humidity sensors on all the readers, routers and active tags. One researcher sat in the warehouse office to watch the server program while two other researchers acted as on-site staff of the HLC. They wore active ZigBee tags and performed passive RFID tagged inventory book in/ship out at the access points, allocating and locating inventory, locating on-site staff and monitoring on-site environment conditions. The demonstration prototype of the system performed as expected in the environment monitoring using sensors on both router and reader devices, freight identification using the ZigBee supported passive RFID readers, staff identification using the worn active ZigBee tag, inventory locating and state monitoring using the on pallet active ZigBee tag. It is also able to send the active tags' ranging information back to server for RTLS purpose. The site manager in the warehouse office could monitor the whole picture of the site on the server screen with real-time resource information regarding the identification, location and state of inventory, staff/equipment and the environment.

To demonstrate the reliability of such a system architecture we turned off one of the ZigBee routers to simulate a device failure caused by possible after effects of the disaster or a technical problem. Because all the virtual active reader devices can also performance routing in network, after one of the routers failed the network automatically reorganized and the information service provided by the system was not affected while the system generated a device time out/failure warning on the server screen for the site manager's information. At the end of the field trial the system components are recovered from the implementation easily and quickly by simply unplugging them from the outlet and no sign was left of the previous deployment.

Two functions have not been implemented in the prototype system; one is the mains power to battery switching mechanism which I discussed in Section 9.3, as all of our hardware devices can be powered either by a battery or by the mains power, and we had not yet have such switch installed. The other is the "up-link" to a remote command centre, which I mentioned at the end of Section 9.5.2, as it was considered to be independent of the architecture design of the on-site resource management system and would require expensive pieces of equipment in order to demonstrate such a link.

9.6 Findings in the Field Trial

As illustrated in the field trial, the proposed information infrastructure met the six design requirements elicited in the early part of this chapter. In summary the system is able to:

- Enable location tracking of freight and streamline logistics process.
- Monitor the storage environment and the product quality of the food, water and medicines, and make sure they are kept in proper conditions.
- Enable location tracking of equipments and people working in the logistics centre for management as well as safety purposes.

Such systems also have a simple but reliable and easy-to-implement architecture and do not depend on any locally-available facilities. In summary, an all-in-one system which provides an easy and fast implementation of a self-organising architecture together with tolerance of destabilized circumstances are the three main features of the proposed system and have been demonstrated in the field trial.

9.6.1 Features of Proposed System Architecture

An all-in-one system with a single system infrastructure: In the field trial I have demonstrated that the system is able to provide comprehensive information for the various resource management requirements. This was the first and fundamental requirement I determined for any HLC resource management system. Dedicated systems exist currently for the accomplishment of a single task, for example using passive RFID for identifying freight, Wireless Sensor Networks for monitoring the environment and active RFID for tracking people and equipment. But none of the systems can handle all of the tasks required in a humanitarian logistics centre. Implementation of several independent systems and integrating them in a single software/management coordinated system may cause various problems in the humanitarian logistics centre application where swift response to an emergency is required. In addition network connections and mains power cables may be needed for devices from each system at each installation point which would be very costly and wasteful. The cost of the system and its implementation will also increase when such duplicated installation is required. Wireless radio influence can be another problem to the co-existence of these different systems. Middleware and GUIs (Graphic User Interfaces) also need to be developed separately for centralised information integration and presentation. To avoid these problems many existing applications have chosen to adopt only one system which is suitable for the most important parts of their requirements and to simply let it assist the relatively less important parts where possible. Such a solution does not usually provide satisfactory performance. The proposed ZigBee RFID sensor network provides a system combining Wireless Sensor Network, passive and active RFID together in both the hardware and network layers. It has an unified, fully integrated and cordless system architecture. The end user just needs to choose for each part of their application the proper hardware modules, which will all operate in a unified ZigBee-enabled wireless network.

Self organized wireless network, easy and fast implementation*:* ZigBee is a wireless sensor network standard that features a self organized network protocol upon a pure cordless backbone. According to the field trial, the system is easy to implement as almost no cable is involved in the architecture. The hardware implementation of a number of traditional duplicated systems that can provide similar information will take up to 5 times longer as well as requiring an increase in system costs. One may argue that a few recent commercial RFID and remote monitoring devices can support the WiFi 802.11 family network protocol which is also a wireless network. But actually if we implement a similar system based on WiFi all the ZigBee routers and virtual active readers need all be replaced by WiFi access points which are also connected to the site server via cable, router and switch link. This means the WiFi technology is still a cable network at the system level. It provides only the end terminal with wireless connection and there will not be much difference in its hardware implementation compared to the LAN architecture I simulated in the field trial. The installation of the ZigBee router/reader devices can be simplified by just plugging them in the wall outlet. The devices will automatically join the sensor network and be configured; their properties, such as location and working mode, could then be set on the server GUI. This not only significantly reduces the time and workload needed for deployment, recovery and redeployment of the system, which contribute to the flexibility of the logistics centre in fast emergency response applications, but also requires much less technical skill for the staff to implement and maintain the system compared to the configuration of LAN router and switches required by the traditional systems.

Self healing network, low power consumption, a more robust system: the system capitalises the self healing feature of ZigBee which means that the network is able to deal with topology changes or node failure by automatically re-organizing the network. As an emergency distribution centre may start operating in a affected area shortly after a natural or man-made disaster and may suffer the possible after-effects of the disaster, systems should have a robust infrastructure such that a certain level of after-effects will not lead to functional failures. With a mesh network topology, the ZigBee RFID sensor network has a more robust network architecture, which can maintain the operation of the system when it loses one or more nodes, or even part of the network due to technical failures, natural or man-made damage. In the field trial I have demonstrated that failure of a network device will not affect the performance of the whole system. As the network automatically re-organized to maintain all the data communications, the overall information service provided by the system will operate correctly while the device failure is being reported and dealt with. A similar device failure in the traditional LAN system architecture will definitely cause service interruption in either a large area (switch failure) or even in the whole site (router failure).

On the other hand, humanitarian logistics may operate in a destabilised infrastructure such as that presented by the lack or non-continuous supply of electricity. ZigBee is designed for low data rate and power-efficient communication. With a low data rate RF transmission and a relatively simple network protocol stack, a ZigBee end device can work for years with a normal AAA size battery depending on its sleep-operating time ratio. As current products are using WiFi and Bluetooth whose power consumptions are far greater than that of ZigBee, this feature makes the devices in our system easier to support batteries when necessary so that the system can have a much stronger tolerance against destabilized circumstances. The active ZigBee RFID tags can also profit from such a feature to have an even longer battery lifetime. The field trial took place over a limit period of time and it was not possible to fully evaluate the system's battery life. However, the experiments carried out in our laboratory has suggested that the busiest device in the ZigBee RFID sensor network can last for 3-4 days using two AAA batteries if the main power is lost. In comparison, a WiFi device can work for only a few hours before the battery run out. This feature enables the system to have more chance to keep working until the main power is restored.

9.6.2 Problems and Challenges

There were also three problems identified from the field trial: the indoor real-time location tracking algorithms exhibited a low accuracy; the upper-link to the remote command centre has a limited choice, finally there exist a number of privacy and system security issues.

Although the installation of a single device can be as easy as plugging a socket in to a wall outlet, and tests have proved that 2.4GHz systems do not strictly require line-of-sight between devices (Timm-Giel et al., 2006), problems may still occur if several obstacles exist between devices. The implemented indoor location tracking was based on the received signal strength (RSS) technology, which is sensitive to the environment, and this signal is affected by issues such as the layout and building materials used. I tested a stand-alone connectionless receiver as a tracked mobile node. It is similar to the mobile node in the demonstration system of Chapter 6 and listens to the communication within the network in its near field. I could see the location of the active ZigBee tag worn by the on-site staff moving on the node screen when they enter the site. The performance of the indoor location tracking was not satisfactory but this is due to the localization algorithm used. In our research I focus only on the network architecture designs that aim to provide the upper level applications with raw data of ranging information from a mobile node in a reliable and energy efficient way. In addition to our research, post-processing of the data and improved location calculation algorithms needs to be further investigated in order to calculate the actual location more accurately. However, those are two separate research areas that are not concerned in the research work presented in this thesis. Moreover, with a pre-designed and surveyed site layout, instructions can be made for field engineers on how to correctly deploy the whole network based on the site map to get most out of the system. This will not affect the implementation of the system on-site, but requires advanced training of the technical staff.

The on-site ZigBee RFID sensor network is a stand-alone system, but an external link has to be used if the transmission of data to a remote command centre is required. For small scale disasters such as plane crashes and mine explosions, existing public or dedicated WAN technologies like GPRS, 3G and TETRA can be chosen. In large scale disasters, such as earthquakes, hurricanes and floods, where the pre-constructed land-based cellular networks may no longer be available due to damage of base stations; satellite communication may be the only choice. This problem exists but is considered to be independent of the architecture design of the on-site resource management system; no matter what up-link is finally chosen our integrated RFID sensor network architecture should stay the same.

Our interviews with logistics personnel also raised the issue of privacy and security, which has always been a debatable topic in RFID research. Although a recent study carried out in hospitals has shown that people do not mind being tracked by wearing RFID tags, it is still important to make sure that they understand why this has to be done, because the tracking information is meaningful only when the people or equipment is really at the same place as the tag and the information system itself cannot guarantee this (Bacheldor, 2006).

9.7 Discussions

The adoption of RFID, sensor and network technologies in a humanitarian logistics centre can help increase the visibility of resource and improve the performance of the site in the supply chain. Dedicated systems exist for accomplishing a single task, but none of the systems can handle all the tasks required in a humanitarian logistics centre. Implementation of several independent systems using traditional system architectures results in high cost, low flexibly and complexity of implementation and maintenance. This may cause various problems in the humanitarian logistics centre application where swift response to an emergency is required.

This chapter contributes to knowledge by presenting the requirements of information infrastructure for HLC resource management system and by implementing the integrated ZigBee RFID sensor network that integrates sensors, passive and active RFID systems into a unified Wireless Sensor Network backbone, and provides the distribution centres in the humanitarian supply chain with a simple, robust, fast-to-implement and multifunctional information system infrastructure. By properly implementing a ZigBee RFID sensor network system, the visibility of resources, including freight, machines, vehicles and staff, can be increased, as well as allowing the environment they are in to be monitored. This enables the distribution centre to operate more efficiently and safely. Other benefits, such as having more power-efficient devices and a self-healing network topology, make the hybrid system more robust to operate under possible destabilised circumstance such as long temporary electricity supply shutdowns.

The proposed system architecture mainly focuses on the network level of the entire information infrastructure; it is a under layer framework which could provide a foundation on which the research at the upper layer regarding resource management or information management for HLC can be carried out. Furthermore, although I have considered in the research of this chapter that a field trial in a typical environment is the best way to prove/demonstrate the system's features, a simulation model of the proposed architecture can be useful and may be developed in the future for better analysis of the technical aspects such as self organizing, self healing and network recovery, which support the system's features. At the current stage it is not preferable not only because a limited change in the performance of those aspects does not have significant impact on the system architecture, but also because most of the these aspects are still lack of well-established models in academic research and each of these aspects will require extensive study that could form another separate research area which falls out of the scope of the research in this chapter. However, as soon as the research in those separate areas advances, it is still interesting to have such a simulation model of our proposed architecture which could indeed be useful for better analysis and understanding of some of the system's features. It could be a considerable part of our future works. Finally, the proposed system architecture is designed for humanitarian logistics centre, but I realise that it also has the potential to be generalized for adoption in general logistics centres, and needs further investigation.

Chapter 10 Conclusions and Future Work

10.1 Summary

Radio Frequency Identification (RFID), which includes passive, active and localization systems, is the hottest Auto-ID technology nowadays; the wireless sensor network (WSN) is one of the focusing topics on monitoring and control. Both of them are fast-growing technologies that have shown great potential in future logistics management applications. An information system for hybrid logistics applications is always expected to answer four questions: Who, What, When and Where (4Ws), and neither of the two technologies is able to provide complete information for all of them. As WSN and various RFID technologies provide information for different but complementary parts of the 4Ws, a hybrid system that combines WSN and RFID together and gives a complete answer to the 4Ws, could be promising for information systems in future logistics management applications.

At the beginning of the research, I reviewed WSN technologies and various types of RFID technologies and introduced a requirement hierarchy for logistics centre management applications. Based on an initial analysis of ZigBee compatibility with various RFID devices, I then introduced two concepts of ‘Reader as a sensor’ and ‘Tag as a sensor’ which lead to three integrated architectures for legacy system integrations. After that I designed the integrated ZigBee RFID Sensor Network architecture in hybrid application scenarios. A connection inventory tracking architecture, the CITA architecture that targets a higher-requirement level, added a real-time inventory localization service into the integrated architecture. For the high-mobility target localization which is on the top of the requirement hierarchy, the Connectionless Stochastic Reference Beacon (COSBA) architecture is designed with mathematical models for its beacon-generating mechanism being investigated in detail. The feasibility of all the architectures proposed is illustrated through demonstration systems with experimental implementation and laboratory testing. Simulations are carried out for comparing technical performance in various architecture designs. Although the case study has been discussed in the scenario of humanitarian logistics centres, the architectures designed for the integrated ZigBee RFID Sensor Networks are in principle extendible to other general logistics centre management applications, such as in military services. Actually, I have also carried out a more sophisticated case study of using the proposed integrated hybrid ZigBee RFID Sensor Network for the real-time tracking of near-misses on construction sites to demonstrate the feasibility of extending our research to non-logistics applications, this research can be found in our recent journal publications (Wu et al., 2010). It can be summarised that the research represents a practical approach/framework for the design and implementation of integrated ZigBee RFID sensor networks in hybrid logistics centre management systems.

10.2 Contributions and Future Works

This thesis aims to develop a framework for the network level architecture design of such hybrid system for on-site resource management applications in logistics centres. The research in this thesis is based on ZigBee/IEEE802.15.4, which is currently the most widely used WSN technology. The various architectures proposed in this thesis are designed to address different levels of requirements in the hierarchy of needs, from single integration to hybrid systems with real-time localization. The contribution of this thesis to knowledge consists of six parts.

Firstly, I proposed two new concepts “Reader as a sensor” and ”Tag as a sensor”, which led to two corresponding architectures of RAS and TAS architectures for integrations of RFID and WSN in various scenarios with different legacy system structures. After discussing the ZigBee compatibility of the devices and communication links in the typical RFID system, I presented two architectures for integrating RFID with ZigBee based WSNs. They are the RAS architecture for both the passive/semi-passive RFID and the active RFID, and the TAS architecture for active RFID only. This is followed by the benefits of having such architectures comparedto the current wireless technologies used in RFID systems. Demonstration systems of both the architectures on a ZigBee-based hardware platform are used to validate the designs.

Secondly, I proposed an integrated ZigBee RFID Sensor Network Architecture for hybrid applications which require multi-system integrations. I discussed the features of the existing architectures used to combine RFID, sensors and WSN in different levels. Those designs are usually developed for very small and simple scenarios or even for demonstration only. Each of them has its own features and is suitable for particular scenarios. As in large and complex applications each of these integrations or architectures could only be suitable for different parts of the whole scenario. In this case, I presented and discussed a preliminary integrated RFID sensor network architecture for hybrid applications. It presents a unified and flexible system structure for multi-system integrations in logistics applications with hybrid inventory types. A demonstration system of the architecture was developed based on a ZigBee-based hardware platform to validate the design.

Thirdly, I proposed the Connectionless Inventory Tracking Architecture (CITA), which adds location awareness for inventory tracking in the Integrated ZigBee RFID Sensor Networks, and its battery consumption model. Current ZigBee based tracking systems either require a dense router implementation that leads to higher cost, less flexibility and more complicated network structure, or suffer accumulated localisation error due to using mobile nodes as part of the reference points. The CITA architecture does not require dense router deployment. Instead, it is mainly based on the existing ZigBee RFID sensor network hardware and does not affect the network structure, implementation and performance. The data collection network could thus support warehouse inventory tracking with the least additional hardware and cost while at the same time avoiding the accumulated localization error. I have also proposed and analyzed the battery consumption model of the CITA architecture, with explicit instructions on how to select the appropriate value for the key operating parameters. A demonstration system of the CITA architecture was developed based on a ZigBee based hardware platform to validate the design.

Fourthly, I proposed a Connectionless Stochastic Reference Beacon Architecture (COSBA) which adds location awareness for high-mobility target tracking in the Integrated ZigBee RFID Sensor Networks. The COSBA architecture inherits many features of the CITA architecture, such as consistent network structure and no accumulated error. But comparing to the CITA architecture, it also has longer hardware battery life, lower network traffic load and enables the tracking of higher mobility targets. At the same time, the COSBA architecture maintains support for normal inventory tracking with the least additional devices, which are the dedicated beacons that are very simple and low cost devices with reasonable battery life and simple deployment. I have shown in the simulation results of network traffic load for both CITA and COSBA architectures to demonstrate the improvement of the COSBA architecture. Demonstration system of the CITA architecture was also developed based on a ZigBee based hardware platform to validate the design.

Fifthly, the mathematical models of beacon generating mechanism and beacon receiving performance in the COSBA architecture were investigated in detail. Two proposed beacon transmission models, the FSRB model and the TSSRB model, were designed to improve the COSBA beacon receiving performance;

Sixthly, I conducted a case study of the proposed frameworks in a Humanitarian Logistics Centre (HLC) environment. I analyzed the requirements of information infrastructure for a HLC resource management system. By discussing the implementation of an hybrid RFID sensor network that integrates sensors, passive and active RFID systems into a unified ZigBee WSN backbone, I concluded that this hybrid architecture provides the distribution centres in the humanitarian supply chain with a simple, robust, fast-to-implement and multifunctional information system infrastructure. By properly implementing a ZigBee RFID sensor network system based on such an architecture, the visibility of resources, including freight, machines, vehicles and staff, can be increased, as well as environment being monitored. This enables the distribution centre to operate more efficiently and safely. Other advantages, such as having more power-efficient devices and a self-healing network topology, make the hybrid systems more robust to operate under possible destabilised circumstance such as long temporary electricity supply shutdowns.

In summary, I proposed a series of different architectures for the integration of various RFID technologies with ZigBee based Wireless Sensor Networks at different application requirement levels. I also demonstrated the proposed architectures through experimental implementation and laboratory testing, as well as mathematic derivation and Matlab simulations for their corresponding performance models. The tests and simulations of our designs have verified for feasibility and features of the designs compared with traditional systems.

My future work could contain several parts. Firstly, the designed framework of RFID sensor network architectures could benefit from possible collaborative work with the researchers whose work is directly connected to the output of our systems. This can further improve the usability and the value of the proposed work in this thesis; Secondly, more research that are closer to the practitioner in various applications could also improve my existing designs; Thirdly, work targeting on the remote integrations architecture for various hybrid systems as well as federated ZigBee RFID Sensor Networks for the collaboration of both remote and local systems could be promising for the future “Internet of Things”.

References

[1]. Akyildiz, I.F., Wang, X., and Wang, W., Wireless sensor networks: a survey. Computer Networks, Volume 38, pp. 393-422, 2002

[2]. Alhmiedat, T., and Yang, S.H., A Decentralised Low-power Zigbee-based Localization Approach, Proceedings of the 14th Internation Conference on Automation & Computing, London, UK, September 2008b

[3]. Alhmiedat, T., and Yang, S.H., A Zigbee-based Mobile Tracking System through Wireless Sensor Networks, International Journal of Advanced Mechatronic Systems, Volume 1, Number 1, pp. 63-70, 2008a

[4]. Bacheldor, B., Hospital tries Zigbee to track patients, RFID Journal. Retrieved May 08, 2008, from http://www.rfidjournal.com/article/articleview/2509/

[5]. Bahl, P., and Padmanabhan, V., RADAR: An In-Building RF-based User Location and Tracking System. Proceedings of IEEE INFOCOM, pp. 775-784, Tel-Aviv, Israel, March 2000

[6]. Barlas, D., Wal-Mart's RFID mandate, 4 June 2003, http://www.line56.com/articles/default.asp?ArticleID=4710, (accessed on 12/12/06)

[7]. Blanco, E., and Goentzel, J., Humanitarian Supply Chains: A Review. Production and Operations Management Society Annual Conference. Boston, 2006

[8]. Blumenthal, J., Grossmann, R., Golatowski, F., and Timmermann, D., Weighted centroid localization in Zigbee-based sensor networks, Folien IEEE International Symposium on Intelligent Signal Processing, WISP, Madrid, Spain, 2007

[9]. Bohn, J., and Mattern, F., Super-distributed RFID tag infrastructures, Proceedings of the 2nd European symposium on ambient intelligence, pp. 1–12, Berlin Heidelberg, 2004

[10]. Bohn, J., Prototypical Implementation of Location-Aware Services based on a Middleware Architecture for Super-Distributed RFID Tag Infrastructures. Personal and Ubiquitous Computing Journal, Vol. 12, No. 2, pp. 155-166, ISSN 1617-4909, 2008

[11]. Bohn, J., Prototypical implementation of location-aware services based on super-distributed RFID tags, Proceedings of the 19th international conference on architecture of computing systems, pp. 69–83, Frankfurt, 2006

[12]. Bravo, J., Hervás, R., Chavira, and G., Nava, S., RFID-Sensor Fusion: An Experience at Clinical Sessions. Workshop PTA2006 - Pervasive Technology Applied, at the Pervasive 2006

[13]. Burda, R., Lewandowski, A., and Wietfeld, C., Precise Clock Distribution in Beacon Enabled, Meshed IEEE802.15.4/ZigBee Networks, 6th International Conference on Information, Communications & Signal Processing, Singapore, Dec 2007

[14]. Burnell, J., Hospital Using RTLS to Monitor Patients' Conditions, RFID Update, http://www.rfidupdate.com/articles/index.php?id=1309, (accessed 10/10/08)

[15]. Cai, Q., Mitiche, A., and Aggarwal, J.K., Tracking Human Motion in an Indoor Environment, Proceedings of Second International Conference of Image Processing, pp. 215-218, Washington, D.C., Oct. 1995

[16]. Cassidy, W., A logistics lifeline. Traffic World, October 27 , pp. 1, 2003

[17]. Chen, G., and Duan, Q., The in-transit visibility system based on RFID and wireless sensor network, Industrial Instrumentation & Automation, Issue:01 Page: 40-42,67, 2007

[18]. Ciurana, M., Barcelo, F., and Cugno, S., Indoor tracking in WLAN location with TOA measurements, Proceedings of ACM Mobiwac 06, pp. 121-125, Greece, 2006

[19]. Collin, J., Mezentsev, O., and Lachapelle, G., Indoor positioning system using accelerometry and high accuracy heading sensors. In Proceedings of GPS2003, pp. 1164–1170, Portland, 2003

[20]. Collins, J., NASA Creates Thinking RF Sensors, RFID Journal, www.sensorwaresystems.com/historical/press/RFIDJrnl_NASA_Oct04.pdf, (accessed on 14/11/06)

[21]. Collins, J., Passive Tag Powers Sensors, Switches, RFID Journal, http://www.rfidjournal.com/article/articleview/1520/1/1/, (accessed on 22/01/07)

[22]. Conduit, J., and Mavondo, F.T., How critical is internal customer orientation to market orientation, Journal of Business Research, Vol. 51, Jan, pp. 11-24, 2001

[23]. Consolvo, S., Technology for care networks of elders, IEEE pervasive computing, Vol. 3, No. 2, pp. 22-29, 2004

[24]. Cook, D., and Das, S., Smart Environments: Technologies, Protocols, and Applications, Wiley-Interscience, ISBN 0-471-54448-5, 2004.

[25]. Crossbow Inc., Mica2Dot Series, http://www.xbow.com/Products/productsdetails.aspx?sid=73, (accessed on 24/11/06)

[26]. Domino Printing Sciences Plc., Secure Track & Trace. Retrieved from http://www.domino-printing.com/uk%2Ffilestore%2FIS%20application%20PDF.pdf, 2008

[27]. Englund, C., and Wallin, H., RFID in Wireless Sensor Network, GÄoteborg, Sweden, April 2004

[28]. EPCglobal, Reader Protocol Standard – Version 1.1, June 21, 2006

[29]. Ferguson, R., Berkeley's Mesh Network: Dust in the RFID Wind, http://www.eweek.com/article2/0,1759,2051310,00.asp (accessed on 10/07/2007)

[30]. Fontana, R. J., "Recent system applications of short-pulse ultra-wideband (UWB) technology," IEEE Transaction Microwave Theory and Technology, Volume 52, Number 9, pp. 2087–2104, Sep. 2004.

[31]. Food Quality News, Spanish Retail Achieves Fresh Fruit RFID Traceability. Retrieved 08 01, 2008, from http://www.foodqualitynews.com/Innovation/Spanish-retail-achieves-fresh-fruit-RFID-traceability, 2005

[32]. Francomme, J., Mercier, G., and Val, T., Beacon Synchronization For GTS Collision Avoidance In An IEEE802.15.4 Meshed Network, 7th IFAC International Conference on Fieldbuses & Networks in Industrial & Embedded Systemes, Toulouse, France, 2007

[33]. Gueaieb, W., and Miah, M.S., Experiments on a novel modular cost effective RFID-based mobile robot navigation system, Proceedings of the IEEE

International Conference on Systems, Man, and Cybernetics, pp. 1658-1663, Montreal, Canada, Oct. 2007

[34]. Hahnel, D., Burgard, W., Fox, D., Fishkin, K., and Philipose, M., Mapping and localization with RFID technology, Proceedings of IEEE International Conference on Robotics and Automation, ICRA '04., pp. 1015-1020, Freiburg, Germany, 2004

[35]. Hamzeh, F., Logistics Centres to Support Project-Based Production in the Construction Industry. Proceedings IGLC-15, (pp. 181-191). Michigan, USA, 2007

[36]. Healthcare-Packaging, RFID smart shelves and cabinets, http://www.healthcare-packaging.com/archives/2007/03/rfid_smart_shelves_and_cabinet.php, (accessed 14/10/08)

[37]. Hightower, J., Want, R., and Borriello, G., SpotON: An indoor 3D location sensing technology based on RF signal strength, Technical report UW CSE 00-02-02, University of Washington, Department of Computer Science and Engineering, Seattle, WA, February 2000

[38]. Ho, L., Moh, M., and Walker, Z., A prototype on RFID and sensor networks for elder healthcare: progress report, Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis, pp. 70-75, 2005

[39]. Ibach, P., Stantchev, V., Lederer, F., Weiß, A., Herbst, T., and Kunze, T., WLAN-based Asset Tracking for Warehouse Management, proceedings of IADIS International Conference e-Commerce, Porto, Portugal, 2005

[40]. Jackson, R., What is RFID – A White Paper, 2004

[41]. Jedermann, R., Behrens, C., Westphal, D., and Lang, W., Applying Autonomous sensor systems in logistics—Combining sensor networks, RFIDs and software agents, Sensors and actuators. A, Physical, vol. 132, no. 1, pp. 370-375, 2006

[42]. Jennic Ltd., JN5139 Module Datasheet. Retrieved Aug 01, 2008, from http://www.jennic.com/files/support_files/JN-DS-JN5139MO-1v4%20released.pdf, 2006

[43]. Jennic Ltd., JN513x Wireless Microcontroller Datasheet, http://www.jennic.com/support/datasheets/, 2009

[44]. Jennic Ltd., JN-AN-1001 Estimating JN5121 power consumption for IEEE 802.15.4-based applications, http://www.jennic.com/support/, 2007

[45]. Kinney, P., Zigbee Technology: Wireless Control that Simply Works. Communications Design Conference, 2003

[46]. Koch, J., Wettach, J., Bloch, E., and Berns, K., Indoor Localisation of Humans, Objects, and mobile Robots with RFID Infrastructure, Proceedings of Seventh International Conference on Hybrid Intelligent Systems, pp. 271-276, Washington D.C., USA, 2007

[47]. Kovacs, G., and Spens, K., Humanitarian logistics in disaster relief operations. International Journal of Physical Distribution & Logistics Management, Vol. 37, No. 2 , pp. 99-114, 2007

[48]. Kulyukin, V., Gharpure, C., Nicholson, J., and Pavithran, S., RFID in Robot-Assisted Indoor Navigation for the Visually Impaired. In Proc. of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004), pp. 1979-1984, Sendai, Japan, 2004

[49]. Kulyukin, V., Gharpure, C., and Nicholson, J., RoboCart: Toward Robot-Assisted Navigation of Grocery Stores by the Visually Impaired. In Proc. of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2005), pp. 2845-2850, Edmonton, Alberta, Canada, 2005

[50]. Lahiri, S., RFID sourcebook, Upper Saddle River, N.J., IBM/Pearson, 2006.

[51]. Lambert, D.M., and Stock, J.R., Strategic Logistics Management, Irwin, pp.862, 1993

[52]. Lee, Y.W., Stuntebeck, E., and Miller, O.C., MERIT: Mesh of RF sensors for indoor tracking, Proceedings of the Third Annual IEEE Communications Society Conference on Sensor, Mesh, and Ad Hoc Communications and Networks, pp. 545–554, Reston, USA, Sept. 2006

[53]. Liang, N.C., Chen, P.C., Sun, T., Yang, G., Chen, L.J., and Gerla, M., Impact of Node Heterogeneity in Zigbee Mesh Network Routing, IEEE International Conference on Systems, Man and Cybernetics (SMC06), Volume 1, pp.187-191, 8-11 Oct. 2006

[54]. Lisman, J., and van Zuylen, M., Note on the generation of most probable frequency distributions, Journal of Statistica Neerlandica, Volume 26 (1), pp. 19-23, 2008

[55]. Liu, Y., Design of an inventory management system based on RFID and WSNs. RF Journal in RFID, http://tech.rfidworld.com.cn/2007_9/20079271110261739.html (accessed on 09/09/2007)

[56]. Long, D., Logistics for disaster relief: engineering on the run. IIE Solutions, Volume 29, No. 6 , pp. 26-29, 1997

[57]. Long, D., and Wood, D., The logistics of famine relief. Journal of Business Logistics, Volume16, No. 1 , pp. 213-230, 1995

[58]. Lu, B.H., Bateman, R.J., and Cheng, K., RFID Enabled manufacturing: fundamentals, methodology and applications, Int. J. Agile Systems and Management, Vol. 1, No. 1, pp.73–92, 2006,

[59]. Mason. A., Show, A., and Welsby, T., RFID and Wireless Sensor Network Integration for Intelligent Asset Tracking Systems. 2nd GERI Annual Research Symposium GARS-2006, Liverpool, UK, 2006

[60]. Melanie, R., Crispo, B., and Tanenbaum, A., The Evolution of RFID Security, IEEE Pervasive Computing, Volume 5, Number 1, pp. 62-69, Jan.-Mar. 2006

[61]. Mesarina, M., Self-configuring RFID System for Warehouses, http://www.ieee-secon.org/2005/demo-abs/HP_RFID_Demo_Abstract.pdf (accessed on 10/11/07)

[62]. Miller, L.E., Wilson, P.F., Bryner, N.P., Francis, M.H., Guerrieri, J.R., Stroup, D.W., and Klein-berndt, L., RFID-assisted indoor localization and communication for first responders. Proceedings of the International Symposium on Advanced Radio Technologies, pp. 83-91, Boulder, USA, 2006

[63]. Nambi, S., Nyalamadugu, S., and Wentworth, S.M.. Radio frequency identification sensors. Proceedings of th 7-th World Multiconference on Systemics, Cybernetics and Informatics, lug. 2003

[64]. National Instruments, IEEE 1451.4 Sensor Templates, http://zone.ni.com/devzone/cda/tut/p/id/3468, (accessed on 22/10/07)

[65]. Nelson, R., Probability, Stochastic Processes, and Queueing Theory: The Mathematics of Computer Performance Modelling, 1st Edition, ISBN:

0387944524, Springer, 1995

[66]. Ni, L.M., Liu, Y.H., Lau, Y.C., and Patil, A.P., Landmarc: Indoor location sensing using active RFID. Proceedings of IEEE International Conference in Pervasive Computing and Communication, pp. 701-710, Dallas, March 2003

[67]. Norman, B., Power Options for Wireless Sensor Networks, Proceedings of 40th Annual IEEE International Conferences Security Technology, pp. 17-20, 2006

[68]. Oloruntoba, R., and Gray, R., Humanitarian aid, an agile supply chain. Supply Chain Management: An International Journal, Volume 11, No. 2 , pp. 115-120, 2006

[69]. Özdamar, L., Ekinci, E., and B., Küçükyazici, Emergency Logistics Planning in Natural Disasters. Annals of Operations Research, Volume 129, No. 1-4, pp. 217-245, 2004

[70]. Philipose, M., Smith JR., and Jiang, B., Battery-free Wireless Identification and Sensing, IEEE Pervasive Computing, v.4 n.1, p.37-45, January 2005

[71]. Power ID, The advantages of battery-assisted UHF RFID labels, http://www.power-id.com/PDF/battery_assisted_rfid.pdf, (accessed on 20/01/07)

[72]. Pradhan, S., RFID and Sensing in the Supply Chain: Challenges and Opportunities, HP Laboratories Palo Alto, Tech report HPL-2005-16, 2005

[73]. Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., Numerical Recipes in C++: The Art of Scientific Computing, Second Edition, ISBN 7-5053-8713-8, Cambridge University Press, 2002

[74]. Priyantha, N.B., Chakraborty, A., and Balakrishnan, H., The Cricket location-support system, Proceedings of the 6th annual international conference

on Mobile computing and networking, pp. 32-43, Boston, August 2000

[75]. Reitemann, M., and Lauer, O., Inner-City Logistics Centre Container Track System Fact Sheet. Retrieved Aug 01, 2008, from http://www.stadtentwicklung.berlin.de/internationales_eu/verkehr/archiv/tellus/www.tellus-cities.net/index93e3.html?id=84%22, 2005

[76]. RFID Journal, A Guide to Understand RFID, http://www.rfidjournal.com/article/gettingstarted/, (accessed on 24/01/07).

[77]. Roundy, S., Wright, PK., and Rabaey, JM., Energy scavenging for wireless sensor networks : with special focus on vibrations, Kluwer Academic Publishers, ISBN 1-4020-7663-0, 2004

[78]. SAP, Logistics Information Systems (LO-LIS), http://help.sap.com/printdocu/core/Print46c/en/data/pdf/LOLIS/LOLIS.pdf, 2001

[79]. Schneegans, S., Vorst, P., and Zell, A., Using RFID snapshots for mobile robot self-localization, Proceedings of the 3rd European Conference on Mobile, pp. 241-246, Freiburg, Germany, Sept. 2007

[80]. Shu, F., Mi, W., and Xu, Z., The Information Sharing Platform for Port Container Terminal Logistics using Virtual Reality. Proceedings of 2007 IEEE International Conference on Automation and Logistics, pp. 2570-2575, Jinan, China, 2007

[81]. Skyetek. Inc., SkyeModule M9 Datasheet. Retrieved Aug 01, 2008, from http://www.skyetek.com/Portals/0/Documents/Products/SkyeModule_M9_DataSheet.pdf, 2006

[82]. Sun, T., Liang, N. C., Chen, L. J., Chen, P. C., and Gerla, M., Evaluating Mobility Support in Zigbee Networks, IFIP International Conference on

Embedded and Ubiquitous Computing, Southampton, UK, 2007

[83]. Sydney Ports Corporation, Intermodal Logistics Centre at Enfield Environmental Assessment. Retrieved Aug 01, 2008, from http://www.sydneyports.com.au/port_development/enfield/environmental_assessment, 2005

[84]. Thiesse, F., and Michahelles, F., An overview of EPC technology. Sensor Review, Volume 26 Number 2, pp. 101-105, 2006

[85]. Thomas, A. and Kopczak, L., From logistics to supply chain management: The path forward in the humanitarian sector. Fritz Institute White Paper, 2005

[86]. Thomas, A., Why logistics, Forced Migration Review, Vol. 18, p. 4, 2003

[87]. Timm-Giel, A., Kuladinithi, K., Becker, M., and Görg, C., Wireless sensor networks in wearable and logistic application. 15th IST Mobile & Wireless Communication Summit. Greece, 2006

[88]. Tomaszewski, B., MacEachren, A., Pezanowski, S., Liu, X., and Turton, I., Supporting humanitarian relief logistics operations through online geocollaborative knowledge management. Proceedings of the 2006 international conference on Digital government research, (pp. 358–359). San Diego, California, 2006

[89]. Trunick, P., Special report: delivering relief to tsunami victims. Logistics Today, Vol. 46, No. 2 , pp. 1-3, 2005

[90]. Tsukiyama, T., World map based on RFID tags for indoor mobile robots, Proceedings of the SPIE, Vol. 6006, pp. 412, Boston, USA, 2005

[91]. Tynheim, S.A., Wireless Home Automation Systems Require Low Cost and Low Power RF-IC Solutions,

http://www.hometoys.com/htinews/jun02/articles/chipcon/chipcon01.htm, 2002

[92]. Ubisense UWB, http://www.ubisense.net/index.php?load=content&page_id=14

[93]. US DoD (United States Department of Defense), Suppliers' Passive RFID Information Guide Version 9.0, Feb 2007

[94]. US DoD (United States Department of Defense), US DoD RFID Policy Memo - July 30, 2004, http://www.productivitybyrfid.com/dod/dod_rfid_policy_7_30_04.pdf, (accessed on 12/12/06).

[95]. Van Wassenhove, L., Humanitarian aid logistics: supply chain management in high gear. Journal of the Operational Research Society, Vol. 57, No. 5 , pp. 475-489, 2006

[96]. Van Wassenhove, L., and Samii, R., The United Nations Joint Logistics Centre (UNJLC): The Genesis of a Humanitarian Relief Coordination Platform. INSEAD case study . Fontainebleau, Paris, 2003

[97]. Vorwerk & Co. Teppichwerke GmbH & Co. KG, Vorwerk is presenting the first carpet containing integrated RFID technology. Press release, Hamlin, Germany, 2005

[98]. Want, R., Falcao, V., and Gibbons, J., The Active Badge Location System, ACM Transactions on Information Systems, Vol. 40, No. 1, pp. 91-102, January 1992

[99]. Whittaker, T., Introduction to Zigbee, http://www.camcon.co.uk/Downloads/interface/39/zigbee.pdf, 2005

[100]. Willis, S., and Helal, S., RFID Information Grid for Blind Navigation and

Wayfinding, Proceedings of the 2005 Ninth IEEE International Symposium on Wearable Computers (ISWC'05), pp. 34-37, Osaka, Japan, Oct. 2005

[101]. Wood, E., Avoiding Active RFID Confusion, RFID SB, http://www.rfidsb.com/showthread.php?t=204, 2007

[102]. Wu, W., Yang, H., and Yang, S.H., "Towards an Autonomous Real-time Tracking System of Near-miss on Construction Sites", Automation in Construction, volume 19, 134-141, 2010

[103]. Yang, G., Anderson, G., and Tunstel, E., A RFID Landmark Navigation Auxiliary System, World Automation Congress (WAC), Budapest, Hungary, July 2006

[104]. Yang, H., and Yang, S.H., RFID Sensor Network - Network Architectures to Integrate RFID, Sensor and WSN. Measurement and Control, 40(2) , pp. 56-59, 2007

[105]. Yang, H., and Yang, S.H., Connectionless Indoor Inventory Tracking in Zigbee RFID Sensor Network. Proceedings of the 35th Annual Conference of the IEEE Industrial Electronics Society. Porto, Portugal, 2009a

[106]. Yang, H., and Yang, S.H., Indoor localization systems - tracking objects and personnel with sensors, wireless networks and RFID. The Journal of the Institute of Measurement and Control, 42(1) , pp. 18-23, 2009b

[107]. Yang, H., Yao, F., and Yang, S.H., Zigbee Enabled Radio Frequency Identification, Proceedings of the IASTED International Conference on Communication Systems, Networks and Applications, Beijing, 2007

[108]. Yang, L., Prasanna, R., and King, M., On-Site Information Systems Design for Emergency First Responders. Journal of Information Technology Theory and

Application, 10(1) , pp. 5-27, 2009

[109]. Yang, S.H., and Yang, L, Design Methodology of Wireless Sensor Networks. Chapter in 'Handbook on Mobile Ad Hoc and Pervasive Communications', Edited by Mieso K. Denko and Laurence T. Yang, American Scientific Publishers, 2007

[110]. Zigbee Alliance, http://www.zigbee.org/en/about/index.asp, 2005