# Hybrid Zigbee RFID Sensor Network for Humanitarian Logistics Centre Management

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**Abstract: Purpose** – 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), destabilized 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. This paper seeks to design a hybrid system architecture at the network level for a resource information management system in humanitarian logistics centres. The aim of the design is to provide a complete, simple easy-to-implement and flexible solution for distribution centres in the humanitarian supply chain providing the ability to monitor all of their resources, including freights, rescue equipment, vehicles and people, as well as the local environment.

**Design/methodology/approach** – The characteristics of a humanitarian logistics centre are investigated to capture the requirements for the design of a resource management system. The research method used, adheres to the principle of participatory design (PD) where a common understanding of both the domain demands and the possible solutions across the disciplines can be achieved and continuously improved through the involvement of the end users. Current technologies used in the resource management system for general logistics centre are then studied. Two new concepts, "passive RFID reader as a sensor" and "active tag as a sensor", are used as basis for the design of a hybrid RFID sensor network architecture followed by a discussion of the implementation of such system architecture in a humanitarian logistics centre. A resource management system based on such architecture was developed and validated in both a laboratory environment and a warehouse field-trial and the results of these trials are discussed.

**Findings** – Compared to the old systems, the system using the hybrid 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.

**Originality/value** – The design of the hybrid RFID sensor network architecture is unique and 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.

Keyword: distribution centre; humanitarian supply chain; RFID; Wireless sensor network.

## 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 & 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 & Kopczak, 2005), while the 100 major relief agencies in 1995 managed only over 1 million each (Long & 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 & Goentzel, 2006).

Both natural and man-made disasters which have occurred in the past few decades have alerted the world community to the importance need to be able to build an efficient and agile humanitarian supply chain (Oloruntoba & Gray, 2006). Current research focuses mainly on planning humanitarian logistics at a macro level (Kovacs & 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 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 & 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 (Radio Frequency Identification) systems 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 paper is to design 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.

### 2. Research Methods

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 was then proposed 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<sup>2</sup> 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 paper.

The project consortium includes an academic institution as the innovative workforce, a fire and rescue service as an end user, and a wireless communication company to provide supportive communication

technology. There are regular progresses meeting every quarter to review the research work. Questionnaires have been completed by British Red Cross and other relevant via a web site. The structure of the consortium and the management of the project allow us to adhere to the principle of participatory design (PD) (Yang et al., 2009) where a common understanding of both the domain demands and the possible solutions across the disciplines can be achieved and continuously improved. As part of the participatory design process we carried out a number of interviews over one year; with emergency personnel from local fire brigades in the East Midlands region of the UK. We also had prototype development discussion with and demonstration to end user partners every three months over a two years period, and finally we carried out one field trial described below. In addition, technology and literature reviews including the study of the existing field studies done by other researchers in the emergency logistic management community have been constantly carried out throughout the duration of the project. The research work was carried out iteratively with many of the activities occurring in parallel.

### 3. User requirements for an 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 freights include large and valuable specialised rescue equipments (Özdamar et al., 2004) as well as forklifts, plants 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 issue cannot be ignored. Possible harsh environments may present another hazard to workers in the centre. Our interviews with emergency personnel also emphasized that the most important issue in any emergency scene is knowing what emergency personnel and equipments 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 equipments 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 characterized as being unpredictable, turbulent and requiring flexibility (Oloruntoba & 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 uncertainly 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 manmade 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 & Samii, 2003). For example, humanitarian logistics may operate in a destabilized 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.

What's more, as the centre may be located in or near the disaster-affected area, the safety issue 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 can not provide satisfactory performance for such on-site tracking tasks; the Global Positioning System (GPS) is not capable of tracking objects indoor, while a mobile network based system relies on local base stations which may have failed during the disaster. Any Wi-Fi based tracking system is power consuming and its implementation is time consuming.

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

- Tag and identify various types of freights, 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, plants 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.

## 4. 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 situation.

Currently, RFID is one of the exciting technologies in logistics applications. Researches have 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 to IC cards when container trucks enter operation zones (Shu et al., 2007). 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 US and Metro in Europe are trying to popularize 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. But 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 a logistics centre, their system architecture cannot be adopted directly by HLCs because a single type of RFID technology is not capable of tagging and tracking 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 only practical in 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, rescue equipments) or too far away from reader when tracked remotely in 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 points. 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 system.

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 & cooling and switching on and off of lights in order to optimise building performance and system control strategies (Sydney Ports Corporation, 2005). At 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 purpose. 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 & Lauer, 2005). These practices have shown the value of sensor devices in logistics centres 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 requires 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 works listed above tried to implement either sensor device or a single type of RFID device in general logistics centres for tracking goods, monitoring freights 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 the 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 with the freights. 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 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 to 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 & sensor system for fruit logistics uses 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 surveil 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 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 new architecture is required which should provide integrated functions on a light weight 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.

### 5. Hybrid Zigbee RFID Sensor Network for HLC Management

### 5.1. Information system infrastructure for HLC management

Based on the previous discussion in 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 propose a solution by designing a unified information infrastructure which can seamlessly accommodate wireless sensors, active tags, and passive tags. Two new concepts needs to be explained before the system architecture is introduced:

<u>Passive RFID reader as a sensor</u>: The interrogation mode of wireless sensor nodes works similarly to a typical passive RFID tracking system where RFID readers generate answers in response to a specific interrogation from the server. Actually, a RFID reader is sometimes called an RFID interrogator. So readers can be considered to be a type of sensor device. While a temperature sensor senses the environment temperature, a RFID reader 'senses' the RFID tags.

Active RFID tag as a sensor: On the other hand, the components that construct a wireless sensor node are similar to those out of which an active RFID tag is constructed. A sensor node is equipped with an onboard battery and transmits sensing information to a sensor network router or coordinator; while an active RFID tag transmits ID information to the active RFID reader using the same components. If we take a tag's ID as one type of sensing information, the concept of 'sensor' is extended to involving the active tags.



Figure 1. Integrated hybrid RFID sensor network system architecture

Out of those two concepts we can construct an integrated hybrid RFID sensor network system architecture as shown in Figure 1, an 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, modularization design can be carried out for developing such types of systems. Sensor nodes, active and passive RFID readers can be made into system compatible, plugand-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 & Yang, 2007). Our recent work also demonstrated the capability of such architecture to be further extended for real-time tracking service (Yang & Yang, 2009a, 2009b).

### 5.2. System implementation in HLC

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



Figure 2: Zigbee enabled RFID sensor network in humanitarian logistics 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 plants, large special rescue equipments 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, badge or be integrated in other personal devices such as watches and mobile phones. The package of the active tags for vehicles and equipments could come with belt or screw holes to help fit them to the vehicle chassis or equipment frame.

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 get 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 freights going through the centre are 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 intervals caused by either man-made accidents or the after affects of the disaster.

### 5.3. Demonstration system and Field trial

### 5.3.1. Demonstration system architecture

The structure of the hardware demonstration system is presented in Figure 3. The Zigbee network is constructed using 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 base.



Figure 3. Structure of the Zigbee RFID sensor network demo system

### 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 are used to develop the active Zigbee tags (Figure 4). 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.

Active Zigbee tags can work in both beacon enabled and non-beacon enabled modes. In non-beacon enabled mode the tags only send ID information to a reader device to answer 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.



Figure 4. Jennic JN5139 Zigbee module and development board

### 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.



Figure 5. Integration of Passive RFID reader and Zigbee router

### Passive tag and Zigbee reader

The passive tags are the typical EPC GEN2 UHF passive RFID tags and the passive Zigbee reader are 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 JN5139 development board and DKM9 reader module, and their connection are shown in Figure 5. With this design the DKM9 reader module is able to transmit the tag information through the Zigbee network constructed by JN5139 chips.

#### 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 JN5139-EK010, we are able to monitor the temperature, light and the humidity of the environment around a specific sensor node.

#### 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 required.

#### Interfaces between sensor node devices and various RFID devices

The Hybrid ZigBee RFID Sensor Network architecture, which we proposed in this paper, 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 passive RFID function we integrated the passive RFID reader with 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. We 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 and for them to be recognized by the middleware/interface on the server, we 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, those control information describes the property of the data transmitted, so that the server could identify from which node the data came from, what the data is about and whether this node is performing active RFID tag function, is integrated with a passive RFID reader or is just a normal environmental monitoring nodes. This protocol has well integrated the data from various types Zigbee RFID Sensor Network nodes at the server part and could be deemed as another virtual interface.

### 5.3.2. Field trial

The demonstration system based on the hybrid 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 paper we 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 m2 warehouse in a local business park where field-trials were carried out. The warehouse comes with a self-contained two storey offices and is located in an industry estate close to Loughborough. 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 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 established 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 existent electric outlets at or close to the planned position. The third required a power extension lead from the nearest outlet to enable it be deployed at a satisfied position. Once a router was positioned it was turned on and automatically joined the system network. The eight Zigbee virtual active readers are then deployed. Three of them also required power extension leads to be positioned at planned places. Like the routers they are turned on automatically after deployment and join the Zigbee network. Two Zigbee compatible passive RFID readers are 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 link. As well as all the reader device deployments, which are required in a traditional system, the researchers need 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 researches did a quick test to demonstrate the performance of the previously implemented Zigbee/RFID sensor network based system. Passive RFID tags are attached to several freight cartons which are then put onto a pallet with an active Zigbee tag. There are temperature and humidity sensors on all the reader, router 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 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 tag, inventory locating and state monitoring using the on pallet active Zigbee tag, but did not achieve very good performance in the

real-time location tracking service of on-site staff. 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 system architecture we turned one of the Zigbee routers off to simulate a device failure caused by possible after effects of disaster or 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 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 main power to battery switching mechanism which we discussed in the requirement section, as all of our hardware devices, can be powered either by a battery or by the main power, and haven't yet had such switch installed; the other is the "up-link" to a remote command centre which we discussed at the end of the system implementation section as it was considered to be independent of the architecture design of the on-site resource management system and would require expensive pieces of equipments in order to demonstrate such a link.

# 5.4. Findings in the field trial / Challenges of implementation

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

- Enable location tracking of freights and streamline logistics processes.
- 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 detail, 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.

### 5.4.1. Features of proposed system architecture

An all-in-one system with a single system infrastructure: In the field trial we have demonstrated that the system is able to provide comprehensive information for the various resource management requirements. This was the first and fundamental requirement we 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 freights, Wireless Sensor Networks for monitoring the environment and active RFID for tracking people and equipments. 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 emergency is required. In addition network connections and main 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 are 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 centralized 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 doesn't usually provide satisfactory performance. The proposed Zigbee RFID sensor network provides a system combining Wireless Sensor Network, passive and active RFID together in both a hardware and network layer. It has 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 Wi-Fi 802.11 family network protocol which is also a wireless network. But actually if we implement a similar system based on Wi-Fi all the Zigbee routers and virtual active readers need all be replaced by Wi-Fi access points which are also connected to the site server via cable, router and switch link. This means the Wi-Fi technology is still a cable network at the system level. It only provides the end terminal with wireless connection and there will not be much difference in its hardware implementation compared to the LAN architecture we 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 skills 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: A self healing feature means that the network is able to deal with topology change 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 we 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 destabilized 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. As current products are using Wi-Fi 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. Although this has not been demonstrated in the field trial, the experiments carried out in our laboratory has

suggested that the busiest device in the Zigbee RFID sensor network can last for several days using two AAA batteries if the main power is lost. In comparison, a Wi-Fi device can only work for several hours before the battery run out. This feature enables the system to have more chance to keep working until the main power is recovered.

### 5.4.2. Problems and challenges

There were also three problems identified from the field trial: the in-door real-time location tracking has a low accuracy; the upper-link to 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 a wall outlet, and tests have proven 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 in-door 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. We could see the location of the active Zigbee tag wore by the on-site staff moving on the server screen when they enter the site, but the movement was not smooth and often jumped suddenly from one side to another. Obviously the performance of the in-door location tracking was not satisfactory and future additional technical research is required. Also, instructions should 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 fast 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 uplink is finally chosen our hybrid 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 to be 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 only meaningful when the people or equipment is really at the same place as the tag is and the information system itself cannot guarantee this (Bacheldor, 2008).

# 6. Conclusions

The adoption of RFID, sensor and network technologies in humanitarian logistics centre can help increase the visibility of resource and improve the performance of the site in 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 emergency is required.

This paper contributes to knowledge by presenting the requirements of information infrastructure for HLC resource management system and by proposing a hybrid RFID sensor network framework 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-toimplement and multifunctional information system infrastructure. By properly implementing a Zigbee RFID sensor network system based on such architecture, the visibility of resources, including freights, 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 destabilized circumstance such as long temporary electricity supply shutdowns.

We noticed that the in-door real-time location tracking performance is not satisfied in the field trial and requires further investigation, a question which is not only related to technical issues but also related to human behaviours and management. Moreover, the privacy and security issue raised while more and more technologies are adopted in logistics applications has become a debatable topic in management research. This work could provide a framework for research in such issue under emergency situation with various information technologies involved. We notice that the proposed system architecture mainly focus 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 we have considered in the research of this paper 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 paper. 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 we realise that it also has the potential to be generalized for adoption in general logistics centres, and needs further investigation. We hope that the proposed architecture can extract further research in this area.

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