Chapter 18

Integrated RFID and Sensor Networks: Architectures and Applications

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CONTENTS

Radio Frequency Identification (RFID) systems and Wireless Sensor Networks (WSNs) represent two key technologies for ubiquitous computing that have attracted considerable attention in recent years because their use revolutionizes diverse application areas. However, these two technologies have separate research and development areas.

The integration of RFID and sensor networks can increase their utilities to other scientific and engineering fields by exploiting the advantages of both technologies. In this chapter we investigate why the integration of RFID systems and WSNs is important and we identify the key requirements to achieve efficient and effective integration. We present possible architectures for integrating RFID and wireless sensor networks and provide a detailed list of real-world application examples.

18.1 Introduction

Radio Frequency Identification (RFID) systems and Wireless Sensor Networks (WSNs) are emerging as the most ubiquitous computing technologies in history due to their important advantages and their broad applicability. RFID communication is fast, convenient, and its application can substantially save time, improve services, reduce labor cost, thwart product counterfeiting and theft, increase productivity gains, and maintain quality standards. Common applications range from highway toll collection, supply chain management, public transportation, controlling building access, animal tracking, developing smart home appliances, and remote keyless entry for automobiles to locating children.

RFID systems are mainly used to identify objects or to track their location without providing any indication about the physical condition of the object. WSNs on the other hand, are networks of small, cost-effective devices that can cooperate to gather and provide information by sensing environmental conditions such as temperature, light, humidity, pressure, vibration, and sound. WSNs provide cost-effective monitoring of critical applications including industrial control, border monitoring, environmental monitoring, military, home applications, and healthcare applications.

RFID technology has received great attention and it has been deployed extensively in industrial applications. On the other hand, sensor networks have been the focus of great research activity but they have been around mainly as a proof of concept with the main exception of their adoption in military applications. The evolution of RFID and WSNs has followed separate research and development paths and has led to distinct technologies. Nevertheless, there are many applications where the identity or the location of an object is not sufficient and extra information that can be retrieved through sensing environmental conditions is important. Although sensor networks may be used in these environments as well, the location and identity of an object remain critical information that can be retrieved through RFID systems. The optimal solution in these cases is the integration of both technologies because they complement each other.

In this chapter, we first investigate why the integration of RFID and WSNs is significant. Furthermore, we list the key requirements for integrating RFID and WSNs in an efficient and flexible way. Subsequently, we present possible integration architectures and discuss the existing and suggested integration scenarios in real applications. A variety of possible architectures for integrating RFIDs and WSNs have also been studied before by Mitsugi et al. [49], Liu et al. [45] and Zhang et al. [75]. In this chapter, we present the different possible integrated architectures based on the proposal by Liu et al. Nevertheless, we provide a detailed and comprehensive study and we update each type of integration strategy with current commercial as well as research academic integrating approaches.

18.2 Why Integrate RFIDs and WSNs

The integration of the promising technologies of RFID and WSNs will maximize their effectiveness, give new perspectives to a broad range of useful applications, and bridge the gap between the real and the research/academic world. This is because the resulting integrated technology will have extended capabilities, scalability, and portability as well as reduced unnecessary costs [46].

Extension of capabilities and functionalities: Considering the fact that RFID networks can provide critical information, such as the identity and the location of an object, by merging RFIDs with WSNs additional information can be retrieved, while the potential for exploiting this information is multiplied. For instance, in supply chain management we are able not only to track food products but also to monitor their environmental conditions and detect when perishables go off.

Scalability–portability: RFID systems integrated with WSNs enjoy the advantages of wireless communication. The transmission and processing of critical data and information is facilitated without the burden and inconvenience of wired transactions while saving valuable time. Portable RFID readers can further speed the collection of data and ease procedures in varying applications. For instance, healthcare applications, including monitoring everyday medication of elderly or monitoring patients for diagnosing deceases, can be extremely facilitated without rendering patients immobile through cumbersome data wirings.

Reduce unnecessary costs: Reducing the cost of employed services is a critical factor in many applications including industrial ones. The requirement is to achieve the desired goal with the minimum possible cost by supporting backup solutions in case of undesired circumstances. For instance, perishable goods can be monitored so that in case they are not preserved properly their transport can be terminated, thus avoiding unnecessary additional transport costs.

18.3 Requirements for Integrating RFID Networks and WSNs

The integration of RFIDs and WSNs should be performed in such a way that specific requirements are met to have an efficient and effective solution. Some of the most important requirements that should be taken in consideration are the following [13,15]:

Accurate and reliable communication: In traditional client server networks large data streams are transferred from servers to clients. However, in integrated RFID and WSNs the data flow is mainly transferred from a large number of devices (clients) to a few servers. Subsequently, servers are expected to process all the received information from RFIDs and sensors in a reliable way and to allow the appropriate action to be taken within a short period of time. Reliability and accuracy are also expected for the data transferred to the applications (or users) of the integrated system within a tolerable latency. Of substantial importance is the capability of the integrated RFID-sensor network to deliver data to the required destination with reliability and to provide a confirmation for the successful completion of a task. The reliability and accuracy of an integrated RFID-sensor network is also dependent on the criticality of the specific application. In not so critical applications a lower degree of reliability is required.

Energy efficiency: Considering the fact that both sensor nodes and active RFID tags present scarce resources, the integrated RFID-sensor network should take into account this limitation. The integrated system should be energy efficient to make sure that accurate and reliable communication will be achieved with the minimum possible energy consumption.

Network maintenance survivability: Considering the large number of devices that can be employed in an integrated RFID-sensor network, among the most important requirements for such a network is the ability to perform remote device configuration and remote device software updates. Thus, we can achieve a high survivability and an efficient maintenance of the network with an acceptable cost. Furthermore, it is important that the integrated network is able to recover in case of possible of devices or possible Denial of Service (DoS) attacks. A possible way to achieve that would be the adoption of intrusion tolerant as well as of mitigation mechanisms such as the use of replicating critical network devices.

18.4 Possible Architectures of Integrated RFIDs and WSNs

18.4.1 Integrated RFID Tags with Sensors

Integrated RFID tags with sensors or sensor-tags, as we are going to refer to them from now on, can be discriminated into two main categories: integrated sensor-tags that are able to communicate only with RFID readers and integrated sensor-tags that are able to communicate with each other and form a cooperative ad hoc network. In this section, we will provide the main features of these two categories of integrated sensor-tags and we will also present an overview of the available research and commercial proposals for each category.

18.4.1.1 Integrated Sensor-Tags with Limited Communicating Capabilities

One of the simplest ways of integrating RFID networks and WSNs is the integration of sensing capabilities in RFID tags. Many RFID tags have incorporated sensors in

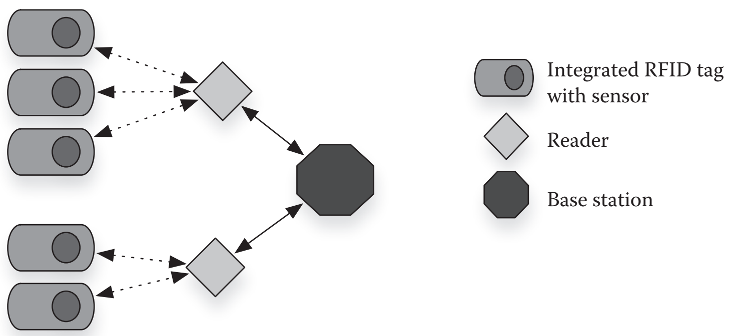

Figure 18.1 Integration architecture of sensor-tags, RFID reader, and base station.

their design and, thus, they are able to take sensor readings and to transmit them later to a reader. Nevertheless, when RFID tags are given sensing capabilities the line between RFID networks and sensor networks becomes blurred because the sensor-tags use the same protocols and mechanisms for reading tag IDs and for collecting sensed data. In this architecture, integrated sensor-tags function as normal RFID tags and they are equipped with a unique identification, while integrated sensors are used to collect sensing information related to the environment, the existing conditions, and the associated objects (Figure 18.1). The integration of RFID tags with sensor nodes is based on converting the sensors' analog signal by the A/D module while the resulting data is forwarded by the readers to the base station [45].

There are many commercial and academic proposals for integration of RFID sensor-tags. However, there is a discrimination between active, semi-active, and passive integrated RFID sensor-tags.

18.4.1.1.1 Active Sensor-Tags

Active sensor-tags use batteries to power their communication circuitry, sensors and micro-controllers. Thus, they have a rather long range (approximately 30 m) and they are able to achieve high data and sensor activity rates. Nevertheless, because a battery is used, the device cost and the weight is increased while the lifetime of the RFID sensor-tag is limited.

An active RFID sensor-tag created through the integration of sensors with UHF RFID tags and printed on low-cost environmental paper for frequencies up to 950 MHz was proposed by Ferrer-Vidal et al. [28]. The proposed integrated sensor-tag uses embedded rechargeable thin film batteries that increase the nodes' lifetime. Considering that paper is one of the cheapest organic materials, the proposed sensor-tags present an attractive advantage that will trigger large-scale adoption of integrated sensor-tags. Rida et al. [64] have also proposed an RFID prototype including sensing capabilities and a battery source on a low-cost paper substrate.

The design of a Sensor-Embedded Radio Frequency Identification (SE-RFID) System based on active RFID tags was proposed by Deng et al. [21]. The main advantage of the proposed system is that the sensors sample the external data independently and periodically with or without the presence of the reader in the tag activation zone. Deng et al. [21] have proposed two different architectures for the SE-RFID tags. In the first proposed architecture multiple sensors may be embedded in a single RFID tag, while in the second architecture each sensor is embedded in a single RFID. Furthermore, they have evaluated one of the proposed architectures by developing a Real-Time Health Monitoring System (HEMS) using a SE-RFID. In HEMS, the goal was to develop a constant monitoring system, which would be able to continually monitor, reevaluate, and diagnose diseases.

A commercially available active vibration sensor-tag (24TAG02V) [11] and an active temperature sensor-tag (24TAG02T) [10] was developed by Bisa Technologies. Both sensor-tags operate at 2.4 GHz, their range is 100 m and they employ an anticollision mechanism. Hundred tags can be read simultaneously and their battery life is four years. The temperature sensor-tag collects real-time temperature from items and transmits them to a reader for logging. When an item's temperature reach a specified intolerable temperature an alarm can be triggered. Its temperature range is from −50°C to 150°C with an accuracy of 1°C. The vibration sensor-tag detects and records either continuous or impulsive vibrations or impacts and it has minimum sensitivity 200 mV/g, resonance sensitivity 4 V/g, and resonance frequency 90 Hz.

Other commercial active sensor-tags include TELID 310 [39], an active temperature sensor-tag by Microsensys, and Callistro and Elara, active temperature and humidity sensor-tags respectively by Adage Solutions [1].

18.4.1.1.2 Passive Sensor-Tags

Passive sensor-tags receive operating power from RFID readers. Thus, a battery does not limit their lifetime. They offer several advantages such as smaller size, lower cost, and longer life cycle. The feature of unlimited lifetime can be exploited in applications where neither batteries nor wired connections are feasible because of the relative cost, weight, or because of other reasons. The main limitation of the passive sensor tags is that they have to be close to an RFID reader to function properly.

A passive sensor-tag with incorporated temperature and photosensors that can be used for environmental monitoring was proposed by Cho et al. [14]. The proposed sensor-tag is powered by an external ISM band RF signal and it senses ambient temperature and light. Zhou et al. [76] have proposed a passive UHF RFID tag RF front end with magnetic sensor. Their system includes a 900 MHz RFID front-end circuit and a mirror-based magnetic sensor in standard CMOS process. Among its main advantages, one can point its high sensitivity and its low-power consumption.

The design of a long range passive RFID-tag for sensor networks was proposed by Kitayoshi et al. [43]. The proposed tag has a range longer than 10 m, operates at 2.45 GHz and 915 MHz ISM bands and it is composed of a divided microstrip antenna and a passive voltage multiplying circuit. The authors in order demonstrate the validity of the proposed tags have also fabricated passive sensor-tags for temperature monitoring for a range larger than 9 m.

The design of a Wireless Identification and Sensing Platform (WISP) was proposed by Sample et al. [66]. WISP is a battery-free RFID sensor device and as all the passive RFID tags, is powered via the RF energy transmitted by an RFID reader. WISP is implemented as a Printed Circuit Board (PCB) and its range is approximately 4.5 m. WISP is the first micro controller integrated as part of a passive UHF RFID tag.

An integrated passive sensor-tag (ICT Tag Sensor) was proposed by Instrumentel [31]. In this passive sensor-tag, power is provided by inductive coupling, enabling the tag to operate without batteries. Thus, the sensor-tag is ideal for applications where the weight and the size of a battery would interfere with the sensing capabilities. These passive sensor-tags can be tailored to support multiple sensors and to interface with many communication protocols. The onboard microcontroller, the onboard differential amplifier and its multiple sensor capabilities are included among their most important features. These passive sensor-tags operate at 13.56 MHz.

Microchip [55] in cooperation with Digital Angel have designed and developed a passive implantable sensor-tag which can be used to determine glucose levels in the bodies of animals and humans, without the need for diabetics to draw blood glucose levels. The RFID sensor-tag is passive, powered by the scanner signal, avoiding the need for a battery on the sensor-tag. Many measurement sensors require an accurate reference voltage; To achieve that, the used glucose sensor has a specific circuit architecture, which provides precise and stable measurements of physiological parameters, allowing for accurate measurement of glucose concentration. The patent was granted in October 2006 and is titled “Embedded Bio-Sensor System” [55].

A passive sensor-tag that can be used to measure the body temperature of animals was also developed by Digital Angel. The passive sensor-tag called Bio-thermo [9] is syringe implantable in a glass-tube form, operates at 134.2 kHz carrier frequency and follows the ISO 11785 standard [32]. It allows the noninvasive monitoring of temperatures in pets and it is able to detect infections and diseases at an early stage. However, in Bio-thermo there is no available memory space to store memory data.*

Commercially available passive RFID tags with integrated sensors were also developed by three Japanese Companies OKI, NYK Logistics Japanese and HILLS [63] as well as by Microsensys (TELID 210) [38] and Alien Technology (ALB-2484) [3].

18.4.1.1.3 Semi-Active Sensor-Tags

Semi-passive sensor-tags function as passive RFID tags when the generated RF power is sufficient to operate, otherwise they operate in a semi-active mode using batteries. An integrated passive and battery-powered semi-passive UHF RFID tag which supports the EPC Gen 2 protocol [25] was proposed by Kim et al. [40] . The proposed sensor-tag functions as a passive RFID tag, when the generated RF power is sufficient to operate. In other cases, the sensor-tag functions in a semi-active mode using battery power. The sensor-tag is also employed with a rewritable nonvolatile memory bank formed by Ferroelectric RAM (FeRAM) and an on-chip temperature sensor.

*Bio-thermo is already commercially available in the United Kingdom, Japan, and Philippines.

There are also commercial semi-active sensor-tags that have been released. The German firm KSW-Microtec has produced the first semi-active RFID sensor-tag with an integrated sensor called VarioSens [44]. The VarioSens sensor-tag operates at 13.56 MHz and it is compliant with the ISO 15693 standard [33]. VarioSens is an upgraded version of an active sensor-tag produced by KSW-Micotec called Tempsens. It has 1024 bytes memory and, thus, it can hold 720 temperature readings versus 292 bytes and 64 readings in TempSens. Furthermore, VarioSens provides increased data security with three levels of security compared to TempSens' password protection. In VarioSens permissions for reading, writing, and erasing data on the tag can be defined. Another important feature that VarioSens provides is the ability to monitor the battery levels and tell the amount of power left. Its operating temperature ranges from −20°C to 50°C, while its temperature accuracy is 1°C.

Phase IV engineering Inc. has produced a CMOS device called SensIC RFID ASIC [56], which is able to measure and transmit temperature as well as the value of an external capacitive MEMS sensor. SemsIC RFID ASIC may operate both in passive or active mode. It operates at 134.2 kHz frequency and is compatible with ISO 14223 standard and ISO 11784/5. It is able to measure temperatures that range from −40°C to 125°C while its temperature accuracy is ±0.2°C. ThermAssureRF is another commercial semi-active temperature sensor-tag that was proposed by Evidencia [26].

18.4.1.2 Integrated Sensor-Tags with Extended Communicating Capabilities

Integrated sensor-tags that are able to communicate only with RFID readers can be considered as RFID tags with some additional sensing capabilities but with limited communicating capabilities. However, it is possible to integrate sensor nodes with RFID tags so that the integrated sensor-tags will be able to communicate with each other as well as with other wireless devices. Thus, this category includes the integrated sensor-tags that exceed the limitations of possible communication only with an RFID reader and are able to communicate with each other through a cooperative ad hoc network (Figure 18.2).

A research approach which integrates RFID tags with sensor nodes was proposed by Ruzzelli et al. [57]. The main goal of the approach was to add an on-demand wakeup capability on sensor nodes to reduce energy consumption and to eliminate idle listening in WSNs. The proposed approach is called RFID impulse and it is achieved by using an RFID tag attached to each sensor node that is also provided with an RFID reader capability. By attaching RFID tags to sensor nodes, it is possible to remotely wake up the microprocessor and to radio the receiving sensor nodes on demand. The RFID impulse technique can use either a passive or an active RFID tag.

A characteristic example of integrated sensor-tags that are able to communicate with each other is the commercially available iRFID tag [37], an active, intelligent Radio Frequency Identification Device, produced by Machine Talker, a constructor of RFID tags designed to serve as wireless network nodes. iRFID tags are active tags with integrated onboard sensors for measuring environmental conditions, such as temperature, light, vibration, or even battery levels. The tags operate at 900 MHz and communicate via a proprietary air-interface protocol. When iRFID tags are activated and they are in

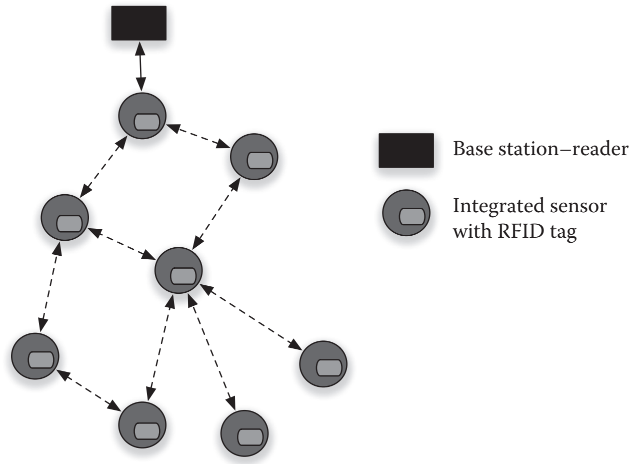

Figure 18.2 Integrated sensor-tags that form a cooperative ad hoc network.

proximity with each other, they automatically form a wireless mesh network and transfer sensor data among themselves. iRFID tags are able to communicate in a range of 200 m. Depending on how the devices are implemented they may communicate with other data systems via WiFi or wired networking protocols. iRFID tags have already been tested at several large oil refineries [8].

Integrated RFID sensor-tags that can communicate with each other were also developed and used in the CoBIs project [17], a European project which focuses on connecting business process management with the physical world. The integrated sensor-tags can collect data related to the conditions around them and transmit and share these data with each other. Their communication is performed using a proprietary peer-to-peer protocol. Each tag is employed with a movement sensor, a wireless transceiver as well as components for storing and processing rules related to business management. The data transmitted between the sensor-tags include apart from their unique ID, information sensed from the environmental conditions. The transmission of each CoBIs RFID tag is 3 m. A trial of this project has been performed in BP by placing the integrated CoBIs RFID tags on 20 to 40 of BP's containers. Integrated sensor-tags are able, depending on the used business rules, to monitor the containers and trigger an alarm if the total volume of stored chemicals allowed in specific locations is violated or if potentially reactive chemicals are stored close to each other. The network of the integrated sensor-tags is able to communicate with a wider network via base stations.

Sensitech has also released an RFID-sensor integrated device called Temp Tale RF-enabled (TTRF) [68] temperature monitoring device. TTRF is built into an active RFID tag and it is composed of a temperature sensor, a radio chip, and an antenna. The sensor periodically records and stores temperatures, while the active tags transmit the sensed data to RFID readers. This data is collected centrally and it can be used to trigger alarms when, for instance, there is a danger of perishable goods to go off because of too high or too low temperatures. This integrated sensor-tag has battery power and a microprocessor and it is able to operate within an RF mesh networking environment. It operates in the 915 or the 868 MHz ISM band and the temperature measurements range from −30°C to 70°C.

Another type of integrated RFID sensor-tags were developed by Aeroscout [2]. More precisely, Aeroscout has produced a WiFi-based active RFID tag that is employed with a motion sensor and it has an optional built-in temperature sensor which is able to sense environmental temperature and trigger alarms based on reaching a configurable threshold. The tags operate at 2.45 GHz and transmit standard WiFi messages that can be transmitted to wireless access points (802.11 b/g). Aeroscout T3 tags (the latest version) have a ten year battery life, a read range of 100 m, 1 byte memory, and the temperature measurements range from 0°C to 100°C.

An enhanced type or RFID tags, referred as "multi-hop" tags, have been developed in NTT lab [62]. These tags are able not only to transmit but also to relay and read data. They can be configured as "reader" or replay devices. They are battery powered, operate in the 429 MHz band, and their range is less than 1 km. This special type of tags were initially developed for repelling monkeys or other intruders and preventing them from vandalizing farms and disturbing domestic animals. To achieve this, RFID tags are attached to monkeys or other disturbers. When these disturbers attempt to approach the farm, they are detected by RFID readers and residents are notified by e-mails. At the same time, light or sound alarms may be used to scare the disturbers.

18.4.2 Integrating RFID Readers with Wireless Sensor Nodes

Another possible strategy of integrating RFID systems with WSNs is by integrating RFID readers with sensor nodes. In this integration scenario, the existence of three types of devices is assumed: the integrated RFID readers/sensor nodes, simple RFID tags, and the sink or base station. This type of integration was first introduced by Zhang et al. [75]. They called the integrated RFID reader/sensor node "a smart node." The integrated smart nodes can be considered as sensor nodes that can be used as RFID readers extending their sensing capabilities. Smart nodes are able to relay information and to be configured as relay nodes of a WSN. They are able to communicate with each other by creating an ad hoc communication network. The integrated RFID reader/sensor node is able to function as a router and to pass messages to the right destination. The smart nodes are responsible for collecting data from simple RFID tags in their range and communicate with each other to relay data to the sink/base station where all the data is collected and processed by a human. The architecture of this integrated network, illustrated in Figure 18.3, is similar to the hierarchical clustering-based two-tiered WSN.

This type of integration strategy gives new perspectives in likely applications. The limitations of traditional RFID readers including their passive operation, their serious mobility issues because of their big volume, and the position of their antennas limit their potential applications. The integrated smart node is smaller, less expensive, and easier to be deployed. However, this strategy of integration presents also some important

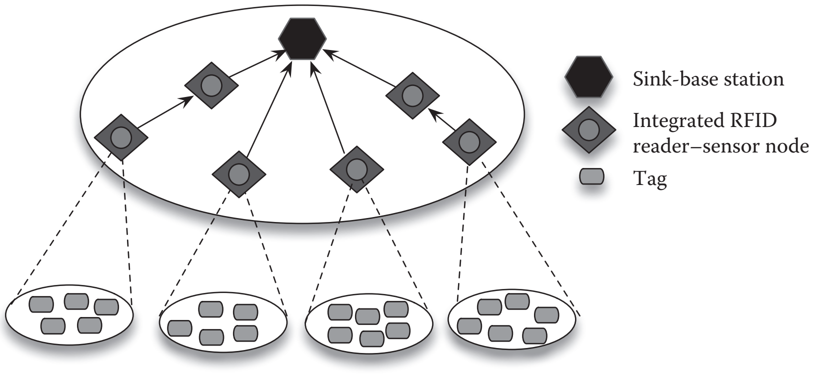

Figure 18.3 Integrating RFID readers with wireless sensor nodes.

disadvantages, because it is characterized by many-to-one traffic patterns and it presents some problems related to energy imbalance among smart nodes. Yang et al. [74] identified that in this type of integration because smart nodes have a fixed transmission range, the amount of traffic that is required to be forwarded will increase considerably as the distance to the base station becomes shorter. Subsequently, smart nodes that are closer to the base station will run out of battery early and areas of the network will remain unmonitored. Yang et al. [74] studied this type of integration and proposed a strategy that can be used to balance the energy consumption of the network and lengthen its lifetime.

Yang et al.'s proposal for balancing the load among the readers is based on adding more readers in the area near the sink. However, by adding more readers in the network, the cost of the network would be increased and subsequently more collisions would be caused. These disadvantages are outweighed by the increase of the network's survivability. More precisely, Yang et al. [74] studied how many nodes should be added in the neighborhood of the sink to get the best trade-off. Furthermore, they proposed a node distribution strategy to achieve a balanced energy reduction and to maximize the lifetime of sensor nodes. They showed that this strategy will substantially improve the network's lifetime.

Another approach for integrating an RFID system into a sensor network was proposed by Englund et al. [24]. The proposed system is able to collect data from RFID tags spread over a large area. More precisely, they have focused on the deployment of a system where RFID tags could be read from distances that overcome the range of ordinary RFID readers. This is achieved by connecting each RFID reader with an RF transceiver. Thus, information can be forwarded to and from the reader in distances of 100–200 m. Thus, a whole network of nodes is created, which are able to function as routers and forward messages to the right destination. Each node consists of an RF reader and an RF transceiver. To make the nodes functional a microcontroller is used to coordinate the different components in each node. More precisely, each node in the network consists of a microcontroller, an RF transceiver, an RF antenna, an RFID reader, an RFID antenna, and a battery. The MICA2 platform [20] from Crossbow technologies was used for the deployment of this project.

Integrated RFID readers/sensor nodes have also been produced commercially. The SkyeRead M1-mini [69] is an RFID reader produced by SkyeTek. It has a diameter of 1 in. and a thickness of 0.1 in. [18]. The reader's small dimensions make it suitable for a range of size-sensitive mobile RFID applications. The M1-mini has battery life that can last over two weeks of operation and offers a read rate of 20 tags per second. It operates at 13.56 MHz frequency and it can read and write to EPC tags and smart labels as well as to tags complying with the ISO 15693, ISO 14443, and ISO 18000 standards. Furthermore, the SkyeRead M1-Mini RFID reader can be connected directly with the Crossbow Mica2Dot [48] sensor mode resulting in an integrated RFID reader/sensor node. Another commercial RFID reader developed by Alien Technology is ALR-9770 [4] which is "equipped" with up to four antenna sets and it is able to communicate via the 802.11b/g standard.

A third commercial solution for integrating RFID readers with sensor networks was proposed by Gentag [27]. Gentag, an IP development company, issued a patent for adding sensor networks to RFID readers in mobile phones, laptops, PDAs, and other wireless devices. The developed patent is the base technology that will allow consumers to use cell phones to read almost any type of RFID tag.

18.4.3 Mix Architecture

In the mix architecture RFID tags and sensor nodes are physically distinct devices but they coexist in an an integrated network and they work independently. The main advantage of such a mixed architecture is the fact that there is no need to design a hardware integrated device. However, there is the possibility of communication interference between the RFID tags/readers and sensor nodes because in that case they are all physically disctinct devices. The procedures that should be followed to avoid this interference may cause additional overhead.

Initially, the mix architecture was discussed by Zhang et al. [75]. According to Zhang et al. [75] an integrated RFID-sensor network that follows the mix architecture consists of three types of devices: the smart stations, the normal RFID tags, and the normal sensor nodes (Figure 18.4). A smart station is a special device which is composed of an RFID reader, a microprocessor, and a network interface. Smart stations do not present power constraints and they are able to aggregate information from RFID tags and sensor nodes and to transmit them to a local host or to a remote LAN.

Information from RFID tags and sensor nodes can be transmitted to the base station. Because smart stations do not face power constraints, the traditional Internet protocol architecture can also be deployed. Thus, smart stations are able to perform not only data processing but also routing protocols and transport protocols such as TCP. A communication protocol that can be used in such a heterogeneous environment is the 802.11/WiFi technology.

An integration framework of RFID and WSNs that follows the mix architecture is SARIF [13] proposed by Cho et al. According to this framework the integrated system is composed of an integration server, RFID networks, and a WSN. The integration server

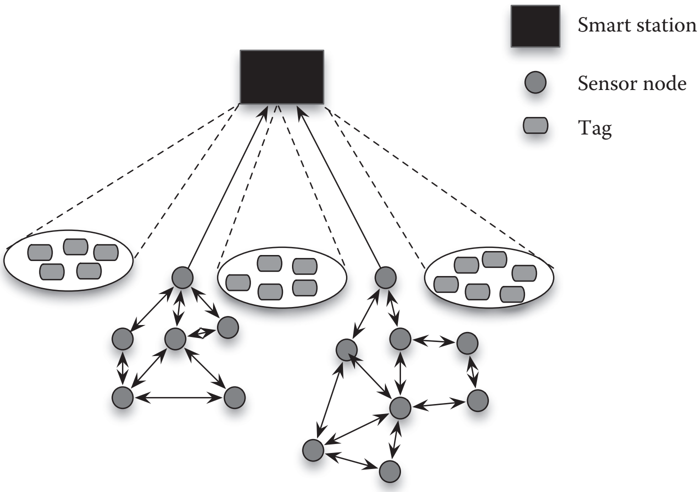

Figure 18.4 Mix architecture of RFID tags and sensor nodes.

is an important component that manages the main tasks of the WSN and the RFID network. The RFID network is composed of an information server, RFID readers, and tags while the sensor network is composed of a gateway and sensor nodes. The information server of the RFID network communicates with the integration server and it transmits information related to the RFID tags. The integration server, depending on the information he has received from the information server, initiates a task in the sensor network. The integration server may also access the RFID network and assign tasks to it. The authors have also evaluated the proposed integration framework by developing a prototype and demonstrated that SARIF can achieve energy efficiency through load balancing.

Some commercial solutions able to support the integration of RFID and WSNs according to the mix architecture have already been proposed. For instance, RFID Anywhere [58] is a commercial platform which includes rich features, broad hardware, standard and protocol support, and architecture flexibility that developers and integrators need to produce integrated RFID/sensor applications. More precisely, RFID Anywhere allows the efficient integration of RFID tags/readers, environmental sensors, barcodes, and mobile devices.

18.5 Integration Scenarios for RFIDs and WSNs in Various Applications

18.5.1 Healthcare Applications

RFID and WSNs have separately been used in medical healthcare applications such as emergency care, stroke rehabilitation [52], dental implants [34], and patient and staff tracking in hospitals. However, by integrating these two technologies their potentials will be extended. The treatment quality can be improved, because patient conditions would be monitored continuously and doctors can be easier notified in cases of sudden deterioration of a patient's situation. The patient's location can be tracked using RFIDs, while their condition can be monitored using sensors. Furthermore, medication errors such as outdated treatments orders, inaccurate medical records, and increased costs can be avoided with the use of an integrated RFID-sensor network [49]. Possible applications of integrated RFID and WSNs in the healthcare sector include sensing temperature, measuring blood pressure, heartbeat rate, or pH value. Among the proposed approaches of integrating RFID and sensor networks in healthcare applications we present some indicative applications.

IMEC-Netherland (IMEC-NL) a Dutch research institute has built prototypes of human-monitoring systems using active RFID tags, which are integrated with sensors [71]. The integrated sensor-tags are used to record and transmit data about a patient's vital signs. The human monitoring system is mainly used for investigating conditions such as epilepsy and sleep apnea. Until now, a hospitalized patient suffering epilepsy is monitored via electrodes, which are attached to his face and scalp and they are connected with wires into a box. The box collects data about the patients' facial and brain activity. This data is analyzed and used to track a patient's condition. Similarly, a patient that suffers from apnea is monitored via electrodes attached to his face to measure eye and jaw muscle movement and brain activity. The IMEC research institute investigated the possibility of providing the patients the ability to move and even the option to be monitored while being at home by making these procedures wireless. The researchers of the institute use sensors to monitor the patients' brain activity. If the sensors detect unexpected brain activity they transmit an alarm to an RF interrogator 10 m away. The prototype has been tested at the Universitaire Ziekenhuizen Leuven (UZ) in Belgium.

University hospital of Ghent in Belgium implemented an RFID-based Real Time Locating System (RTLS) to provide nurses and other caregivers with a patient's location in the event of an emergency [6]. The implemented integrated RFID-sensor network detects when a patient is having cardiac distress and sends to the caregivers an alert indicating the patient's location. In the proposed prototype Aero Scout T2 active Wi-Fi tags are used, which transmit the tags' unique IDs to the hospitals Wi-Fi network.

An integrated scheme of RFID and WSNs for in-home medication monitoring and elder healthcare was developed by Ho et al. [30]. The goal of the system is to monitor the quantity of medicine required by elder people and to assist them in taking the accurate amount of medicine as an extension of the Caregiver's prototype by Intel labs. The system is composed of an HF RFID reader, a UHF RFID reader, a weight scale, a base station, and three modes. HF RFID tags are placed on each medicine bottle in order identify each bottle, while the HF RFID reader is used to monitor the location of the medicine bottles within its range. The movement or replacement of a bottle is detected by regular reads on a readers' range. By using a weight scale, in combination with RFID tags embedded on medicine bottles, it is possible to determine which medicine and how much of the medicine was used by the patient. Each patient also bears an RFID tag and the patient is notified by the associated RFID reader to take the required medicine (via sound or light alarm). The proposed prototype is an extension of the approach proposed by Intel Labs [29], where a HF RFID reader and some tags are used along with two sensor nodes (motes) to monitor a patient's intake of medicines.

Intel Research Seattle and University of Washington also proposed a smart home prototype system, called "Caregiver's Assistant and CareNet Display" [22,67] that is able to detect, monitor, and record the daily living activities of elder people by collecting data through postage stamp-size wireless RFID tags attached to household objects. Information regarding the objects and the time that they were touched, are collected and transmitted using a WSN. Statistical methods are used on this data to detect high-level activities and to fill out entries from a state-mandated Activities of Daily Living form (ADL). The goal of the proposed prototype system is to help elder people manage their everyday activities without the need for an around-the-clock caregiver. Thus, caregivers may focus on the quality of care of elder people rather than on performing tedious tasks.

Integrated sensor-tags in order deploy a blood monitoring and management system that can be used in hospitals were proposed by Kim et al. [41]. The proposed system can be used to continuously monitor the temperature of the blood bank refrigerator as well as to track the location of a blood bag. Moreover, the proposed system can be used to prevent patient-blood mismatching as well as to perform temperature monitoring of blood bags. This is achieved using a sensor network in blood banks and RFID sensor-tags that are attached to blood bags. Crossbow Technology MTS420CA sensors were used to record the temperature of the refrigerator, blood bank room, and the temperature of the blood bag. The TempSens KSW RFID sensor-tags were used to tag the blood bags, which have enough memory to save 64 measurements of temperature data.

A passive wireless RFID sensor, which can be implanted in the patient's esophagus wall to detect impedance changes associated with gastroeophageal reflux was developed by Ativanichayaphong et al. [5]. Integrated sensor-tags have also been used to monitor patients' dental health. More precisely Intsrumentel [31] in cooperation with a U.K. dental school has attached pH sensor-tags in dentures to monitor the levels of food's acidity or alkalinity in a patient's mouth [16].

18.5.2 Integrated RFID and WSNs in Supply Chain Management

RFID systems and WSNs have extensively been used in the supply chain for inventory control, product tracking, and asset monitoring, while sensor networks are used for space and environment monitoring. Nevertheless, the integration of RFID systems with sensor networks open new directions. RFID systems are able to accurately identify objects, but often sometimes provide unreliable information concerning the location of an object. Sensors on the other hand, present many advantages in recognizing the location of an object but they are unable to identify it. The efficient integration of RFID and WSNs offers great advantages in accurate location tracking [49]. Furthermore, the integration of RFID and WSNs allows the condition monitoring of products and the detection of "dangerous" environmental conditions, such as a high temperature or humidity for fragile, sensitive or valuable products. Furthermore, integrated RFID and WSN technologies allow for the automatic condition and tamper detection from a distance without direct and manual inspection in a convenient, inexpensive and less error prone way. There is a great range of possible integration approaches of RFID and WSNs in the supply chain management. We list some of the most important ones.

An integrated scheme of RFID and WSNs for automated asset tracking was proposed by McKelvin et al. [47]. The proposed scheme integrates wireless sensor nodes and RFID readers. More precisely, a wireless sensor node is connected to a host (i.e. ordinary PC) in which an inventory of tagged products is maintained in a database. Another wireless sensor node is integrated in an RFID reader (reader node). A user of the host node is able to perform queries on the database which are later relayed to the reader node via the WSN. The query is then transmitted to the RFID reader and the required data is retrieved. The communication is bidirectional. Thus, data can be sent from the reader to the host device using the same interface.

PROMISE [53] was a European project that focused on monitoring and tracking a product through its life cycle using smart embedded devices. One of the goals of this project was the use of intergraded RFID tags and sensors to retrieve information and subsequently to improve the way that products are made, used, and recycled. Furthermore, some companies such as InfraTab [35] and CliniSense [19] have focused on developing integrated sensor-tags to monitor the freshness of perishable goods. Their focus was the combination of temperature and time duration to estimate possible bacterial growth.

18.5.3 Other Applications

Apart from applications in the field of healthcare and supply chain management, numerous other real-world scenarios of integrated RFID and WSNs exist. In this section we present application scenarios in diverse areas of science and engineering including fire detection, monitoring shipping containers, the condition of weapons in battlefields as well as managing cattle. In all cases integrated RFID and WSNs facilitate procedures and provide efficiency. However, in all cases different technical challenges existed that had to be overcome to achieve smooth operation of the integrated system.

An application of integrated RFID and sensor networks to notify firefighters [7] in case of a fire's ignition, was introduced by a wireless communication company in Melbourne, called Telexpath. The proposed scheme is based on the integration of RFID chips that operate at 433 MHz and use a proprietary air interface protocol and wireless thermal sensors. In case a thermal sensor senses temperatures within 2° of a predetermined setting, it sends its unique ID number to an interrogator. The next step is the cross check of the tag's ID number and a notification is sent to a person's cell phone. Thus, the firefighters are notified very quickly and they are able to respond to a fire incident faster and more efficiently. This approach can also be extended for alerting people not only in case of fires but also in case of other emergencies or equipment failures.

A similar approach that can be applied for early fire detections was proposed by researchers at the University of California in Berkeley [23]. This approach is based on the development of a GPS-enabled wireless sensor, called Firebug, which collects real-time data from sensors about approaching fires and transmits these data via an RF tag which contains a Chipcon mote. Thus, firefighters have access to information related to the speed and the intensity of an attack and are able to respond appropriately.

Siemens IT Solutions and Services [73] have conducted a thorough research on the use of integrated RFID and sensor network technologies used to monitor shipping containers. They have proved that it is possible to achieve continuous monitoring of shipping containers from their departure until they reach their final destination. The proposed approach uses active RFID transponders and sensors. The collected data via RFID are transmitted over GSM and GPRS telecommunication networks to a satellite telecommunication service. Information that is transmitted may include the temperatures or the location of the containers. The advantages of continuous monitoring of shipping containers provide significant advantages regarding the placement of order. For instance, in case an alarm is triggered, while the goods are still on the sea, the customer can be notified and perform a new order.

BP has also adopted the integration of RFID and WSNs to manage efficiently the chemical inventory and increase the stock visibility at a petrochemical plant in the United Kingdom. This project involves the communication and cooperation of integrated RFID sensor-tags and data sharing between each other. In the integrated RFID-sensor network each RFID sensor-tag collects data and transmits them to any other node in the network. The employed RFID sensor-tags are designed to monitor the conditions around them and to provide alerts according to predetermined rules. Each tag is employed with a movement sensor, a wireless transceiver, and it uses a proprietary peer-to-peer protocol to communicate with each other. Each sensor-tag transmits except from its unique ID, details about environmental conditions to all other nodes within 3 m range.

A mixed heterogenous architecture of RFID systems and sensors to track multiple people was proposed by Mori et al. [50]. The proposed system integrates distributed floor pressure sensors and a complete RFID system. By using floor pressure sensors or pyroelectric sensors it is possible to detect an area that indicate the presence of a person. RFIDs are used to identify people, because sensors fail to track each person when their existing areas overlap. Experimental results prove that the proposed approach is able to track multiple people in daily life situations effectively.

Integrated RFID-sensor networks have also been embraced by the U.S. Navy [65] to monitor the condition of valuable aircraft parts in storage. The U.S. Navy in cooperation with the George Institute of Technology in Atlanta employed an RFID system that doesn't need RFID readers to scan each tag, but instead it uses battery-powered sensor-tags that are able to communicate with each other and transmit information between themselves. The data is transmitted from the final transponder to a single reader. The RFID sensor-tags are able to measure temperature, humidity, and air pressure and to communicate with other RFID sensor-tags. The RFID sensor-tags are self-powered and they have a two year battery life. The tags transmit information only after being interrogated by a base station, which needs to send a specific security code as well. Thus, the possible leakage of information to unauthorized enemies, that could reveal sensitive information concerning the location of the ship or other sensitive inventory information, is prevented.

HP also uses integrated RFID-sensor networks in two prototype applications, namely the smartLOCUS and the smartRack [51]. SmartLOCUS controls and monitors a sensor network of cameras and readers. A sensor overlay network connects RFID readers to inexpensive video cameras via an 802.11b network. The cameras provide information concerning, for instance, the movement of items in a warehouse.

In the smartRACK project thermal sensors and high-frequency RFID readers are used to monitor the temperature of servers' cabinets. Each shelf in the rack is equipped with an RFID reader designed to read high-frequency signals from servers with special chips storing the machine's unique ID number. An RFID reader is employed on each server cabinet and 14 antennas are employed (configured) on the server door to read the 13.56 MHz RFID tag attached to each of the servers in the cabinet. Five to six thermal sensors are wired to the cabinet door and linked to the reader. The thermal sensors monitor the temperature of the servers located in the servers' cabinets. HF RFID readers and sensors are networked and the collected data is used to produce two-dimensional graphics in real time that represent the temperature profile of each cabinet. This application is essential for companies that use a large number of servers. Abnormally high temperatures would send an alarm and notify the personnel about the possible problem.

Another application of integrated RFID and WSNs is their use in battlefields [36]. Recently, a prototype was produced that can be embedded on weapons to track how many times war fighters fire their weapons during a battle. Thus, the Army can assess when each weapon has reached the end of its lifetime. The prototype is based on integrating RFID tags with sensors. This is achieved by placing on each weapon a piezoelectric sensor, a tiny processor, and an RFID tag. The piezoelectric sensor is able to determine when the weapon has been fired by sensing the recoil. The tiny processor has limited memory and it is able to record and store the output from the sensor. Finally, the RFID tag is used to transfer the data to an RFID reader. The prototype is able to track the number and times of rounds fired as well as to deduce characteristics from the intensity of the firing, such as acceleration, heat, and resonant electromagnetic frequencies. All these characteristics can help on estimating the useful time of the weapon.

Integrated RFID and WSNs have also been used to sense the level of oil in tanks [8], to monitor the vibration levels of large cooling fans used in the oil-refining processes as well as to monitor and facilitate the mixing of different crude oil levels during the formation of gasoline. All three uses are pilot projects performed by Sense-Comm using the i-Sense Talker devices which are an enhanced version of an iRFID tag [37] containing sensors different from those normally used in iRFID tags. Integrated RFID sensor-tags will facilitate considerably the above-mentioned processes in oil refineries. For instance, traditionally to monitor the fluid levels in tanks a mechanical gauge is used which should be checked manually or by dipping a wired sensor into the tank. However, neither solution is optimal considering that these areas are hazardous and it is expensive to perform these procedures either with wires or with manual controls.

Another application of integrated RFID and WSNs is the easy management of cattle. Zigbeef [70] is marketing hardware that can be used by ranchers to manage their herds easier. Zigbeef uses integrated RFID sensor-tags, which can sense animal movements and transmit these data to an RFID reader. These data could also be used in rodeos where the sensor-tags can be attached to rodeo Bulls. Thus, using a mobile reader, the audience will be able to observe data regarding how much the bull was actually bucking the rider before throwing him. ZigBeef is also planning to extend the present system with mesh capabilities so that ZigBeef tags will be able to transmit data from one to another. Thus, the read range will be extended depending on how many cattle are spread throughout the area and, finally, the data will be sent to a reader.

Other applications of integrated RFID-sensor networks is the development of an RFID-based memory assistant [59], which is able to notify a person when leaving the house without carrying all the necessary items. All the essential items are tagged, while a pressure sensor detects her presence at the house's front door and activates an RFID reader if something is missing. Another project included the use of temperature sensor-tags attached in a cow's stomach [60] to predict its child birth. The system is based on measuring the cow's body temperature and the indication of an abrupt decent in a cow's body temperature 24 hours before its calf birth.

The Japanese Ministry of Internal Affairs and Communication (MIC) has also developed a system that is based on integrated sensor-tags for gathering information about a disaster area [61]. The sensor-tags are sprinkled from helicopters and important information is collected from the disaster area including the possible existence of human disaster victims.

An integration scenario of RFID and WSNs for a tour group system was proposed by Chen et al. [12]. According to this integration scenario the guide of each group holds a badge which emits 4 kHz signals. Each group member carries a ticket with a passive RFID tag in which is stored in the group's ID. Sensor nodes are attached to direction boards to display simple guiding directions. The signals from the leader's badge are recognized by the wireless sensor nodes and thus, the leader's location can be tracked. Some nodes in the WSN are selected as help centers and they are connected to a laptop and an RFID reader.

Integrated RFID and WSNs is also a research direction for Aerospace in Auto-ID Labs [54]. By using such systems on aircraft parts, the configuration of the aircraft will be known precisely. It is expected that by doing so, the aircraft's maintenance and repair will be considerably facilitated. Moreover, the delivery of customer-related services such as ticketing, baggage-processing, and meals are also being considered as research directions for using integrated RFID and WSNs.

18.6 Conclusions and Open Issues

Undoubtedly, the integration of RFID and WSNs is an imminent step that will lead to a high level of synergy and more technological advances. This integration will give us the advantage not only to reveal an item's location and identity but also its current state. These integrated networks will extend traditional RFID systems and will give us an important advantage in controlling environments and industrial processes. However, more effort is necessary to achieve efficient integration of RFIDs and WSNs.

To achieve a broader adoption of integrated RFID and WSNs, it is important to resolve some open issues and challenges such as the reduction of possible interference in large integrated RFID networks and WSNs, because the greater the number of wireless devices in a network, the larger the potential of a possible interference. Thus, it is important to define a good collision-free schedule for both WSNs and RFIDs.

An important step towards the wide integration of RFID and WSNs would be the deployment of tools, methods, and approaches that would be general enough to be used in a wide range of applications. However, it is important while deploying these tools methods and standards to take into consideration the restrictions concerning the available resources. Moreover, the developed approaches should be general enough so that their evolvement into standards shall be a possible option.

An interesting initiative towards this direction was the IntelliSense RFID project [72] part of the Nordic research program NORDITE. IntelliSense's goal was the development of multi-protocol RFID devices that are able to operate at different frequency bands with different communication protocols. Thus, dual-band sensor-tags can be developed, that could be used in multiple applications. For instance, a multi-band sensor-tag may be used by UHF RFID readers for a logistics application and by consumers to retrieve data stored in its memory through an HF RFID reader integrated in a cell phone.

Additionally, the creation of simulators that combine RFID and WSN technologies would be significant in the wide deployment and study of integrated RFID and WSNs. Furthermore, considering that the market is cost driven the success of integrating RFID and WSNs will highly depend on the choices of the lowest cost material and the simplest and most effective manufacturing processes.

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