Taxonomy and Challenges of the Integration of RFID and Wireless Sensor Networks

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Abstract

Radio frequency identification and wireless sensor networks are two important wireless technologies that have a wide variety of applications in current and future systems. RFID facilitates detection and identification of objects that are not easily detectable or distinguishable by using conventional sensor technologies. However, it does not provide information about the condition of the objects it detects. WSN, on the other hand, not only provides information about the condition of the objects and environment but also enables multihop wireless communications. Hence, the integration of these technologies expands their overall functionality and capacity. This article investigates recent research work and applications that integrate RFID with sensor networks. Four classes of integration are discussed: integrating tags with sensors, integrating tags with WSN nodes and wireless devices, integrating readers with WSN nodes and wireless devices, and a mix of RFID and WSNs. Finally, a discussion of new challenges and future work is presented.

RFID (radio frequency identification) is a means of storing and retrieving data through electromagnetic transmission using a radio frequency (RF)-compatible integrated circuit. Today, RFID is applied widely in supply-chain tracking, retail stock management, parking access control, library book tracking, marathon races, airline luggage tracking, electronic security keys, toll collection, theft prevention, and healthcare. An RFID system usually consists of two main components: tags and readers. A tag has a unique identification number (ID) and memory that stores additional data such as manufacturer name, product type, and environmental factors including temperature, humidity, and so on. The reader can read and/or write data to tags through wireless transmissions. In a typical RFID application, tags are attached or embedded in objects that must be identified or tracked. By reading nearby tag IDs and then consulting a background database that provides mapping between IDs and objects, the reader can monitor the existence of the corresponding objects.

A sensor network is composed of a large number of sensor nodes that can be deployed on the ground, in the air, in vehicles, inside buildings, or even on human bodies. Sensor networks are employed in environment monitoring, biomedical observation, surveillance, security, and other applications. Sensors in wireless sensor networks (WSNs) sense the environment and forward data to a sink that usually is far away from the data source. Because a long communication range is not provided due to the limited energy of sensors, multihop wireless connectivity is required to forward data to and from remote sinks.

The main differences between RFID and WSN technologies are summarized in Table 1.

As can be seen from the table, RFID networks and WSNs represent two complementary technologies, and there are a number of advantages to merging these two technologies. RFID tags are much cheaper than sensor nodes. It is economical to use RFID tags to replace some of the sensor nodes in WSNs. Moreover, because an object that is embedded with an RFID tag is trackable, RFID technology provides a reasonable addition to wireless sensor networks in tracking objects that otherwise are difficult to sense. On the other hand, WSNs offer a number of advantages over traditional RFID systems. Sensors can provide various sensing capabilities to RFID tags, push logic into nodes to enable RFID readers and tags to have intelligence, and provide an RFID system with the capability of operating in multihop fashion, which potentially can extend the applications of RFIDs.

Currently, the application of RFID systems is much wider than that of wireless sensors. Wireless sensor networks have not yet reached the mainstream in the same way RFIDs have. Significant industrial interest in RFID exists because of:
- Mandates from large companies
- Capability of easily replacing and improving the functionality of existing applications, including all the applications where bar code technology is used
- Existence and development of RFID standards
- Relatively inexpensive tags

By combining the properties of RFID (identifying and posi-

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Attribute	WSNs	RFID systems
Purpose	Sense parameters in environment or provide information on the condition of attached objects	Detect presence of tagged objects
Component	Sensor nodes, relay nodes, sinks	Tags, readers
Protocols	Zigbee, Wi-Fi	RFID standards
Communication	Multihop	Single-hop
Mobility	Sensor nodes are usually static	Tags move with attached objects
Power supply	Battery-powered	Tags are battery-powered or passive
Programmability	Programmable	Usually closed systems
Price	Sensor node — medium Sink — expensive	Reader — expensive Tag — cheap
Deployment	Random or fixed	Fixed, usually requires careful placement
Design goal	WSNs are general-purpose	Tags are optimized to perform a single operation, such as read

■ Table 1. *WSNs vs. RFID systems.*

tioning) and WSNs (sensing, identifying, positioning, and multihop communications), we can define several different application scenarios for combining RFID and WSNs including:

- Integration in which RFID is used for identifying and WSN is used for sensing
  - –Sensors and RFID are attached to the same object. They can be used to sense temperature, PH value, vibration, angular tilt, blood pressure, heartbeat rate, and so on. [1]. Usually, communication is achieved using RFID protocols.
  - –An RFID tag is attached to the object, and a WSN is used for sensing the object [2]. An example of this type of application is for museums where the RFID reader is integrated to the camera, and tags are attached to the objects in the museum. After the object is sensed, RFID can provide additional information about the object.
  - –An RFID tag is attached to the object, and a WSN is used for sensing the environment. A typical application includes mobile robots that rely on RFID for detecting non-sensible objects and on WSN for collecting information about temperature, humidity, and other environment-related information.
- Integration in which both RFID and sensors are used for identifying objects or people. A representative application is one in which RFID information can be read from a tag only after the fingerprint scan matches the one that is already stored in the chip.
- Integration in which a WSN is used for providing location and RFID is used for identifying objects or people [3] or assisting with positioning that is performed using sensors [4]. In [4], a positioning system for first responders is described in which different sensors are used to estimate the position of first responders, and RFID tags, placed at known positions, are used to correct the estimated position.
- Integration in which a WSN is used for providing multihop communications and RFID is used to identify [5] and track [6] objects or people in an elder healthcare network.

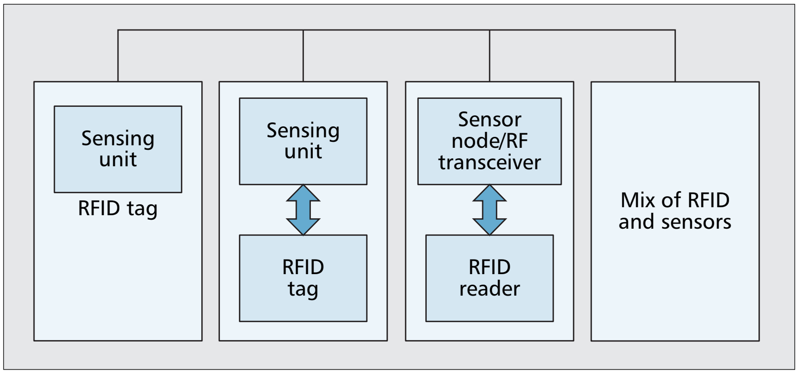
Surveys and classifications on the integration of RFID and WSN technologies were attempted in several publications, but they are either outdated or missing a comprehensive study. In [7], three types of integrations are suggested that are similar to our classes 2 and 3. However, in this article we perform a comprehensive study of many current and potential solutions that correspond to these classes in addition to pointing out specific solutions described in [7].

In [8], several different classifications are presented. The paper describes possible ways of integrating WSNs into an existing RFID network based on the standards defined by EPCglobal (www.epcglobal.org). Reference [8] is different from this article because it considers only integration of WSNs into RFID frameworks, and on the RFID side, it considers only the EPCGlobal-based RFID technologies. However, a number of useful classifications and architectures are defined. At the level of integration, four reference models for integration are proposed. They include:

- Mix of RFID and WSN with integration at the application level
- Mix of RFID and WSN with integration at the filter and collection level
- Hardware integration in which the RFID reader is responsible for collecting data from both tags and WSNs
- Logical integration at the electronic product code information services (EPCIS) level that allows for a mix of RFID and WSNs

In [2], classification of combinations of WSNs and RFID is presented, and it is similar to classes 1–3 presented in this article. In addition, the network topology and the software architecture of the integrated network are analyzed. Three software architectures are proposed based on the software layer in which the two networks are connected. In this article, we describe in much more detail each type of hybrid system classification.

This article surveys recent research work, new product and patents, and applications that integrate RFID with WSNs. We discuss four types of integrations (Fig. 1): integrating tags with sensors, integrating tags with wireless sensor nodes, integrating readers with wireless sensor nodes and wireless devices,



■ Figure 1. *Four types of integration.*

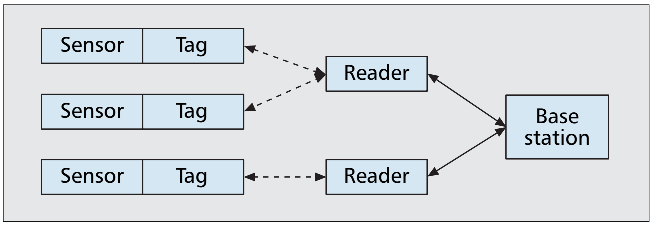


Figure 2. *System architecture.*

and a mix of RFID components and sensors. Future directions are presented in the final section.

Class 1 — Integrating RFID Tags with Sensors

Integration of this class enables the adding of sensing capabilities to RFID systems. The RFID tags with sensors (sensor tags) use the same RFID protocols and mechanisms for reading tag IDs, as well as for collecting sensed data. Because integrated sensors inside RFID tags are used only for sensing purposes, current protocols of these RFID tags rely on single-hop communication.

In this section, the classification is based on the way sensor tags are powered up. Hence, we can distinguish among the following sensor tags:
- 1a) passive
- 1b) semi-passive
- 1c) active

Passive tags do not use batteries for communication and sensing, and as such, they are basically maintenance-free. However, the requirements of very low power sensors lead, as well, to a lower quality of sensing. Semi-passive tags use power-generating circuits to generate power for RF components on the chip and battery power for powering up the rest of the chip. Active sensor tags rely completely on batteries.

Depending on the phenomena that are sensed, we can distinguish between applications: (1) in which the phenomena must be monitored constantly and (2) that require sensing only at specific time instants. Type 2 is an excellent candidate for integration with passive RFID tags.

An example of the architecture for RFID sensing networks is studied in [9]. The EPCglobal ultra-high frequency (UHF) Class 1 Gen 2 protocol defines allocation of data in the memory of a tag. A user-defined data segment of the memory can be used for storing sensor data. Thus, sensed data can be selected and read by EPC Generation 2-compliant readers by using properly configured commands. The system architecture is shown in Fig. 2.

Class 1a — Passive Tags with Integrated Sensors

Passive tags with integrated sensors operate without batteries and gather power from the RF signal of readers. They belong to the class of applications in which sensing is required only at specific time instants. Sensing is performed when the sensor tag is in the reading range of the reader, and the reading and sensing is triggered by the reader.

Passive tags with integrated sensors are used in several applications including temperature sensing and monitoring [10, 11], photo detection [10], and movement detection [12]. In all these applications, power that is harvested from the reader must be used for both RFID communications and sensor operations. The major research directions include:
- Ultra low-power design of integrated sensor tags
- Antenna design for improving reading range
- Improving precision of sensing devices by providing more stable clock and/or voltage references
- Development of dedicated protocols that allow for additional power savings

An RFID tag with temperature and photo sensors is studied and designed in [10]. The focus is on designing low-power sensor tags, as well as more precise clock references used to improve the accuracy of sensing (research direction (3)). One of the characteristics of this solution is that the clock is generated from the internal clock generator (it is not extracted from the incoming RF signal) and then synchronized to sample a demodulated bit stream. The internal clock reference is more stable and is used in sensors. The tag is fabricated in a 0.25-μm complementary metal-oxide semiconductor (CMOS) process. The total power consumption is 5.14 μW during an active state. The communication protocol is based on the EPCglobal UHF Class 1 Gen 2 protocol.

The solution presented in [11] follows research direction (2) in which the antenna design is improved to achieve a longer communication range. The solution consists of a divided micro-strip antenna and a rectifying circuit, which is used to boost the DC voltage. Two passive tags were implemented, and the one working at 860–950 MHz achieved a 30-m read range. The tag working at 2.45-GHz was integrated with the temperature sensor and had a range of approximately 9 m.

Class 1b — Semi-Passive Tags with Integrated Sensors

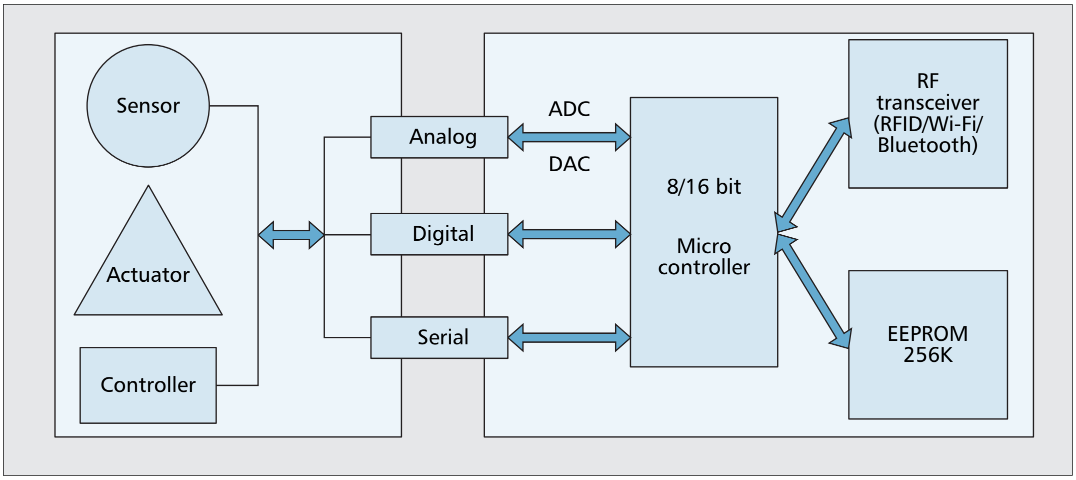
Semi-passive tags with integrated sensors could be used in temperature sensing and monitoring, location recording, vehicle-asset tracking, and access control. In comparison with passive sensor tags that can perform measurements only when interrogated by the readers, semi-passive sensor tags can perform independent measurements when they are not in the proximity of readers. This requires a greater amount of memory for storing measured values. Many tags include a real-time clock as well so that it is possible to record measurement times together with the measured values. In this area, we noticed a greater number of industrial solutions than of academic solutions.

TempSens developed by KSW Microtec AG (www.ksw-microtec.de) can be attached to or embedded in any product that could spoil during transport due to temperature fluctuations. It operates at 13.6-MHz and performs periodic measurement and recording of temperature. An example of an industrial solution at 2.45-GHz is a tag developed by Alien Technology (www.alientechnology.com). It provides reliable read/write capabilities with a range of up to 30 m. The tag has on-board temperature sensors and is easily extendable so that many different types of sensors can be connected to it through a serial inter-integrated circuit (I2C) bus. The tag is able to store 4 kilobytes of data, which includes locally acquired sensor data.

Research directions are related mainly to tackling general challenges of designing semi-passive tags, such as extending the reading range and prolonging the battery life. Battery life can be extended by including energy scavenging from vibrations. The 2.45-GHz tag from Alien Technology is used for experiments in [13]. The Piezoelectric power generator was implemented together with the power conditioning circuit to generate DC power for the RFID tag.

Class 1c — Active Tags with Integrated Sensors

Active tags with integrated sensors are used in several applications including temperature sensing and monitoring (American Thermal Instruments; www.americanthermal.com), vibration detection, blood pressure and heartbeat rate moni-



■ Figure 3. *Architecture of the smart sensor node.*

toring [1], and so on. Sensor tags in this class have more memory and improved range and functionality in comparison with Class 1b tags. Some tags have external buses that allow for attaching external sensors. The research in this class includes different applications of sensor tags, as well as different architectures of active RFID sensor networks.

An industrial solution, Log-ic Temperature Tracker developed by American Thermal Instruments, is used as a watchdog in temperature-regulated or temperature-sensitive environments. It operates at 13.56-Mhz and can store 64,000 readings. The 2.4-GHz Temperature Sensor tag from Bisa Technologies (www.bisatech.com) is capable of collecting real-time temperatures of tagged items, as well as identifying them and locating them coarsely. The reading range is up to 100 m, and the reading rate is 100 tags per second.

In [1], two different architectures for sensor-embedded RFID (SE-RFID) systems are proposed based on the complexity of the sensor tag:
- Intelligent tags with multiple sensors attached
- Simple tags with one integrated sensor

In both architectures, sensors sample environment data periodically and independently, and the sensing data is transmitted to the reader. Because the type-2 tag contains only one sensor and the microprocessor is embedded inside the reader, the tag in the second architecture consumes much less energy compared with that in the first architecture. Moreover, it allows different sensing sources to be located at different geographical positions. To validate the proposed architectures, a real-time health monitoring system is further developed in [1].

Active tags may be compliant with existing RFID standards, or they can rely on existing wireless protocols such as wireless local area network (WLAN) or ZigBee. Tags that rely on non-RFID wireless protocols usually use a medium access control (MAC) address as a unique number that identifies the tag. The disadvantage of these solutions is that they cannot rely on existing well-defined higher layers of the RFID standards. The advantage is that the tags can be integrated easily into the existing wireless infrastructure, and they do not require expensive readers.

A number of industrial solutions that use WLAN RFID tags are used for real-time location systems (RTLSs). T3 tags (www.aeroscout.com) are Wi-Fi-based active RFID tags used to track assets and people in real time in both indoor and outdoor applications. The tags are integrated into the existing architecture, based on off-the-shelf WLAN access points. The tag has a built-in temperature sensor; and to preserve battery life, it is integrated with a motion sensor that disables reporting when there is no motion.

Class 2 — Integrating RFID Tags with WSN Nodes and Wireless Devices

Sensor tags from Class 1 have limited communication capabilities. In high-end applications, it is possible to integrate RFID tags with WSN nodes and wireless devices, such that the integrated tags can communicate with many wireless devices, not just the readers.

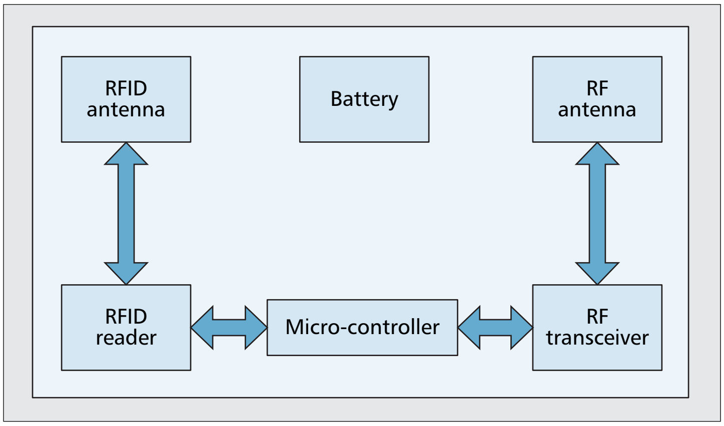
Based on the complexity and function of the integrated node, we distinguish between:
- 2a) WSN nodes with RFID capabilities
- 2b) Advanced WSN nodes with multiple radios that include both RFID and some other protocols
- 2c) Sensor nodes in which RFID tags are attached for the purpose of saving battery life or providing identification information

In Class 2a, we consider WSN nodes that act as tags in that they have a unique ID number that can be used in identifying objects or people. In addition, Class 2a nodes can have multiple sensors and additional communication capabilities in comparison with RFID tags. These capabilities include: communication between the nodes to form a multihop network, forming self-organized networks, and using power-efficient routing protocols to exchange information.

Integrated tags and WSNs mainly rely on existing wireless standards such as Zigbee and WLAN. Current solutions include mainly UHF and microwave frequencies because of the need for communication over long distances. On the implementation side, there is a significant difference between Class 2a and Class 1 because the solutions in Class 2a are processor-based versus mainly hardware-based implementations in Class 1.

Integration defined as Class 2a is an open research field in which a small number of solutions exist at this point. In [14], the Zigbee technology for an active RFID system is analyzed. The advantage of that system is that it enables communication between a reader and a server, between two readers, between a reader and an active RFID tag, and between two active RFID tags using the same ZigBee protocol. The active RFID tag is actually a Zigbee-enabled WSN node with an additional identification number.

Class 2b includes advanced WSN nodes with RFID capabilities. A wireless smart sensor platform studied in [15] uses wireless technologies such as Wi-Fi, Bluetooth, and RFID for communications in a point-to-point topology. The platform uses external sensors that are equipped with a smart sensor interface (SSI). The interface extracts data from sensors and provides a data communication interface to the central con-



■ Figure 4. *Structure of the integrated WSN node and RFID reader.*

trol unit. The sensor/actuator coupled with SSI is the smart sensor node. The architecture of the smart sensor node is shown in Fig. 3. A proportional gyro motor-encoder is implemented using this sensor node.

Class 2c is the combination of RFID and WSNs in which RFID can be used to wake up the WSN node. Each sensor node is integrated with an RFID tag and is also provided with an RFID reader capability. The integrated tag listens to the RFID reader radio of neighboring nodes. If channel activity is detected, the tag awakens the sensor to listen to the channel and then receives data through the RF sensor radio. Otherwise, the sensor node can stay in sleep mode. Because an RFID radio uses much less energy than an RF sensor radio, the RFID-impulse technique can reduce energy consumption significantly while providing short end-to-end delay.

Class 3 — Integrating Readers with WSN Nodes and Wireless Devices

Another type of integration of RFID and sensors is the combination of RFID readers with WSN nodes and wireless devices. The integrated readers can sense environmental conditions, communicate with each other in wireless fashion, read identification numbers from tagged objects, and transmit effectively this information to the host. Based on the type of the device that can be integrated with the RFID reader, we distinguish three types of integration:

- 3a) RFID readers with attached sensors
- 3b) RFID readers with WSN nodes, where we can distinguish between systems in which the WSN nodes are used to provide multihop communication to the network of RFID readers and more intelligent reader/WSN units that can sense, read tags, perform elementary operations/decisions, and perform multihop communication with other WSNs or readers/WSN units
- 3c) RFID readers integrated with sensors through more advanced wireless devices such as pocket-PCs

Based on the level of integration, in all three types, the RFID reader can be integrated with the other devices or connected with the other devices through the external bus/network.

An example of Class 3a is a solution from HP Labs called Smart Rack. It uses thermal sensors and HF RFID readers to identify and monitor the temperature of servers that are in large metal server cabinets. A 13.56-MHz tag is attached to each server, and each server cabinet is mounted with a reader that is connected to several thermal sensors.

There are several industrial and academic solutions for the integration of RFID readers and WSNs (Class 3b). An integrated system that connects the RFID reader to an RF transceiver that has routing functions and can forward information to and from other readers is presented in [5]. The integrated node consists of an RFID reader, an RF transceiver, and a micro-controller that coordinates different components in the node. The micro-controller also is used to control the RFID reader and other components that go into sleep mode when they are not busy. The structure of the node is shown in Fig. 4. The Philips ICODE HF RFID standard was adopted for the RFID system and Mica 2 platform for WSN.

A prototype of RFID and a sensor network for healthcare for the elderly was studied in [6]. The system consisted of multiple sensor and RFID components. HF and UHF readers were attached to the WSN nodes, which were used mainly to forward information from the readers to the central unit for processing. The HF RFID reader was used to track all medicine bottles within the range of the reader. A UHF tag attached to a patient could be detected by the associated RFID reader within 3~6 meters. The system could determine if the patient is in the neighborhood and would remind the patient to take the required medicines.

In Class 3c, RFID readers and sensors are combined with multi-functional devices, such as personal digital assistants (PDAs) and cell phones. The RFID-based sensor networks patent from Gentag (www.gentag.com) provides a way to add sensor networks to RFID readers in wireless devices such as cell phones, PDAs, and laptops. The basic idea of the patent is that by combining RFID cell phones and RFID sensors in cellular networks or the Internet, consumers will be able to read any RFID sensor tag in almost any application. Information on RFID tags also can be downloaded to a cell phone from a remote database for some applications. For example, a consumer can pay bills using a cell phone after credit card information is embedded in the cell phone.

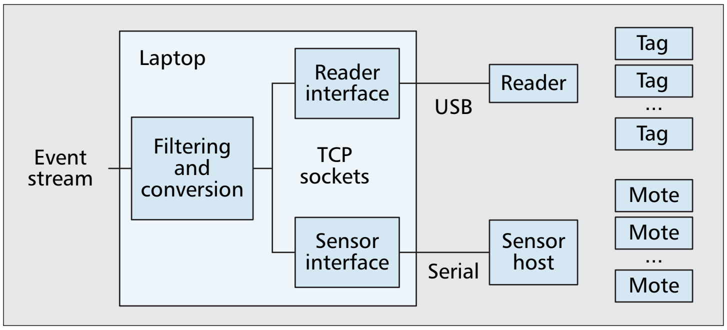
Nokia already has developed a cell phone that is embedded with HF RFID readers.

Class 4 — Mix of RFID and Sensors

Unlike the previous cases, RFID tags/readers and sensors in this class are physically separated. An RFID system and a WSN both exist in the application, and they work independently. However, there is an integration of RFID and WSN at the software layer when data from both the RFID tags and the WSN nodes are forwarded to the common control center. In such scenarios, successful operation of either the RFID system or the WSN may require assistance from others. For example, the RFID system provides identification for the WSN to find specific objects, and the WSN provides additional information, such as locations and environmental conditions, for the RFID system. The advantage of the mix of RFID and sensors is that there is no need to design new integrated nodes, and all operations and the collaboration between the RFID and the WSN can be done at the software layer.

A representative application of the class can be found in [3]. It introduces a framework for group tour-guiding services in which each group has a group leader and several members. Each member may follow the moving path of its leader or occasionally roam around randomly, based on his or her interest. The system performs positioning of the group leaders using WSN technology. If a group member must find the leader, it is done by reading the member's tag, associating the member with the leader, and then showing the location of the leader based on the information obtained from the WSN.

The system architecture of a mix of RFID tags and sensor



■ Figure 5. *System architecture of the implementation that supports a mix of RFID components and WSN nodes.*

nodes was studied in [7]. The system consists of three classes of devices:

- Smart stations that have no serious power constraints
- Tags
- Sensor nodes

A smart station consists of an RFID reader, a microprocessor for data processing, and a network interface that can be the 802.11b/Wi-Fi network. Smart stations gather information from tags and sensor nodes and then transmit that information to the local host PC or remote LAN. The information coming from the RFID and the WSN can be integrated further into the base station for a specific application. For example, detection of sensed data values that exceed a certain threshold may trigger RFID readers to read tags in the area.

Another architecture used for querying streaming RFID and sensor data in a supply chain was studied in [16]. The architecture is decomposed into four layers: physical, data, filtering, and application. An implementation of track and trace and cold-chain model was further presented. The implementation consisted of a laptop, a server, readers, and sensors as shown in Fig. 5. The reader operates at 13.56 MHz, and its reading range is about 1 cm. The WSN nodes are motes from Crossbow.

The EPCGlobal based sensor network for the RFID and WSN integration infrastructure was studied in [17]. The system consists of a large number of nodes with various sensors that are utilized to monitor property assets. To integrate distinct technologies in one system, the basic idea is to introduce a reader management component that is able to include WSN by adopting universal plug and play (UPnP) and the Simple Network Management Protocol (SNMP). RFID data and WSN data are configured by the reader management component to provide a proper and uniform interface, such that the WSN data can be delivered to upper layers as the RFID data. Therefore, upper layers do not need to distinguish between the data sources of RFID and WSN.

Currently, software platforms for integration of RFID and sensors are available. For example, RFID middleware software — RFID Anywhere, developed by Sybase iAnywhere (www.ianywhere.com), is a software platform that integrates business logic and processes with a variety of automatic data collection and sensor technologies, including RFID, barcodes, mobile devices, locating systems, environmental sensors, and feedback mechanisms. Another example is the WinRFID and reconfigurable wireless interface for networking sensors (ReWINS) technologies developed by the Wireless Internet for Mobile Enterprise Consortium (WINMEC) RFID lab (www.winmec.ucla.edu/rfid/). WinRFID is the middleware that supports a variety of readers/tags from different hardware vendors and provides intelligent data capturing, smoothing, filtering, routing, and aggregation. ReWINS consists of two components: a wireless interface for remote data collection and control architecture with a central control unit for data processing. ReWINS can support integration with a RFID network through the WinRFID middleware.

Future Challenges

In this section, we discuss the research direction for each class of integrated RFID/WSN systems. Currently, the largest number of industrial solutions exists for class 1 sensor tags. RFID technology is seen as a cheap way to add wireless capabilities to sensors. Passive sensor tags are a new area, and we expect a number of new solutions to appear in the near future. The major challenges here are the need for extremely low power consumption and the limited accuracy of very low-power sensors.

An interesting research direction is the combination of sensors and new architectures in the RFID field that include dual-frequency tags, near-field UHF tags, and Rubee tags. Dual-frequency tags have two radios on the same chip (e.g., low frequency [LF] and UHF). Near-field UHF technology currently is provided by several major manufacturers of UHF RFID tags (e.g., Impinj) and enables the reading of tags in the vicinity of metal and liquids at short ranges (1–3 ft.) using near-field. Rubee is a new LF technology in which large reader antennas are placed in the area and all the tags in the area can be read by the reader. All these technologies are novel, and integration of these technologies with sensors is in a very early stage, offering great potential for innovation.

At this point in time, ZigBee and WLAN networks are used for multihop communication. Multihop is not envisioned as a part of the RFID standards at this point. We see an opportunity in using multihop networks to extend the range of passive RFID networks.

In classes 3 and 4, significant challenges will come with ubiquitous deployment of RFID and WSNs. Current RFID deployments have not yet included hundreds of readers in a single environment. Having such a large number of readers in a single place will require detailed analysis of several related issues to minimize the cost of RFID equipment and query time. These issues include the selection of the appropriate RFID components, positions of the readers, network topology, and synchronization of the readers in time and frequency. The situation will be even more complicated when the network is composed of a large number of RFID and WSN components. An RFID and WSN deployment simulator must be developed to tackle these problems. To the best of our knowledge, there are no simulators that combine WSN and RFID technology. We expect that significant research effort will be made in that direction.

There have been several attempts to incorporate WSNs into existing RFID standards. In [9], it is suggested that the whole framework of the EPCGlobal network is used in the integration of RFID tags and sensors. The sensor data will be stored in the tag's memory and accessed using the EPCglobal UHF Class 1 Gen 2 protocol. Several different solutions for the integration of a WSN into the existing RFID layers defined by EPCGlobal are described in [8]. We already commented on these in the Introduction. Significant work must be performed toward the integration of RFID standards and prevailing standards that are used for sensor technologies such as IEEE 802.15.4.

We envision that the integration of RFID and WSNs will open up a large number of applications in which it is important to sense environmental conditions and to obtain additional information about the surrounding objects. Because RFID readers have relatively low ranges and are quite expensive, we envision that the first applications will not have RFID readers deployed ubiquitously. The applications that enable mobile readers to be attached to cars, robots, or to a person's hands are good candidates. The use of semi-passive or active RFID technology in combination with WSNs also has a promising future as the reading range of RFID systems becomes larger.

Acknowledgments

This work is partially supported by NSERC Strategic Grants STPSC356913-2007B and STPGP 336406-07 and the UK Royal Society Wolfson Research Merit Award. The authors would like to thank Daniel Shapiro for his constructive review of the first version of this manuscript.

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