Future technologies and applications for the Internet of Things (IoT) will evolve the process of the food supply chain and create added value of business. Radio frequency identifications (RFIDs) and wireless sensor networks (WSNs) have been considered as the key technological enablers. Intelligent tags, powered by autonomous energy, are attached on objects, networked by short-range wireless links, allowing the physical parameters such as temperatures and humidities as well as the location information to seamlessly integrate with the enterprise information system over the Internet. In this paper, challenges, considerations and design examples are reviewed from system, implementation and application perspectives, particularly with focus on intelligent packaging and logistics for the fresh food tracking and monitoring service. An IoT platform with a two-layer network architecture is introduced consisting of an asymmetric tag–reader link (RFID layer) and an ad-hoc link between readers (WSN layer), which are further connected to the Internet via cellular or Wi-Fi. Then, we provide insights into the enabling technology of RFID with sensing capabilities. Passive, semi-passive and active RFID solutions are discussed. In particular, we describe ultra-wideband radio RFID which has been considered as one of the most promising techniques for
ultra-low-power and low-cost wireless sensing. Finally, an example is provided in the form of an application in fresh food tracking services and corresponding field testing results.

1. Introduction

The Internet of Things (IoT) is a revolution of the information and communication technology (ICT), with a vision of bridging the physical world with the Internet cloud. Radio frequency identification (RFID)-enabled wireless sensing has been considered as the key technological enabler to realize the IoT [1]. The future RFID tags will be equipped with sensors and other peripherals for interaction with their carriers, monitoring their surrounding environment as well as their geographical information. Such intelligent tags with unique addressable identification number or IP address will be attached on objects, networked by short-range wireless links to existing ICT infrastructures, allowing the connections between the virtual world on the Internet and the physical world of things.

This technological revolution brings many emerging applications and services, creating added value in the marketplace. Numbers of early-bird applications of IoT in logistics, tracking and healthcare have already been deployed [2]. In particular, there have been several papers that introduced the RFID-enabled wireless sensor networks (WSNs) in fresh food tracking for intelligent logistics, aiming to improve the process of the fresh food supply chain and create added value of business [3–7]. For example, RFID-enabled temperature loggers are used to monitor and record the transportation and distribution temperature for perishable food products. This information is used for shelf-life prediction to identify and rank items with respect to their remaining shelf-lives which can enable the necessary insights for intelligent supply chain logistics such as first-expired-first-out (FEFO) instead of more traditional first-in-first-out (FIFO). From those research and early industrial deployments, three major issues are concerned:

- the development of the IoT platform that can early adopt novel RFID and wireless sensing technologies while seamlessly integrating with existing ICT infrastructures;
- advancing wireless sensing systems and intelligent tags with extended functionalities and reduced cost; and
- facilitating the integration of RFID-enabled wireless sensing systems into global information systems.

This review presents challenges, considerations and design examples of the future RFID-enabled wireless sensing for IoT from system, implementation and application perspectives. An IoT platform with a two-layer network architecture is introduced consisting of an asymmetric tag–reader link (RFID layer) and ad-hoc links between readers also known as master nodes (WSN layer), which are further connected to the Internet via cellular (3G/GPRS) or Wi-Fi. The review focuses on the state-of-the-art and the future trend of the RFID technologies for sensing and tracking applications. Three different technical approaches of (i) passive RFID with ultra-wideband (UWB) radio, (ii) active RFID using 2.4 GHz radio, and (iii) semi-passive ultrahigh frequency (UHF) RFID are reviewed. Finally, we show a deployment example of the system in a global fresh food tracking service.

2. IoT platform for fresh food tracking and monitoring applications

(a) Application requirements and system considerations

IBM has reported that over 50% of food globally ends up going to waste [8]. Another statistic from Billerud [9] indicates that approximately 10% of the fresh fruits and vegetables coming from
different parts of the world into the European market are damaged during the transportation process. This causes not only a loss of 10 billion euros per year, but also a big threat to public food safety. The cases of food spoilage have been intensively studied in [10,11], and the desired sensing target has been summarized in [6]. The main causes of fresh food damage during transport include microbial infections, biochemical changes (e.g. owing to respiration or ripening), physical damages and mishandling [12]. Early food tracking systems usually focused on the ability to follow the movement of a food through specified stages of production, processing and distribution [13]. Introduction of RFID to replace the barcode for automated identification aimed at reducing labour costs and process time. Recent advances in RFID with sensing and networking capabilities allow continuous monitoring of simple parameters such as temperature and humidity in a real-time manner, then further control the environmental conditions [3]. More recently, Pang et al. [6] suggested an income-centric fresh food tracking system leveraged by the latest IoT technologies, creating additional values through shelf-life prediction, sales premium, precision food production and insurance cost reduction. Beyond simple RFID systems with temperature and humidity sensors, in the study, a sensor portfolio was carefully selected based on the value creation, availability analysis and cost assessment, including the GPS coordinates, temperature, relative humidity, carbon dioxide (CO₂)/oxygen (O₂)/ethylene (C₂H₄) concentration and three-axis acceleration.

In order to realize a fresh food tracking system that is able to continuously monitor and trace the food quality and safety during the whole food supply chain from farm to table, there are several requirements that need to be considered in addition to traditional RFID systems. Visibility, traceability and controllability of food quality and safety by monitoring the surrounding environments and smartly governing the parameters should be available at all levels of packaging or carriers in the food supply chains. Therefore, RFIDs with different capabilities in terms of sensing functionalities, energy source, processing and storage capabilities, and wireless interfaces will be deployed in containers, packaging boxes or even attached to food itself at an item level. The RFID tags can be either disposable such as printed chipless tags, or reusable such as active wireless sensor nodes, for a most cost-effective solution. Moreover, the system installation and maintenance should be simple without the need of specialized staff or knowledge. To this end, solutions simply extended from a traditional RFID system cannot cope with all of these issues, and therefore a networked platform that embraces varieties of sensors and different classes of tags with heterogeneous radio interface and functionalities is expected.

(b) System architecture

As discussed in §2a, an IoT platform that can adopt the emerging technologies while keeping the compatibility with existing ICT infrastructure is crucial. Figure 1 illustrates the network and system architecture of an intelligent tag system which is ideal for fresh food tracking and monitoring applications. A two-layer network hierarchy is used which is connected to the Internet through an IP gateway [14]. Layer 1 is essentially an RFID system where tags are coordinated by a reader also known as the master node. In layer 2, ad-hoc networks are self-organized between master nodes as a WSN. Layer 1 (RFID layer) is a heterogeneous network with asymmetrical links providing wide range selections of RFIDs. Intelligent tags are ideally embedded in food packaging, such as paper boards or other flexible substrates, communicating with a reader by micropower wireless links. The intelligent tag usually consists of a power harvesting block, sensor interfaces, a digital processor and memory and a radio transceiver. The radio interface can be standard RFID by means of near-field coupling or far-field backscattering in high frequency (HF) or UHF bands, or active tags in the industrial, scientific and medical (ISM) radio bands. Meanwhile, the RFID layer can embrace non-standard RFID which usually presents attractive features and unique advantages for sensing applications. For instance, an RFID tag incorporating UWB technologies enables high-speed identification, accurate positioning and time-domain sensing. Another example is the printed chipless tag with inherent sensing characteristics through RF measurements of the impedance changes as a response to the varying environment, such
as temperature and humidity. Tags and sensors in this layer should be extremely low-cost and energy-efficient under energy autonomy conditions. The master node serves as a reader to collect the sensory data from the tag and link to the Internet cloud through standard air interfaces such as WiFi, GSM/GPRS and 3G. Also, the master node can be a superior wireless sensory station, which is usually equipped with sophisticated sensors such as chemical sensors and imaging sensors as well as GPS for geographical tracking.

3. RFID technologies for future IoT

Here, we focus on the RFID technology as a key enabler for fresh food tracking and monitoring applications towards the context of the IoT. After a brief review of the principles of RFID, technical challenges of the future of RFID for sensing applications will be discussed. Afterwards, two design examples for passive and active RFID technologies and a summary of the hybrid semi-passive technology to address those challenges will be introduced in §3c–e, respectively.

(a) RFID basics

An RFID system comprises readers and tags, also named interrogators and transponders. Basically, tags can be divided into two major categories based on how they communicate with the reader and their power source: active and passive.1 Active RFID tags contain an internal power source (e.g. battery). Thus, a tag’s lifetime is limited by the stored energy. Passive tags, on the other hand, usually harvest operating energy from the reader’s signal. Passive RFID is more attractive for applications where it is best for tags to not require batteries. In a typical passive system, the tag is powered up in the interrogating field and transmits the data to the reader [15]. Operation principles and frequency bands essentially dominate the performance and potential applications of an RFID system in terms of operating range, data rate as well as the cost. Frequencies of RFID range from a few kHz of low frequency (LF) to microwave band (e.g. 2.4 GHz), and further extend to the UWB. Among them, 125 kHz (LF) tags, 13.6 MHz (HF) tags and 900 MHz (UHF) tags are the most common ones for passive systems.

Conventional passive RFID technologies work in either magnetic/electrical coupling or electromagnetic coupling (backscattering), corresponding to the near-field and the far-field, respectively. The far-field backscattering RFID tags at the UHF band (860–960 MHz) are getting more attractive for wireless sensing and monitoring applications. Such tags are more powerful

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1 In some literatures, the grey area between active tag and passive tag is further defined, i.e. semi-passive tag: a battery for the tag’s circuit and backscattering for communication; semi-active tag: power-harvest for energy and active transmitter for communication.
than near-field RFID tags, ensuring a larger operating distance (up to several metres), a higher data rate (up to hundreds of kb/s) and a smaller antenna size. The tag captures the energy of continuous waves (CWs) from the reader. A power converter rectifies the alternating potential difference (electromagnetic energy) across the antenna. The scavenged energy is used to power up the circuitry on the tag. The tag sends data to the reader using a backscattering mechanism. The modulation is performed by changing the antenna’s impedance over time, so the tag can reflect back more or less of the incoming signal in a pattern that encodes the tag’s ID. By contrast, the active RFID is usually associated with short- or medium-range wireless in ISM band such as ZigBee and Bluetooth. It usually uses traditional CW modulation, providing superior performance to passive RFIDs, in terms of operating distance and network throughput, at the expense of higher power consumption and complexity.

(b) Technical challenges and design trends

Beyond simple identification function in traditional RFID, the new paradigm of intelligent tags with multiple functionalities of sensing, computing, networking is to keep or reduce the cost compared with today’s RFID. The performance of the enabing RFID technology needs to be improved in several aspects, mainly including (i) development and integration of sensors and interface circuitry into RFID tags, (ii) improved link performance in terms of data rate and reading distance, and (iii) system integration of integrated circuit (IC) chip and non-silicon blocks such as antennas and sensors on RFID tags, etc.

(i) Sensors and interface circuits

The sensing function determines the application of the intelligent tags. For packaging and transportation applications for food logistics, the sensing targets of interest include temperature, humidity, CO₂/O₂/C₂H₄ concentration and three-axis acceleration. Existing wireless sensor nodes are composed of multiple components on a printed circuit board, resulting in a milliwatt-powered system with bulky battery for limited lifetimes, and the sensors in most cases dominate the overall cost of the node [16]. The advances in RFID are creating the opportunity to combine the sensing functionalities with ID tags, which significantly reduces the cost and size. Silicon-based sensors integrated on the IC chip are the most feasible solution providing the best trade-off in terms of cost and performance. For example, on-chip complementary metal–oxide–semiconductor (CMOS) temperature sensors are usually implemented using bipolar junction transistors with delta–sigma analogue-to-digital conversion (ADC) readouts, as demonstrated in [17]. Law et al. [18] demonstrated a CMOS temperature sensor based on serially connected subthreshold MOS operation for passive RFID food monitoring applications. However, it is still challenging to integrate sensors and their interface circuits into wirelessly powered RFID tags. First, sensors usually have high power consumption. For instance, the reported temperature sensors for RFID applications still consume a few tens to hundreds of µW, whereas chemical and gas sensors are even more problematic, which usually consume mW-level power and (or) require extra heating of the sensing film [19]. Second, data from analogue sensors need to be digitalized before being processed, stored and transmitted. Therefore, extremely low-power ADCs are essential to cope with µW-level power budget for a wirelessly powered application. In order to address these issues, µW successive approximation register ADCs with a figure of merit down to 4.4 fJ per conversion step have been designed for RFID applications, providing promising energy efficiency and good scalability for power and performance [20]. Nevertheless, the additional power consumed by the ADC still limits the reading distance of the tag.

Over the past a few years, advances in large-area electronics and printing technologies have enabled the realization of printed electronics and sensors on various substrates including such mediums as papers and organic substrates. Some exciting research focuses on various printed sensors, including biosensors, pressure sensors and temperature sensors. More recently,
a significant amount of research work has focused on ‘RFID technologies as sensors’ or ‘RFID-enabled sensors’ [21]. By integration of sensing materials such as water absorbing materials for humidity sensors and carbon nanotubes for chemical sensors on RFID tags, the changes in electrical characteristics such as capacitance or impedance can be observed by the reader through the backscattered signal, as shown in figure 2. The humidity sensors and the temperature sensors are most relevant for food monitoring. An inkjet-printed humidity sensor tag has been presented in [22] for UHF RFID systems, and a passive wireless temperature sensor based on a chipless UWB RFID tag was demonstrated in [23].

(ii) Wireless transmission

Extended operating distance and high data rate are highly desired for the future of RFID technology. The wireless sensing applications present transmitter-dominated asymmetric communications, i.e. tag-to-reader communication dominates the traffic, and the RF transceiver dominates the power budget. The digitized sensor data not only complicate the circuit design of the tag, but also substantially magnify the need for wireless transmission, e.g. greater than 10 metres and greater than 1 Mbps [24,25]. The UHF backscattering RFID provides superior performance among passive RFID systems, i.e. a few hundreds of kbps and less than 10 m coverage, but it is still insufficient for sensing applications where data from multiple sensors need to be sent wirelessly. On the other hand, the active transceivers provide ideal performance, but are either too complex and/or have high power consumption to cope with the µW-level power budget of passive RFID tags.

The UWB impulse radio is a promising solution for future RFID systems to overcome most of the limitations of current narrow bandwidth RFID technology [24,26]. It uses ultra-short pulses in time domain instead of CW modulation, spreading the spectrum up to a few GHz [27]. The wideband signal exhibits strong advantages for RFID to achieve both high-speed identification and precise tag localization. Dari & D’Errico proposed a passive UWB RFID based on backscatter modulation [28] achieving more than 20 m operating range. A UWB transmitter integrated in a conventional passive UHF tag has also been proposed [29], with −18.3 dBm downlink sensitivity and 10 Mbps uplink data rate. More recently, chipless RFID incorporating the UWB technology has been developed for ultra-low-cost item-level tracking [30]. Such research has demonstrated the feasibility of UWB to provide both reliable identification and high-definition localization of tags, in spite of the increased complexity of the reader design [31]. Another approach to extend the reading distance is to use semi-passive UHF tags. Semi-passive tags include a battery, much like the active tags; however, the battery is used only to ‘assist’ communications in the presence of a reader rather than supporting fully active transceiver circuitry. Semi-passive tags communicate...
with the reader, as do the passive tags, but their battery can be used to increase the sensitivity of the tag to reader signals in the environment and to boost the backscattered signal power to increase the communication range.

In addition to enhancing the link capacity in terms of the data rate and the communication range, reducing the amount of data to be transmitted is an alternative solution to relax the communication requirements. Sensors gather large amounts of data about the conditions of their surrounding environment, but not all of these data contain useful information. Compressed sensing has been widely studied in recent years [32,33]. The principle is to use sub-Nyquist rate to sample sparse events, thus reducing the amount of data to be stored or transmitted. Moreover, technology scaling of the CMOS allows more complex microprocessors on the tag to perform signal processing and extract useful data before transmission. The concept of ‘on-tag intelligence’ has been proposed [34], aiming to leverage more digital circuits on the RFID tag to relax the analogue and RF circuits as well as the communication overhead. There have been a few ultra-low-power processors with near-zero leakage power featuring less than 100 µW per MHz, which demonstrate feasibility in RF energy harvesting applications [35].

(iii) Integration and miniaturization

Intelligent tags attached on objects are intended to be small in geometry. Seamless integration of intelligent devices into food packaging, the human body and various everyday objects calls for novel approaches. Beyond existing system-on-chip integrations, future sensor tags could be a multi-module system mounted on different materials or substrates. Therefore, it creates new demands for interconnecting and packaging solutions, such as flexible electronics and system-in-package. Meanwhile, as the antenna and its integration are up to 50% of the total tag cost nowadays, innovative manufacturing processes need to be exploited. Technologies such as printed antennas or on-chip antennas are expected to facilitate system miniaturization as well as cost reduction. Although inkjet printing with functional inks enriches the functionalities and lowers the cost of RFID tags, there is still a need to embrace silicon-based chips in most application scenarios. Heterogeneous integration [36] offers a solution of faster adoption of new technologies without sacrificing the overall system performance. It enables assembly of silicon circuits and non-silicon materials on a flexible substrate, such as sensors, antennas, displays and IC chips. This not only benefits from the advancement of new technologies for additional functionalities and cost reduction, but also keeps the advantages of the current technologies such as performance, robustness, availability, compatibility and more importantly time-to-market.

(c) Passive RFID with ultra-wideband

(i) Chipless UWB RFID

In contrast to conventional RFID tags with ICs, chipless RFID uses the radar principle, with the tag information embedded into the electromagnetic signature of the structure. It does not need any IC and communication protocol, and avoids the connections between IC and antenna. It features high reliability and ultra-low cost, and facilitates fully printable tags through an inkjet printing process on various substrates such as paper [37].

The simplest approach is to encode the ID number by variations of the impedance over the transmission line, resulting in the on–off-keying modulated data by means of UWB pulse reflections in time domain. The tag receives an interrogation signal from a reader via a UWB antenna. The signal is then sent onto a transmission line and propagates forward until reflected by a train of codes encrypted in the tag. The reflected signal is received by the reader and compared with the original interrogation signal to pick up codes in sequence. The tag as illustrated in figure 3a mainly consists of a microstrip line (ML) and a set of capacitors. The received UWB pulse propagates over the ML until it encounters a shunt capacitor, which will introduce an impedance discontinuity and reflect part of the incident signal back, denoting the coding of the digit ‘1’. Meanwhile, the left signal will propagate forward, until it arrives at the next coding point, where
if no capacitor exists, it means the coding of ‘0’ and otherwise a coding of ‘1’. An implementation example of the chipless UWB tag on photo paper with fully inkjet printing of metallic inks is shown in figure 3b [38].

(ii) Passive UHF RFID with active UWB radio transmitter

The chipless tag shows strong potential for ultra-low-cost applications such as item-level tracking. However, its performance such as reading distance and the system (coding) capacity is limited. In order to overcome the shortcomings of the chipless solution to achieve extended reading distance and system capacity, an alternative approach using an active UWB transmitter powered by UHF RF energy harvesting has been presented [29].

Previous studies have found that a UWB receiver has high power consumption and is too complex to be implemented in wirelessly powered systems such as RFID. On the other hand, a UWB transmitter can be extremely simple and low-power. Approximately 10 to approximately 100 pJ per pulse energy consumption with an aggressive duty-cycling scheme is able to cope with μW-level energy scavenged by RF waves as conventional passive UHF RFID. We also have identified the similar asymmetric nature of passive identification and sensing applications, in terms of the traffic load and the hardware complexity, i.e. tag-to-reader transmission dominates the traffic, and therefore an energy-efficient and low-complexity transmitter at the tag side is highly necessary.

Combining the asymmetric natures of RFID systems and UWB systems, a UHF/UWB hybrid tag has been designed and implemented, as shown in figure 4a [29]. In the downlink (reader-tag), the tag is powered and controlled by UHF signals as conventional backscattering tags, whereas it uses a UWB transmitter to send data for a short time at a high rate in the uplink (tag-reader). Such an innovative architecture has the benefits of UWB transmissions, whereas the tag avoids the complex UWB receiver by shifting the burden to the reader. The silicon tape-out and
experimental results have demonstrated that the tag has comparable complexity in terms of the die size. The sensitivity of the tag is $-18.5\, \text{dBm}$ ($14.1\, \mu\text{W}$). It corresponds to approximately $13.9\, \text{m}$ power-up distance, assuming $4\, \text{W}$ effective isotropic radiated power for the reader, a matched antenna with $0\, \text{dB}$ gain for the tag, and free space propagations. Meanwhile, the UWB transmitter consumes $91.8\, \mu\text{W}$ instantaneous power at $10\, \text{MHz}$ pulse rate corresponding to $9.2\, \text{pJ}$ per pulse, ensuring high data rate transmission ($10\, \text{Mb/s}$) and high-precision positioning (submetre to centimetre) [39]. Low-duty-cycle packet transmissions owing to a high data rate reduce collisions, thus improving the energy efficiency and overall system throughput (greater than $2000\, \text{tag/s}$).

(iii) UWB tag with time-domain sensor interface

As discussed in the previous sections, the ADCs to sample the sensing data not only complicate the tag IC, but also significantly increase the amount of data to be transmitted. A sensor sampled at $f_s$ with $N_b$ resolution ADC requires a transmission rate at $R_{\text{data}} = f_s \times N_b$. Passive backscattering tags with a few hundred kb/s limit the quantization accuracy or sampling rate, whereas active transmitters are power-consuming. There have been a number of sensors that can easily be represented by time-domain information (pulse durations), because capacitive and resistive sensor interfaces can directly convert the analogue signal into time-domain information. Some ADCs for sensor interfaces use a time-to-digital converter to digitize data for wireless transmissions [40].

As an attractive feature of UWB, ultra-wide signal bandwidth with fine resolution in time domain provides high-precision time-of-arrival (ToA) estimations. Making use of this advantage, we suggested an ADC-free time-domain sensor interface with pulse-position-modulated (PPM) UWB signals. As shown in figure 4b, the analogue value is first converted into the time-domain wave and modulated by UWB pulses. The time interval of the pulses represents the value of the sensors which is recovered on the reader side by a ToA estimator. It eliminates the ADCs on tags and, more importantly, it relaxes the amount of bits to be transmitted from the tag to the reader. Using this approach, Bao et al. [25] presented a UWB sensor tag achieving $15\, \text{MS/s}$ sampling and transmission with $85\, \mu\text{W}$ power consumption that is nearly three orders of improvement over traditional approaches.

(d) Active RFID with hierarchical sensor portfolio

In spite of the need for battery replacement and relatively high cost, active RFID is still the primary choice for most large-scale industrial level deployments for wireless sensing and monitoring. The major reasons are the maturity for a guaranteed quality of service, and the well-established development flow for software and applications. The most popular sensor nodes commercially available include iMote2, TelosB, WaspMote and Arduino. They use off-the-shelf components with standard radio and a simple application-programming interface. An active RFID tag consists of three basic components. (i) Transceiver: IEEE 802.15.4 compliant transceivers are the most common ones, such as TI CC2420, XBee and Nordic nRF24L. (ii) Processor: the processing unit, which is generally associated with a small storage unit, performs tasks and executes the communication protocols. Depending on applications, a variety of processor cores with different trade-offs on power and performances are available, such as the eight-bit 8051, 16-bit MSP430, to 32-bit ARM Cortex M. (iii) Energy source: in addition to traditional batteries, there have been several alternatives, such as fuel cells and thin-film batteries. Moreover, energy harvesting for active RFID sensors is widely investigated [41], which extracts energy from the environment of the sensor tag, offering another important way to prolong the lifetime of the tags.

Figure 5a shows a design example of an active tag (sensor node) developed by Fudan University, China, specifically for smart packaging and food tracking and monitoring systems. It is in a credit-card-sized enclosure, with a temperature and humidity sensor, an accelerometer

2PPM UWB signal can be directly generated for time-domain sensors which use the duration of pulses to represent the sensing value.
and a magnetic stripe to detect the open/close information of the food packaging. This sensor tag is to be placed in each first-level packaging, e.g. paperboard box, and communicates with the master node (reader) installed in the cargo. The chipset of CC2530 is used to integrate an 8051 microcontroller and a ZigBee transceiver powered by a 1500 mAh soft battery. Figure 5b shows the cost breakdown of the tag, and figure 5c depicts the measured power consumption of the sensor tag. The tag works in a duty-cycle model and updates the data every minute. The operating time is 29 ms encompassing 24 ms processing time and 5 ms transmission time. The current consumption of the tag is 11 $\mu$A, 9.7 mA and 31 mA in sleep, processing and transmission cycles, respectively. The corresponding tag lifetime is more than 8 years assuming the battery capacity is automatically decreased by 15% to account for self-discharge.

The master node, with a large battery capacity, powerful processing unit, GPRS/3G module and local storages, collects data from the tag. The cost of the master node is strongly dependent on the sensors and the sensor portfolio as discussed in [6], with respect to the deployment density and sensing targets. In the prototype presented in §4, the configuration of sensors includes CO$_2$, O$_2$, C$_2$H$_4$, GPS, soil moisture and hydrogen sulfide sensors.

(e) Semi-passive RFID

Both passive and active technologies, as previously discussed in the paper, come with their unique advantages and disadvantages depending on their application scenario. For example, passive tags are ideal for high volume, low-cost tracking applications, whereas active tags have significantly improved communication ranges and auxiliary capabilities for applications such as remote sensory monitoring. To address some of the technical limitations of passive tags, such as the lack of auxiliary functions and limited read range without the high cost of active technology, a hybrid solution in the form of semi-passive RFID was introduced [42]. Instead of relying solely on passive power harvesting, semi-passive tags use the battery to supply power to parts of the tag circuitry used for encoding/decoding/processing/memory, etc. Because read range for passive RFID is mostly limited by the forward link, this significantly increases the read range for semi-passive tags (assuming comparable antenna sizes).

As far as communication performance of semi-passive tags is concerned, they are subjected to the same type of performance tests as passive tags, such as tag sensitivity and read range because they still use passive radio backscatter to communicate with the reader. Tag sensitivity defines the minimum amount of radio frequency power that needs to be present at the tag location to power up the tag, so it can transmit information back to the reader. However, for most commercial applications, a far more useful performance parameter is the communication (or read) range of the tag, which is directly correlated with the tag sensitivity.

One of the key differences between semi-passive and passive tags in terms of communication performance is how the battery helps supply power to parts of the tag circuitry used for encoding/decoding/processing/memory, etc. This means less power needs to be harvested by the tag to turn on and operate thus easing the power requirements of the forward link.
Figure 6. Forward read range for a fully passive RFID tag—P1 (a) and a semi-passive RFID tag—SP1 (b). (Online version in colour.)

Based on the ratio of antenna apertures and assuming similar aperture efficiency, we expect to see a gain difference of \((50 \text{ mm}\times 50 \text{ mm})/(50 \text{ mm}\times 20 \text{ mm}) = 2.5\), which should theoretically correspond to a read range increase of \(\sqrt{2.5} = 1.6\) for P1 compared with SP1. As shown in figure 6, P1 has a maximum forward read range around 5 m, whereas for SP1 with a much smaller aperture, the maximum forward read range is also around 5 m. These findings suggest that a semi-passive tag with a similar antenna aperture will achieve a significantly larger read range compared with a fully passive tag which supports our original observation that the battery supplied power should help improve tag sensitivity, which, in turn, increases the true limiting factor of forward read range.

The most common areas of use for semi-passive RFID tags include sensory applications where a certain environmental variable, such as temperature or humidity values across time, is measured and stored in the tag memory to be used for first-, second- and third-order supply chain logistics. First-order logistics look at the stored raw data for compliance issues, such as to see whether the cooling equipment in the transporting truck failed, or if the product temperature remained within its prescribed temperature range. Going one step further, second-order logistics involve processing raw temperature data for more useful information such as product quality and remaining shelf-life. Finally, third-order logistics further use product quality and remaining shelf-life data for intelligent supply chain decisions such as FEFO instead of FIFO to minimize waste and maximize product quality in the case of perishables. For instance, RFID in any type of perishable food logistics or monitoring agricultural products from farm to fork are applications of semi-passive RFID within this domain.

Testing sensory circuitry is similar to measuring the accuracy and performance of any temperature logger. However, compared with a general use temperature monitor, semi-passive RFID sensor tags have more uniquely defined application fields in cold chain where temperature accuracy may not be the most important criteria next to other specifications such as cost, RFID read range, product durability, etc. For instance, for semi-passive temperature tags used in cold chain monitoring and shelf-life prediction, researchers have come up with a more tailored approach to measure the real-life sensory performance with the help of context-based accuracy metrics instead of other objective measures such as root-mean-square error [43]. A more recent version of this performance metric can be generalized to both continuous and discrete shelf-life models as well as any other application involving the processing of recorded temperature data and/or other environmental variables such as humidity, gas concentrations, etc. [44].
To conclude, each RFID application naturally comes with its own unique requirements that might benefit from different technologies within the passive-to-active spectrum. In this context, semi-passive tags provide an effective trade-off between functionality, performance and cost especially when it comes to smart supply chain logistics.

4. Global fresh food tracking: an application example

Here, we present an application example of an RFID-enabled wireless sensing system deployed for fresh food tracking services [45].

(a) Architecture and operation flow of the global fresh food tracker

The sensor tags and master nodes (MSN) were deployed based on the two-layer network topology as mentioned in the previous sections. The system collects all real-time primary condition
parameters, including GPS, temperature, relative humidity, CO₂/O₂ concentration and three-axis acceleration. Furthermore, user-friendly service access tools for service registration and specification, real-time data monitoring and tracking, alarm and closed-loop controlling and reliable information sharing are provided as Web-based services running on the service-oriented architecture. The service is managed by an operation centre, which controls all the tags, MSNs and database. Services are accessible through different kinds of terminals from complicated enterprise resource planning systems to the TCP/IP network. Typical user interface comprises a Web-based data analysis and visualization tool, a Google Maps-compatible route tracking tool and a short message service-based alarming and query tool for mobile phone users.

(b) Field testing and data analysis
A six-week field test was performed for sweet melons shipped from Brazil to Sweden, including handling of the process from harvest to packaging, storage and pre-cooling to air and road transportation, shipment, distribution and finally to retail (figure 7a). During the whole transportation, the sensor tags and master nodes measured conditions in the environment including O₂, CO₂, temperature, humidity and mechanical stress such as vibrations and shocks. The measurements are stored and transmitted through the cellular network. The software at the Web server monitors and analyses the measured samples, and triggers alarms to subscribers with event time and the location.

Analysis of data in figure 7b reveals that the transportation route can be divided into four phases. In phase 1, sensor tags and master nodes were delivered to Brazil by air. Then, in phase 2, they were assembled in packages and transported by cargo truck in Brazil, where the hot and wet environment was evident. In phase 3, melons were transferred onto a container ship, where the air conditions were much better controlled by a cooling machine. Relative humidity increased slowly from 90% to 95% for the evaporation of water in melons in a well-sealed container. It took 1 day to cool the melons down to the expected temperature. It took 1 day to cool the melons down to the desired temperature, because the dense packing in a container degraded performance of the cooling unit. They were transported again by cargo truck after they arrived at a port in Sweden where the weather became much drier and cooler than in Brazil (phase 4). Damage threats are observed at T1, T2 and T3 in figure 7b. Human interferences are the main causes of these threats, such as bad maintenance of air conditions inside the container, transportation between vehicles, opening of cargo doors and shocks observed in vehicles.

5. Summary
This paper reviewed state-of-the-art technologies and future trends for RFID-enabled wireless sensing applications, including fresh food tracking and monitoring. As promising as the prospects of wireless environmental monitoring are, complete implementation of RFID for such applications is challenging in more than one area owing to technical limitations of both passive and active technologies. For example, passive tags are cost-efficient and do not require batteries to operate but they suffer from reduced communication range, relatively low data transmission rates and insufficient functionalities for sensing. Even though active tags do not have the same range and speed limitations as passive tags, they come at higher price levels and require batteries to operate. In this review, we have highlighted the research which specifically addresses and overcomes the challenges. For example, a passive tag with an active UWB transmitter was developed which displayed a more than 10 m power-up distance with a 10 Mb/s uplink data rate. High time-domain resolution UWB pulses enable ADC-free sensor interfaces and high-precision tag localization. In addition, the proposed active tag architecture reduces the power requirements of the tag to have an estimated battery life of more than 8 years. Finally, semi-passive tags act like a hybrid technology to combine the advantages of both active and passive systems in one design solution.
Networked intelligent tags with multi-functionalities will lead to RFID being considered a key element for intelligent food logistics. It is safe to say that the future trend of the RFID design will focus significantly on extending the functionality while reducing the cost to create a smart combination of heterogeneous technologies towards a better system solution. As we have reviewed in this paper, hierarchical network architecture is critical to fast adoption of novel RFID and sensing technologies while facilitating the integration of RFID solutions into networked information systems through existing ICT infrastructures.

References


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Correction


Radio frequency identification enabled wireless sensing for intelligent food logistics

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One of the authors’ names was spelt incorrectly. Qing Chen should be Qiang Chen.

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