An Overview of Passive RFID

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Abstract

This article discusses the basics of passive RFID technologies, with an emphasis on tags, for general readers and entry-level practitioners. Following a brief history of RFID, it describes the types of tags and their operation, and regulations and frequency ranges. It then presents representative applications and describes the major technical hurdles still to be overcome before the adoption of RFID can be widespread, and offers a vision of the technology's future.

Introduction

A Radio Frequency Identification (RFID) system consists of readers (also called interrogators) and tags (or transponders). A typical system has a few readers, either stationary or mobile, and many tags, which are attached to objects, such as pallets, cartons, bottles, etc. A reader communicates with the tags in its wireless range and collects information about the objects to which tags are attached. Depending upon their operating principle, tags are classified into three categories: passive, semi-passive, and active.

A passive tag is the least complex and hence the cheapest. It has no internal power source but uses the electromagnetic (EM) field transmitted by a reader to power its internal circuit. It relies not on a transmitter but on "backscattering" to transmit data back to the reader. A semi-passive tag has its own power source but no transmitter and also uses backscattering. An active tag has both internal power supply and an on-tag transmitter.

A Brief History

The concept of communication using reflected radio energy is quite old and dates back to the origin of radar technology. Many developments in the early 20th century applied radio back-scatter. For example, the Identify-Friend or Foe (IFF) transponder developed by British was used by the allies in World War II for identification of friendly aircraft. It relied on passive radar reflectors, tuned to the home radar frequency, which made a friendly aircraft much brighter to a home radar than an enemy aircraft.

Among the earliest and significant works related to RFID is the continuous time modulation of reflected signals, published by Stockman in October 1948 [1]. While working at the Air Materiel Command in Massachusetts, he designed a device that modulated human voice on reflected light signals.

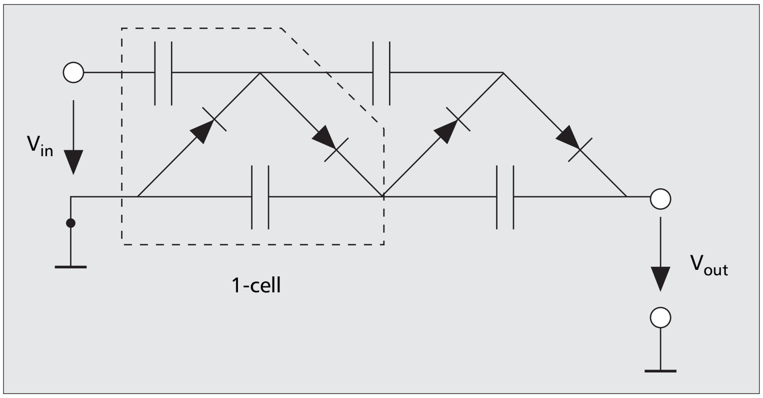
The decades of the 1960s and 1970s were marked by the research community's interest in RFID. An early breakthrough of this period was a passive RFID transponder developed and patented by Richardson in July 1963. The device could couple and rectify energy from an interrogator's EM field and transmit signals at a harmonic of the received frequency. Later in the decade, Vinding developed a simple and inexpensive interrogator-transponder system based on inductive coupling, which was granted a U.S. patent in January 1967. The transponder used repetitive tuning or loading of its antenna circuit at a rate characteristic of the particular transponder under interrogation.

Koelle, Depp and Freyman, while at Los Alamos Scientific Laboratory (LASL) in northern New Mexico, introduced the novel concept of transponder antenna load modulation as a simple and effective way for backscatter modulation in August 1975.

The first commercial application of RFID — Electronic Article Surveillance, was developed by companies such as Kongo, Sensormatic and Checkpoint in the late 1960s. Commercialization picked up in the 1980s and 1990s with varying interest in different parts of the world. Interest in the United States included transportation and personnel access, while European countries were interested in short-range systems for tracking animals, industrial and business applications and electronic toll-collection. The first RFID-based toll-collection system became operational in October 1987 in Ålesund, Norway.

The increase in commercial use of RFID prompted a need for standards, which led to many standardization activities in the 1990s. Most of these were conducted by the International Standards Organization (ISO) and International Electrotechnical Commission (IEC). ISO, a global organization to which 157 countries belong, develops industry-wide standards in a number of fields. IEC is also a global organization, but it concentrates on standards for electrical, electronics, and related technologies. Initial standardization interests were in animal tracking (ISO-11784 and ISO-11785) and contactless proximity cards (ISO-14443) applications.

The 1990s saw the acceptance of RFID as an important enabler in supply chain management, which spurred a further series of standardization activities. A milestone came in 1996 with the standardization of RFID as a data carrier by the Article Number Association (ANA) and European Article Numbering (EAN) groups. In 1999, EAN International, and the Uniform Code Council (UCC) of the United States, now both known as GS1, adopted a UHF frequency band for RFID and established the Auto-ID Center at the Massachusetts Institute of Technology. This organization was charged with developing a global RFID standard for product labeling called the Electronic Product Code (EPC). The Auto-ID Center later evolved into Auto-ID Labs and EPCglobal Inc. The latter is a nonprofit organization, set up by UCC and EAN International, pursuing the commercialization of EPC technology.



■ Figure 1. *Two-stage Greinacher half-wave rectifier [2].*

Only recently have advances in silicon technology made RFID tags cheap and reliable. Thus, the first decade of the 21st century sees the world moving toward the technology's widespread and large-scale adoption. A major landmark was the announcement by Wal-Mart Inc., in the United States, to mandate RFID for its suppliers in "the near future," at the Retail Systems Conference in June 2003 in Chicago. This was followed by the release of the first EPCglobal standard in January 2005. Till date more than 1000 Wal-Mart locations have already implemented EPC RFID standard.

TYPES OF TAGS

Without a power supply of their own, passive RFID tags depend upon the electromagnetic field of the reader. The coupled energy is rectified and the voltage multiplied to power up internal circuits. A multi-stage Greinacher half-wave rectifier or a derivative is commonly used for this purpose (Fig. 1).

Two different coupling techniques, near and far fields, are used by passive tags.

NEAR-FIELD COUPLING

The EM field in the near-field region is reactive in nature-the electric and the magnetic fields are orthogonal and quasi-static. Depending upon the type of antenna, one field (such as the electric field for a dipole or magnetic field for a coil) dominates the other. Most near-field tags rely on the magnetic field through inductive coupling to the coil in the tag. This mechanism is based upon Faraday's principle of magnetic induction (Fig. 2). A current flowing through the coil of a reader produces a magnetic field around it. This field causes a tag's coil in the vicinity to generate a small current.

Communication between a reader and a tag is through a mechanism called load modulation. Any variation of the current in a tag's coil causes a small current variation in a reader's coil due to the mutual inductance between the two, and the variation is detected by reader. A tag varies the current by changing the load on its antenna coil, and hence the mechanism is called load modulation. Because of its simplicity, inductive coupling was initially adopted for passive RFID systems.

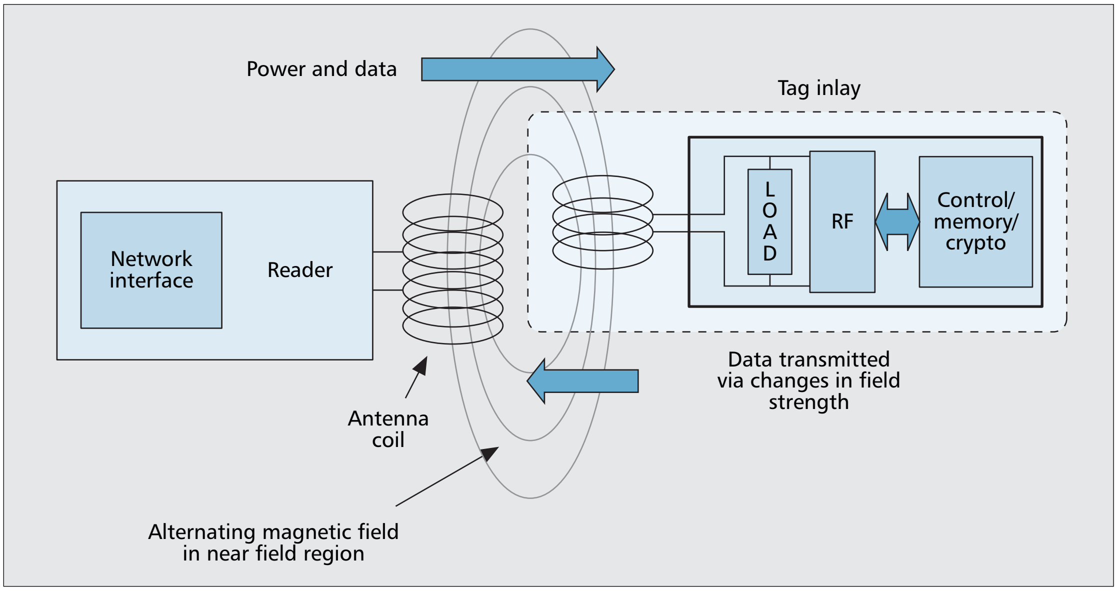
Depending upon the application, near-field tags come in many form factors. Some examples are shown in Fig. 3.

The boundary between near-field and far-field regions is inversely proportional to frequency and approximately equal to $c/2\pi f$, where c is the speed of light [3]. Therefore, only low carrier frequencies are used in near-field coupling tags; the two most common are 128 kHz (LF) and 13.56 MHz (HF). For example, the boundary distances are 372 m[1] for 128 kHz and 3.5 m for 13.56 MHz. One problem with use of low frequencies is that a large antenna coil is required. Also, the power of magnetic field of a magnetic dipole loop drops as $1/r^6$ in the near-field region, where r is the distance between a reader and a tag. Another downside is the low bandwidth and, hence, the low data rate.

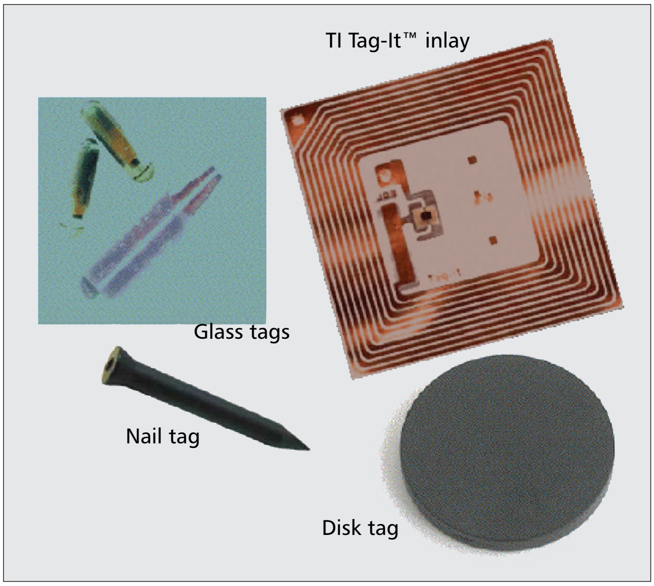
FAR-FIELD COUPLING

The EM field in the far-field region is radiative in nature. Coupling here captures EM energy at a tag's antenna as a potential difference. Part of the energy incident on a tag's antenna is reflected back due to an impedance mismatch between the antenna and the load circuit. Changing the mismatch or loading on the antenna can vary the amount of reflected energy, a technique called backscattering. Figure 4 illustrates the mechanism.

Far-field coupling is commonly employed for long-range (5–20 m) RFID, and, in contrast to near-field, there is no restriction on the field boundary for far-field RFID. The



■ Figure 2. *Near-field communication using inductive coupling.*



■ Figure 3. *Different types of near-field RFID tags.*

attenuation of the EM field in far-field region is proportional to $1/r^2$, which is smaller by orders of magnitude than in the near-field range (which is $1/r^6$). An advantage of a far-field tag operating at a high frequency is that the antenna can be small, leading to low fabrication and assembly costs. Innovative circuit designs combined with advances in silicon technology have made far-field passive tags, which consume only a few microwatts, practical.

Far-field tags usually operate in the 860–960 MHz UHF band or in the 2.45 GHz Microwave band. Various form factors and antenna shapes are used for far-field tags to meet application requirements. Some of these tags are shown in Fig. 5.

[1] *The boundary value may be too loose to be useful.*

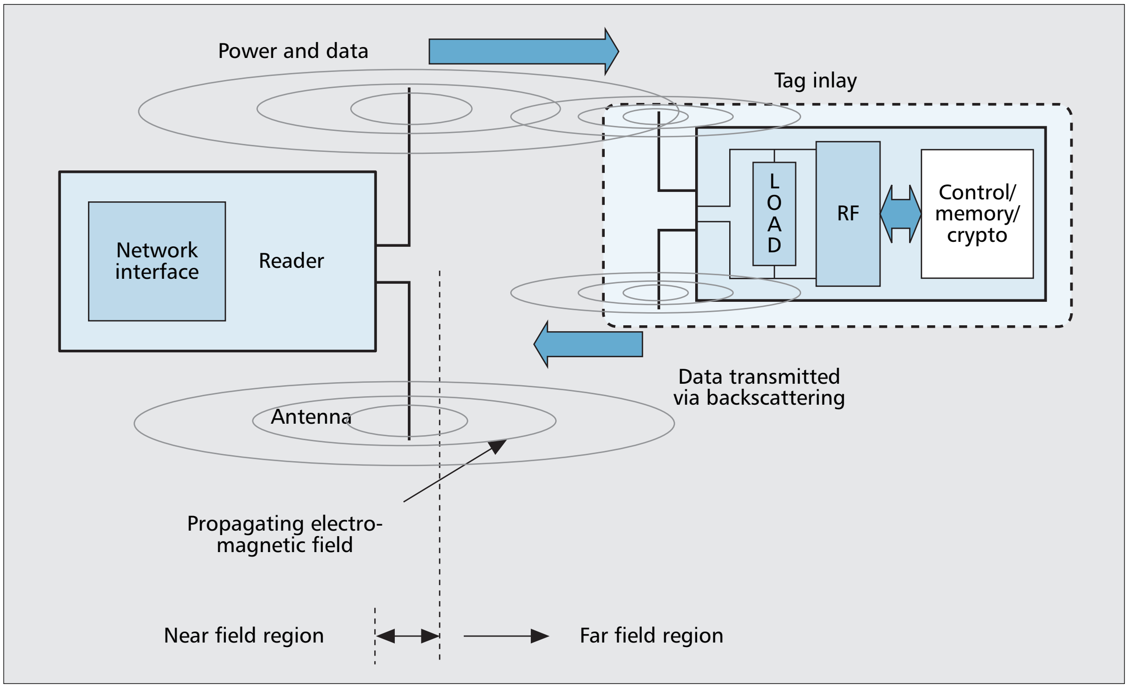
Several emerging technologies in the UHF and LF bands try to exploit advantages of both near-field and far-field tags. UHF proponents are promoting near-field UHF tags for label tagging, which has been the sole domain of HF near-field tags [4]. The advantage of using UHF here is the low tag cost, resulting from small antenna size. RuBee, a relatively new active RFID technology, operates in the LF band and employs long-wave magnetic signaling [5]. It can achieve a read range of 30 m. Long-wave magnetic signaling has a great advantage: it is highly resistant to performance degradation near metal objects and water, a serious problem for UHF and Microwave far-field RFID.

SAW Tags

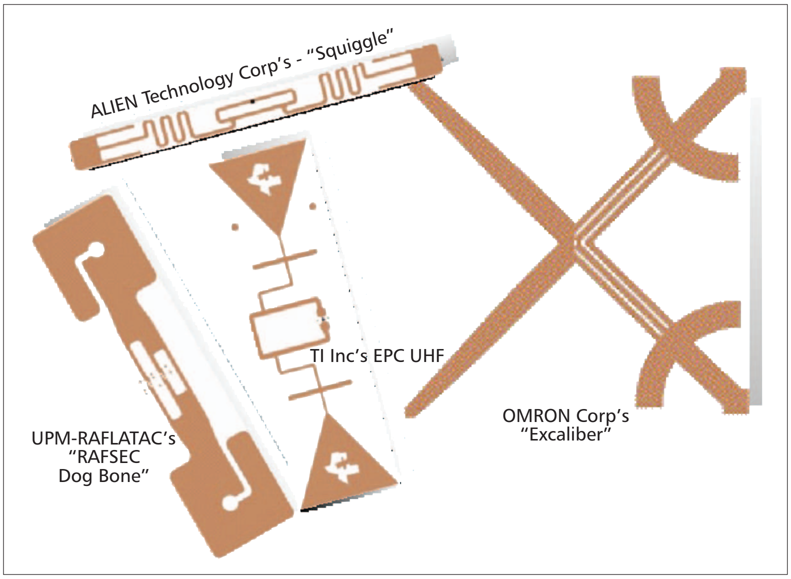
A third type of passive tag, which operates on a completely different principle, relies on surface acoustic wave (SAW) technology. The key component of a SAW RFID is an interdigital transducer (IDT), which converts a radio wave pulse into a surface acoustic wave on a nanoscale SAW chip. An IDT, which is based on the piezoelectric effect, does not require DC power for operation.

In a SAW RFID system, a reader emits electromagnetic pulses, which are converted into nanoscale acoustic wave pulses by an IDT. These pulses travel away from the IDT on the surface of the SAW chip. A set of wave reflectors on the chip produce a unique sequence of reflected acoustic wave pulses. These reflected pulses travel in the opposite direction, towards the IDT, and are converted back to radio pulses and transmitted back through the tag's antenna. The reader receives the radio pulses and identifies the ID of the SAW tag, based upon the time-gaps in the pulse sequence received. Figure 6 illustrates the operation.

SAW technology was bulky and expensive in its early days, and so received little attention. Recent advances, including device miniaturization, precision amplitude and phase weighting of reflectors, and accurate control of parasitic effects, have opened the possibility for smaller, lighter and relatively cheaper SAW tags, as compared to silicon-based RFID tags [6]. Other advantages of SAW tags are their built-in ability to measure an object's temperature and to estimate real-time location. It is also claimed that RF SAW tags can achieve a



■ Figure 4. *Far-field communication via backscattering.*



■ Figure 5. *Various UHF tag inlays [adopted from www.paxar.com].*

longer read range and greater reliability in the presence of water and metal. In spite of these possible advantages, RF SAW tags have not gained a wide acceptance.

Regulations and Standards

Performance of RFID is sensitive to the carrier frequency because of the frequency-dependent properties of an electromagnetic field. Therefore, it is important to select the right frequency band for an application. Some important frequency-dependent parameters are:

Data Transmission Rates

A higher carrier frequency can achieve a higher data-transmission rate owing to a larger available bandwidth. A higher data rate can accommodate a sophisticated anti-collision algorithm during read attempts and so support a larger population of tags for a single reader.

Reflections and Interference

Reflected and transmitted EM waves interfere, which is more severe for a far-field RFID operating at a UHF or microwave band. Destructive interference leads to nulls in the EM field, which can cause a reliability problem for far-field RFID. Interference is not so significant for near-field RFID.

Eddy Current Losses

Such losses in conducting surfaces are proportional to frequency. This means that performance degradation near metal objects is more severe for UHF and Microwave RFID frequencies as compared to LF and HF frequencies.

Absorption by Non-Conductors

Nonconductors with a high dielectric constant can cause severe performance degradation for UHF and Microwave RFID, yet have little impact on low-frequency RFID. Therefore, LF or HF tags are preferred for animal tagging or those involving humans.

A summary of RFID bands, frequency characteristics, and corresponding standards are tabulated in Table 1.

RFID tags and readers fall under *short range devices*, which normally do not require a license for operation. However, their frequency emissions are governed by regulations varying from one country to another. Currently, only the 13.56 MHz and 2.45 GHz bands are globally accepted, but the 2.45 GHz band regulations are not as uniform as for the 13.56 MHz band. Regulations for the 900 MHz band vary the most among RFID bands. However, with adoption of EPC Class-1 Gen-2 as a global UHF RFID standard for supply chain management, countries throughout the world are amending their spectrum allocations and/or opening up portions of spectrum in the UHF band for RFID. Table 2 summarizes radio regulations of representative countries and continents.

Applications

Applications of RFID are limited only by our imagination. The applications listed below by no means, cover all of them, either existing or emerging.

Supply Chain

The benefits of RFID in supply chains have been well-known for a while, but the high cost of tags has so far limited them only to box or pallet tagging. Recently, this application received a major push after Wal-Mart and the U.S. Department of Defense mandated use of passive RFID in their respective supply chains. Advantages of using RFID in the supply chain include:

- Automation of warehousing and distribution such as being able to send advanced shipping notices
- Superior tracking of goods, leading to a reduction in lost goods
- Anti-counterfeiting using embedded RFID tags to identify genuine products, and
- Improved stock management through real-time awareness of stock

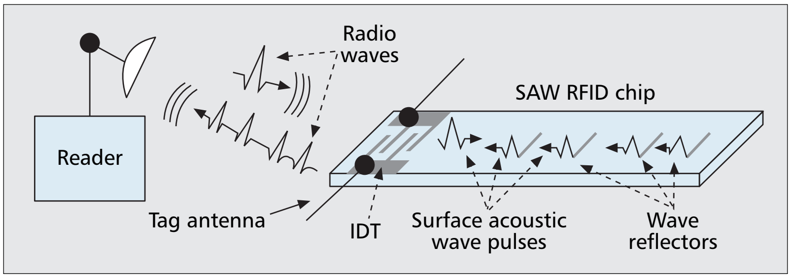
Access Control

RFID is employed here as an electronic key for controlling access to secure locations and equipment, such as office buildings and safes. Proximity cards, containing an inductive passive RFID tag, are widely used in access control systems. These cards are covered by the ISO/IEC 14443 standard, and companies usually add their own proprietary encryption layers to enhance security. Related applications include airport security, school ID cards and computer security.

Transport Payment

RFID for transport payment is used for person/vehicle identification or for recording prepaid balances. Applications include:

- Electronic vehicle tolling — such as the E-ZPass system common in the eastern United States, AutoPass in Norway, and passive tags in Argentina's Neuquen Province.
- Transit fare collection — examples include Octopus



■ Figure 6. *Operation of SAW tag [adopted from www.rfsaw.com/tech.html].*

Frequency range	< 135 KHz [LF]	13.56 MHz [HF]	860–960 MHz [UHF]	2.45GHz [Microwave]
Relevant standards	• ISO 11784 & 11785 • ISO/IEC 18000-2 • ISO 14223-1	• ISO/IEC 18000-3 • EPC class-1 • ISO 15693 • ISO 14443 (A/B)	• ISO/IEC 18000-6 • EPC class-0, class-1	• ISO/IEC 18000-4
Typical read range	<0.5 m	~1 m	~4–5 m	~1 m
Tag type	Passive-inductive coupling	Passive-inductive coupling	Passive or active	Passive or Active
Typical applications	Access control, animal tagging, vehicle immobilizer	Smart cards, access control, payment ID, item-level tagging, baggage control, biometrics, libraries, transport, apparel	Supply chain pallet- and box-level tagging, baggage handling, electronic toll collection	Electronic toll collection, cold chain management, environment monitoring
Multiple tag ead rate	Slower → Faster			
Ability to read near metal or wet surfaces	Better → Worse			
Passive tag size	Larger → Smaller			

Table 1. *Frequency characteristics of RFID systems [7].*

Cards in Hong Kong, EZ-Link cards in Singapore, and the Charlie Cards of the Massachusetts Bay Transport Authority.

E-passports

Introduced in Malaysia in 1998, RFID tags store the information contained in passports. Currently, the United States and United Kingdom are issuing e-passports.

Automotive Security

RFID is now commonplace for automotive security applications. For example, ignition keys equipped with RFID are used in most high-end cars as an anti-theft measure.

Livestock ID

Animal identification for livestock managements and disease control is important for the animal products industry. The United States is running the National Animal Identification System (NAIS), which promotes RFID for animal identification to improve animal health and to control disease outbreak. NAIS recommends button RFID tags for the purpose and considers implantable RFID as well.

Automated Libraries

RFID can be useful in streamlining library work-flow including:.
- Check-in and check-out of books
- Books inventory, performed without removing books from the shelves
- Maintaining a library inventory in real time.

The United States leads worldwide in RFID application to libraries, followed by United Kingdom and Japan. Around 30 million library items worldwide are estimated to have RFID tags attached.

Healthcare

RFID offers great benefits for the healthcare industry, which include:
- Tracking hospital personnel, equipment, and supplies
- Checking for counterfeit products
- Preventing errors in healthcare administration, and
- Maintenance of shared yet secured medical records

Hurdles to Adoption

RFID has the potential for a significant impact on many business sectors. However, a number of hurdles are holding back its widespread adoption.

Cost

The first and foremost hurdle is its relatively high cost. Three major sources of cost for tags are the IC chip and antenna, and the tag's assembly. Fortunately, the price of IC chips is dropping rapidly. Companies are also developing less expensive assembly processes, such as Alien Technology Corp.'s Fluidic Self Assembly. In fact, SmartCode Corp. announced it had broken the barrier of 5 cents per tag, in quantities of 100 million, in the summer of 2006, which was considered a significant milestone.

However, the relatively high cost of RFID still poses the major barrier for applications such as labels. RFID tags should be dirt cheap if they're to replace bar codes on small items such as 50-cent candy bars.

Reliability

Performance of an RFID system depends on several factors such as the orientation of tag and reader antennas, the material of the item to which a tag is attached, and the environment in which the system operates. Performance degradation can be severe enough in some situations to pose reliability problems. Several measures such as better antenna designs (for example, omni-directional antennas and multiple antennas orthogonal to each other) and use of back-plates to improve signal strength have improved reliability [8], but further research is necessary.

Security and Privacy

These concerns are inherent with any wireless systems, including RFID. Security concerns in RFID have been especially highlighted after many demonstrations of successful hacking of *secure* systems. A recent example is the hack of HID Corp.'s Prox cards by Chris Paget of IOActive Inc. at the RSA Conference in February 2007 [9]. Some RFID applications and standards have compromised security and privacy in favor

a. LF Band (119–135 kHz)			
USA/Canada	**Europe**	**Japan**	**China**
2400/*f*(inkHz)$^{\mu V/m}$ @ 300m	119 – 127 kHz: 66 dBµA/m @ 10 m 127 – 135 kHz: 42 dBµA/m @ 10 m	30 V/m @ 3m	P_{peak} < 1W
b. HF Band (13.56 MHz)			
USA/Canada	**Europe**	**Japan**	**China**
13.553–13.567 MHz 42 dBµA/m @ 10 m	13.553–13.567 MHz 42 dBµA/m @ 10 m	13.553–13.567 MHz 42 dBµA/m @ 10 m	13.553–13.567 MHz 42 dBµA/m @ 10 m
c. UHF Band (860-960 MHz)			
USA/Canada	**Europe[1]**	**Japan**	**China**
902 – 928 MHz $P_{e.i.r.p.}{}^{2}$ = 4W	865.0 – 868.0 MHz $P_{e.r.p.}$ = +20 dBm 865.6 – 868.0 MHz $P_{e.r.p.}$ = +27 dBm 865.6 – 867.6 MHz $P_{e.r.p.}$ = +33 dBm	952 – 955 MHz $P_{e.r.p.}$ = 1 W +6dB antenna gain = 4 W	840.5 – 844.5 MHz $P_{e.r.p.}$ = 2 W 920.5–924.5 MHz $P_{e.r.p.}$ = 2 W (Available since May 2007)
d. Microwave Band (2.45 GHz)			
USA/Canada	**Europe**	**Japan**	**China**
2.400 – 2.483 GHz $P_{e.i.r.p.}$ = 4W	2.446 – 2.454 GHz $P_{e.i.r.p.}$ = 500 mW or 4 W (indoors)	2.400 – 2.4835 GHz 3 mW/MHz(Pe.i.r.p. = 1 W)	2.400 – 2.425 GHz 250 mW/m @ 3 m (Pe.i.r.p. = 21 mW)

[1] Listen-before-talk for 200 kHz channels. [2] Equivalent isotropically radiated power (e.i.r.p) = 1.64 × Effective Radiated Power (e.r.p.)

Table 2. *International telecommunication union frequency regulations.*

of low cost, consequently making them prone to counterfeiting, illicit tracking and information leakage.

A conventional approach for secure RFID is to encrypt the tag ID [10]. It is difficult for this approach to incorporate full-strength keys because there is not enough energy for powering up encryption circuits. Another approach is to secure the communication between a tag and a reader by employing asymmetric modulation schemes, narrowband for power-up and ultra wideband (UWB) for communication [11].

System Integration

A large-scale RFID system, especially for some applications such as supply chain management and luggage tracking, makes the integration process complicated. It involves integrating new data into the system as it is obtained and using the accumulated information for greater efficiency. The process is further complicated by lack of a single industry-wide standard for both hardware and software. The EPCglobal Inc. standard eases adoption of RFID for supply-chain management, but evolving standards still pose a major inconvenience for existing users.

To ease the problem, many vendors like Sybase Inc., headquartered in Dublin, Calif., are developing RFID middleware, which link new RFID systems into existing back-end infrastructures.

Vision for the Future

With the current level of progress in RFID, IDTechEx forecast that the RFID market would rise to $28 billion in 2017 [12]. Foreseeable technological developments, which will further expand RFID applications include:

Printed Electronics

To reduce cost, printed RFID tags using non-silicon or polymer-based semiconductor technologies have been investigated extensively, and RFID based on polymer semiconductors was demonstrated at 13.56 MHz [13]. However, polymer semiconductors have drawbacks such as the availability only of PMOS transistors, a low cutt-off frequency (f_T) of 300 kHz, and an extremely low threshold voltage of –20 V [14]. Further advancements in non-silicon-based semiconductors may make future RFID tags dirt cheap.

Localization Capability

Tracking assets such as medical doctors and instruments requires being able to localize each tag. The most common method involves triangulation, in which distances from known reference readers are measured. Alippi et al. achieved accuracy of 0.6 m using a Bayesian statistical method based on readings collected from multiple RFID readers [15]. The accuracy may be improved with tags employing UWB. Further research on the localization of tags is expected to improve accuracy over greater distances.

Integration of Sensors

RFID tags with built-in sensors can open up a wide range of new applications such as temperature monitoring, care giving for the elderly, and personal activity-based prompts. A key requirement is low power sensors (as well as tag circuits) that can be powered from the energy harvested from the radio wave of a reader or scavenged from the ambient. Various low-power sensors have been investigated for integration with RFID.

ENERGY SCAVENGING

Scavenging enables passive tags to assume the benefits of active tags. Energy can be scavenged from ambient heat, light, radio waves, and mechanical vibration. Energy scavengers can harvest energy in the range of a few tens of a microwatt to a few hundred miliwatts [16]. Efficiency and miniaturization of energy scavengers are important issues, and intensive research is ongoing. The amount of energy scavenged from the ambient is critical. It is often the deciding factor for the types of sensors that can be selected, and their performance.

CONCLUSIONS

RFID finds relatively limited applications these days, and must overcome many technical hurdles for wide acceptance. However, none of these hurdles seems to pose a fundamental barrier, and it is evident RFID will soon be pervasive in our daily life. We envision that RFID has the same potential as the Internet. As the Internet has affected everybody's life and impacted every business sector, so may RFID in the near future. It is only our imagination that limits how and where RFID is going to be used, and it is exciting to witness how RFID will unfold its great potential to revolutionize society.

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BIOGRAPHIES

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