Radio Frequency Identification

Michael Goshey
Department of Computer Science and Engineering,
University of Minnesota

SYNONYMS
RFID; RF Identification; Electronic Identification; Radio Tagging; Electromagnetic Tagging

DEFINITION
Radio Frequency Identification (RFID) exists as a distinct subset of the larger family of automated identification technologies that includes things like bar codes, visual scanning devices and biometric readers. RFID is a means of automated identification that features electronic tags used both to store data and to act as transponders for sending the stored data as the payload in electromagnetic waves (radio waves) sent to detached listening devices (RFID readers) [8] [25]. The tags can be affixed to animate or inanimate objects by a variety of methods and the readers that receive emissions from the tags translate the wave-embedded data into meaningful information (Figure 1). They are a significant improvement over bar codes, for example, in that they do not require any human intervention. Currently deployed RFID systems provide real-time identity tracking and monitoring and make possible a wide variety of access control and inventory management solutions [23] [16] [14]. Beyond this primary value of real-time identification monitoring, the back-end of a typical RFID solution offers a distinct secondary value through storing the rich set of identity data captured by the system, enabling sophisticated data mining techniques to be applied to a number of interesting scenarios [1]. Additionally, while RFID systems primarily deal with automating identity management they are frequently deployed in combination with Geographic Information Systems (GIS) to yield even more powerful solutions that track both identity and spatial location [2] [13].

![Figure 1: Simple system diagram of grocery store point of sale RFID](image)

HISTORICAL BACKGROUND
While the practical application of Radio Frequency Identification has grown tremendously in recent years the technology has a long and interesting history.

1920’s - 1940’s
The seminal paper in the field is considered by many to be *Communication by Means of Reflected Power* by Harry
Stockman in 1948 [15] which proposed the key RFID notion: power generated at the base (often fixed) end of a point-to-point electronic communication pair is reflected and reused in order to power the return transmission from the remote (often mobile) end of that pair. Stockman’s paper echoed work that was already being done in radar to track the location of an object through the use of reflected radio waves which began in the early 1920’s [8]. The 1930’s and 1940’s saw steady development in both the radio and radar fields paving the way for Stockman’s work which was also reflected in the progress of another prominent technology of the era- Identification Friend or Foe (IFF) systems [21]. IFF systems employed transponders in attempts to avoid ‘friendly fire’ situations and were early predecessors of today’s air traffic control systems. They were utilized during World War II to gain military advantage by identifying the allegiance of approaching aircraft before visual confirmation was possible [3] [8].

1950’s - Present
The 1950’s saw the first work combining microwaves with RFID [22]. In the 1960’s and 1970’s the field gradually advanced on multiple fronts: academic research, patent activity and commercialization [8]. There were a number of patents related to remote measurement, communication and activation using radio frequency power, perhaps the most well-known of which was Charles Walton’s 1973 patent for keyless door entry using passive RFID [24]. This was an especially important year for RFID as it also saw the first patent dealing with active RFID systems where tag memory could be rewritten and updated [20]. A couple of years later a landmark paper was authored by a group at Los Alamos [7] where work was being conducted on animal tracking and automated vehicle control systems. Large companies such as Phillips, Westinghouse, Raytheon and General Electric were ramping up work on shipping, transportation and factory automation systems based on RFID-related technologies. Automated toll-collection systems were in place both in the United States and in Europe by the mid-1980’s and ultra-high frequency (UHF) RFID was developed in the early 1990’s by IBM [20]. A team from MIT sponsored by Gillette and Procter & Gamble later carried UHF-based RFID further applying it to low-cost supply chain management applications that featured dumb tags containing only identification numbers rather than rewritable memory. Finally, in recent years it has been mega-merchant Wal-Mart (along with fellow retailers Target and Tesco and the U.S. Department of Defense) that has had perhaps the most influential hand in pushing RFID to the forefront of the global technology landscape [14]. Recent mandates by these large organizations to convert all of their vendors and suppliers to RFID-based supply chain management systems have impacted entire industries while raising significant concerns over the potential intrusiveness and other privacy drawbacks now associated with RFID [12] [9].

SCIENTIFIC FUNDAMENTALS
A good first step toward understanding a Radio Frequency Identification system is to inspect its primary components. RFID systems are supported through a network of application software, middleware and computing resources. While these play a role in the overall delivery of RFID and are perhaps specialized for this purpose they are not unique to the RFID domain. However at the center of these general actors are several RFID-specific components: tags, readers and label printers [19] [18].

Tags
RFID systems exist for the purpose of capturing information about entities of interest (i.e. things one wishes to identify, track and monitor). In an RFID environment this information is stored on electronic tags. An RFID tag is simply a silicon microchip bundled with an antenna and attached to an entity of interest (Figure 2). Not surprisingly the chips store identifying data such as unique serial numbers and other information required by the ID system. The tags act as transponders receiving and responding to radio signals to and from RFID readers. RFID has some distinct advantages over bar code technology including the ability of tags to function without line of sight and the ability of readers to process hundreds of chip reads virtually simultaneously. There are three main types of RFID tags: Passive, Active and Semi-Passive.

Passive Tags Passive RFID tags do not have their own power supply. They harvest necessary power from the electromagnetic fields emanating from the incoming radio wave transmissions they receive from RFID readers. As transponders they ‘awake’ on demand by the reader’s signal and induce a small current in the on board antenna to power-up the internal (CMOS) microchip and send back data to the reader. The term ‘backskatter’ is used to describe the process by which the tags reflect the signals they receive from readers as their message-
laden reply. The reflected signals are modulated variations of the signals that are received and therefore produce meaningful data—the difference between the original and the (modulated) variant. Today’s chips hold up to about two kilobytes of data, enabling the storage of rich information about the tagged entity. Because passive tags do not require on-board batteries they have a significantly longer life expectancy than active tags, can be made much smaller and are therefore cheaper to produce. Unit costs vary with capabilities and purchase volume but the lowest cost passive tags currently sell for about twenty U.S. cents per unit in high volume purchases. New non-silicon (polymer) roll-printable tags are currently being prototyped and these should further reduce the manufacturing cost. Typical sizes range from postage stamps to postcards though the smallest passive tags are thinner than a standard piece of paper and approximately three millimeters across and therefore can be inserted under the skill of animals and people or fit nicely on a sticker or paper label (Figure 3). The lack of internal power creates a limitation on broadcast distance—passive tags are generally used for short distance transmissions (under 10 feet). Passive tags are typically write-once-read-many (WORM) devices, meaning that their memory cannot be overwritten.

**Active Tags**  Unlike their passive counterparts that employ backscatter to send message replies to readers active tags have an internal transmitter that allows them to send waves under their own power and conduct what amounts to ‘sessions’ with readers. Most have on-board batteries though some use solar and other power supply options to harvest energy to power the transmitter. The resulting larger form factor and higher cost is offset by the distinct benefit of being able to transmit stronger signals, useful in situations where required read distances are much further as well as in environments that are difficult for passive tags to function well (such as those high in metals or water). Active tags often have readable ranges of hundreds of meters and vary in price from a few dollars up to twenty dollars or more per unit. Life expectancy of active RFID chips tends to be based on battery life and is typically up to 10 years. In addition to environments that challenge passive tags, active RFID tags are often used to track valuable assets. They usually have more data storage capability than passive tags and
may also provide read-write capabilities so that internally stored data can be updated and changed. Active tags are frequently combined with environmental sensors to produce sophisticated monitoring devices that can, for example, track a product in its shipping route while monitoring the temperature and other conditions in which it is being transported.

**Semi-Passive Tags** Semi-passive tags are a hybrid of active and passive tags. They have on-board battery power like active tags but they use backscattering to reflect radio waves back toward the readers that produce them rather than transmitting their own message broadcasts. The battery is used to power the microchip and (optionally) environmental sensors. While their versatility exceeds that of passive tags they are cheaper than active tags and their low battery consumption means they live longer.

**Readers**

In an RFID system the readers are the components that directly communicate with and fetch data from tags. Readers may be stationary or mobile (Figure 4) and have one or more antennas which broadcast signals to nearby tags, querying information stored in the embedded chips as well as (occasionally) from on-board sensors. Agile readers are highly functional and can read tags at different frequencies and use multiple communication protocols in communicating with various tags. Some readers (especially those in the ultra-high frequency range) can have a 'null spot', a blind-spot of sorts for an RFID reader. There are two primary types of RFID readers: **read-only** and **read-write**. As implied by the name the former class are limited to reading and extracting data from tags. Some in this category are referred to as 'dumb' due to limited computing capabilities. Dumb readers convert the radio waves they receive from RFID tags into binary values and simply forward the converted values to a server for processing of actual business logic and filters. Unlike read-only devices, the latter class of readers can read from RFID tags as well as write to them. The roles of read-write readers include initializing chips on new WORM tags and writing to updateable chips during RFID transactions.

![Mobile RFID reader with tags in foreground. (Source: PM J-AIT)](image)

**Air Interface Protocol**

In any field the work of establishing and refining protocols and standards is long term and ongoing. An area of obvious focus in RFID is the communication between readers and tags. Whether articulating the differences between **tag talks first** (new tags crossing a reader’s threshold ‘announce’ themselves to the reader) and **reader talks first** (readers initiate contact with tags by sending out inquiries to all listening tags) protocols, following mutual encoding rules, establishing system commands for reading and writing data or knowing the rules for how tags should modulate responses back to readers, the standards and protocols are critical to the success of RFID. Among the many standards governing the RFID industry the air interface protocol provides specific directives concerning the communication between readers and tags. As of July 2006 the new 'Gen 2' air-interface protocol was incorporated into the ISO 18000-6 standard [10].
Singulation and Anti-Collision  One of the specific technical challenges of RFID readers is identifying unique tags amongst many tags within a given read field and being able to gracefully handle the resulting collisions from simultaneous radio responses by multiple tags (singulation). This is a common problem in environments such as warehouses and grocery stores where RFID readers routinely have hundreds of tags within close proximinity. One commonly used singulation protocol is known as ‘tree walking.’ The RFID reader logically traverses a binary tree in a recursive, depth-first algorithm. Each node has only two children: 0 for the left subtree and 1 for the right subtree (the root node is considered empty). The reader broadcasts each successive bit sequence (i.e. tree node label) to all of the tags within its range instructing only those tags with serial numbers matching the broadcast sequence to respond (by providing their next serial number bit)- the rest of the tags remain silent. When collisions result between responses from both the left and right subtrees of the broadcast node the reader detects the collision and interprets it as a requirement to descend into both subtrees (recursively and sequentially). The algorithm ensures that the reader descends into every required subtree (i.e. those containing currently present leaf nodes). As the reader recurses through the tree it captures the leaf nodes bit strings resulting in a list of all (binary) serial numbers of the individual tags in its range [6]. Though it is widely used the tree-walking protocol exposes RFID systems to substantial threats of privacy and security. The identify of tags within range of the reader can be deduced by eavesdropping on only one side of the electronic conversation (the reader side) and the longer broadcast range of readers enables such eavesdropping to be conducted at distances well beyond the range of the tags themselves.

Label Printers
The RFID industry distinguishes between tags and labels: transponders mounted to a substrate for the purpose of attaching to a carton or other surface are considered RFID tags. Transponders with the smallest (thinnest) form factor that are bound with adhesive between paper in order to be used in labels are called RFID labels. RFID label printers are highly specialized printing machines that output ‘smart’ labels which combine bar code printing technology with RFID. The printers simultaneously print bar codes on the front of the labels while writing (related) data to the on-board chips of RFID transponders embedded between the sheets of label paper (Figure 5).

Figure 5: Smart label printer combining bar codes and RFID tags. (Source: DLA)

KEY APPLICATIONS
RFID is broadly utilized across a wide array of identification systems addressing such problems as inventory control, tracking and supply chain management, passport, currency and border control, transportation access and automated fare/toll collection, hands-free ski lift access, bovine control, wildlife tracking and pet identification, building access control, performance monitoring and sensor reading, prisoner tracking, hospital bed management and crime (theft, tampering, counterfeiting) deterrence. The technology has become ubiquitous in modern society and is embedded in the products sold by mass retailers, the currency and credit cards used for payment, vending machines, library systems, warehouse pallets, airline baggage handling machines, automobile tires, keys, sports match timing devices, animals and people.

Inventory Control
In 2003 mega-retailer Wal-Mart single-handedly initiated a major industrial trend when it announced it would be requiring top suppliers to implement RFID technology for inventory management. Others were quick to follow the world’s largest company down the RFID path including the Department of Defense, Target Stores, Best Buy, Kroger, Circuit City and others. Prior to this one of the biggest obstacles to adoption was the relatively high cost of producing tags but by throwing its (unparalleled) business volume behind the technology Wal-Mart played a significant roll in driving down cost and ensuring RFID’s long term viability. In inventory management systems RFID tags are affixed to pallets, boxes and even individual products to facilitate inventory tracking with little required human intervention. For example entire cartons of products can be added to the inventory pool without requiring they be scanned individually or even removed from the box. In the long term RFID may also be used to track the movement of products through stores. Though Wal-Mart has lagged behind its original goal of having its 100 top suppliers converted by January 2005 it continues to push ahead and recently announced it would double the number of its stores that have implemented RFID and that the number would reach 1000 locations by the beginning of 2007 [17].

Supply Chain Management
Wal-Mart’s entry into RFID in the retail space was echoed by a similar move at the U.S. Department of Defense (DOD) to transition its supply chain management structure to an RFID-based system. Over the past several years the DOD has implemented RFID on a broad, international scale across its operations. One of the interesting RFID issues in supply chain management is tag ownership. Unlike in-house applications where a single entity invests in and maintains a set of tags for RFID, a supply chain by definition contains many actors and goods pass through many boundaries of ownership and control as they traverse the chain from source to destination. In such an environment tags simply become part of the shipping material and are rarely recycled or reused by the originating party. These are precisely some of the requirements driving tagging technology toward extremely low cost tags that can become as ubiquitous and disposable as bar codes are today. Tag disposal and recycling are related concerns that take on new meaning in such cooperative systems. Finally, just as the lines of tag ownership blur in supply chain applications so too does the ownership of technology standards. Privately controlled proprietary standards do not meet the requirements of systems punctuated by repeated hand-offs from one party to another. Applications such as supply chain management will compel the state of RFID technology to continue to move toward open industry standards.

Passport, Currency and Border Control
Another key RFID application is in the area of protecting national assets such as passports, currency and physical borders. RFID passport control systems already exist in many countries. The U.S. has had an off-again on-again relationship with passport-embedded RFID but as of October 2006 is now issuing all new passports with ISO 14443 RFID tags. Security is an obvious and critical requirement for such systems yet this is an area where RFID has struggled. In the Netherlands in early 2006 the Dutch security company Riscure demonstrated a successful compromise of a Dutch RFID-passport based on the same ISO standard [11]. Even human-embedded RFID tags have been unable to escape security controversy. In July of 2006 hackers at a conference in New York City demonstrated the cloning of an ‘uncloneable’ implanted RFID chip and successfully fooled the RFID reader concerning the identity of the bearer [4]. Another area of broad concern has been the tracking of national currencies for the purposes of reducing fraud and criminal enterprise. While the complete materialization of a plan may be years away there has been a great deal published in both academia and industry on the specter of embedded
RFID tags in European currency [5]. Finally, while contact-less toll collection systems have been in place for many years they are now being applied to certain border crossings between the US and Canada. Completely automated border security may not be realistic but in such cases RFID is facilitating speedy identification of those wishing to pass national boundaries.

FUTURE DIRECTIONS
As seen in the previous section radio frequency identification is a technology with seemingly limitless potential for future growth. When combined with GIS that landscape of future possibilities appears to grow without bound. Systems are being pioneered and developed today that bring the two technologies together in interesting ways such as wildlife management, military field training and exercises, monitoring of children through embedded RFID/GIS devices in school bags, automated manhole monitoring and intelligence, remote forestry management, election support and targeted voting campaigns, ‘pervasive retail’ and ‘smart’ environments that are aware of and respond to entities passing through them. However as RFID and GIS converge with other technologies such as bar coding, digital cameras and biometrics, security and privacy concerns will continue to grow. Issues such as data privacy and identity theft, RFID tag blocking, data leaking and RFID viruses will grow in prominence and public awareness. RFID’s impact on the environment in such areas as device disposal and increased radio wave transmissions will likely become a major area of emphasis, as will increased efforts toward further standardization of worldwide RFID systems. Finally, one would expect that as systems begin to mature and require less break-fix attention the systematic mining of considerable amounts of newly captured data will likely become a major area of increased research and emphasis.

CROSS REFERENCES
This section to be completed by the Encyclopedia editors.

RECOMMENDED READING


