The Evolution of RFID Networks: The Potential for Disruptive Innovation

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March 2006

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Executive Summary

RFID technology has generated much hype in the last few years. The major driver for its development has been the tagging of physical objects – people, places, and things – with single chip radios so they can interface with computers.

While the technology has been available for several decades, the 21st century has marked the beginning of a new era in RFID development and usage. The efforts of EPCglobal have dominated RFID application growth, creating a global infrastructure that is focused on improving supply chain management. Its supporters, including big players like Wal-Mart in the U.S. and Metro in Europe, treat RFID as a technology that will sustain their market power through incremental innovation. However, the scope and style of RFID technology extends far beyond this key initiative.

This paper examines several key trends in the latest phase in RFID's history. First is the evolution of standards for the various components of an RFID system including the transmission technology (the "RF" part) and unique identifiers (the "ID" part). Efforts to standardize the various components of an RFID system are leading towards interoperable RFID technology and applications. Key initiatives include ISO standards and the EPCglobal Network.

Second, while dedicated RFID systems will continue to develop, we will see more RFID applications exploit the growing base of short-range radio-based communication networks like Bluetooth and WiFi that have thus far evolved independently of RFID technology. More intelligent – and more expensive – active RFID chips are required for these types of applications (compared to the envisioned 5¢ EPC passive tag for example), but they involve far fewer objects than the supply chain and enable richer and higher revenue-per-transaction services.

Third, despite the important advantages RFID offers over light-based systems, there are cases where some of the newer optical tagging systems could compete with RFID. This is particularly true for consumer-oriented applications involving mobile phone readers where cost and ease of use factors outweigh RF's performance advantages.

Lastly, both RFID and other tagging technologies are making their way to the edges of the network and into the hands of end-users, significantly increasing the potential for disruptive rather than incremental innovation. We anticipate the development of grassroots projects that would provide a counterbalance to more centralized efforts such as EPCglobal.

INTRODUCTION

RFID technology has generated much hype in the last few years. The major driver for its development has been the tagging of physical objects – people, places, and things – with single chip radios so they can interface with computers. RFID technology is both hailed as the key to the "Internet of Things," and condemned as invasive surveillance technology, and in more extreme circles it is feared as the Mark of the Beast.

While the technology has been available for several decades, the 21st century has marked the beginning of a new era in RFID development and usage. In North America, the efforts of EPCglobal have dominated RFID applications growth, creating a global infrastructure that is focused on improving supply chain management. Its supporters, including big players like Wal-Mart in the U.S. and Metro in Europe, treat RFID as a technology that will sustain their market power through incremental innovation. However, the scope and style of RFID technology extends far beyond this key initiative. This paper examines the latest phase in RFID's history including the establishment of the EPCglobal standards body, and other initiatives in tagging technology that collectively, are expanding the RFID roadmap beyond the EPC thrust and may lead to more disruptive scenarios.

Identity tagging development is proceeding on multiple fronts. First, standards are evolving for the various components of an RFID system including the transmission technology (the "RF" part) and unique identifiers (the "ID" part). Second, outside the realm of dedicated RFID systems, short-range radio-based communication networks like WiFi and Bluetooth have emerged which are increasingly used in RFID applications. Third, optical tagging solutions (using light rather than RF as the transmission medium) may compete with certain RFID applications, particularly those aimed at consumers. Lastly, both RFID and other tagging technologies are making their way to the edges of the network and into the hands of end-users, significantly increasing the potential for disruptive rather than incremental innovation.

Before examining these trends and their implications in more detail, we will review the basics of RFID technology.

RFID TECHNOLOGY OVERVIEW

An RFID system can be broken down into two key dimensions. The technical infrastructure includes the actual data capture technology comprised of tags, readers, and transmission medium. The logical infrastructure refers to the overall identification (ID) scheme used in representing objects. The ID scheme includes the actual coding or naming system for objects, the database or registry that contains the information relating to the codes or IDs, and lastly an ID resolution mechanism for matching the ID data with object information.

The logical infrastructure of an RFID system

In a typical RFID application, tag data acts as a reference to more detailed information about the tagged object. Unique identifiers (or codes) resolve to information stored in databases, similar to how a license plate works. This model is based on the principle of moving intelligence (and therefore cost and complexity) off the tag and onto the network. Storing all required data about the object on the tag itself can be expensive and therefore limited to applications that involve tagging fewer, high-value items, whereas the license plate model serves applications that require mass production of chips (e.g., supply chain applications) and/or those that require microscopic tags.

Just as there are many license plate numbering schemes, there are many different coding systems used in RFID applications. Many of these are proprietary; others are based on more open standards. Some RFID applications use codes specially created for a new service while others might use existing numbering systems, like an ISBN or UPC for example, which are simply encoded and stored on RFID tags instead of barcodes.

For every set of codes there exists a database or registry that contains the records that match the IDs. In a toll collection system for example, the vehicle's transponder transmits a unique ID that refers to the user's account information. A pet's RFID tag will call up the owner's contact information when entered into the system's database. Each database of objects in these examples comprises a unique naming context or "namespace," and is owned and controlled by the RFID service provider.

In some cases the tag ID is actually a pointer to the Internet address of the associated database. In other words, the unique identifier resolves to an IP address, like a URL. In these cases, ID resolution becomes a separate service. RFID applications that use Internet pointers are discussed further down.

Not all tags store codes that require ID resolution. While many applications require the "dumb tag/smart network" approach described above, others will store complete data on the tag. Before the Internet, many of the older RFID applications stored all information on the tag. Some of today's applications do the same. The Surgichip, for example, works like an electronic Post-It note.[1] The 1" x 2" tag is programmed with all critical information pertaining to a procedure, e.g., date, patient's name, site of surgery, the exact procedure to be performed, and the surgeon's name. The tag can store up to 256 characters, and if more space is needed a second tag is used. The tag is stuck to a patient's skin prior to surgery, near the area of the body where the surgery will take place. Tags are scanned with a handheld reader before the surgery begins to confirm that the correct procedure is being performed on the right patient. The information is printed out in typed script to avoid problems with illegible handwriting. (Doctors reportedly make 5-8 surgery errors, like the wrong limb or the wrong patient, per month.)[2]

In the case of library systems, vendors are moving toward adding the book title, author, borrower's name and card number, etc. to RFID tags (in addition to the call number) as a security measure. If the system goes down and back-end database systems are inaccessible,

the books can still be processed off line. Transactions are later synched to back-end systems.[3]

The technical infrastructure of an RFID system

The technical infrastructure comprises a radio transponder and receiver, more commonly known as a tag and reader. Information related to a given object is stored on an affixed tag and transmitted to a reader over a radio frequency (RF) connection. The reader in turn connects via wired or wireless networks to servers hosting RFID applications that make use of transmitted RFID data, and, in the case of supply chain applications, middleware manages the flow of RFID data between readers and enterprise applications. Figure 1 shows the key technical components of an RFID system.

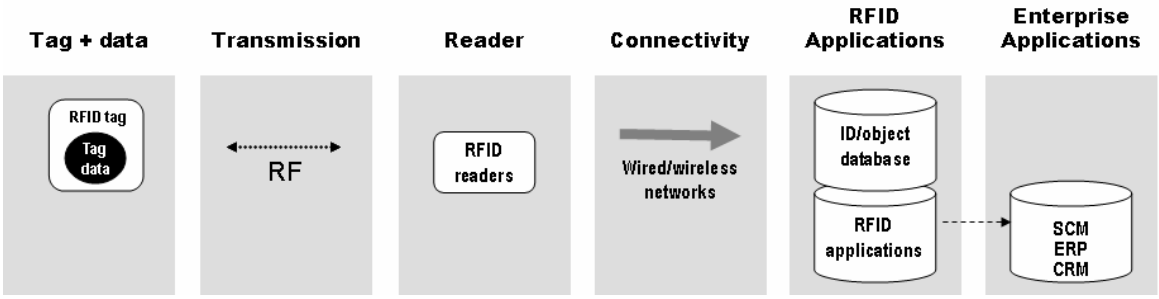

Figure 1: Key technical components of an RFID system

RFID Tags

Tags contain a microchip and a transponder. The microchip stores data related to the object and the transponder transmits that data to readers. Tags are initially programmed (data is written to the tags) at the point of manufacture (factory programming), but can also be programmed by an OEM or end user (field programming). Tag data usually includes a unique identifier code and sometimes additional information, depending on the application and the amount of memory on a tag.

Tags are either passive or active. Passive tags are smaller -- about the size of a grain of rice, and getting smaller. They are activated when they enter the range of a reader's signal. The reader's antenna sends power to the transponder, activating the data stream. (Semi-passive tags have a battery that runs the circuitry of the chip, but does not power transmission of data to the reader.) Passive tags are much smaller in size and memory than active tags, and cheaper to manufacture. Passive tags currently cost about 50 cents, although with mass adoption of RFID, the goal is to eventually produce a 5-cent tag. In October 2005, Smartcode Corporation announced a 7.5-cent tag, when produced in volumes of 1 million, and 7.2-cents for orders of 10 million or more.[4] As discussed above, passive tags are most suitable for supply chain applications that require billions of tags with small amounts of memory.

Active tags are larger than passive tags, about the size of a small coin, and cost $20-$100 each, depending on volume. They contain their own power source, thereby constantly transmitting their signal up to several hundred feet, compared to a passive tag's read range of a few inches to a couple of meters. Active tags are therefore more appropriate for items that are high in value and/or are tracked from a distance, like rail cars and shipping containers. Active tags can also be rewritten or reprogrammed by readers, whereas most passive tags are read-only.

Sensors can also be integrated with an RFID tag for more dynamic information, for example, the tag on an automobile tire may integrate data from temperature and pressure sensors for remote monitoring.

Tags can be printed on paper or plastic and attached to an object, or they can be embedded under the skin of animals and humans. (In one more creative experiment they were *eaten* by pigeons, which then activated a network of closed-circuit cameras throughout an urban area as they flew by.[5])

RF Connection

Tags transmit data to readers over different radio frequencies, depending on the application needs. RF frequencies are dividing into several bands including low frequency (LF), high frequency (HF), ultra-high frequency (UHF), and microwave. Passive tags transmit at all frequencies while active tags transmit at higher frequencies only (those in the UHF and microwave bands). The exact frequency that can be used within the various bands, as well as power (output) levels, are controlled by the regulatory body of each country.

Each frequency varies in terms of regulation, performance (range, bandwidth, output), and the size and cost of the associated technology. Over the last few decades, RFID solutions have emerged around only a few frequencies, each of which optimizes these variables to meet the needs of the different application types (see Figure 2).[6]

RFID Readers

Readers are larger, more complex, and more expensive pieces of RFID hardware compared to tags. The typical fixed readers used in supply chain type operations cost $1,000-$3,000. With mass adoption, the goal is closer to $10-$100 per reader.[7] Mobile handheld readers cost a few hundred dollars, and are being used increasingly in supply chain operations. Wal-Mart recently announced that it was exploring readers embedded in forklifts that would replace reader portals, as well as wearable readers that employees would attach to their belts.[8] Consumer-oriented readers are also appearing on the market, particularly in Japan. For example, specialized PDAs called "ubiquitous communicators" are being tested for use in several consumer applications.[9] RFID readers embedded in cell phones are also becoming increasingly common – also primarily in Japan at this time -- enabling a variety of mobile services including information and marketing applications, and tracking children, elderly friends and relatives, patients, etc.

The reader captures the information transmitted by a tag, decodes it and delivers it to a host computer for ID resolution (if applicable) and further processing. Some readers come with "write" capabilities, meaning they can add or change (reprogram) the data on a tag. Readers have traditionally connected to the host computer over wired networks, but some of the newer readers will use Bluetooth, WiFi, or WiMax connections to transfer data to servers. For example, the IDBlue is a handheld Bluetooth-enabled RFID reader that connects to the RFID application server via a Bluetooth connection.[10] Readers embedded in cell phones connect to content using the mobile phone network.

Multi-protocol readers have been developed for reading multiple frequencies within a particular band, as well as between bands. However, reading between bands usually involves a trade off in speed and other performance characteristics.

Frequency Range	**LF (125-134 KHz)**	**HF (13.56 MHz)**	**UFH (400, 868-915 MHz)**	**Microwave (2.45 & 2.45 GHz)**
Read Range (Passive Tags)	< 0.5 m (1.5ft)	- 1 m (3 ft)	- 3 m (10ft)	- 1 m (3ft)
Typical Applications	Access control, animal tracking, vehicle immobilizers, POS application including SpeedPass	"Smart Cards", Item-level tracking including cases & pallets, luggage (non-US), library books	Pallet tracking, toll collection, baggage handling (US)	SCM, toll collection
Data Rate	Slower →			Faster
Ability to read near metal or wet surfaces	Better →			Worse

Figure 2: Characteristics of RFID tags

THE EVOLUTION OF STANDARDS

The RFID components described above operate on the basis of standards. Hardware standards establish the air interface protocol and tag data format, which define how an RFID reader communicates with a tag. Tag ID standards define the coding system or namespace. Related standards include the ID resolution mechanism, if applicable.

Beyond data capture technology and ID resolution, application standards define how data is used in an actual RFID service. It's important to note that standards are also being developed at the process level, particularly for supply chain management applications.[11] Efforts include those of the Supply Chain Development Association, the Supply Chain Network, and MIT's Center for Coordination Studies, which is developing a "periodic table"

of business processes. (Process standardization is particularly crucial to the success of supply chain applications, as is the integration of RFID with other enterprise applications.)

For a given RFID implementation, the standards for each of these components can be either proprietary, shared among an established group of users, or open.

Traditional RFID systems and many of today's experiments are highly-specialized, closed-loop applications that use proprietary technology. In other words, the various hardware and software components are tightly integrated and specific to a particular implementation. Consequently, today's RFID landscape is comprised of many islands of custom-built networks. Efforts to standardize the various components of an RFID system are leading towards interoperable RFID technology and applications.

Unique identifiers

In terms of the logical infrastructure, there are increasing opportunities to build services based on coding or naming schemes with open standards. This is especially true in the case of supply chain applications, where tagged objects cross organizational boundaries.

The EPC was developed to provide an open, universal naming scheme for supply chain objects. The EPC number is similar to a UPC but is more complex and is able to identify objects at the item level. (However, most of today's EPC implementations tag cases and pallets rather than the individual items.) EPCglobal is the namespace authority for the system and assigns EPCs to manufacturers. Users pay a registration fee, ranging from about $1,000 for small firms to $200,000 for the largest companies.

In the original design, EPCs were to be resolved (matched to databases) through a centralized ID resolution system called the Object Naming Service (ONS). The ONS functions like the DNS, translating EPCs into the IP addresses of EPC-Information Service (EPC-IS) servers, which host the databases containing the product descriptions. The ONS enables the open aspect of the Network, however, this element of the Network has been shelved, in part due to limited demand for an open, centralized system. Some companies fear that a centralized system is more vulnerable to security breaches, while most others feel that the kind of information sharing enabled by the ONS is not desired by users.[12] For the time being, subscribers like Wal-Mart use EPCs with their existing EDI-based network, resolving codes to product data internally, using local databases, similar to how they currently resolve UPCs.[13]

Other ID schemes that require centralized ID resolution involve using URLs as the tag's unique identifier. The existing DNS effectively functions as the ID resolution mechanism and ICANN as the registry or namespace authority. URLs have also been used in other auto-ID systems based on infrared or visible light technology as well. HP's Cooltown project, for example, tagged objects with infrared beacons that transmitted a URL directly to a PDA equipped with an infrared sensor and Web browser. However, because URLs change, they aren't always the best choice, but they do allow the use of XPath expressions. An Xpath expression is essentially a more complex URL that can refer to individual components within an XML document for more precise data retrieval.

Using an actual IP address as a unique identifier has also been considered, using the IPv6 protocol, which will allow every networked object to have its own IP address.[14] However, IP addresses are considered a bad choice as an ID because, like URLs they are not stable, whereas, using a code (like an EPC) persistently identifies a given object. Furthermore, in complex RFID applications, different instances or states of an object would require multiple IP addresses.

As more ID schemes are developed it becomes increasingly important to address how to manage multiple systems. Rather than trying to adopt a single coding scheme for all tagged objects, we envision a more unifying system that incorporates a scheme for identifying the various types of ID schemes, where responsibility for the "ID type" assignment and registration would be undertaken by a governing body similar to the IANA (Internet Assigned Numbers Association).

Japan's Ubiquitous ID Center has already begun development on such a system using the uCode. In many ways the Center competes with EPCglobal, and Ubiquitous ID (uID) technology with EPC technology. The two systems share the basic principle of a unique identifier and a resolution server, and in the same way that EPCs can be used without the ONS, uCodes can be used without the uCode resolution server for internal implementations. However, the uCode is a meta-code system, intended to support the variety of emerging RFID applications as well as other tagging systems for both physical and digital objects. (It is also intended to work with various technical infrastructures.) UCodes are assigned and managed by the Ubiquitous ID Center.[15]

The Evolution of RFID Networks

In terms of the technical infrastructure, two key standards activities include those of the ISO (International Organization for Standards) and EPCglobal. The ISO has ratified standards for air interface protocols for frequencies across all bands, used in a wide variety of RFID applications, including livestock and pet tracking, contactless smartcards, proximity and vicinity cards, and more recently, supply chain management. These communication standards have enabled interoperability between equipment from different manufactures, promoting competition between vendors and lowering the cost technology.

The EPCglobal Network

The EPCglobal Network is a more comprehensive effort in the sense that it is developing an integrated set of universal standards for all components of an RFID system – the EPCglobal Network -- including the air interface protocols and tag data format, as well an ID scheme described above. EPCglobal chose not use ISO's air interface standards because the ISO protocol is more complex and therefore more costly to implement.[16]

The vision is for trading partners around the world to adopt EPC-compliant technology to enable global data synchronization. The concept was originally developed by MIT's Auto-ID Center. When the Center shut down in October 2003, EPCglobal was formed and took over the management of EPC standards, while the Center spun off into a handful of Auto-ID Labs around the world.[17] The new organization is a joint venture between the Uniform Code Council (UCC) and EAN International. Key supporters include Gillette, Procter & Gamble,

Wal-Mart, Johnson & Johnson, and Hewlett-Packard. EPCglobal's mandate is to commercialize EPC technology originally developed at the Auto ID Center, while it continues to work with Auto-ID Labs.

So far, EPCglobal has issued standards related to the electronic product code itself (described above); standards related to the hardware (tags and readers); and most recently for the middleware that manages the incoming data from readers.

Hardware standards have gone through several iterations, with the most recent UHF Generation II (Gen II) standards ratified by the EPC in December 2004. Gen II standards overcame some of the problems with first generation protocols, including the ability to accommodate the differences in UHF frequency standards among the various countries in the world. Other improvements include faster and more accurate reading, lower levels of power consumptions as well as support for "kill" technology (used to deactivate tags when items leave the store, for example) to help ease consumer privacy fears. EPCglobal expects that these changes will accelerate adoption of EPC technology by producing better results for users, sooner. [18]

The most recent standard to be ratified by EPCglobal is called Application Level Events (ALE). ALE is a software standard that defines how EPC data is filtered and collected so that applications can extract precise information from a raw read.[19] In other words, an ALE-based application can specify details such as which locations to read from, the time interval between reads, and how to filter and organize the data (e.g., include only a certain company's products, organize by product name).

The EPCglobal initiative has gained the support of many leading firms. Wal-Mart and the Department of Defense issued the first round of EPC mandates in 2003, followed by several other large retailers in the U.S. and Europe. This handful of mandates has driven most of the recent hype and innovation related to RFID. Their scope and scale is enormous; the DoD initiative alone addresses 60,000 suppliers handling $29 billion worth of items a year.[20] But in addition to the hype, EPC-related efforts have led to some controversy.

For the large retailers in particular, the benefits are obvious. For example, studies have shown that Wal-Mart can reduce inventory costs by 5% and logistics costs by 7.5%, achieving savings of more than $8 billion every year.[21] But for suppliers, fulfilling the EPC mandates represents an extra cost, with no substantial business case and little to no ROI at this time. In fall 2005, reports were issued showing a 16% reduction in stock outs, but for an individual supplier this gain is not enough to drive demand outside mandates, especially since most projects are still at a small scale.[22] Tagging cases and pallets is still an exception to the rule, and occurs outside the normal flow of production, which only adds to the cost. (Interestingly, the DoD mandate has become an extra cost to the Department itself because the mandate specifications allow suppliers to pass on the extra costs of tagging to the DoD, whereas retail suppliers are not permitted to do so. With tens of thousands of suppliers, these costs add up, and given increasingly tight military budgets, RFID is not as much of a priority as it was at the time the mandate was issued.[23])

Some of the technical issues include undeveloped hardware standards. Gen II standards are expected to go through several more iterations in the near future, making some companies

hesitant to invest. According to one industry spokesperson, the current state of EPC's retail-focused RFID is about where the computer industry for small systems was in the 1970s.[24] The immaturity of the industry also has serious implications regarding the availability of RFID technology. According to the managing director of one tag manufacturer, the needs and mandates of retailers – the key drivers behind the EPC initiative -- are outside the capacity of current suppliers, which means the technology may simply not be available for all companies wanting to implement an EPC-compliant RFID network. BT Auto ID services, for example, stated in fall 2005 that you simply couldn't buy the technology in the UK at that time.[25] Although EPC mandates have accelerated RFID implementations, the larger-scale initiatives are considered premature.[26] While pilots flourished throughout 2005, most analysts don't expect mass adoption of RFID technology before 2008.

There are also unresolved political issues with certain potential user groups. Hospitals for example are resisting subscribing to the EPCglobal Network because the technology emerged out of, and is currently led by the retail industry. Some organizations would prefer to start their own system, serving the specific needs of their industry, with their own registry.[27]

Furthermore, although EPC standards are being promoted globally, there is some competition in Asia from uID technology described earlier. There is speculation that Asian countries could adopt the Ucode instead of the EPC. The Korean government announced in spring 2005 that it would collaborate with the Ubiquitous ID Center,[28] and the Chinese government has threatened to choose the uCode standard, partly in response to having been excluded from participating in formulating the standards for the EPCglobal Network – although private enterprise seems more interested in cooperating with North American business.[29] Nonetheless, EPCglobal is generally recognized as being American-centric, and according to one research firm, many of Wal-Mart's suppliers expressed concern that the country producing 70% of Wal-Mart's products has not played a significant role in defining EPC standards.[30]

The trends examined in this section have pertained specifically to dedicated RFID networks. The next section will look at the convergence of traditional RFID technology with other wireless networks.

CONVERGING TECHNOLOGIES

RFID systems are essentially short-range, low frequency, low-bit rate wireless networks. Since their origins in the late 1940s, they have been developed specifically to exchange small amounts of data over relatively short distances using tags and readers based on proprietary air interface protocols, and more recently ISO and EPC standards. Up until now, these dedicated RFID networks have evolved independently of the new generation of short-range wireless data networks like Bluetooth, Zigbee and WiFi and NFC (near field communication). But these old and new trajectories have begun to converge, and the "RF" component of RFID has expanded to include these more recent wireless technologies. In other words, RFID applications are starting to "piggy back" onto today's established WPANs and WLANs using active tags that communicate with these networks' air interface protocols. In this sense, active RFID tags are a subset of more common communication

devices like cell-phones, PDAs, and WiFi-enabled laptops, only with fewer input/output features (like keypads, screens, etc.) and transmitting less data.[31] Similarly, traditional RFID networks are a subset of today's broad menu of wireless networks, as shown in Figure 3.[32]

	Technology	Frequency	Typical Range	Data Rate
	Dedicated RFID	125-134kHz (LF) 13.56 MHz (HF) 400-930 MHz (UHF) 2.5 GHz & 5GHz (microwave)	20' (passive) 400' (active)	1-200 kbps
	Near field communication (NFC)	13.56	0-20 centimeters	106, 212, 424 kbps
WPAN	**Zigbee 802.15.4**	2.4 GHz	70 meters	250 kbps
WPAN	**Bluetooth 1.1 802.15.1**	2.4 GHz	10 meters	780 kbps
WPAN	**Bluetooth 2.0**	2.4 GHz	10 meters	3 Mbps
WPAN	**Ultra-Wideband 802.15.3a**	3.1 GHz	10 meters, 2 meters	110, 480 Mbps
WLAN	**802.11a**	5 GHz	100 meters	54 Mbps
WLAN	**802.11b/g**	2.4 GHz	100 meters	54 Mbps
WLAN	**802.16 WiMAX**	10–66 GHz	1–3 miles	134 Mbps
WLAN	**802.16a WiMAX**	2–11 GHz	30 miles	75 Mbps
WLAN	**802.16e WiMAX**	6 GHz	1–3 miles	15 Mbps
WWAN	**GPRS**	900, 1800, 1900 MHz	National network	160 kbps
WWAN	**EDGE**	900, 1800, 1900 MHz	National network	473.6 kbps
WWAN	**UMTS**	900, 1800, 1900 MHz	In selected cities	2 Mbps
WWAN	**CDMA2000/ 1XRTT**	1900 MHz, others	National network	156–307.2 kbps
WWAN	**CDMA2000/ 1xEV-DO**	1900 MHz, others	In selected cities	2.4 Mbps

Figure 3: The broader wireless landscape

While dedicated RFID systems will continue to develop, we will see more RFID applications that exploit the growing base of Bluetooth modules in consumer devices,[33] while cell phones will increasingly integrate NFC technology for "touch-based" RFID applications. ZigBee-enabled RFID will use wireless sensor networks to track mobile assets[34] and WiFi-enabled RFID will allow organizations to leverage existing WLAN investments or choose to invest in a wireless infrastructure that will have multiple purposes, rather than building separate networks. Of these possibilities, WiFi- and NFC-based RFID have seen the most activity so far.

WiFi-enabled RFID

WiFi-enabled RFID is commonly used for location-based services that track objects in a specific physical context, like children in a theme park, cars in a parking lot, equipment in a manufacturing plant, etc. It is considered a more accurate system than a traditional RFID network for determining the location of tagged objects.[35] A regular RFID system can give what is called the "choke point" location, or zone-based location, meaning the location of

the tag is known only in relation to the reader detecting its presence. A WiFi network on the other hand can determine the precise x,y coordinates of a tag using triangulation methods, similar to how GPS works.

In these RFID systems, tags are WiFi devices, and WiFi access points function as readers. The MAC address[36] on the tag serves as the unique identifier, and location software determines the specific coordinates. Additional application software can transform coordinates in terms that are meaningful to a user by matching them to specific locations, e.g., Room 222, or quadrants on a map of the area. A WiFi application then, can identify both what the device is, e.g., a wheelchair, a truck, etc., and where it is, e.g., in corridor 12, in parking spot 45C. Some tags may contain additional data derived from integrated sensors.[37]

Kidspotter is an interesting example of an application that has successfully used active WiFi-enabled tags to track children in theme parks. Kidspotter's child tracking system was installed at Denmark's Legoland in 2003. A WiFi-based system was chosen after having considered more traditional RFID technology, which would have required hundreds of readers in order to pinpoint the location of a child with the same precision as the WiFi network, which comprises only 34 readers. Furthermore, Legoland was able to leverage its existing WiFi infrastructure, which it uses for point-of-sale equipment, WiFi hotspots, and other functions in its theme park.[38] In addition to generating revenues from the Kidspotter service, the application has also been used to determine traffic patterns within the park, including where people travel and how fast or slow, i.e., it can determine if a patron slows down in front of a particular billboard.[39]

Children wear tagged wristbands or badges that have been registered to the caretaker's mobile phone number for a fee. If the child goes missing, the caretaker sends an SMS message to the Kidspotter application server, which will return the child's location in terms of Legoland's map coordinates (based on 5x5-meter quadrants). The MAC addresses for Legoland's tags are registered with the application server so that Kidspotter tag signals are recognized as such by the WiFi access points. The WiFi tags cost $85 each, and the readers between $3,000-$4,000.

The same technology is also being tested in Yokohama, Japan for tracking school children. The I-Safety system uses the city's WiFi infrastructure for tracking children within a specific area called the "Watch Spot." Parents can track their child's location on their PC or cell phone, but additionally, cars are tagged so that they will be notified of any children playing in the area as they drive through it. Also, children can press an emergency button on their tags to alert a network of tagged security guards and volunteers chosen by the parents, so that the closest one to an emergency call can respond.[40]

NFC-enabled RFID

NFC is very short range -- about 0-20 centimeters. It is essentially a WPAN with an even shorter range and lower data rates than Bluetooth. NFC operates in the 13.56 MHz range with data rates of 106kbps and 212kbps, or up to 424 kbps between dedicated NFC devices, and uses both active and passive tags.

The technology was designed to support a "touch" paradigm. NFC devices are brought very close together, or actually touched, to intuitively create a connection between a reader and a tag. (One analogy that is often used to capture the essence of NFC is whispering in someone's ear rather than shouting across a room.) NFC technology is designed to be integrated into consumer devices.

One of the key areas being explored with this wireless technology is the use of NFC in mobile phones, where NFC tags and/or readers are embedded in the devices. In 2004, ABI research predicted that 50% of mobile phones will be NFC-enabled by 2009.[41]

Nokia developed the first NFC-enabled mobile phones in 2004 and 2005. Application scenarios include retrieving information from RFID tags in posters or on product packaging in a grocery store, for example. An NFC mobile phone can touch or be waved in front of the tag, which would transmit information instructing the phone to download information from a particular Web site via the mobile network.

Tags may also transmit more dynamic data about the object. Field force applications for example enable security guards to download time and location information to prove they visited a particular site. This method is more secure than using barcodes, which apparently could be photographed or photocopied and then read from somewhere other than the site. Another example involves automatic reading of electricity meters. Field workers read the tag embedded in the meter using their mobile phone, and the data is then sent directly to a central database over the mobile network.[42]

In some cases, the mobile phone functions as the tag as well as the reader. NFC technology is compatible with the established smart-card infrastructure[43] used for contactless smart cards (wave instead of swipe[44]), which enables NFC-enabled phones and other devices to function as the smart card for mobile payment applications. Frankfurt's public transportation system tested a service in 2005 that allows Nokia's 3220 NFC phones to access the system. Instead of buying a special transit card for buying and storing fares, users can perform the same functions using their phone.[45] Mobile payment using cell phones is already very popular in Japan.

Another interesting use for NFC-RFID is automatically establishing a P2P connection between wireless devices. For example, two NFC-enabled mobile phones in close proximity would exchange configuration data, i.e., the MAC address, the Bluetooth pairing code, etc., thereby eliminating the need for using Bluetooth's service discovery operations and typing in pairing codes by hand, a process that discourages usage of Bluetooth functionality on consumer devices.

More intelligent – and more expensive – active RFID chips are required for these types of applications (compared to the envisioned 5¢ EPC passive tag for example), but they involve far fewer objects than the supply chain and enable richer and higher revenue-per-transaction services.

COMPETING TECHNOLOGIES

As a tagging solution, traditional, dedicated RFID is not only converging with other radio-based wireless technologies, it may also compete with *optical* tagging solutions – but not the barcode technology it intended to surpass. Despite the important advantages RFID offers over light-based systems -- no line of sight or human interaction required; tags can be as large or as small, as complex or simple, as expensive or cheap as required -- there are cases where some of the newer optical tagging systems could compete with RFID. This is particularly true for consumer-oriented applications involving mobile phone readers where performance, cost and ease of use factors outweigh RF's advantages as the data capture and transmission technology.

Several automatic identification applications have emerged in the last few years combining 2D visual symbols called matrix codes and camera phones. Matrix codes are essentially a richer form of barcode.[46] Examples include Semacodes, Shotcodes, QR Codes, and ColorCodes, shown in Figure 4. The transmission technology used is plain old visible light. The phone's built-in camera essentially takes a picture of a unique symbol, which is then decoded using software installed in the camera. The application then uses the mobile phone network to connect to a server on the Internet, similar to an NFC application described above.

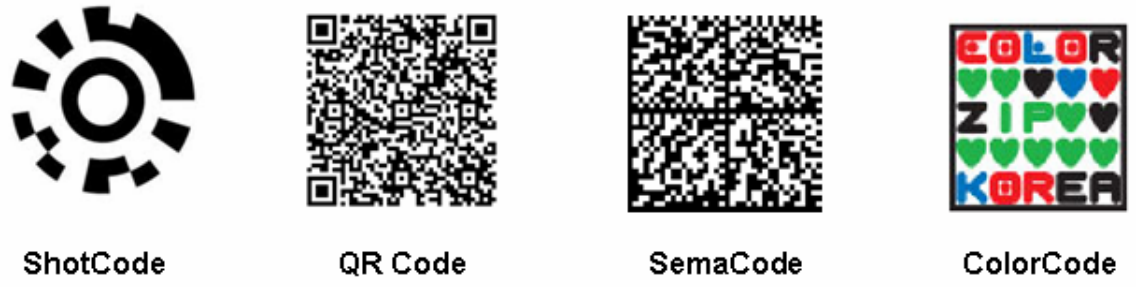

Figure 4: Examples of 2D matrix codes

One key difference between these "visible-light-ID" systems and both RFID and "IRID," is that they are driven by an existing -- and growing -- user base of camera phones among consumers. In other words, applications use existing hardware with an established purpose, i.e., the reader is not a dedicated device (like a barcode scanner for example), and no new investment is required on the part of the user, other than the task of downloading the required tagging and scanning software onto the appropriate devices. (Some have suggested creating a separate service for decoding the photographs of symbols, so that a camera phone could be used without scanner software. A user would simply email the photograph to the service, which would then send back the decoded content.[47])

In Japan, most camera phones come with QR Code software pre-installed, which has led to the increasing popularity of these applications in the last couple of years. The QR Code is the most popular matrix code used in Japan, and appears in on gigantic billboards, in smaller print ads, on products in stores, and more recently in TV advertising. There is even an

application for identifying lost children. Rather than actively tracking their location like the Kidspotter example above, the QR Code is used to simply identify the child and automatically notify the parents that she has been found by sending an SMS. QR Codes are sewn onto the child's jacket or backpack. The application avoids attaching an electronic device on the child, and relies on the fact that most people in Japan have a cell phone equipped with a camera and scanner software.

In addition to giving consumers the ability to read object tags, these optical systems enable end users to easily *create* their own codes as well as scan them. Online tools like the NFG QRCode Generator let users automatically encode text, email shortcuts, Web bookmarks, etc. [48] The QR Code for a URL or a business card can be generated in a few seconds. Tags are also created using existing consumer equipment, i.e., standard printers and paper. They can also be printed on t-shirts, burned into wood, tattooed onto skin, etc. (One experiment involved creating a large QR Code out of dark and white chocolate.) And, the transmission medium – light – is free and unregulated (although not always present or adequate).

While these visual tags can be more obtrusive and/or precarious than RFID tags (sometimes printed on a standard 8" x 11" piece of paper), there are scenarios where, from a usability and cost perspective, they would be a better choice, especially for more grass-roots consumer applications. For example, tags can be stuck onto landmarks like a historical building (similar to placing a historical plaque), or a bus stop shelter. For example, San Francisco's NextBus real-time schedule system is normally accessed by typing in the URL for a particular schedule into a wireless device. Volunteers have created and pasted Semacodes at bus stops in several cities in the U.S. to let camera phones automatically connect to the tracking data from the NextBus site, saving the user from typing in the URL.[49]

THE BIGGER TAGGING PICTURE

In this sense, RFID must be understood, not only within the larger wireless landscape, but also within the broader context of all tagging technologies. The various properties of a tagging solution must be evaluated in terms of cost, performance, ease of use, ROI, process changes, etc. The coding scheme is generally independent of the technical infrastructure, meaning a UPC or ISBN for example, can be encoded in a barcode or stored on an RFID tag. Some experiments have encoded a matrix code with an EPC.

Figure 5 maps out the infrastructure for the bigger tagging picture for physical objects as we see it today. In terms of tag data, multiple coding systems are emerging, some of which will continue to serve closed-loop or internal applications, while others like the EPC provide an open, universal scheme for supply chain objects. We envision a meta-code system, similar to the uCode, that could be adopted to unify all coding schemes.

In terms of the actual tagging infrastructure for communicating these codes, we include both radio-based systems -- including all short-range wireless networks – and visual systems, from the more primitive barcode to QR Codes. While barcodes are generally viewed as inferior to both RFID systems and 2D matrix systems, they are still a legitimate technology. In fact, when UPS upgraded its network of parcel scanners in 2005, it continued to use barcode

technology with infrared scanners. The key change involved replacing the cumbersome cables that previously connected the scanners to terminals attached to employees, with a Bluetooth connection, which solved a more immediate problem (cables getting caught or ripped out of the scanners) than any limitations inherent in the barcode system. UPS did consider replacing barcodes with RFID tags, but the RFID technology proved to be less accurate and far more costly, and would require significant changes in business processes to produce a return on investment.[50]

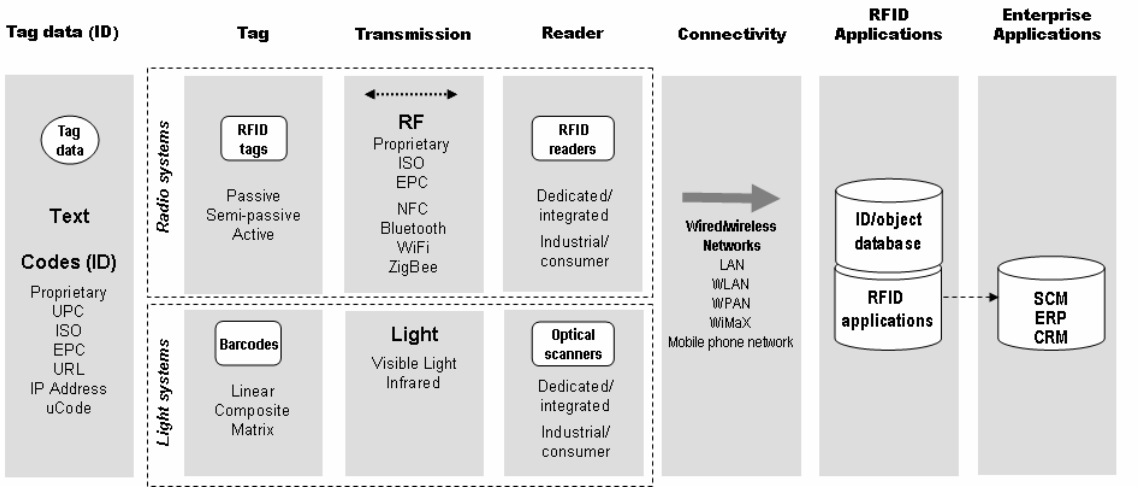

Figure 5: The bigger tagging picture

INNOVATION AT THE EDGE

This broader scope of RFID activity and tagging in general stands in contrast to the EPCglobal vision of the "Internet of Things." And yet the EPC effort has driven much of the hype surrounding RFID in the last few years, and largely defined the agenda. It has in the process accelerated the RFID technology market, and for the big players, supply chain efficiency has and will continue to improve, as will associated profitability. And more suppliers are looking beyond "slap and ship" compliance to experiment with innovative ways to integrate EPC data into their operations.

However, within the narrower context of supply chain applications, RFID innovation has largely been incremental, rather than disruptive. EPCglobal is creating an infrastructure for the larger players, most of which is focused on the supply chain. Unresolved privacy concerns further confine these efforts to back end processes as some of the more innovative point-of-sale and product lifecycle applications have been held back by consumer groups. A true "Internet of Things," is unlikely to spring forth from these efforts alone.

But, the potential to tag "everything" and create billions of "objects that talk" is a tempting vision to those who view greater connectivity and ubiquitous network elements as the handmaidens of innovation. At some point, we speculate, a community of users, or a small competitor will figure out a unique killer application for tagged objects. As RFID and other tagging technologies increasingly find themselves in the hands of consumers, it is more likely

that grassroots tagging will emerge as end users read tags with their personal devices, and more so when they create their own data relating to an object code, or their own tags.

One useful analogy exists in the world of tagging digital objects, namely Gracenote's CDDB (compact disc database) online CD database. The database was essentially created by users for free, where the key enabler was the huge installed base of PCs with built-in CD players. (The database was later privatized and licensed to software developers for a fee.) As tag reading and writing technologies become available at the edge, RFID and competing technologies like matrix codes may enable similar edge-based innovation. The Semapedia application for example, links objects tagged with Semacodes (a matrix code) to Wikipedia entries via camera phones. A user could, using their PC and Internet connection, create a Semacode symbol that encodes the URL for the Wikipedia entry for a historical building, print the symbol on a piece of paper using a regular printer, and tape it to the referenced building. Semacodes are both created and read using consumer devices, while Wikipedia is a user-created online resource. The system is completely edge-based. The example is rather primitive, and raises interesting issues regarding the tagging of public space, but it illustrates the potential for edge innovation.

In this way grassroots projects could develop that would provide a counterbalance to more centralized efforts such as EPCglobal. Such a process is well adapted to the creation of technology to meet shared needs but also is good at accommodating differences by spinning off related projects. We await such developments with great anticipation.

ACKNOWLEDGEMENTS

Many of the ideas and concepts in this paper reflect the numerous discussions among participants in the Value Chain Dynamics Working Group of the Communications Futures Program at MIT. The authors would like to thank the individuals involved in these discussions, in particular Chintan Vaishnav (MIT), John Watlington (France Telecom), Sylvie Bokshorn (France Telecom), and Kai Miao (Intel). It is to be made clear that opinions expressed in this paper and in the contributions leading up to this paper are drawn from the contributions of these individuals and do not represent official views or policies of CFP's sponsoring companies or universities.

NOTES

[1] Surgichip, Medgadget, http://www.medgadget.com/archives/2004/12/surgichip.html.
[2] Marianne Kolbasuk McGee, "RFID Goes to the O.R.," *Information Week*, May 2, 2005, http://www.informationweek.com/story/showArticle.jhtml?articleID=162100356&tid=13692.
[3] Jonathan Collins, "Tag Encryption for Libraries," *RFID Journal*, July 14, 2004. http://www.rfidjournal.com/article/articleview/1027/1/1/.
[4] "Smartcode Corp. announces the industry lowest cost EPC Gen 2 inlays," Smartcode News & Analysis, October 2005, http://www.smartcodecorp.com/newsroom/05-10-05.asp.
[5] See Jussi Angelsleva and Marcus Kirsch, "Urban Eyes: A paradigm shift in our perception of urban space through the use of wireless technology and mixed networks, http://www.unvoid.net/downloads/UrbanEyes.pdf.
[6] Figure adapted from "RFID Technology," Samsys, http://www.samsys.com/default.php?alpha=company&beta=tech.
[7] "Multi Frequency, Multi Protocol Readers," *ID TechEx*, June 9, 2004. http://www.idtechex.com/products/en/articles/00000020.asp.
[8] Mark Roberti, "Wal-Mart Explores New RFID Form Factors," *RFID Journal*, January 25, 2006, http://www.rfidjournal.com/article/articleview/2105/1/1/.
[9] "Advent of RFID in Towns," *RFID in Japan*, June 25, 2004, originally published in Japanese in Nikkei Shimbun, June 21, 2004. "Shinjuku Plans to Tag 10,000 Street Lamps," *RFID in Japan*, December 2005, http://ubiks.net/local/blog/jmt/archives3/004570.html.
[10] "Handheld Bluetooth RFID reader is unprecedented," *RF Design*, September 8, 2004, http://rfdesign.com/news/handheld-Bluetooth-RFID/.
[11] See "The MIT Process Handbook," Center for Coordination Science, MIT, http://ccs.mit.edu/ph/.
[12] Ed Schuster, MIT Data Center, Interview by Natalie Klym and Milind Tavshikar, MIT CFP, August 24, 2005.
[13] Suppliers provide regular updates of UPCs and product data to their customers on CDs.
[14] http://www.rfidjournal.com/article/articleprint/609/-1/1/
[15] www.uidcenter.org
[16] "A Summary of RFID Standards," *RFID Journal*, http://www.rfidjournal.com/article/articleview/1335/1/129/
[17] http://www.autoidlabs.org/
[18] Laurie Sullivan, "Next-Generation RFID Standard is Approved," *Information Week*, December 17, 2004, http://informationweek.com/story/showArticle.jhtml?articleID=55800518.
[19] Ken Traub, «ALE : A New Standard for Data Access , » RFID Journal, April 18, 2005.
[20] "Effect of RFID mandates," *RFID Gazette*, November 21, 2005.
[21] "Effect of RFID mandates," *RFID Gazette*, November 21, 2005.
[22] Laurie Sullivan, "Wal-Mart RFID Trial Shows 16% Reduction in Product Stock-Outs," *Information Week*, October 14, 2005, http://informationweek.com/story/showArticle.jhtml?articleID=172301246.
[23] Ed Schuster, MIT Data Center, Interview by Natalie Klym and Milind Tavshikar, MIT CFP, August 24, 2005.
[24] Mike Marsh, Managing Director, Trolley Scan, interview in *Transponder News*, May 2005, http://rapidttp.com/transponder/interv1.html.
[25] Geoffrey Barraclough, BT Auto-ID Services, Interview by Natalie Klym, MIT CFP, August 23. 2005.
[26] Fahmida Rashid, "The Great RFID Experiment that Wasn't," *Forbes*, August 22, 2005, http://www.forbes.com/logistics/2005/07/22/rfid-shakeout-consolidation-cx_fr_0722rfid.html.
[27] Ed Schuster, MIT Data Center, Interview by Natalie Klym and Milind Tavshikar, MIT CFP, August 24, 2005.

[28] "Ucode expanding to Korea," *RFID in Japan*, April 29, 2005, http://ubiks.net/local/blog/jmt/archives3/003765.html.
[29] Howard Stockdale, CIO, Beaver Street Fisheries, Interview by Natalie Klym, MIT CFP, August 15, 2005.
[30] Michael J. Liard, "The RFID Business Planning Service," Venture Development Corporation, May 2005, http://transpondernews.com/vdc2005.pdf.
[31] Raj Bridgelall, Symbol Technologies, Inc., IEEE, 2003.
[32] Table adapted from Craig Mathias and Lisa Phifer, "The Evolving Wireless Landscape, *Business Communications Review*, pp. 18-23, April 2005.
[33] Frank Seigemund and Christian Florkemeier, "Interaction in Pervasive Computing Settings using Bluetooth-enabled Active Tags and Passive RFID Technology together with Mobile Phones," Institute for Pervasive Computing, Department of Computer Science, ETH Zurich, Switzerland.
[34] Mary Catherine O'Connor, "RFID's Urge to Converge," *RFID Journal*, January 23, 2006.
[35] Jens Strandbygaard, director, Kidspotter, Interview by Natalie Klym, MIT CFP, November 23, 2005.
[36] MAC stands for Media Access Control. The MAC address uniquely identifies each node of a network.
[37] Mary Catherine O'Connor, "RFID's Urge to Converge," *RFID Journal*, January 23, 2006.
[38] Jonathan Collins, "Lost and Found in Legoland," *RFID Journal*, April 28, 2004.
[39] Jens Strandbygaard, director, Kidspotter, Interview by Natalie Klym, MIT CFP, November 23, 2005.
[40] RFID kids tracking in Yokohama, Japan, *RFID in Japan*, October 7, 2005, http://ubiks.net/local/blog/jmt/archives3/004343.html. Claire Sedberg, "RFID Watches Over School Kids in Japan," *RFID Journal*, December 16, 2005, http://www.rfidjournal.com/article/articleview/2050/1/1/.
[41] Claire Swedbert, "Developing RFID-Enabled Phones," *RFID Journal*, July 9, 2004, http://www.rfidjournal.com/article/articleview/1020/1/1/.
[42] Christoph Seidler, ITU-T Technology Watch, International Telecommunications Union, May 2005, http://www.itu.int/ITU-T/techwatch/docs/rfid.pdf.
[43] The NFC technology promoted by the NFC Forum is compatible with Sony's FeliCa and Phillips' Mifare protocols. A competing technology, R2R, recently renamed eNFC integrates additional standards that have been adopted by several market segments. For more information on the NFC Forum, see http://www.nfc-forum.org. For more information on eNFC, see Bruno Charrat, R2R provides an "open" alternative to NFC for contactless and RFID in '05," Contactless news, December 14, 2004, http://www.contactlessnews.com/news/2004/12/14/r2r-provides-open-alternative-to-nfc-for-contactless-and-rfid-in-05/.
[44] Radio frequency replaces the magnetic field as the interconnection technology.
[45] Christoph Seidler, *ITU-T Technology Watch*, International Telecommunications Union, May 2005, http://www.itu.int/ITU-T/techwatch/docs/rfid.pdf.
[46] For more information on the evolution of barcodes to 2D matrix codes, see http://www.denso-wave.com/qrcode/aboutqr-e.html.
[47] http://www.lewismoten.com/2005/09/qr-codes.html
[48] The QR Code generator can be found at http://nfg.2y.net/system/qrcodegen.php#
[49] Douglas Heingartner, "Connecting Paper and Online Worlds by Cellphone Camera," *New York Times*, October 7, 2004, http://www.nytimes.com/2004/10/07/technology/circuits/07kios.html?ex=1254801600&en=91b906c33959db2e&ei=5088&partner=rssnyt.
[50] Tom Mashberg, "One Decision: UPS Goes Bluetooth," *Technology Review*, June 2005, http://www.technologyreview.com/articles/05/06/issue/brief_ups.asp?p=1.