RFID Convergence: The Internet of Things 2.0

Michael Goshey
Department of Computer Science and Engineering
University of Minnesota
200 Union Street SE, Minneapolis, MN 55455
mgoshey@cs.umn.edu

Abstract—*RFID represents a significant improvement over other automated identification technologies (such as bar coding) in that RFID readers do not require line of sight to tags nor do RFID systems require human assistance when functioning properly. These and other attributes make RFID an excellent candidate for convergence with a variety of networking technologies, and recent research has paired RFID in a broad range of mashup-like partnerships with IP networks, sensor networks, the Internet, mobile phones, wireless networking, Bluetooth, social networks, peer-to-peer, SMS and others. While other studies have provided overviews of RFID security and privacy [1], relevant protocols [2] and overall technical introductions [3], this appears to be the first work to survey the landscape of RFID's increasing convergence with other networking technologies.*

1 Introduction

Radio Frequency Identification (RFID) is a networking technology with a distinct primary purpose: the automated identification of remote objects. For this reason it has often been referred to as the 'Internet of Things' [4]–[6]. RFID features electronic tags which are used to store small amounts of data and to act as transponders for establishing connectivity with readers in order to transfer the stored payload via radio waves [7] [8]. The tags are typically affixed to objects of interest with adhesive backing. The readers translate the data embedded in radio waves into meaningful information. In addition to these 'stand alone' identifying and tracking uses, in recent years the proliferation of RFID has led to interesting combinations of RFID with other networking technologies. This paper will consider a broad overview of the use of RFID with other technologies and show that RFID appears to be on a clear path toward converging with a number of these. The rest of the paper is organized as follows:

- Section two provides a brief background on radio frequency identification, its constituent components and 'standard' uses
- Section three focuses on the convergence of RFID with a number of networking technologies: IP networks, sensor networks, the Internet, mobile phones, wireless networks, Bluetooth, social networks, peer-to-peer networks, SMS and optical networks.
- Section four provides a brief summary and closing observations

2 Background

A brief description of radio frequency identification and an explanation of its key relevant components should serve to set the stage for a better understanding of the increasing role it plays in networking mashups that combine multiple technologies.

2.1 Hardware

At the center of the RFID system are several key components: tags, readers and label printers [9]–[11]. These system are also supported by application software, middleware and other generalized computing resources, but it is the readers and tags that are somewhat unique to the RFID domain. The purpose of RFID systems is to capture information about physical objects of interest, typically involving tracking and monitoring of those objects. The data that uniquely identifies such objects is stored on electronic RFID tags which are simply silicon microchips bundled with antennas and affixed (usually with adhesive) directly to the objects to be tracked. In addition to storing small amounts of data, the tags act as transponders for sending and receiving radio signals to and from readers. RFID's obvious advantages over bar code technology include the ability to operate without line of sight between tags and readers, and the ability of readers to process hundreds of concurrent tag reads. RFID tags come in three flavors: Passive, Active and Semi-Passive [11].

2.1.1 Tags

2.1.1.1 Passive Tags: A passive tag has no on-board power source and rather 'harvests' required power from the electromagnetic fields on the inbound transmissions it receives from the reader. As a transponder it responds to the reader's signal and induces a small amount of current into its on-board antenna for the purpose of powering-on its internal chip and responding to the reader with data. 'Backscatter' refers to the process a passive tag uses to reflect and modulate the signal it receives from the reader. The modulation variations are interpreted into meaningful messages by the reader- that is, the difference between the original signal and the (modulated) response provides the ability to embed binary data. At present passive chips store around two kilobytes of data, enabling a surprisingly large amount of data storage about the object of interest. The absence of batteries give passive tags a much longer duration than their active counterparts. They are also smaller and cost much less to manufacture. Average unit costs for passive tags in the US (for high volume purchases) were around 20 cents as of 2006. The thin, flat tags vary in size, though the smallest in mass use are around the size of postage stamps. They are thin enough to be used in embedded applications (both human and animal) and can be fed through special 'printers' that initialize the tags for use or in some cases combine the RFID tags with bar code labels. While the absence of battery has the above mentioned advantages, it is also a constraint in the form of a limitation on broadcast distance and therefore passive tags tend to be used in environments where readers and tags can be brought into close proximity. Typically passive tags function like ROM devices- once they have been initialized they become read-only.

2.1.1.2 Active Tags: Active tags function quite a bit differently from passive. Because they have on-board power (batteries, mini solar cells, etc.) they tend be to larger and include a transmitter that facilitates longer-distance transmissions back to readers. Not only can their exchanges with readers be conducted from longer distances, they can extend for longer duration and can typically carry larger payloads, as well as provide read-write capability. The larger form factor translates into higher manufacturing cost, which is justified by the benefits mentioned above. Active tags are invaluable in situations where tags and readers cannot be brought close enough together for passive tag use, and also outperform passive tags in environments with high concentrations of water and/or metal. For comparison sake, whereas passive tags are typically read within a distance of ten feet, active tags can be read from hundreds of meters. Whereas the cost of passive tags is measured in pennies, active tag costs are measured in dollars. They also tend to live much longer than passive counterparts. The life of an active tag is often constrained by its battery life- ten years of usefulness is not considered excessive. Given the various benefits mentioned above, its not particularly surprising to find out that active tags tend to be used for tracking and monitoring more valuable assets than passive tags.

2.1.1.3 Semi-Passive Tags: Hybrid tags that combine aspects of both active and passive are referred to as semi-passive. For example, they typically have battery power (an active tag feature) but also typically use the backscatter method of transmission (passive tag feature). The resulting combination typically exceeds passive tags in capability but are still cheaper to produce than active tags.

2.1.2 Readers

RFID readers exist primarily to send and retrieve data to and from RFID tags. Whereas early readers tended to be stationary, many today are mobile (hand held) devices with one or more broadcast antennas. There are readers of varying capabilities- for example, some that read signals at multiple frequencies, understand multiple RFID protocols, etc. There are both read-only and read-write types of readers. Read-only readers simply read signals from tags and extract data payloads. Most typically they render radio signal data as a binary message and then hand it off to a server for processing and distribution to a database. Read-write readers can do everything that the read-only type do, but as the name implies they also have the ability to write directly to writable (i.e. active) tags during transmission and can also be used to initialize read-only tags.

2.1.3 Printers

Tags and labels are still considered distinct technologies: tags are mounted with adhesives to some substrate and then attached to a box or other object of interest. RFID Labels are extremely thin chips mounted between sheets of paper and affixed on objects as labels. Special printing devices are used to both print and initialize RFID labels.

2.2 Software Protocols

The RFID industry uses the term 'air interface protocol' to describe the communication rules between tags and readers. As of 2006 the updated 'Gen 2' protocol was adopted as an ISO 18000-6 standard and it establishes rules for bit encoding, modulation, anti-collision, and a standard set of CRUD-like operations for tags [12]. As one might imagine collisions occur frequently in this domain and handling such collisions appropriately can be a significant challenge. This issue is particularly acute in grocery stores and wholesalers where readers may be subject to hundreds of concurrent transmission attempts/responses from nearby tags. Singulation is the name for the process RFID uses to 'single out' or identify one tag from a group of tag peers. There are various singulation methodologies including tree walking (narrowing the responder set of tags one bit at a time by broadcasting requests for matching bits in succession) and aloha (tag back-off and retry). Of the two, tree walking is considered less secure since the reader broadcasts collectively reveal all but the last bit of a given tag [13]. A surreptitious listener would be able to infer identify of tags in close proximity of the reader by eavesdropping only on the reader-side transmissions. Since readers have longer broadcast range, it opens the door for the counter-intuitive circumstance where tags with very low broadcast range can effectively be the target of electronic eavesdropping from significant remote distances.

2.3 Mainstream Applications

Typical applications of RFID include inventory control, pet identification, supply chain management, border control, building access control, performance monitoring, automated fare/toll collection, prisoner tracking, hospital bed management and theft deterrence. RFID is used by mass retailers, in vending machines, payment (credit-debit) cards, warehouse, libraries, airlines, car keys and in many, many other ways. Wal-Mart may be the largest single adopter, imposing the same on its suppliers. The U.S. Department of Defense also has a significant investment in the technology for use in its supply chain management. Of particular interest in this space is the question of tag ownership. If a data tag traverses with an object from the site where it was manufactured to the shipping destination, as it changes hands from one entity to another, the question of who 'owns' the tag is both interesting and unresolved. Another very interesting area of research has to do with RFID tracking of currency. Some plans along these lines are in their infancy but are showing promise, such as the proposal to embed RFID tags in European currency [14].

3 RFID Convergence

Having established a basic understanding of how RFID works, the hardware and software components associated with it and the 'traditional' applications in which it is popularly used, it is time to examine several recent areas of convergence featuring RFID in innovative pairings with other forms of networking. The section is divided into several of the more prominent areas where such combinations can be seen.

3.1 RFID and IP Networks

An indirect relationship has always existed between most RFID implementations and the IP networks that are used to accomplish the majority of interconnected computing today. Once data travels from a tag to a reader, the natural next step is to process and store that data on a database server for eventual reporting, analysis, alerting and other uses that transform it into valuable information. Therefore, in addition to understanding and transmitting RFID protocols, the readers typically act as proxies at the edge of the network, providing an on-ramp back into the IP world, either through on board Ethernet or wireless network cards, serial ports, blue tooth or other transmission capabilities that push the data back into the primary network stream. This section looks beyond this de facto relationship that exists at a slight remove and examines the works of those who are looking at the longer term impacts of RFID on the IP network.

One such example is a three year old white paper commissioned by Cisco [15]. It begins from the premise that- given the widespread adoption of RFID in the area of supply chain management- large-scale proliferation of RFID networks in inevitable and its long term impact on existing IP networks must be taken into consideration both by those making micro (LAN) and macro (WAN) level decisions. As a leading manufacturer of routing and switching devices, perhaps it is not surprising that they find great hope in the advent of IPv6, particularly along the lines of the possibility of its convergence with RFID in the form of embedding native RFID support into the network protocol layer, or link layer support through standards such as IEEE 802.15.4, which, for example, is the basis for ZigBee. Such optimism is echoed by researchers in the field [16]. To the extent that this is possible, it represents significant advances in integrating the flow of RFID data into some of the primary networks in use today, though the potential volume impact would require in depth advance planning. Since many of the larger promoters of RFID (Wal-Mart, DoD, etc.) are gradually imposing that suppliers bring RFID on-line throughout the length of the supply chain, increases in data volume will be obvious concerns, as well as subtler impacts that will also require further analysis, such as the high-availability requirements of RFID and its specialized security needs. As networks converge in other directions to include voice, rich media streaming and ongoing support of traditional transaction processing, the likely convergence with RFID must take all of these factors into consideration. On the other side are proposals that suggest the instead of converging RFID and IP, that portal-like entities using HIP (host identity protocol) be developed to function as edge devices that bridge the network at large with constellations of RFID device networks [17]. While there is great variety in approaches, it is clear from the literature that the convergence of RFID with major IP networks will continue to be a primary consideration in the near term.

3.2 RFID and Sensor Networks

RFID has a long and rich history of being coupled with sensor devices. One interesting observation with respect to the convergence of these two networking paradigms is that collectively they have the ability to bind together physical and virtual worlds. In combination with environmental sensors (temperature, humidity, heat, sound, light, etc.) and GPS capabilities, RFID is already used in a vast array of novel applications ranging from tracking the whereabouts of young children to remote monitoring of the state of manhole covers [3]. Much of the research in this area focuses on improving base station technologies (which somewhat calls to mind the end-to-end network debate) and expanding sensing capabilities. One difficulty faced by researchers in this area is that innovations on both sides are progressing concurrently and it makes it difficult for progress in one area to stay in sync with gains made in the other. On a slightly different note, one of the long-discussed directions for future RFID applications centers around the notion of *pervasive* computing [18], where computing-enabled entities will eventually move through space broadcasting their presence (or identities, or affinities, etc.) and automatically plugging-in (in the sense of a 'network of things') to environments they encounter. Much well-publicized research is being done in this area [19], including the creation of 'wearable' computers and 'smart' spaces (both private and public) and building adaptive, context-aware environments. Others focus their research efforts on the supporting data structures and metadata capabilities that will be required by the ubiquitous, highly distributed, concurrent, real-time data interchanges demands that will be required on scales never before considered as increasingly sophisticated sensors provide data sets far richer than available in the past [20]. Enterprise databases will compete with sensor networks for database resources and the notions of 'global query', semantic reconciliation and open interchange standards are each worthy of significant ongoing research. Research in this field has progressed enough that a number of researchers are now focused on prototyping middleware and application frameworks specifically designed to address the unique concerns of combined RFID sensor networks [21]–[23].

3.3 RFID and the Internet

In recent years the Internet has become the focal point of much development and progress in computing, and as demonstrated by the research in this area, it is being combined with RFID in a number of interesting and forward-looking ways. As a starting point, some proposals call for the development of ASP-like publicly available RFID services, surfaced over the internet [24]. Such services might be used to conduct real-time data trades with partners and suppliers and could represent some significant advantages over current approaches given the point-to-point nature of traditional EDI. In supply chain scenarios involving many partners and data moving progressively through multiple stages that may be of interest to multiple partners, exposing such data over the internet via secure (web) services may represent the most efficient and economical way to achieve the level of data distribution required. Another novel application is demonstrated by HyCon framework [25], which combines into a contextual tapestry hypermedia and content links with RFID and Bluetooth enabled objects and locates them spatially on maps and within the hypermedia context. This innovation as seen as a direct effort to improve the limited browsing capabilities of PDA devices and to integrate such devices much more deeply into web-based content for richer browsing experiences. For example, one of their ideas is to enable 'surfing' of the physical world in the same hyper-contextual way as one browses the web. This is accomplished through web-services based guided-tours of actual physical spaces that utilize GPS and/or RFID reading capabilities to 'lead' someone through physical checkpoint/tags, for example, as one might wish to do on a tour of a walking tour of a historic destination like Boston. Currently they have realized a prototype based on Denmark. Others have looked at similar ideas utilizing RFID, bar codes and GPS as ubiquitous 'links' in landscapes of urban computing [26] that combine physical sites (museums, restaurants) with virtual capabilities (blogging, tagging, rating). Another interesting convergence between RFID and the internet demonstrates the two technologies complimenting one another to achieve collectively what neither could achieve alone. The idea has to do with using RFID-capable sensors in probabilistic ways to generate rich textual models of human behavior [27] which can in turn be trained to run unsupervised on the web in order to reverse-engineer other text-based behavior models. Models such as 'paying bills' or 'cooking dinner' can be useful in a number of human-behavior-dependent applications such as alerting and monitoring, automatic appliance control, etc. Still others have proposed entire web-services architectures upon which RFID systems can be managed and implemented throughout an enterprise [28].

3.4 RFID and Mobile Phones

There are obvious and deep synergies possible between mobile phone technology and RFID given the near-identical form factor of cell phones and small RFID readers and the fact that both are devices for remote data transmission. Not surprisingly, there are a number of interesting areas of research in this space, especially along the lines of combined devices, that is, RFID-enabled cell phones. Location-based games [29], for example, are a significant area of research. In Japan, researchers are using RFID-enabled cell phones to construct (private) profiles of user activity [30] which are then visualized in graphical front-end applications and include the ability to retrace actions, etc. This application echoes a frequently voiced concern in all aspects of RFID- privacy and security. For all of the richness and interesting possibilities that each of the RFID convergences imply, there are equally impactful privacy concerns that must be addressed. Given the sheer variety of convergent combinations of RFID and other networking technologies, one suspects that some of the data security and data privacy issues will almost certainly be overlooked and result in well-publicized breeches and unintended consequences. The specter of RFID cloning [31], for example, has proven to be a controversial issue especially in the area of human-embedded RFID chips where identify can effectively be stolen in much more permanent ways than those that are common today. On an entirely practical note, secure electronic payment through contactless RFID-enabled credit cards [32] is another example of the convergence of RFID and cell phones. In this case, the proposed system dramatically reduces the ability for thieves to steal one's credit card, as the payment method would require both cell phone and credit card RFID-based verification. Another idea that combines cell-phones and RFID technology has to do with location-specific web services [33], which are discovered by bringing RFID-enabled cell phones into the reading range of fixed RFID readers. These researchers are also prototyping their system with Bluetooth as well.

3.5 RFID and Wireless Networking

As is apparent in the various sections above, much of the research in the area of RFID combines more than one networking technology with RFID. In order to organize the paper we've only looked at two-dimensional categories (that is, those that portray combinations of RFID with other individual networking technologies) however many of the ideas presented thus far may be applicable to more than one of the particular combinations mentioned and that is certainly true in the case of converging systems involving RFID and wireless networking. One of particular interest has to do with an integrated home health care system [34] that actually monitors physical phenomena representing basic health metrics- such as blood pressure and heart rate- using RFID (for example, RFID tag embedded in blood pressure arm band), and then transmits the data via RFID to a local reader connected to a home PC. Once the data hits the PC, it is wirelessly interrogated by or uploaded to a remote health manager (such as a nurse or physician) for remote monitoring and safety checking. In particular it is thought to have applicability monitoring elderly and shut-in populations.

Another interesting RFID convergence has to do with leveraging the increasingly widespread (for example, city-wide) wireless networks provided in local areas in tandem with RFID to provide location-based services [35], similar to those mentioned in the section on mobile phones. Such services would leverage existing 802.11 networks and may include a 'locate your friend' service where you identify a friend's specific physical location at a crowded meeting spot.

3.6 RFID and Bluetooth

U-commerce extends the notion of e-commerce (electronic commerce) and m-commerce (commerce conducted over mobile devices) to include, among other ideas, the notion of *ubiquity*. One of the more interesting convergences between RFID and Bluetooth networking technologies has to do with enabling u-commerce [36]. The idea is ambitious- create a semantic annotation (middleware) capability for goods and products which enables enhanced discovery- i.e. richer semantic information, served individually and quickly to my device. To accomplish this system the authors created extensions to both RFID and Bluetooth protocols in order to make them interoperable at this level. Ultimately the system supports better consumer decision making and is a yet another novel example of bridging distinct networking technologies to derive new capabilities. Mobio Threat [37] is an educational game (teaching biology and chemistry) based specifically on the integration of Bluetooth and RFID, which allows the interrogation and interplay of locale and physical objects. A particularly interesting aspect of this research has to do with specialized reconnection protocols required for game play recovery.

3.7 RFID and Social Networks

RFID networks are also being combined with social networks in interesting convergences. One such example encourages multimedia data sampling and capture from various devices (including those which are RFID-enabled) to create blogs depicting the world(s) around us [38]. While such convergence of RFID and social networking hasn't yet become a major trend, Twitter can be viewed as a close cousin of such an idea- taking blogging down to a much smaller-grained, simpler process and simply capturing data for presentation, analogous in some ways to the role of a journalist. In a similar idea but with an interesting twist, some researchers have turned the RFID-enabled academic conference badges into social networking devices for collocated conferences where there are constraints on physical proximity [39]. Given the collaborative nature of academic relationships, one could imagine interesting possibilities by infusing one's paper-writing co-authorship relationships as part of the metadata exposed through such social networking channels.

3.8 Other

This final section briefly mentions a number of smaller but equally interesting areas where RFID is being combined in unusual ways with other types of networking to produce interesting results. The strength of peer-to-peer networking is leveraging one-another's computing resources to achieve some goal. In this case, the goal is cleaning RFID data (to facilitate more efficient reading) and P2P networking turns out to be an interesting choice of collaborative vehicle for accomplishing it [40]. The technique employs the RFID reader nodes as members of P2P networks that utilize shared information in helping to cleanse each-other's data, thus alleviating one of the most serious constraints in supply chain use of RFID-data reading congestion. RFID has also been brought together with SMS (text messaging) and Web-based GIS (geographical information systems) for an interesting implementation of remote asset management and spatial tracking [41]. Finally, some have proposed the implementation of RFID technology within optical telecom networks to capture the RF signals and leverage the increasingly ubiquitous logistics data they carry [42].

4 Summary

The wide range of networking technologies with which RFID has been paired makes this a perfect topic for a survey paper of this type. We have considered RFID convergence with other networking technologies in a variety of scenarios: RFID and IP networks, sensor networks, web-based networking, mobile telecommunications, wireless networking, Bluetooth, social networking, P2P networks, SMS and optical networks. Given the vast amount of ongoing activity in this field and considering that most of the research referenced is contemporary, this would definitely be an interesting survey to conduct periodically, perhaps every 18 months, to follow the changing trends and new ideas and to look retrospectively on which ideas, if any, emerge as dominant.

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