Computing with RFID: Drivers, Technology and Implications

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Abstract

Radio Frequency Identification or simply RFID has come to be an integral part of modern computing. RFID is notable in that it is the first practical technology to tightly couple physical entities and digital information. In this survey, we cater to the computing professional who is not familiar with the specifics of RFID which we discuss in the context of supply chain management, its most popular application. We begin with a primer on supply chains with particular reference to the relationship between efficiency and information flow. We recognize universal identification with bar codes and electronic data interchange as the two principle computing technologies that have played a central role in the optimization of supply chains. We then discuss RFID and supporting network technologies, and identify their novel features and capabilities. We proceed by examining the performance improvements in supply chain management due to RFID and differentiate between different levels of tagging. We explore consumer applications and services using item-level RFID in particular. Such applications offer novel opportunities for business but also raise important social and policy challenges primarily related to privacy protection which we discuss in more detail. We conclude by exploring how European law is attempting to address the new issues arising from the use of RFID, and look ahead at the challenges that computing with RFID faces before it can become an effective end-user technology.

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1 Introduction

Several authors would have you believe that RFID is the greatest information technology innovation: it will deliver cheaper, better quality and safer food for the global market; it will simplify the manufacturing of cars and airplanes; it will save the environment by allowing every single product to be recycled; it will save human lives by preventing medical mistakes; it will make the world a safer place by averting acts of terrorism; it will do away with counterfeiting, especially of drugs; and of course it will spark the next computing revolution by creating the Internet of Things. Few computer technologies have sparked such excitement.

In this survey we attempt to separate fact from fiction, and develop an understanding of RFID based on evidence and the experience gained through field implementations of this technology. A common theme will be RFID as the catalyst for change in business information system implementations due to its capability to intimately link physical and digital assets, and establish relationships that can be processed automatically without need for any manual intervention. For this reason, and despite its relative simplicity, RFID has found numerous applications. Its influence is nowhere more pronounced than in the supply chain, where its popularity has been growing rapidly. There are already several very large scale deployments of RFID within this sector, which often takes a leading role also in the development of RFID technology. RFID in the supply chain and its extensions in consumer services will also be at the center of our discussions.

We structure this discussion as follows: first we introduce the basics of supply chain management and the role that computing pays within it. Then we provide an analysis of RFID technology in this context and identify the role that it can play to provide novel information sources that significantly enhance its efficiency. Yet, the use of RFID in the supply chain has unintended consequences especially when objects are tagged at the item – rather than the container – level. We conclude by reviewing such implication with particular reference to privacy protection and identify areas where law and policy have to play a significant role if RFID would have a long term effect.

2 Supply Chain Basics

Supply chains are at the core of modern globalized open markets. Each supply chain has unique characteristics and requirements but they all comprise of a network of coordinated organizations which collaborate in diverse activities to transform raw material and components into finished products, and deliver

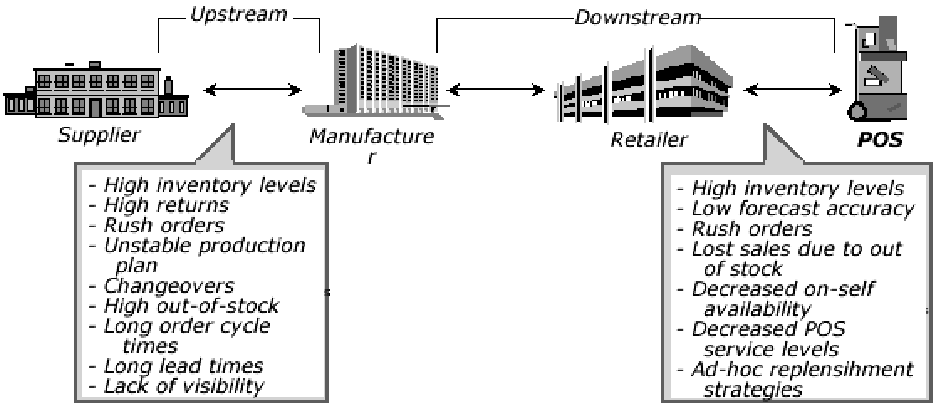

Fig. 1. An idealized typical grocery supply chain.

them to the end consumer. Such material and information resources move link by link from supplier to retailer across the supply chain adding value at each stage, bringing the product farther from the point of production and closer to the point of consumption.

A simplified example of a supply chain for grocery products is displayed in Figure 1: Raw materials are received by suppliers, who process them in usable forms for example, turning polystyrene and polypropylene granules into plastic film rolls that can be used for packaging, or fresh milk into pasteurized milk and stored into large containers suitable for travel over long distances. Processed materials are received by the manufacturer and used to fabricate and package the product which is then transported to a retail distribution center. From this location, products are delivered to retail outlets and displayed at the point of sale for purchase by consumers. To be sure this is a somewhat simplified view of the process, as at each link there would be more than a single bilateral relationship for example, several suppliers would be needed to provide the full list of materials required for the manufacture of a particular product, and many manufacturers would deliver products to the same distribution center. Nevertheless, Figure 1 provides a good model for thinking about the process and helps identify the main issues related to the performance of each step of the process. In practice the majority of supply chains would include a much longer and complex network of exchanges which spans great distances and more often than not state borders. Needless to say that supply chains provide great variation. As a point in case, consider the delivery of munitions to the field needed to support operations for the Department of Defense, or the special traceability requirements of so-called cold chains where products are temperature and environment controlled.

One could argue that it is possible to avoid such complexity and the complications of developing and maintaining a multi-partner supply chain by keeping full control of the whole process within a single company. Although this idea may be conceptually attractive, in actual fact this approach would require a single organization of enormous size which in some cases would far exceed even the largest companies in existence today. In fact, there is some evidence that such a massive organization would be highly inefficient and would suffer from internal difficulties that would negate any benefits derived from the internalization of the supply chain. Furthermore, collaborative supply chains have gained in prominence as a result of the globalization of production and commercial activity, and due to the dominance of network effects within this environment. Consequently, supply chain management has increasingly attained greater significance and is today a core factor in establishing competitive advantage. In turn, this fact has brought into focus the role of business relationships which extend beyond traditional enterprize boundaries.

According to the Council of Supply Chain Management Professionals, supply chain management (SCM) encompasses the planning and management of all activities involved in sourcing, procurement, conversion, and logistics management. These activities include coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. Note that SCM activities travel both upstream (from retailer to supplier) and downstream (from supplier to retailer) across the supply chain. For example, new products (traveling downstream) could be produced and delivered as a result of an order (transmitted upstream) placed to the pertinent distribution center by a particular outlet.

The principal metric for measuring SCM success is consumer satisfaction that is, whether the product on offer completely satisfies the needs of a particular consumer and if it is available for purchase at the appropriate time and location as required. This task clearly requires that demand for specific products must be predicted and matched to production and the ability to deliver so that the two sides are in sync. There are many reasons why this may not happen: products may not be produced or delivered in time or may not be delivered in the required mix (for example of colors, sizes, quantities and so forth), may be misplaced, may be stolen by employees or externals, or may have expired. Making an inaccurate prediction in excess of true needs can also have negative effects since the extra stock will not be sold and will have to be discarded at a loss. Finally, there are performance issues that are inherent to the modus operandi of the supply chain itself, primarily related to the time lag between ordering and delivery. For example, in cases when demand fluctuates considerably and cannot be met responsively, it is common practice that products are ordered in excess of what is required so as to maintain a stock buffer. Unfortunately, such safety stock orders create false demands lower in the supply chain which are amplified downstream and result in wasted effort and resources – this condition is often referred to as the bullwhip effect.

To provide good performance, it is necessary that SCM addresses the following tasks:

- Distribution network configuration, that is how to structure all levels of the supply chain network including the selection of suppliers, the number and location of production facilities, distribution centers, warehouses and retail outlets.
- Distribution strategy, that is the organization of transportation of products between the different links of the distribution network. Options available to SCM are centralized versus decentralized coordination, direct shipments, cross docking between trading partners, pull or push strategies, and the use of third party logistics.
- Inventory management, how to ensure that records of the quantity and location of inventory levels are accurate and updated in a timely manner, including raw materials, work-in-process and finished goods.

To be sure, to effectively conduct these tasks SCM requires detailed information management and coordination across business boundaries throughout the supply chain. As a result a particularly critical component in implementing any SCM strategy as this scale is the effective use of information technology. Despite the fact that to a certain extend SCM is about processes, training and business partnerships, it is inconceivable that its objectives can be achieved to any significant extent without computing and communications. In particular, it is necessary to integrate systems and processes taking into consideration the complete structure of a particular supply chain, to share information including demand signals, forecasts, inventory and transportation, and reduce delays in transmitting this information between trading partners.

3 Business Computing and the Supply Chain

Thursday 29 November 1951 marks the beginning of business computing. Before then, computers had only been used in scientific and military applications. On that day, at the offices of J. Lyons & Co [1] LEO, the Lyons Electronic Office, became the first ever software used to conduct business. LEO was able to calculate the amount and cost of raw materials required to meet the nationwide orders for bread placed with the company [10] and initiated a trend for computers to support and improve the efficiency of business processes through a detailed understanding of the objectives of business users.

Supply chains offer great variety ranging from supplying fresh food from the farm to the supermarket shelf, to delivering uniforms from the manufacturer

[1] J. Lyons & Co. was founded in 1887 to became one of the largest catering and food manufacturing companies in the world. At its height, Lyons owned the popular Baskin Robbins and Dunkin Donuts brands but in the 1970s the company was severely affected by high interest rates, and finally became defunct in 1998.

to the soldier in the desert. Yet, they all share the same objective: to keep the process simple, standard, speedy, and certain [32]. To achieve this goal, it is necessary that all trading partners across a particular supply chain exchange information frequently and accurately, that supply chain costs be minimized, and that all goods and services moving through the supply chain be unequivocally identifiable at all times. An essential element to any solution that can meet these requirements is the use of open, worldwide data standards for globally unique product identifiers and a universal product classification system, combined with internetworked information services that can be used to track and trace goods and services.

Automation in open supply chains is becoming even more important due to the increasing use of RFID which can provide the required high product visibility and the free-flow of information into fullu automatic systems that can identify product items and link them to their associated information without any manual input. This level of interoperability through direct machine-to-machine interactions at such large scale, demands the availability of open shared specifications describing every aspect of business activity.

In the decades since LEO became operational, two ingredients in particular have played a central role in facilitating such automation: the availability of standard product identification and classification schemes, and the ability to exchange messages in standardized formats about business processes between trading partners across a supply chain. Unique product identification in particular has become ubiquitous and highly visible through the popularity of bar codes which are exactly representations of such identifiers. Moreover, the majority of transactions between trading partners is carried out through some dialect of the Electronic Data Interchange (EDI) standard which defines templates for common business actions for example ordering and invoicing. We discuss each of these developments in turn in the following sections.

3.1 Unique Product Identification

Tracing the history of business computing in the supply chain, identifies a second landmark date as Wednesday 26 June 1974, when the first bar code was scanned, and the collected identifier used for a commercial transaction. This was the culmination of a long process that lasted over 30 years to develop automated ways of capturing product data. Since then, supply chain automation has grown rapidly and the use of bar codes has spread from retailers to suppliers and ultimately to the suppliers' supplier.

The history of modern bar coding begins in the 1940s, when in response to a challenge by the president of an American food chain, Woodland and Silver of Drexel University created a system to encode information in combinations of concentric circles printed on paper. At the time their solution was limited by the inability to automatically input the encoded product identifier in a computer system. This problem was not addressed until the mid-1960s and the advent of lasers which made reading bar codes practical. The initial idea received little attention in the grocery sector until 1968 when RCA, which had acquired the intellectual property, developed a similar symbol and corresponding scanner and tested it extensively during the early 1970s [3].

Bar coding was also investigated in the rail industry as a means of tracking individual railway wagons. By 1962, Sylvania Corporation introduced a system using optical scanning devices to read orange and blue colored bars on a non-reflective black background. By 1968 the colors were eliminated, and by 1971 about 95% of all railway wagons had been bar coded. At that point only 120 scanners had been installed, and recession in the mid 1970s led to the system being abandoned.

Owing to such diverging activities, it soon became apparent that separate groups would develop different and incompatible systems for product identification that could considerably hinder the wider acceptance of a common standard. As a result, in 1969 the American National Association of Food Chains (NAFC) proposed a product marking system to representatives of all sections of the grocery industry, including manufacturers, retailers, and retail associations. The result of these efforts was the recommendation in 1973 by the Ad Hoc Committee of the Grocery Industry of the Universal Product Code (UPC), a common standard for the representation of the information held in bar codes. By the end of 1973 over 800 manufacturers were assigned UPC numbers, and the following year scanners from IBM and NCR were supplied to retailers. It was such a UPC code that was used in 1973 for the first bar code based transaction.

3.2 Universal Product Identification

The original UPC was a ten digit code with five digits used to identify the manufacturer and another five for the product line, and also defined a symbol design that would be printed on products. A core management activity under the scheme is the allocation of prefix numbers to companies, to manage the numbering space and ensure that each number is unique. This task was assigned to the Uniform Grocery Product Code Council established for this purpose in 1971 and became Uniform Product Code Council in 1974 by which time it had over three thousand members. Since 1984 the Council is known under its current name, the Uniform Code Council (UCC).

Naming this solution the *Universal* Product Code was of course an exaggeration. Not only was it not universal, but it did not even extend beyond North America. Soon after their introduction, these ideas were taken over by European retailers and manufacturers and made truly international. Moreover, they were extended and developed in several ways for example, where UPC concentrated on the point of sale, the European approach adopted a supply chain perspective, and code semantics were further developed beyond the manufacturer/product identification pair.

This work was carried out by a core group of collaborating companies, which formed for this reason in 1977 under the so-called European Article Numbering (EAN) system. EAN worked closely with its national counterparts such as the UK based Article Number Association (ANA). Such collaboration was uncommon within the fiercely competitive consumer goods sector, and was the result of the clear need to adopt common open standards.

One of the new features of the EAN system that make it particularly flexible is the separation of data from the data carrier that is the product identifier from its bar code representation. This feature has enabled the introduction of more types of bar code symbols in addition to the original EAN specifications. For example, RFID tags can be used to encode existing EAN product numbers and this is indeed the method of choice for the ISO item-level tagging standards which we discuss in the following section. In any case, the focus on *item identity* rather than *product information* in automatic data capture has provided great adaptability and efficiency over the years, which seems to suit well current technologies.

EAN extends well beyond Europe and to mark this orientation in 1981 EANA was renamed to International Article Numbering Association (IANA). EAN codes are the standard product identification scheme across the world except North America, where UPC is still the dominant form. Several provisions ensure that the two systems are compatible, notably the formal agreement in 1990 between EAN and UCC to co-managed global standards for identification of products, shipping units, assets, locations, and services, as well as a variety of other business standards that have become known as the EAN.UCC system. To complete the integration of UCC within EAN International the organization was re-launched across the globe as GS1.

Looking closer at a typical bar code for example, the one following the EAN-13 standard[2] displayed in Figure 2, it is a symbol which encodes strings of 13 decimal digits, which represent unique identifiers for specific products following the Global Trade Item Number (GTIN-13) specification. This symbol can be read into a computer system using a (portable or fixed) low power laser scanner which can translate the sequence of white and black bars into the corresponding digits.

The encoded number follows a scheme designed to ensure that each number assigned to a product line is unique and includes a unique number which identifies a particular user (most commonly its manufacturer):

- The first two digits are called the indicator digits and specify the particular numbering system used. In the case of the EAN-13 bar code of Figure 2 the indicator digits correspond to the GTIN-13 system.
- The following five digits is the GS1 company prefix, which represents the manufacturer of the product.
- The following five digits represent the product code, which identifies a product line (but not individual items).
- Finally, the last digit is a checksum used by acquiring computer systems to confirm that the code has been retrieved correctly.

The company prefix which is also known as the manufacturer code is assigned to the particular business by GS1, while the digits corresponding to the product code are selected by the manufacturer.

The GTIN number itself does not contain classification information in it − information about the industrial sector, the country or the region where the product was manufactured, or the type of product (for example clothing, food, electronic device, and so forth) cannot be retrieved from the code. It is a simple unique identifier akin to a key in database parlance, and to obtain associated product information it is necessary to query a related product information repository. Moreover, the unique identifier characterizes the product for example, one carton of 1-liter orange juice made by the Squeezed Juice company, rather than a particular instance of the product for example, the specific carton of Squeezed Juice orange juice which was produced at 12:15:01 on January 1st 2007 at the Orange Grove facility.

Note that these are many bar code varieties several of these outside the EAN.UCC system, some of which carry additional information for example,

[2] Other EAN schemes follow a similar structure but support different identifier lengths.

Fig. 2. A typical example of an EAN-13 bar code.

sell by dates or product weight, or designed to deal with specific environments including pallets, locations, and returnable assets. Specialist formats have also been employed in specific situations, for example the datamatrix standard for small items used to mark surgical instruments, and new higher capacity symbologies have also been introduced some of which employ color and three-dimensional structures.

3.4 Electronic Data Interchange

The second core ingredient of modern supply chain management information systems unfortunately is not associated with a specific landmark, but has come about as a process rather than as a single event. Electronic Data Interchange (EDI) is the ability for direct computer-to-computer transactions between vendor and ordering systems for example to place orders, create invoices and reconcile transactions. EDI has very considerable advantages over paper based procurement systems since it can reduce the time needed for product replenishment, labor costs, accuracy and access to information. The final point is of particular importance: by recording detailed information about patterns of consumption over time it becomes possible to develop an accurate model of product use and a strategy for prodcut movement through the supply chain.

Development of EDI started in the early 1960s as a response to the perceived need for a common vocabulary of business exchanges. Of particular relevance to the current discussion is the work carried out under the remit of the United Nations Directories for Electronic Data Interchange for Administration, Commerce and Transport (UN/EDIFACT). Unfortunately, the resulting system has been particularly complex and overloaded, hard to deploy, and often leads to unnecessarily irksome implementations. As a result, several groups have identified and promoted the independent use of particular subsets that satisfy the needs of specific industrial sectors, specific business processes, or specific supply chains. For example, GS1 has developed EANCOM to support cross-border trade and cover only the functions required to effect a complete trade transaction.

Another case of a partial EDI vocabulary within a specific market segment defined with the EAN.UCC system is the Trading Data Communications standard (TRADACOMS). TRADACOMS was developed in the early 1980s and employs EAN codes for product identification. Similar to other EDI activities, TRADACOMS came about as a response to the desire of several leading retailers in the UK at the time to establish electronic communications with their suppliers which was failing due to different and incompatible message structures and content used by each company. Successful implementation of TRADACOMS in trials allowed electronic invoicing to become supported in law, and indeed the system is still widely used in retail applications.

3.5 The GS1 System

The benefits of the common product identification schemes and business message exchange formats outlined in the previous sections highlighted the advantages of an open and standard supply chain management system but fall short of providing a complete solution. The incorporation of GS1 as a global umbrella organization for such activities provided the structure for the formalization of the so-called GS1 System (One Global System), which aims to support the efficient operation and management of supply chains and in this way create added value for the consumer. This objective is addressed through the provision of the technological foundation for the construction of interoperable systems for asset tracking, traceability, collaborative planning, order management, and logistics across all the organizations participating in the supply chain. GS1 standards address three areas:

- Part I deals with unique identifiers for products, companies, and so forth and data standards for attribute encoding.
- Part II relates to the encoding of this information into data carriers such as bar codes and RFID tags.
- Part III sets data standards for automatic electronic communication through supply chains, including conventional EDI standards (mostly employed in closed networks) as well as the ebXML family of standards for open supply chains.

ebXML in particular is a recent development which employs modern technologies including the Unified Modeling Language (UML) and the Extensible Markup Language (XML).

In practice, GS1 is a complex system in perpetual development which affects a large business community coordinated by more than 100 national organizations operating across 133 countries. Over a million member companies worldwide use GS1 and every day more than five billion transactions are made using GS1 standards. GS1 national organizations play a critical role within this community: they help members implement current bar coding systems and business-to-business communications such as EDI, and also they represent their corresponding countries in international initiatives for new standards and solutions. Notable recent additions to the GS1 standards include reduced space symbology (RSS) bar codes, radio frequency identification (RFID) tags, and the EPCglobal network.

3.5.1 Messaging for Open Supply Chains

The design of EDI is limited by its focus on closed, proprietary networks and as a result in many ways it is not suitable for use over the Internet. This is primarily due to the fact that it was designed primarily as an one-to-one technology and lacks in flexibility. Moreover, the requirements for the development and operation of an EDI-based system have proven in practice to be quite significant and hardly affordable by small and medium sized companies, which until recently have been largely excluded from participating in electronic data exchanges as a result.

To address these restrictions and to capitalize on the business opportunities opened up by the Internet, ebXML has been introduced as an altogether new messaging technology for GS1 under the Organization for the Advancement of Structured Information Standards (OASIS). Unlike EDI, ebXML assumes that the communications substrate is the Internet and aims to provide a modular rather than a rigid set of specifications for conducting business. The use of open and well understood Internet standards implies that ebXML can be implemented at relatively low cost due to the fact that it is supported on commodity internet platforms.

Nevertheless, ebXML is a very extensive set of specifications with universal scope both in terms of geography and industrial sector [27] and is structured around the following parts:

- **Messages.** ebXML messaging functions directly extend EDI functionality and follow the standard Simple Object Access Protocol (SOAP) envelope-and-message format.
- **Business Processes.** ebXML offers standard models that capture the flow of business data among trading partners recorded using UML. This systematic definition of specific business processes is then used as the basis for common message sequences across industry boundaries. Several such processes have been recorded in detail.
- **Trading Partner Profiles and Agreements.** Complementing models of specific processes, ebXML also provides systematic representations of company capabilities to conduct e-business in the so-called Collaboration Protocol Profile (CPP). Using the CPP, a company can list the industries,

business processes, messages, and data-exchange technologies that it supports. Trading partners use such CPPs to specify Collaborative Protocol Agreements (CPA) that define the business processes, messages, and technologies employed.

- **Registries.** Registries are ebXML shared repositories that hold descriptions of industry processes, messages, and vocabularies used to define the transactions exchanged with trading partners in CPP and CPA formats. Such repositories can be queried by other business to retrieve details of e-business capabilities for inspection so as to locate companies with the capabilities desired in forming partnerships.
- **Core Components.** Core Components (CC) are standardized XML schemas that represent the core entities involved in ebXML scenarios. CCs are lower level descriptions of the main entities that participate in business transactions and can be viewed as the extension of more traditional GS1 data structures updated for use by open supply chains operating over the Internet.

3.5.2 Global Product Information Repositories

The final ingredient for effective data dissemination in the supply chain according to GS1 vision is the Global Data Synchronization Network (GDSN) specification [5]. GDSN maintains master data alignment, or else authoritative information about any entity that can be assigned a unique identity within the EAN.UCC system including products, prices, promotions, and locations. GDSN is a database-based mechanism (called GS1 Data Pools in GDSN parlance) of global reach that guarantees accurate and synchronized information across supply chains.

GDSN acts as a shared electronic directory between supply chain partners used to increase the quality of information across all supply chain activities and thus the efficiency of transactions. GDSN is a highly controlled environment supported by a small number of providers authorized by GS1, which are responsible for ensuring that the service is available and provides good quality information at all times. GS1 operates the root of the directory called the GS1 Global Registry, with holds information about the location of all participating data pools. Individual suppliers and retailers gain access to GDSN via subscriptions to local data pools (often provided by GS1 national organizations) and either publish or retrieve information pertaining to specific supply chain tasks.

Product information maintained within GDSN must be organized in categories so as to be useful and easy to access. Such structure is provided by yet another GS1 standard, the Global Product Classification (GPC), which defines a exactly such a hierarchical scheme. At the top of this hierarchy is the Segment which represents a particular industrial sector for example Food, Beverages and Tobacco. Within a particular Segment there are one or more Families which represent broad sub-divisions following in the same example a particular family would be Milk, Butter, Cream, Yoghurts, Cheese, Eggs and Substitutes. The next level in the GPC hierarchy is the Class which represents a collection of like product categories for example Milk and Substitutes and at the bottom is the Brick which represents product lines. Each Brick is associated with Attributes that define the specifics of the product line.

Products manufactured by a particular company would correspond to one Brick can also be assigned GTIN numbers which, as noted earlier, are printed on bar codes and affixed on products. The mapping between the GTIN and the corresponding Brick as well as detailed associated information about the product would be published by the manufacturer and via its local Data Pool into the Global Repository of GDSN. So, when a vendor receives a shipment of such items they need only query the GDSN to retrieve complete information about the product. This information is guaranteed to be fully up to date and authoritative and the whole process can be completed without any manual intervention and without the need for any direct bilateral communication.

Although clearly this is a much more complex system this approach removes all limitations inherent in closed systems like EDI, and does provide a scalable information infrastructure which is dynamic and open to all partners. The main benefit of this approach is that by federating responsibility for the maintenance of such data it is possible to improve accuracy of orders, invoices and other business documents, to reduce the number of delivery errors, and last but not least, reduces the administrative requirements related to maintenance of product and location information.

4 Supply Chain Optimization

Improving the performance of a supply chain depends on identifying inefficiencies and resolving their causes. Typically, this require detailed measurements of performance and then implementing changes at those areas that appear to block of products, services or information. Information technology can play a central role in two ways: providing the information needed to identify the causes of inefficiencies, and in improving communication between partner organizations.

4.1 Causes of supply chain inefficiencies

Recent research in supply chain efficiencies has identified several common problems and quantified their effects on performance, concentrating on five areas: out-of-stock, shrinkage, invoice accuracy, unsealable products and inventory accuracy [41]. Upstream supply chain inefficiencies affect the relationships of all trading partners and result in high out-of-stock conditions at the point of sale, high rate of returns and prolonged lead times. Inefficiencies in the downstream direction negatively affect demand forecast accuracy, which results in low on-shelf availability and thus loss of revenue despite the fact that products are available on site.

Preventing out-of-stock situations. Recent investigations of out-of-stocks [19] estimate their level for the retail industry to 8.3% (varying between 7.9% in the US and 8.6% in Europe). According to this study, in 47% of the cases this was a result of erroneous forecasting and ordering, in 28% by various upstream activities, and in 25% by inadequate shelf restocking. The latter requires particular reference as in this case the required product was available in the backroom of the retail store but was not available on the shelf). Another study [17] specific to the grocery sector found that for promotional items, the out-of-stock level was almost twice as high.

Preventing Shrinkage. Inventory shrinkage or simply shrink refers to the loss of products and can happen anywhere between their manufacture and the point of sale. In recent years shrinkage has been identified as a considerable problem [22] which may be as high as 1.7% of sales. Almost half of it is due to employee theft, but shoplifting and administrative errors also play a significant role.

Improving invoice accuracy.: Inaccurate invoices have a particularly painful effect as they lead to reduction of the expected revenue, and give a misleading view of the financial standing of the organization. Yet, they are not uncommon and on average they lead to deductions estimated to between 4.9 and 9.9% of annual invoiced sales [18]. Even top-10 retailers face invoice deductions averaging 5.9%. The main causes for such deductions are erroneous pricing, coupons and penalties.

Reducing unsaleables. Products may become unsaleable for a variety of reasons with damage being the most common, followed by expired and discontinued items. Loses due to this cause amount to about 1% of sales [30].

Improving inventory accuracy: In a recent case study of inventory accuracy over 70% of SKU records per store were found to be in error [35]. These figures are based on actual inventory counts at six stores in the US (each representing in excess of 9,000 SKUs) conducted specifically for this study and compared against the records held. Higher than actual quantities were recorded for 42% SKUs and lower for 29%. For an average inventory of 150,000 product items per store, the total difference was 61,000 items or else about 7 items per SKU.

Among all retail sectors, supermarkets are the most competitive as they operate with minimal profit margins. It is then even more important for grocery retailers to exploit any opportunities to reduce the inefficiencies outlined above wherever possible using information technology. Over the past fifty years they have certainly pursued this objective with considerable success.

4.2 Efficient consumer response

Grocery products or else Fast Moving Consumer Goods (FMCG) have been one of the main beneficiaries of the improved understanding of the structure and performance of supply chains. The development of strategies that employ this new understanding to achieve improved performance has become possible through the use of technology notably bar codes, messaging, and resource-planning and optimization software. Implementation of these techniques in the field requires extensive coordination between trading partners and to a large extent is orchestrated by Efficient Consumer Response (ECR), a voluntary industrial initiative to raise performance levels across the entire retail sector [31]. ECR promotes the premise that improvements will come about as a result of the continuous and detailed self-examination of processes and procedures across the sector, the development of concrete guidelines and recommendations, and by closely promoting their implementation. ECR was initiated in the United States but its perceived advantages from a business perspective have extended its scope to the rest of the world, with national and regional initiatives in action.

ECR has developed a specific strategy around three objectives:

(i) to increase consumer value,
(ii) to remove costs that do not add consumer value, and
(iii) to maximize value while at the same time minimizing inefficiency throughout the supply chain.

In practice, these priorities are used to identify and fulfil specific goals for example providing consumers with the products and services they require, reducing inventory, eliminating paper transactions and streamlining product flow. To meet these goals distributors and suppliers are making fundamental changes to their business processes that can only be enabled through the implementation of novel information and communication systems.

Nevertheless, fifteen years of ECR involvement and the introduction of information systems in production and logistics control have not completely removed inefficiencies in modern supply chains, which directly impact retail operations. Despite the fact that information is shared between trading partners more frequently and in finer detail, such exchanges are still not adequate to provide the required accuracy of demand forecasts and thus the scheduling of the replenishment process. Indeed, changes in patterns of consumer demand change frequently but propagate relatively slowly through the supply chain. As a consequence, upstream partners have an inaccurate, time-delayed view of the current situation, which is often the cause of the bullwhip effect discussed previously. Another direct consequence of low demand forecast accuracy is that trading partners have to maintain increased inventory levels as a security measure in response to unpredictable increases in demand, which further increased warehousing and logistics costs.

In practice, it is still common to forecast consumer demand by processing historical point of sale data, using decision support systems that utilize data warehousing and data mining techniques. One core limitation of forecasts conducted in this way is that they are not effective in taking into account the influence of promotions and other marketing instruments since the success rate of such mechanisms is generally hard to quantify beforehand. Even when the use of real-time point of sale data is possible, forecasts still have lower accuracy because demand patterns are changing rapidly and such fluctuations cannot be captured in a timely manner at the point of sale but have to be identified earlier in the consumption process.

One approach developed within ECR to address the problem of accurate forecasting is the so-called Vendor Managed Inventory (VMI) where the vendor, rather than the customer, specifies delivery quantities sent through the distribution channel [40]. This reversal of roles in the procurement process has become possible through the deployment of EDI. VMI had succeeded in reducing stock-outs and inventory buffers in the supply chain. Common benefits of VMI implementations include a significant reduction in supply chain length, the centralization of forecasting, and frequent communication of inventory levels. VMI has a particularly noticeable effect on fleet management since the order in which delivery vehicles are loaded is defined by the system with items that are expected to stock out have top priority, then items that are furthest below the targeted stock levels, then advance shipments of promotional, and finally, items that are least above targeted stock levels.

In addition to EDI, VMI also depends on the common use of universal product identifiers and bar codes to record and process shipments with only limited manual intervention. Bar coding in particular is essential for the automated initiation and entry stages of the order cycle and can reduce the total cycle time by several days at a time. When used together, standardized messaging and bar codes can enable collaborative relationships in which any combination of retailer, wholesaler, broker and manufacturer can work together to seek out inefficiencies and reduce costs by looking at the net benefits for all participants in the relationship. Such techniques work at the Store Keeping Unit (SKU) or container level for example a case, a pallet or a truck. However, an inherent limitation of existing SG1 bar code schemes is that they cannot differentiate between two SKUs from the same product line. As a result, the specifics of a particular SKU cannot be recorded unambiguously and so large inaccuracies in inventory levels can be observed [24].

Overall VMI has been successful in significantly reducing inventory levels and the number of stock-outs. The latter issue is particularly important not only because of lost sales but also because shelf availability is central to supermarket strategy. Indeed, a significant proportion of supermarket profit margins are due to interest free periods for products already available on the selves. Thus, one of the main concerns of retailers implementing VMI has been the perception that reduced inventory will result in less product being available on the shelves at any one time and therefore loss of market share. A partial solution to the problem is to fill shelf space with other SKUs from the same vendor but this approach does not fully address the problem.

The quality of information flow between trading partners can be improved in two ways that can have significant impact:

(1) By extending unique identifier schemes at the containment level and in such a way that different instances of the same type of SKU can be unequivocally identified. This way individual containers can become traceable and associated with location and other related meta-data. Moreover, the concept of identification can be taken into the next level and develop schemes that identify uniquely specific product items thus assigning a single identity to a particular product item.
(2) By fully automating the product identification process so that the need for manual operation is removed. This can remove a variety of errors in data input but also with the appropriate hardware provisions it can supply faster and more points of control across the supply chain.

Both of these improvements can be achieved using RFID technology which we discuss in detail in Section 5. A more ambitious approach to improve forecasting accuracy involving RFID would aim to capture information much earlier in the consumption cycle for example, when products are removed from the display, or even earlier when already purchased products are used by the consumer and their packaging discarded thus initiating the replenishment process. The latter approach would require fully automated unique product item – rather than container or SKU – identification and is further explored in Sections 8 and 9.

5 RFID Technology Basics

Although RFID is a relatively simple technology it offers a unique advantage in that it allows highly compact battery-free electronic devices, the so-called tags, to be embedded in objects, artifacts, locations or living organisms and automatically identify their carrier using wireless communication and without any need for manual processing. Commonly, this identification information would be a code that would uniquely pinpoint the carrier within a numbering scheme. In some cases, a tag would also hold and transmit a small amount of additional data associated with it. The information help in a tag is retrieved by a higher capability device called the reader which transmits power to the tag and directs the communication. As a result, RFID is never used in isolation but it depends on a variety of supporting information technologies to create usable systems.

In this section we will consider each element of a complete RFID system, but before delving into the details it is worth exploring how the different components fit together. Unlike other wireless communication systems, RFID is asymmetric in that the tag and the reader are devices with very different characteristics that take distinct roles in the process. In addition to readers and tags, an RFID system would also have a number of associated services which provide the reader with a scan plan and receive the results of the actions specified. The sequence of operations follows the following common pattern which is depicted in Figure 3:

(1) An observation plan is programmatically specified by the system developer and implemented in purpose specific middleware, which relays the instructions to one or more readers for execution.
(2) Upon receipt of the observation plan the reader starts transmitting with the immediate effect that tags within its vicinity receive power which they can use to power up.
(3) After conducting an inventory of all tags that are within range, the reader selects a specific tag according to the parameters specified in its observation plan, and interrogates it specifically for its product identifier and possibly associated information.
(4) The tag receives instructions, checks the contents of its memory and responds to the query of the reader (the actions in steps 3 and 4 may be repeated several times per second).
(5) The responses from all relevant tags are processed, filtered and aggregated

by the reader and a report is returned to the middleware or some other consuming application.

Further to the actual RFID processing steps, the reader would often communicate with network management software to report its status and also with reader-specific management software that would monitor operational parameters specific to RFID for example the correct operation of all antennas attached to the reader.

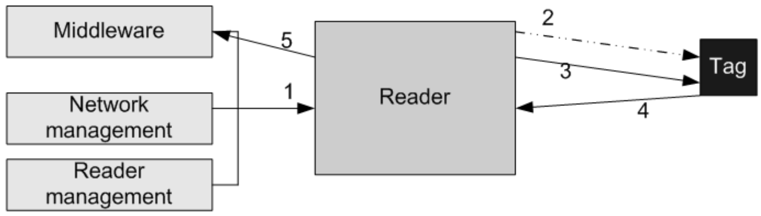

Fig. 3. Components of a complete RFID system and sequence of events.

5.1 Operating Principle

Despite its numerous applications, RFID is a relatively simple technology which allows for the short-range wireless transmission of small amounts of information often representing a single identifier that gives it its name. As noted earlier, RFID is asymmetric in that communication is established between peers with distinct roles: one peer, the so-called reader or interrogator, takes on the role of the transmitter and the other, the so-called tag, the role of the responder.

This split of roles allows the tag to to communicate by modulating the electromagnetic waves emitted by the reader instead of creating its own transmission (cf. Figure 4). This approach implies that a complex reader can be used with a very simple tag of small size, which can be built at very low cost. Moreover, in the case of passive RFID tags electromagnetic waves emitted by the reader carry enough energy to be used by the tag (using the coupling effect induced on the tag antenna by the electromagnetic carrier wave) as its source of power.

These two core ideas behind RFID, namely communication by reflection and remote activation using radio frequency, were first discovered in the 40s and the 60s respectively. But it was not until the mid-70s that fully passive relatively long range systems became possible (for a more detailed discussion of the history of RFID see [29]) although early tags were still limited by the non-availability of high capacity, high-performance chips. At that time, RFID could only provide up to a dozen read-only bits on massive die sizes which occupied most of the tag volume. Shrinking electronics, especially in the 90s, have been critical in the development of the current generation of tags which

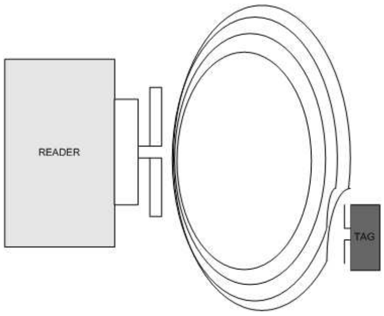

Fig. 4. Communication by reflection in ultra high frequency RFID tags.

are both significantly more power efficient and provide higher storage and computational capability - both as a result of miniaturization.

5.2 RFID types

One particular type of RFID, the so-called active tags, use batteries as their source of power and are not wholly dependent on the reader to provide energy. Such tags have considerable advantages over passive tags that draw all their power from the reader signal, as they transmit at higher power levels and thus have longer range and support more reliable communication. Moreover, active tags can operate in particularly challenging environments for example around water, it is easy to extend them with additional sensing capability for example temperature sensors, and they can initiate transmissions, but they stop operating when their battery expires. Despite their advantages, the current interest in RFID is solely due to passive tags which do not depend on batteries and thus do not require recharging or replacement. Active RFID on the other hand is just one of an increasing number of wireless local area communication technologies and as such it is of limited interest to this survey. In this review we only consider passive tags as they are the only viable solution for large scale deployments. For this reason, we will refer to passive RFID simply as RFID, without further qualification.

RFID tags naturally split into two main categories: those that use the magnetic component generating the near field of the radio wave, against those that use the electric component, which generates the far field. Near-field tags communicate by changing the load of the tag antenna in such a way that they control the modulation of the radio signal in a process appropriately called load modulation. These changes can be detected by the reader and decoded by examining changes in the potential variation in its resistance. Because the magnetic field decays very rapidly with distance from the center of the reader antenna (inverse cube ratio), the changes to be detected by the reader are tiny compared with its own transmission. For this reason, the tag modulates the radio signal in such a way that it responds in a slightly shifted frequency from that of the reader (what is often referred to as the sub-carrier frequencies).

Power transmission from the reader to the tag is by magnetic induction (the principle employed by power converters) and for this reason near-field readers and tags have a characteristic antenna design that also makes them easily identifiable: their antenna is a simple coil. The effectiveness of this process depends on the strength of the near field at the tag location which in turn depends on the distance between the center of the reader and the center of the tag antennas (and the particular frequency used). In any case, at frequency f the near field ends at distance proportionate to $\frac{1}{2\pi f}$ from the reader antenna. For example, at 13.56 Mhz, the frequency used by the popular ISO 14443 standard, the near field extends to about 3.5 meters from the reader. However, in practice ISO 14443 systems would consistently work at a maximum range of approximately 30 cm using medium size antennas on the reader (radius approximately 20 cm) and credit-card size tags.

One of the advantages of the 13.56 Mhz frequency that makes it so popular, is the fact that this section of the wireless spectrum is assigned worldwide to smart cards and labels and hence it is globally available to the vast majority of RFID applications. Other frequencies commonly used by near-field RFID are within the 120-136 kHz range but these are loosing rapidly in popularity as they can only be employed for very short range communications. Their short range makes them unattractive for applications as in most practical situations they necessitate contact of the card and the reader (but not of the electronics directly).

RFID systems using the far field of the carrier wave operate using a technique called backscatter rather than load modulation. This process is very similar to the operation of the radar in that the tag reflects back a small part of the electromagnetic wave emitted by the reader. The reflection can be used to transmit information by examining the so-called reflection cross section, that is the signature of the component of the wave that has been sent back to the reader, and comparing it to the original. In practice, data are encoded by the tag by turning on and off the load connected to its antenna and thus shifting the reflection cross-section between two clearly identifiable characteristic signatures. Similar to near-field RFID, also in this case there is very considerable loss of power during the reflection process and readers have to be sensitive to less than a microwatt in most cases.

Because of the involvement of the far field, tag and reader antennas are dipoles. This fact can again be used to identify far-field tags via simple visual inspection. Far-field RFID commonly operates in the UHF band between 865-956 Mhz but note that the complete range is not available to applications globally (and there are also radically different signal power output limitations especially between Europe and the US). Instead, common far-field tags are able to

	HF (near field)	UHF (far field)
Frequency	≈ 13 Mhz	≈ 900 Mhz
Spectrum Allocation	Uniform	Fragmented
Cost (per tag)	< 15 cents	< 15 cents
Range	< 30cm (1m max)	< 4m (10m max)
External Interference	No	Cellular phones
Memory capacity	4Kbits	256bits

Table 1
Comparison of HF versus UHF RFID technologies.

respond in the complete range and it is the responsibility of the reader to select frequencies that are allowed within a particular regulatory region (typically 865-869 Mhz in Europe, 902-928 Mhz in the US and 950-956 MHz in Japan). Far-field systems allow for longer range communication and it is common to achieve between 3 and 4 meters using approximately 30cm antennas and 10 cm tags. Using larger antennas and power amplification the range of such a system can reach up to 10 meters. More detailed descriptions of far-field RFID performance can be found in [8].

5.3 Readers

An RFID reader or interrogator consists of three main components (cf. Figure 5):

- One or more antennas, which may be integrated or external.
- The radio interface, which is responsible for modulation, demodulation, transmission and reception. Due to the high sensitivity requirement, RFID readers often have separate pathways to receive and transmit.
- The control system, which consists of a micro-controller and in some cases additional task and application specific modules (for example digital signal or cryptographic co-processors) and one or more networking interfaces. The role of the control system is to direct communication with the tag and interact with applications.

RFID readers are increasingly becoming complete network computing devices (akin to routers) that provide advance processing of RFID observation streams, and wired or wireless connectivity to the internet. Such readers would receive a scanning plan from a driving application or other middleware, which they would implement by issuing state transition instructions to the tags within their range. The latter step usually has three stages: broadcasting to all tags within range and receiving responses, selecting a particular tag as the peer

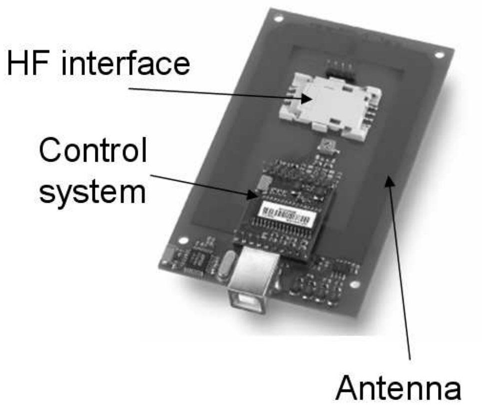

Fig. 5. RFID reader and subsystems.

for communication, and exchanging information with the selected tag. This process can be quite complex especially in the case where a large number of tags are within range or when two or more readers overlap. In such cases, additional collision avoidance techniques must be implemented to ensure that communication is organized in a structured way so as to allow all tags to participate in this process [11].

5.4 Tags

The tag is a far simpler device and consists of:

- The antenna.
- A capacitor that stores harvested power.
- The chip, which in most cases implements a simple state machine and holds the object identifier.
- A protective paper or polymer enclosure, which guards against rupturing the antenna that would result to the immediate expiration of the tag.

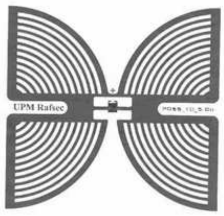

Fig. 6. Gen2 RFID tag operating at UHF frequencies.

A typical example of a modern tag is the EPC Class 1 Gen 2 [8, Chapter 4] which operates at UHF frequencies (cf. Figure 6). The chip has a relatively complex non-volatile memory structure divided in four distinct areas (cf. Figure 7). The reserved memory bank holds two 32-bit passwords the “access” password for gaining access to the contents of the tag, and the “kill” password that when presented permanently disables the tag. The EPC memory bank contains the Electronic Product Code, a universaly unique identifier assigned to the object, location or other asset on which the tag is attached, and optionally other metadata. The Tag Identification bank contains information about the type and the manufacturer of the tag including a unique serial number which identifies the tag itself. The user bank is optional and can be used freely by applications.

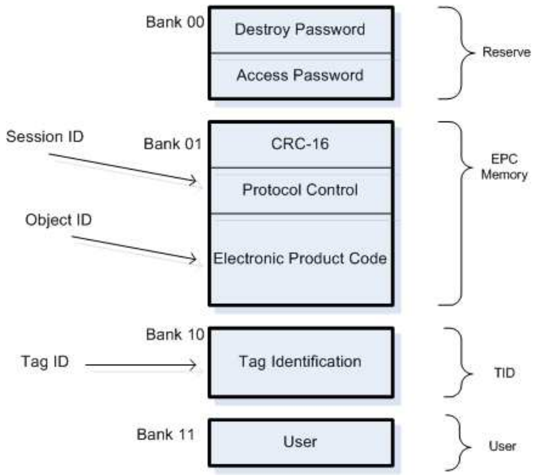

Fig. 7. Memory layout of a EPC Gen 2 tag.

It should be clear from this discussion that a single tag holds several identifiers or codes that correspond to different functions and have distinct roles and semantics, including a fixed tag ID and a writable object ID. Tags often use a third identifier the so-called session ID (in the case of Gen 2 tags, this is a pseudorandom number generated by the Protocol Control section), which is used by the reader to address the tag during a particular session. The session ID is roughly equivalent to the MAC address of a typical wireless networking physical layer protocol but in the case of Gen 2 it is only locally unique. Alternatively, the session ID may be fixed and stored in the tag memory as is the case for ISO 14443 Type A tags. Note that tags that employ this approach can be easily traced using the session ID as a handler, a fact that raises very considerable privacy and security issues which we discuss in more detail in Section 10. For this reason most recent tag protocols implement a randomization process whereby tags use a pseudo-random number each time they are interrogated by a reader so as to avoid easy tracing.

5.5 RFID as smart product labels

Although it has been noted that more than one identifiers stored in a tag, all but one are involved in low level operations and are thus of limited interest for enterprize computing. The object ID is the identifier that is related to the product, container or location where the tag is affixed. One clear use of this stored information is as a direct replacement of bar codes: the exact same information stored in a visual representation can be stored in a tag in electronics and transmitter over radio frequency. Even this simple substitution of bar codes with RFID provides considerable advantages, namely:

- higher capacity, so that larger identifiers can be stored or even additional metadata
- higher data read rate, so that many more product labels can be read in very short period of time
- the tag is rewritable, so new data can be added during the product lifetime or old data can be updated or changed to reflect changes in the product
- greater resilience to damage, especially since the RFID tag could be embedded safely in the product fabric itself
- greater read range and independence from line of sight requirement
- anti-theft support, as tags can be identified at exit points.

Of course, despite these advantages a direct replacement of bar codes with RFID tags has very considerable cost implications since bar codes are more often printed with packaging and have no cost at all.

Although valuable in in some cases clearly desirable, such a direct substitution of bar codes for RFID would fail to capitalize on the full range of opportunities offered by the technology. Moreover, it would fail to recognize and build on top of the current generation of network infrastructures which have advanced since the introduction of the bar code. As a result, the new circumstances combined with the capabilities of RFID offer a unique opportunity to re-think and re-design systems of unique product identification. There are several current proposals on to best extend current schemes and in the next section we review some of these proposals with particular reference to the work conducted within the EAN.UCC system.

5.6 Identifiers

The most successful numbering scheme in terms of industrial adoption so far that is specifically developed for RFID and use in the supply chain is defined within the Electronic Product Code (EPC) specifications, part of the EAN.UCC system. Unlike other generally available RFID standards, EPC defines both how and what data will be stored in the tag including the tag memory layout (as described in the previous section), for communication with readers, and for the composition and layout of a unique identifier scheme which

HEX	30700048440663802E185523
Binary	0011000001110000000000000100100001000100000001100 110010000000000000101110000110000101010100100011
URN	urn:epc:tag:sgtin-96:3.0037000.06542.773346595

Filter	Company Prefix	Item reference	Serial Number
3	0037000	06542	773346595
Shipping Unit	P&G	Bounty Paper Towels (15 pack)	Item UID

Fig. 8. Example of an EPC SGTIN-96 tag and its decoding. The top table shows the actual forms of the EPC in different stages of the encoding process and the bottom shows the interpretation of the SGTIN-96 identifier in particular.

extends existing GS1 schemes.[3] The EPC identifier in particular can follow one of several schemes depending on whether the tag is used to identify a product container or item, a location or some other asset.

The most important type of identifier encoded in EPC is the Serialized Global Trade Identification Number (SGTIN) which comes in two version of different lengths (96 and 198 bits correspondingly). SGTIN-96 codes are made up of six parts namely,

- Header, which identifies the tag as an SGTIN-96 (8 bits).
- Filter Value, which allows the pre-selection of the object type (3 bits).
- Partition, which indicates the split of the last 82 bits between the remaining three fields (3 bits).
- Company Prefix, contains the GS1 company prefix (20-40 bits).
- Item Reference, contains the GTIN reference number and identifies the product line (4-24 bits).
- Serial Number, is the unique identifiers of the specific tagged item (38 bits).

In following with common practice within GS1, the Header, Filter, Partition and Company Prefix sections of the EPC are provided by GS1 so that their use and assignment is coordinated and guaranteed to be uniquely defined, but the Item Reference and Serial Number are assigned by the manager or else the manufacturer of the product. An example of an EPC encoding an SGTIN-96 and its interpretation is displayed in Figure 8.

[3] The specification also includes a Filter Value which is not part of the identifier but provides a shortcut in that it is a quick way to identify the particular type of identifier encoded in the tag and used for fast preselection of particular tag types.

ECP also provides schemes for tagging other types of resources in addition to product items, including shipping containers (for example pallets and other SKUs), returnable assets (for example fruit cases) or general asset items, and locations. In additional to these identifiers defined by GS1, there are also provisions for the inclusion of general purpose identifiers within EPC as well as resource identifiers following the Department of Defense numbering schemes.

Looking closer at the Serialized Global Location Number, this identifier is a serialized form of the Global Location Number (GLN) defined within the standard EAN.UCC system, and includes provisions for an extension serial number that represents internal company locations that are not openly available to external parties. SGLNs follow a very similar structure to SGTINs with header, filter, partition and company prefix. The last past of the GLN is the location reference which is a number the semantics of which are at the discretion of the manager. Since these numbers cannot be interpreted without access to their definitions, it is necessary for a company to publish the appropriate correspondence in a publicly available location which is often the GDSN.

One point that sets GLNs apart from other similar systems is that they define a rather extended concept of location in addition to physical places, which in the context of the supply chain would often be stores, warehouses, manufacturing plants, warehouse gates, loading docks or vending machines. GLN also includes within its scope legal (for example companies, subsidiaries or divisions) and functional entities (in most cases these would be departments within the company for example, accounting or fulfilment). In any case, this unique identifier can be encoded in an RFID tag which can be automatically read by interrogators within its vicinity, which can subsequently resolve this information through the GDSN and thus discover their location.

The Serial Shipping Container Code follows the common structure with the notable exception that its serial number segment is defined by the standard EAN.UCC systems. Similar structure is also followed by the final two types of indemnifiers called Global Returnable Asset Identifier (GRAI) and Global Individual Asset Identifier (GIAI). Finally, EPC provides for two additional types which are defined outside the EAN.UCC system, namely the resource codes defined by the Department of Defense specification for military supply chains and a general purpose type predictably called General Identifier (GID-96) which is a catchall for other uses of the EPC tag specifications.

A competitive scheme to EPC is the ISO/IEC 15459 specification on unique identifiers with provisions on registration (Part 2), common addressing rules (Part 3), transport unit address provisions (Part 1), and item-level tagging for the supply chain (Part 4).

Data Identifier	Issuing Agency Code	Company	Serial Number
25S	LE:EDIFICE	E999	C204060897294374

Fig. 9. ISO/IEC 15459 world wide unique serial identifier example. The object ID stored in user memory of the tag is 25SLH:EDIFICEE999C20406089.

Under this scheme, a guaranteed world-wide unique serial object identifier (i.e. the object ID) is associated with an artefact by its manufacturer at production time. ISO 15459 codes have four parts: data identifier (DI) header, issuing agency code, company ID, and serialized item code (cf. Figure 9 for an example). In conformance to previous related ISO standards each part of the code holds alphanumeric digits rather than numbers. The DI specifies the structure of the contents of the object ID and follows the specification of ISO/IEC 15418 encoded under ANSI MH 10.8.2 provisions. For example, DI set to 25S specifies that the object ID is a globally unique serial object number, and DI set to 2L specifies that the object ID is a location specified in a format defined in a subsequent field, for example a post code. Rules for the coordination of the address space are also defined in the standard with the Netherlands Normalization Institute being the only authorized registrar that can assign IACs. EDIFICE, an association of electronics suppliers, is such a registered issuing agency and can thus provide its members with their individual unique company identification numbers. Each member can then decide internally on how to structure the object serial numbers. A common approach is to separate the number in two parts, the first identifying the type of the object – often referred to as product class – and the second identifying the particular item within this class – often referred to as item serial number.

An important feature of ISO 15459 is that unlike EPC it accommodates a variety of existing product classification schemes that can be used as object identifiers. For example, the currently most popular way to tag objects is by way of a barcode, mostly using identifiers specified with in the EAN.UCC system that are excluded under EPC. This approach also allows the incorporation into the system of a number of other domain specific numbering schemes under a unified hierarchical classification. For example, ISO 14223-2 defines a code structure specific for use for animal tracking including information on the the species and the premises where it is held. These codes are incorporated under ISO 15459 simply by setting DI to 8N. This facility also allows improved interoperability with other competing or emerging numbering schemes which can be incorporated under particular DIs as well as provide flexibility for future extensions.

Although not evident from the previous descriptions, EPC also supports interoperability with ISO standards albeit at a lower protocol layer. Gen 2 tags provide a parity bit as a toggle to indicate the type of identifier stored in their EPC memory bank (cf. Bank 01 in Figure 7, the Numbering System Identifier is part of the Protocol Control section) so that other numbering systems can be used instead of EPC. Although the EPC scheme clearly has few differences with the previous ones and indeed several limitations when compared against ISO, it has nevertheless attracted considerable interest due to its exclusive supply chain focus and the fact that it provides a complete set of specifications for middleware, resolution, discovery and repository services (cf. Section 6). Moreover, several IT vendors have already integrated these specifications into their products and as a result the EPC standards have gained considerable advantage against competitors.

6 RFID Software and Network Services

A recurring theme in the discussion of modern GS1 standards is their dependence on the Internet for disambiguating the semantics of the different types of identifiers that are retrieved either from bar codes or RFID tags. Until now, we have only considered static data, that is mappings between identifiers and their representations which are defined at the time of manufacture and do not change over the lifetime of the product. Such data are well served by the repository and network infrastructures developed for GDSN that can provide pointers to authoritative information.

However, GDSN is limited in one particularly important way that is critical for effective supply chains, namely in that it does not trace products as they move from trading partner to trading partner and from location to location. Rather, the GDSN maintains general information about product lines and their attributes including pricing. The capability to do so is clearly fundamental in monitoring the flow upstream or downstream. To this end, in addition to GDSN a complimentary set of network services are defined within the EPC specifications that target information related to specific product containers and items and their complete history as they cross the supply chain [16].

6.1 Middleware

One immediate implication of the construction of such a network is its massive size: the scope of the network is for every single product manufactured everywhere in the world to be tagged and tracked. Clearly this process generates enormous quantities of data that must be available online for querying by all participants. As a result it is necessary to supply as a core feature of the network mechanism that reduce the volume of information that propagates between systems. One way to achieve this is by only recording events that make sense at the business level rather than for example every sighting of a particular tag.

Recall that communication is always initiated by RFID readers that may scan for tags several hundred times per second. As a result, a particular product may be observed by a certain reader several times although its condition has not changed. Keeping a record of all these observations would be unnecessary and would not provide any useful information. Instead, such raw observations should be aggregated and filtered into higher level events that are significant. This is the role of RFID middleware which provide exactly this functionality. Moving in sequence from the lower level where observations are acquired by a reader towards application level processing, RFID captured data enters the following stages:

- *Collect observations:* Readers interrogate their vicinity for the presence of tags and subsequently request and retrieve object IDs and potentially additional data stored in the chip memory (some systems would require an intermediate authentication step to allow access to this information). Depending on the application, the duration of the interrogation cycle can vary considerably. For example for e-passport applications a read cycle could last up to a minute, while in supply chain applications several hundreds of tags would be read per second. The read phase could be followed by a further write cycle as is the case in ticketing applications where information about the current trip would be added to the ticket. Additional sensors and actuators may be activated at this stage for example temperature sensors could be used to record the environmental conditions in which a particular object has been observed and LED displays could be operated to indicate the state of the object.
- *Smooth observation data:* Raw observation data can be erroneous and incomplete as a result of read errors. Smoothing observations is the process of cleaning the collected data from incomplete reads that are discarded; from IDs recorded due to transient and thus irrelevant objects that must also be removed; from indeterminate reads must be resolved (for example using authoritative records from local persistent storage); and last but not least tags that have not been read must rescanned.
- *Translate observations into events:* Following smoothing, observation data are still not useful to applications which are interested in higher level events. For example, in a supply chain application it is not relevant to the business logic layer if a tag has been read by a particular reader but rather the fact that a specific pallet containing particular product items has entered the warehouse through a specific portal. This transformation of lower level observations into higher level application events is typically achieved via filtering and aggregation.
- *ID resolution and context retrieval:* Specific object IDs recorded in observations and events must be associated with object descriptions and related contextual-use data retrieved. This conversion requires access to network

services that play a twofold role: (i) to map object IDs to network service locations that can be further queried about object details, and (ii) to respond to specific queries related to the current condition, the properties and the history of the object.
- *Dispatch and processing of event data:* Application level events must be returned to consuming applications for further processing. For example, a pallet entry event would trigger updates of inventory records to include the items contained in the identified shipment.

Of course this process works bi-directionally that is, applications control data flow by defining events of interest and by declaring their interest to the RFID infrastructure. An orthogonal layer to the application execution profile is infrastructure management that is, maintaining configuration and status information related to the operating condition of RFID readers and other sensor elements [7].

The sequence of tasks outlined above is carried out by distinct network segments [6]: observations are collected at the reader level outside the IP network; observation processing and event translation at the network edge by the event manager; and application logic at the network core (or data center) level. A layer of mediation between the network core and edge is provided by the network services and other event consuming applications, which have the role of resolving identifiers into object descriptions and the subsequent querying for associated and context data. Put together, these distinct elements define the RFID stack depicted in Figure 10. A notable feature of this approach is the introduction of the event manager [4], which implements the translation of observations into events by:

- Bridging the IP and RFID networks by translating RFID observations into higher level events via filtering and aggregation.
- Managing the RFID reader infrastructure and related sensor and actuator devices.
- Offering a single interface to applications.

6.2 Programming RFID

Event managers require specific rules to translate observations into events. Such rules are often defined in terms of a tag scan and query plan, specified through an appropriate reader abstraction layer, which is relayed to and executed by the reader infrastructure. A scanning plan specifies the frequency of data acquisition, how many attempts are made, triggering conditions, and so on. It may also include information about the specific components of each participating reader that is employed for example which of the attached an-

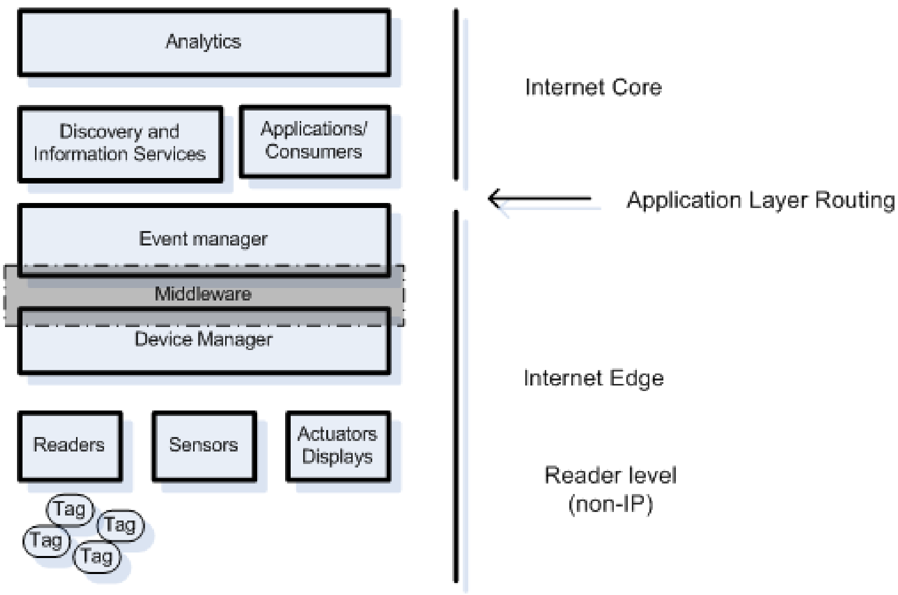

Fig. 10. The RFID stack.

tennas will be activated. Naturally, this device abstraction layer also provides facilities for the discovery of reader capabilities (for example supported functionality, attached components, software versions and so forth) and can also request the pre-processing of the observation data if this functionality is supported by the reader. Finally, the device abstraction layer can also potentially support actions predicated on a triggering observation for example when a motion sensor detects movement. Examples of such device abstraction layers are offered by the Reader Protocol [RR] part of the EPCglobal standards and the generic interface of WinRFID [34]. Particular reader manufacturers have also developed such abstract device interfaces but these are less useful as they can only be used with readers from specific suppliers.

The event manager provides application programming interfaces for event discovery, subscription and reporting [12,36]. This allows client applications to find what events are available and define new ones, subscribe to those of interest and receive reports with results. Events are defined over event cycles that is, delimited time intervals over which observations are processed. Note that although observations and events are related to read and event cycles correspondingly, the event manager decouples their respective domains and provides a clear separation of scope (cf. Figure 11). While the adoption of cycles as the main modus operandi for the event manager may appear limiting this is not so, as in addition to defining cycles either periodically or within fixed time slots, it is also possible to have arbitrary bounds defined on triggers fired by specific observations or by software interrupts or by external notifications.

Filtering and aggregation processing by the event manager aims to identify

Fig. 11. The RFID event manager.

specific patterns in the event data and to summarize data collected from different readers over several event cycles correspondingly [42]. Filters work by applying include or exclude regular patterns that is, by setting rules that define ID lists or ranges to be included (or excluded) in the processing of observations. For example, following the EPC filtering specification, the exclusion filter `epc:gid-96:18.[321-326].*` encountered while processing EPC tags specifies that the product range that corresponds to product codes between 321 and 326 will not be processed irrespective of the serial number of the objects recorded. Similarly the aggregation pattern `epc:gid-96:*.*.X.*` results into grouping observations by product code and reporting only the total number of observations for each class of product. Due to relatively frequent read errors such filtering and aggregation techniques are rather complex to implement in practice and recent work highlights the significance of statistical techniques to improve data fidelity [23,43].

The programming interface provided by the event manager can be implemented using different methods: the Application Level Events (ALE) specification [2] is a middleware specification and the Java RFID System provides the same abstraction as a language specific implementation of a component model built on top of the Jini event management framework. While there seems to be some consensus about the desired functionality of the application event interfaces, the actual implementation of the event manager can be done in several alternative ways. These alternatives are not mutually exclusive but adapt to their operational context and explore different tradeoffs between levels of functionality and performance guarantees [21,25]. In practice, the event manager may consist of one or more distinct physical devices and logical service end-points with the responsibility for specific tasks shared between them.

6.3 RFID Network Services

To provide full functionality, the upper three layers of the RFID stack of Figure 10 require access to discovery and repository management services accessible on the internet. Discovery services resolve captured object identifiers into network service locations where repository services reside. Repository services in turn can be further queried via standard service profiles to obtain trace and other meta-data related to a particular ID.

Discovery Services. Mapping EPCs to network service locations is a relatively straightforward task, which can be easily accommodated within current internet infrastructures. One way to accomplish this is by simply using the directory capabilities of the Domain Name System, which can support an extended collection of record types. This approach is advocated by the Object Naming System (ONS) specification within the EPCglobal family of standards, which employs the Naming Authority Record [33] to provide associations of EPC codes to Universal Resource Descriptors. Under ONS, the serial item segment of an EPC code is removed, and the remainder segments reversed and appended to a pre-determined well known domain name (as of this writing onsepc.com). Of course, one problem with this approach is that ONS inherits and perpetuates the well known limitations and vulnerabilities of DNS, though some of these issues are addressed by the use of a single domain where delegation and updating can be handled with greater effectiveness.

ONS is limited since it only retains the most recent service location related to a particular EPC for example, the URI published by the current owner of an artefact. This is hardly enough in many cases: in addition to the description of the current situation of the object, many pervasive computing applications need to gain access to historical use data collected during its lifetime or at least over a considerable length of time. This is not only due to the importance of context history for system adaptation but also because of a practical consideration: Object IDs are assigned at production time from the address space controlled by their manufacturer while the artifact itself changes ownership several times during its lifetime. As a result, such naive resolution of the EPC would point to the initial owner of the identifier rather than the current custodian of the artifact and hence authoritative up-to-date information would no longer be available at the returned service location. Moreover, the full object history is fragmented over different service locations corresponding to the different custodians that possessed the artifact at different times and a single service location could not represent the complete data set.

Hence, rather than mapping an EPC to the service point provided by its manufacturer, the resolution process could alternatively point to a secondary discovery service instead, which maintains the record of the complete sequence of successive custodians, from production to the present day. This approach is implemented in the so-called EPC Discovery Service which can be registered with the ONS and provide the list of URIs of all custodians for a particular object ID. This solution to maintaining a complete trace is preferable over the alternative whereby the current custodian would be identified via sequence of links through past holders. Such chaining is vulnerable to broken links that can easily occur for example, if any one of the custodians seizes to exist. One broken link would be enough to result in the complete loss of the ability to trace the object history.

Repository Services. The second element of RFID network services aims to manage and maintain object usage information and is provided by custodians. Conceptually, it is little more than a federated distributed database, and provisions for this task are offered by the EPC Information Service. From a usage perspective both standards are little more than a set of web service specifications to access object specific data repositories. Both provide methods to record, retrieve and modify event information for specific EPCs. What does stand out however is the massive size and complexity of such a data repository which - if successfully implemented - would be unique. This task is complicated by the complex network of trust domains, roles and identities which requires the careful management of relationships between authorization domains and conformance to diverse access policies and regulations. Yet, these challenges are inadequately understood at the moment as neither system has attracted significant support.

One feature of such repository services that merits further discussion today is the so-called containment profiles. This technique is necessary to form single objects out of individual components and be able to reference them directly. Consider the case of an automobile for example: it is made up of thousands of individual components, mostly sourced from third party manufacturers, which at a certain point in time come together to be assembled in a single entity. Over the lifetime of a particular car, these components will change as a result of maintenance, upgrades or changing use. In most cases, the only requirement would be that the car as a whole is identified but in others it would be necessary to identify individual components as well. The containment profile has been introduced to address exactly such time-dependent processes, and is used within the EPC Information Service to group together components that are assembled into a new entity with its own unique EPC code. The composite object has an associated creation and expiry date and its elements can be modified via related containment interfaces.

7 Practical RFID in the supply chain

In previous sections we have discussed at length the information requirements of efficient and effective supply chains, and how network RFID technologies can be used to provide up-to-date and detailed information about product items, containers, service locations and other assets used in support of operations. In this section we turn out attention on how the latter can be used to satisfy the former by highlighting in practical terms how and where RFID shall be used. Note that there are significant differences when tagging at the container and at the item level and these will be identified and discussed.

Let us consider a typical although somewhat simplified supply chain scenario: a variety of consumer products are manufactured at a specific facility, packaged in cases, loaded an pallets and then on trucks for delivery to a retail distribution center (DC). Upon arrival at the DC pallets are dismantled and individual product cases separated and stored. At a later time, product cases are picked (and in some cases loaded on new pallets) and shipped to a local retail store. At the store, products are stored in the back room and used for restocking the selves of the storefront in response to sales. Customers pick up products from the self, place them in the shopping cart and take them to the check out where they complete their purchase. Clearly, this is a rather long process which is carried over a potentially very extensive geographic area and involves many individuals and organizations. It is thus not practical to monitor the progress of a particular product at every point, but rather it is necessary to identify control points, where the product changes state, and employ them to update the information held.

Revisiting this scenario from an RFID perspective, at the manufacturing facility products are fixed with individual tags encoding their EPC code including their GTIN which contains their item-specific serial number. Individual product items are then packaged in cases which are also tagged individually using EPC and assigned with their particular SSCC (or in some cases a GTIN representing a case of product items). At this stage, each case SSCC is associated with the GTINs all all the items it contains and this information is published on the local EPC IS. Cases are then loaded on pallets and often enclosed within some protective material, usually either cardboard wrap or transparent stretch film, and again tagged with their corresponding SSCC. A particular pallet may contain cases from different product lines which are mixed due to the specific quantities included in the order placed by the retailer. The SSCC of each pallet is also associated with the SSCCs of the cases it contains and this information is also published on the local EPC IS.

When all the necessary pallets are prepared for shipping, they are placed in a container and loaded on a truck for delivery to one or several DCs. This point offers the first opportunity to establish a control point for the movement of products downstream in the supply chain: readers located at the exit gates of the loading bay of the manufacturer facility scan the shipment as it is being loaded on the trucks and record every product item, case and pallet identifier, grouping them together and associating them with the corresponding retailer order details and DC destination. This information can be transmitted to the retailer to anticipate the arrival of the shipment.

On their arrival at the DC, pallets are individually unloaded and moved into the warehouse via a portal which records the arrival of the scanned EPC codes and cross references the recorded numbers against those expected. If the products are confirmed to be the ones expected for delivery, the warehouse management systems are automatically updated and the pallets are forwarded for storage on the facility. The same process is followed in loading the product cases for delivery to retail shops. At the shop, cases are again received, automatically checked against the expected deliveries and if confirmed, the store WMS is automatically updated.

Fig. 12. Typical RFID enabled warehouse loading bay portal.

In this process, a central role is reserved for the loading bay doors into the warehouse, as in most cases they represent the best location to place a control point for checking and updating the flow of products. As a result, dock doors are often turned into RFID-enabled portals where pallets are scanned and where the actual items delivered can be cross-referenced and inventories updated. This location works equally well as a control point for manufacturing plants as for distribution centers and retailer stores, and for both incoming and outgoing shipments.

Looking closer at the sequence of events involved in the operation one such portals, the retail store receiving dock, the process starts with the receipt of an Advanced Shipment Notice (ASN). This is a common EDI message which is prepared and transmitted by the DC at the time when the pallets for a particular shipment have been loaded on a truck and leave the DC warehouse. The ASN is a notification of pending delivering and is send to all parties responsible for the movement of freight from DC to store and the contents and configuration of a shipment. In this case, the ASN would contain at least the SSCCs of every pallet and possibly also of the cases and the GTIN of the products included (the latter as a means of providing redundancy to EPC IS). The ASN would also record the total number of pallets, address and related details of the DC and retailer and can also contain numerous other related details.

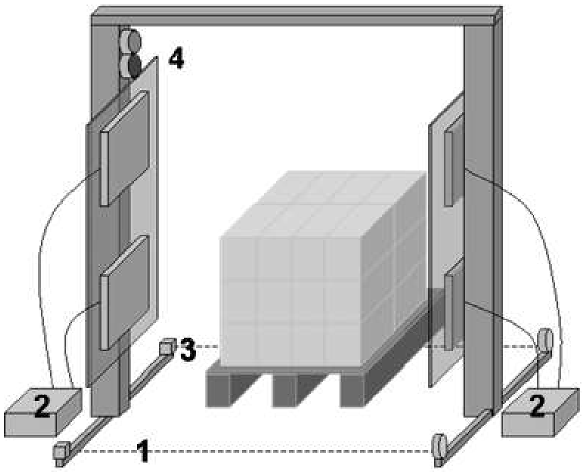

Fig. 13. Schematic of the components of an RFID enabled warehouse portal: item 1 and 3 are motion sensor which activate on entry and deactive on exit the postal operation; 2 are RFID readers each of which has two external antennas attached; and 4 are red and green indicator lights that signal shipment approval or rejection.

At the store receiving dock the external motion sensor is tripped by the movement of the first pallet passing through the portal (cf. item 3 in Figure 13). Tripping the sensor results in the publication of a sensor-event message to the ALE engine operating on the warehouse event manager. This event marks the beginning of an event cycle which instructs the readers attached to the portal (item 2 in Figure 13) to begin collecting observations. The readers keep scanning and discover all tags marking individual products, cases and pallets. Each tag is typically discovered and read several hundred times and the observations are passed to the ALE engine either residing on the reader itself or at the event manager (depending on the model and the capability of the reader). Observations are processed according to the event cycle specification and reported to the WMS. An event cycle may be time constrained or terminated in response of a motion-sensing event tripped by the second, internal sensor (item 1 in Figure 13).

Upon receipt of the event cycle report by the WMS the list of products recorded is compared against the expected deliveries as specified in active ASN messages within the system. If the details match, then the pallet is expected and the portal switches on the green light on its frame (position 4 in Figure 13) indicating that the delivery has been accepted. At the same time, the inventory is updated with the new item received and cross-checked against the relevant purchase order. In case the codes retrieved by the pallet are unexpected the red light is switched on instead and the pallet returned to the truck.

During the aggregation cycle, the event manager filters duplicates, removes transients and codes that are not requested by the event cycle specification and returns the gathered EPC codes in a report. For example, if the event cycle specification requires that only pallet codes are collected then all other types of tags (for example item GTINs and case SSCCs) are observed but ignored.

Making the assumption that each product item is individually tagged with its own EPC, information gathering does not need to stop at the time when products are moved to the storefront for display and purchase. Indeed, it is perfectly feasible that a variety of locations within the storefront will be equipped with readers which will support a number of consumer applications but also product demand data. For example, RFID readers at the point of sale (POS) would allow the rapid scanning of products selected by a consumer and thus a much quicker checkout which would minimize queuing time. Another related application would see readers installed in shopping carts together with embedded displays which can support a variety of personalized shopping applications for example recommendations on the basis of the content of the cart and the user profile or tracking its total cost. Last but not least, RFID readers can be installed below shelves to monitor the number of items stored and would possibly be combined with price and quantity displays that would change automatically depending on the conditions of the product.

The later application for example would have dual use, both as an assistive technology for consumers and as an effective means to monitor the availability of product on display and provide early warning of impending out-of-stock conditions. Even the simpler case where portable or hand-held readers are used to take stock at the end of the day can have considerable benefits: in case where a product is available in several different versions that are not necessarily easily discernible without checking their GTINs, quick stock taking using RFID can provide significant improvement for the replenishment process.

This is especially relevant in the case of apparel retail for example consider the case of a retailer of formal menswear. Suits in particular come in various sizes and colors which are often identified by a single GTIN. Nevertheless, it important that a full mix of the different types is always available to fulfil consumer demand, and it is often the case that after closing sales personnel have to manually conduct an availability survey, which is a time consuming task that becomes particularly onerous due to the timing constraints. Instead, a quick scan of the racks you immediately identify current stock and missing ranges and colors would become automatically identifiable without further need for manual intervention. Of course, such applications would be feasible for higher cost items like garments that provide a higher return and profit margin.

8 Business drivers

Having developed an understanding of the information requirements for effective supply chain optimization in Section 4, and the capabilities of RFID technology in Section 5, we can now turn our attention on how the latter can cater to the former. In doing so, we shall make a distinction between container and item-level tagging since extending the application of RFID to every product item has significant implications in terms of extra capabilities and applications that become possible but also far higher associated costs.

Handling efficiency. A clear benefit of RFID is that it allows for the fully automatic identification of products and containers without the need to preserve line-of-sight between reader and tag as is the case for bar codes. In Section 7 for example, we discussed in detail how RFID portals at the distribution center docking bay doors are used to reduce manual data capture needs and expedite the delivery confirmation process. Similar scenarios can be developed for most shipping and receiving situations where container-level tagging would satisfy all logistics requirements. Further, item-level tagging would allow the development of additional consumer facing applications, notably fast-scan point of sale portals that can considerably reduce queuing times for checkout.

Out-of-stock reduction. Despite the considerable progress of ECR and other such industry initiatives, stock-outs remain common at the retail store level. Case and pallet-level RFID tagging can increase product availability by reducing the number of delivery errors, by increasing inventory accuracy, and by improving the timely replenishment of products from the back store. Item-level tagging can further reduce stock-outs by providing precise information about inventory levels in the store front, rather than estimates based on sales data which can be erroneous in excess of ten per cent. Especially for clothing, item-level RFID can provide detailed information about the product mix that is actually available on the storefront shelves and thus significantly increase availability. This information can be captured either with portable readers and periodic inventory scans or by embedding readers in shelves as part of their construction. Although the latter approach is far more costly, it allows for the development of "smart" shelves which also include additional small displays that expose additional inventory information for example, products sizes that are available in the back room but not in the store front, an approach that has been proven especially successful for higher cost garments and shoes [26].

Inventory reduction. At this stage of RFID development it is not possible to quantify or even confirm the possible potential of this technology to lower inventory levels for some or all trading partners, a fact which is especially critical in the case of FMCG. Although in some cases this would clearly be possible for example, by helping avoid excess stock due to reorders of products already available but not immediately locatable in the storeroom, there is insufficient evidence that either container or item-level tagging will increase the accuracy or the timeliness of demand forecasts, which still appear to remain intractable. Similar reasoning applies to the case of unsaleables where traceability and common sense can play a role in reducing inventory levels. Further experience and research in this area is required although some estimates based on simulations employing simplified models of the FMCG supply-chain appear to be encouraging [24].

Order reconciliation. Container-level RFID can prevent delivery errors (as highlighted in the scenario of Section 7) and reduce the manual effort associated with delivery confirmation as well as the time required to complete this process from several minutes to almost immediate verification. This technology may also prove sufficient as a means of proof for shipment delivery and thus simplify dispute resolution. Nevertheless, in most cases disputes relate to pricing which is best addressed through the implementation of GDSN and RFID has little to offer in this respect. Item-level RFID does not appear to have any impact for order reconciliation.

Theft. While RFID at the container level does not prevent theft, it may assist with the detection of specific sections of the supply chain where this problem is of particular significance. Item-level RFID on the other hand can have considerable implications as it is already a proven technology for anti-theft systems for retail. Furthermore, item-level tagging makes far more challenging the re-introduction of stolen or indeed counterfeit products into the supply chain and for this reason it has attracted intense interest especially in the case of medicines and medical supplies in general.

Nonetheless, the focused performance metrics discussed in the preceding paragraphs may not be the whole story. In addition to the specific new information sources afforded by RFID which can be related directly to quantifiable optimization effects, it is likely that the technology has a secondary role as the catalyst for change. Indeed, to capitalized on the data produced by RFID systems and gain a competitive advantage it is not enough to simply implement the technology but also to be able to transform data into meaningful business information that can be acted upon. This requires advanced integrated information technology infrastructure across the enterprize including warehouse management and enterprize resource planning systems, but perhaps more importantly a reorganization of business processes and strategies. Such changes require a long term commitment and considerable investment in human resources and can potentially completely transform the way business is conducted.

Hence, the decision or not to implement RFID may in many cases extend well beyond a simple automation decision into a business change [38]. In this case, the implication is that the decision to implement the technology is associated with significant business risk and requires very careful planning and execution. In view of that, the business that decides to be involved in such technology implementation must be convinced of its benefits and be able to implement such a programme of change. But with convincing evidence lacking in many cases, this risk cannot be justified only on the basis of a cost benefit analysis. Nevertheless, it is characteristic that the pioneers of bar code, the previous generation of auto-identification technology, have emerged as the dominant corporations in their respective domains and it is likely that this will be repeated for those willing to take well calculated risks.

The rationale for making a decisions is quite different between container-level and item-level implementations. The former would be completely related to benefits in the supply chain and would explore the issues that we have already discussed in this and previous sections. Item-level tagging on the other hand, is has quite different value proposition as its high cost cannot be justified today or indeed the foreseeable future for all types of products although specific application of limited scope can be easily developed for higher cost items.

In fact, widespread item-level tagging for products irrespective of their price is unlikely to be justified on the grounds of supply chain needs alone. Instead, item-level RFID is valuable for a variety of consumer services and indeed this is the most promising area for investigations of this technology and offers the promise of the most likely return on investment. Applications of this type have already appeared and are gaining in popularity [26]. For a discussion of related service development using a variety of sensors in addition to RFID refer to [15].

Nevertheless, extending supply chain technologies in this way has significant repercussions for consumers who become directly involved in the enterprize data processing pipeline. Services employing item-level RFID use personal data associated with individual consumers in intimate ways and that can be used to reconstruct their private activities at an unprecedented level of detail. Moreover, recent studies indicate that the implementation of this technology, may transform the consumption experience in unpredictable ways.

9 Consumer acceptance of item-level applications

Recent research in item-level RFID retail applications has identified a generally positive stance by consumers, especially when considering situations within the store. Project MyGrocer was the first to explore opportunities to develop such applications by focusing primarily around the concept of the smart shopping cart [28]. The working assumption of this work was that each product sold in a supermarket is individually tagged. The MyGrocer cart was fitted with a

RFID reader so that every time a product was placed in it, it would be scanned and its code retrieved. The cart also carried a wireless computer with a large touch screen display connected to the reader.

The main application provided three distinct areas of functionality. The first would present a shopping list, that is a list of item for purchase selected by the individual shopper. This list would be associated with the profile of a specific user and created using historical purchase data which can be further edited manually via a web interface on the supermarket web site. Each time one of the products on this list would be placed in the cart the item would be crossed out to confirm that it has been picked. The second application displays a running list of items in the cart, their quantities, their cost and the total cost of all the products in the cart. Finally, a third application would display information related to the last item picked for example, ingredients, directions for use, health warnings and so forth. The same area of the screen may also be used to display offers and promotions, or comparisons with similar products to the ones in the shopping list. Finally, use of the smart shopping cart allows rapid checkout as the products are already scanned and the total price directly calculated.

Fig. 14. MyGrocer shopping cart in action at the Atlantic supermarkets during system testing.

This in-store scenario developed around item-level RFID received a favorable response with the main benefit perceived to be the improvement of the shopping experience, which was understood to be faster, easier and to offer better value for money. The features of the applications that proved most attractive to consumers during the trials were:

- constant awareness of the total cost of the shopping cart content, which offers to the opportunity to accurately control spending during a shopping trip,
- access to complete and accurate descriptions of products including price, size, ingredients, suitability for particular uses and so forth,
- the ability to compare the value of similar products,
- the provision of personalized, targeted promotions that reflect the individual consumer profile in addition to the usual generic promotions as well as the fact that they could access all offers available in the specific supermarket at a single contact point,
- the proposed in-store navigation system especially in the case of hypermarkets where orientation is particular complex,
- the smart checkout and the ability to bypass queues and reduce waiting time.

However, not all comments were positive. Focus groups and survey findings highlighted the collection of detailed personalized purchase statistics by the retailer and collaborating service providers to be of concern, even though the participants were aware of the provisions (albeit not the practicalities) of the data protection act. Their negative reaction to data collection was triggered primarily after (eponymous) authentication during log in to the shopping cart when, after presenting their RFID enabled loyalty card and entering their private credentials, they were presented with their personalized shopping list. Two issues were raised, both relating to the immediate recognition that for the construction of the list their past purchase data has been recorded, preserved and processed.

This reaction was more pronounced when considered in the context of MyGrocer applications outside the physical space of the store. In following with the ideas of consumer VMI explored in the previous section and in an attempt to collect supply chain data as early on in the consumption process as possible, the project also developed two additional scenarios that provided shopping list and ordering facilities: "on the go" employed a cell phone to place orders, and "at home" enabled the automatic collection of items for replenishment using RFID readers embedded at several positions at the use residence. The latter scenario in particular was the main source of concern since private data, collected in the sheltered space of the home, would be delivered to commercial organizations without the explicit control of the consumer.

Indeed, even in the more acceptable case of the store scenario the vast majority of participants did not trust the retail service provider or the provider of the infrastructure to protect their privacy, irrespective of whether it was a contractual obligation or not. Moreover, the collection of very detailed information about their purchases over an extended period of time raised concerns about the use of the data for purposes that they have not consented to. They were also concerned that such availability of data could reveal their habits or private behaviors especially to third parties that would subsequently could gain access to these data.

Another major concern related to the overall shopping experience, which was perceived to point towards a technology controlled, fully standardized lifestyle. Two issues interrelate on this point. On the one hand, participants rejected the claim that a software system could predict accurately their wishes just by collecting historical data and monitoring habitual purchases. Indeed, this aspect of the system appeared to be patronizing and overtly rationalized but most importantly contrary to the experience of being human. In fact, the majority of participants discarded the possibility of a computer system that could successfully predict their wishes, while some of them went as far as becoming offended by this suggestion as they interpreted it as denying their free will. On the other hand, the participants of the study perceived that such a system promoted primarily the interests of the supplier while the consumer only received marginal benefits.

This issue of directly verifiable consumer value, or rather the lack thereof, was one of the two fundamental reasons for rejecting the system as a whole. Yet, this was not an absolute rejection of the system as the majority of participants in the studies would consider its use if they would receive appropriate compensation for the loss of privacy that they experience. The main challenge they set for retailers was how to fairly and appropriately strike a balance between their and the consumer benefit. The second core challenge before the system could become acceptable was that of control, in the sense that users demanded control over its operation. The form that this feature would take depended on the circumstances of its use and could vary from the anonymous use of the smart shopping cart (at the loss of the personalized shopping list feature), or indeed and off button for the RFID recording at home.

More recently, Metro Supermarkets in Germany has developed its so-called "Store of the Future" which investigates ideas very similar in spirit to those explored by the MyGrocer store scenario. Although this activity is much more extensive in scope and intends to provide a full technological validation of modern RFID supply chain technologies, user studies have revealed that the same issues of control are still critical for consumers [20]. Although in this case again shoppers would be willing to negotiate a loss of privacy in exchange for extra value, they wish to have control over when and how this would occur.

10 Privacy implications of item-level tagging

Item-level RFID can provide retailers with unique sources of information that can be employed for applications beyond supply chain management. Such applications may offer welcome new shopping facilities to consumers, but at the same time, they also make possible new ways to violate personal privacy. Moreover, attacks on privacy enabled by item-level RFID are not limited to the physical confines of the store, but to all purposes extend to any public space and even to the intimate space of the home. In these cases, the risk is not solely due to the use of RFID by the retailer but rather by third parties using the availability of the technology to mount independent attacks on consumers.

There are two main types of privacy attacks that can be developed capitalizing on the widespread availability of item-level RFID tagging. In *tracking* attacks, the actions of individuals are recorded through the observation of RFID tags associated with their person, and their future behaviors potentially inferred. For example, an RFID tag that remains embedded into an item of clothing long after its purchase can be used to identify its wearer wherever they go. *Information leaks* happen when personal or intimate information stored in RFID tags is revealed without the consent of its owner [14, Chapter 4]. For example, when personal details encoded in a tag are skimmed from an e-passport without the owner consent. Both types of attacks become particularly likely when item-level tags affixed or embedded in consumer goods are not removed at the point-of-sale, so that stored identifiers can be retrieved by unauthorized readers, recorded and processed without any visible indication to the user that this activity occurs.

A closer examination of tracking attacks identifies several distinct scenarios that become possible through item-level tagging [13]. For example, one of the earliest uses of RFID outside the supply chain that was explored during the development of the EPC system, was in anti-theft applications. This is of particular relevance to items of small size but high value such as replacement razor blades, which are the most common target of shoplifting. In this scenario, smart shelves would monitor high value items placed on them, and in case where a relatively large number be suddenly removed, a camera would take a photograph as evidence against a potential thief. But in practice, it is hard to differentiate between lawful behavior and attempts to steal and as a result photographs were taken in many more cases than it was necessary. Although this may appear as a minor compromise of privacy it is nevertheless highly suggestive of the type of applications that are possible and how easy it is to develop applications using flawed heuristics.

Consumer privacy violations can be are examined in finer granularity in terms of specific threats, to pinpoint the many ways in which data analysis techniques, profile data, and the presence or absence of specific products can lead to violating ones' rights [13]. As noted earlier, the widespread availability of RFID tagged products present opportunities for covert data collection in locations and situations without the consent of the consumer. Individuals associated with particular product item tags can in this way linked with visits to specific locations at specific times. Even more, if readers observe several locations, sequences of visits can be reconstructed and using simple inference techniques common behaviors, habits or routines can be discovered.

Simpler but equally effective uses of the technology are also possible: a consumer carrying a particular type of product can be identified and approached with a discriminatory intention for example, because they carry a particular book title. A related use of the technology but with different intent, would see the consumer being approached as a result of their possessing a particular item or brand which reveal their preferences. Identification of such preferences can be an effective marketing tool for competing retailers or simply used to identify the value of ones' property and identify them as a worthwhile target of criminal intentions.

Such techniques are more effective when considering constellations rather than single products. Depending on the fact that a particular person is singularly associated with a specific product item may be haphazard as products can be shared between several consumers, tracing collections of product identifiers moving together in a single constellation can provide much more accurate results. Even more so, when individual items are shifted from an established constellation into another, then it is possible to conclude that a transaction has taken place between the two persons involved.

Observing product items or product constellations over extended periods of time can provide adequate information to predict or infer preference or behaviors. Although this is to some extend possible today through the use of loyalty schemes and cell phone records, tracking RFID tags does not require a contractual relationship with the consumer due to the technical characteristics of RFID. Moreover, RFID readers can be installed in such a way that there is no perceptible indication of their existence. Even when data collection in this way is carried out within the provisions of a mutually agreed upon contract the wealth of information collected makes the indirectly enforced use of the technology through preferential pricing particularly attractive can significantly reduce the capability of consumers to make free choices.

Last but not least, RFID tags can be used as a physical equivalent of cookies with the vast majority of preferential pricing techniques developed for the web directly applicable [1]. Indeed, historical information about acceptance or rejection of offers or other transaction opportunities can be stored on one or more tags carried by an individual and used to tailor future approaches to fit their profile. This is certainly feasible for the retailer that supplier the particular item used as carrier but due to the generally inadequate security provisions of RFID, this technique could well be accessible to third parties.

RFID technology has been the cause of the majority of privacy concerns, early commercial applications have not helped to develop public confidence as many events show. For example, Metro Supermarkets in Germany violate their own stated privacy policy by embedding covert RFID tags in their loyalty cards, and an early briefing of Auto-ID Center sponsors urged them to capitalize on consumer apathy and push for item-level tagging thus creating a de-facto situation before consumer organizations could react [9].

The lack of adequate security and privacy protection provisions has sparked intense interest in this area of RFID technology. It is characteristic that during the year 2006 almost a century of research papers have been published in this area and the trend is accelerating. Despite this fact, the main RFID standards have already been ratified without adequate provisions and during the time of publication of these research over 1.5 billion tags entered circulation.

11 RFID and EU Law

Although the consensus appears to be that RFID is a critical technology for future economic growth across several industrial sectors, it is also clear that its application must also be socially and politically acceptable, ethically admissible and legally allowable. This aim becomes even more complex to achieve due to the universal scope of RFID technology, which must respect the policies, ethics and law of every region and country where it is employed. To be sure, this is a challenging task and in an attempt to make the main issues tractable from a computing perspective, in this section we will discuss the main considerations as they relate to the legal framework of the European Union.

11.1 Data protection and privacy

The EU founding treaty declares the fundamental freedoms that its citizens may expect including liberty, democracy, and respect for human rights. Article 30 of the treaty in particular requires the enforcement of appropriate provisions for the protection of personal data including the collection, storage, processing, analysis and exchange of information. Moreover, Article 8 of its Charter of Fundamental Rights proclaims the protection of personal data as one of the freedoms that each citizen has a right to enjoy.

These principles are interpreted and implemented in practice through the legislative framework for data protection and privacy. The Data Protection directive in particular has been developed aiming to provide the general rules and the long term vision, and to be robust despite technological innovations. Privacy protection is specifically addressed within the directive and is expressed in a way that is independent to the specific techniques and mechanisms employed in information processing and thus also applies in the case of RFID.

This directive is complemented by the more recent Privacy and Electronic Communications directive (also known as ePrivacy directive). This extension applies the general principles to the processing of personal data for the provision of public electronic communications services over public communications networks as well as to the recording and use of location data. It also specifies that direct marketing communications are only allowed when the recipient has agreed to be contacted in advance or in the context of an existing customer relationship, in which case companies can continue to market their own similar products on an opt-out basis. However, since RFID in most cases operates over private or corporate networks it has been argued that the provisions of the ePrivacy directive do not apply although this is only one interpretation which does not take into account the case of the use of RFID readers in public spaces.

11.2 Commercial transactions

The Electronic Commerce directive regulates the process of contract offer and acceptance and applies to the fast checkout process supported by RFID points of sale. The eCommerce directive has several provisions regarding appropriate ways of notifications of contractual terms and conditions and dictates that explicit consumer consent be given at all stages. Although exceptions apply to cases in which the interaction medium does not allow for information-rich interactions, RFID's predominantly silent operation stresses this requirement to its limit.

11.3 Governance

A central issue that affects the implementation of RFID is governance in the sense of access to RFID-related standards and infrastructures. The EU has been conceived as a vehicle for economic collaboration and has a tradition of creating a common open and non-discriminatory set of rules which strive to promote fairness and inter-operable infrastructures. As such, its regulating bodies take a particularly negative view of any attempt to fragment public or shared infrastructures or the deployment of proprietary systems with the specific objective to prevent competitors from entering a market.

Arguably, the EPC system is tightly controlled by a group of companies and developed with a view to serve their interests and specific specific ends which relate to commercial, security and political aspects of governance. Furthermore, the spirit of the community is one where protection is not limited to individuals but extends to companies, whose sensitive commercial information is also protected as is the case of data within RFID-enabled business processes. As such, it is natural to expect the two opposite sides of the EPC proposition, namely rapid development of a new market sector and proprietary technology and infrastructures, will cause considerable friction and can potentially lead to closer regulation.

11.4 Spectrum regulation

Recently, the EU has opted to liberate more spectrum for the growing demand for RFID usage, implemented through Decision 12 for RFID frequencies in the UHF band adopted by the Commission.This establishes a harmonized base for RFID applications across European states but nevertheless does not completely address the problem. In some cases, for example in distribution centers and shopping malls, it is necessary to operate hundreds or even thousands of readers in close proximity to each other in event driven mode. However, ETSI, the European Telecommunications Standards Institute, in standard EN 302 208 requires the use of Listen Before Talk to prevent a base station from transmitting if the channel is already occupied by another transmission. This limits the number of readers able to operate simultaneously in a particular radio neighborhood to about twenty if all available channels are used and has some incompatibilities with Gen2 tag operation.

11.5 Environmental issues

There are two directives that have already had very significant repercussions for electronics in general and RFID in particular, namely on waste electrical and electronic equipment (WEEE) and on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS). RoHS in particular bans the use of certain hazardous substances which are rather common in electronics.

Relating to public health, the EU has some of the most strict regulation of the level of electromagnetic regulations that workers or the general public may be exposed to. Moreover, the Commission has in place a regular program of monitoring the possible effects of electromagnetic fields on human health through its Scientific Committees. Moreover, restrictions on EMF emissions from products available in any European state have been established to ensure the safety of both users and non-users. Although electromagnetic fields created by RFID equipment are generally low and thus exposure of the general public and workers is expected to be well below current limits, RFID nevertheless contributes to the total radiation in working and home environments and its widespread use may well have significant results especially when taking into account wireless networking technologies used in tandem.

12 Discussion and conclusions

Many believe that technology and business dominate culture today, yet it is a society's privacy culture that defines its values, sensibilities, and commitments. To be sure, attitudes toward privacy change as technologies emerge that blur the distinctions between what is public and private. Deploying any new technology involves risk, and society relies on experts to accurately assess that risk; failure to do so compromises their role as gatekeepers. It is thus the responsibility of the computing profession to confront the challenges of RFID in retail. How we deal with these issues will determine the chances of widespread adoption of not only RFID but potentially the whole range of emerging ubiquitous computing technologies.

Advising that deployment of RFID, or any technology for that matter, should exploit "consumer apathy" does little to inspire public trust, as does making a tag impossible to remove. Two aspects of the technology accentuate the trust problem and dictate collaboration across disciplines:

- RFID-based systems' silent and transparent operation; and
- the fact that trust is not a purely cognitive process and thus is not amenable to a strictly quantitative treatment-for example, as a personal utility optimization problem, a popular view within computer science today.

In fact, many of the core challenges involve managing the enormous amounts of data that RFID generates and monitoring the massive increase in points of contact between user and system rather than developing cryptographic algorithms and security mechanisms that control access to tag data. While individuals' initial entitlement to control their data is well recognized, economic coercion mechanisms based on price discrimination are less so. Such mechanisms result from negotiations between private organizations and public institutions, and this is where our professional social responsibility must play a critical role. Dealing effectively with misuse will become more urgent in the near future.

This survey has attempted to provide an in-depth description of issues and technologies and supply computing professionals with the information to be involved. Yet, several issues related to large scale deployments of RFID are still poorly understood and we could not conclude this discussion without exploring the additional implications from a waste management perspective caused by the extensive use of RFID.

Indeed, RFID tags routinely embedded in a variety of products affect a wide gamut of recycling processes both of materials used in containers for the supply and in product item packaging. For example, as relates to paper recycling adhesives, chips, pieces of metal from antennae and conductive inks affect the process of reclaiming containers and paperboard and prevent the manufacture of new board from recycled feedstock. Similar effects would be caused by RFID tag debris contamination on steel, glass and plastic recycling processes. Furthermore, at the end of their useful life pallets are ground up for use as landscape mulch, animal bedding, compost, soil amendment, or core material for particle board. However, metallic pieces from antennae will be shredded, but cannot break down and would pollute the composting process and render the material unusable. It is ironic that RFID is often seen as the solution for reclaiming materials from consumer products due to its capability to record an accurate and complete history of the product. At least in the short term, its effect will almost certainly be negative.

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