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Models for Cost-Benefit Analysis of RFID Implementations in Retail Stores

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***Abstract*—In this paper, we focus on the models for analyzing radio frequency identification (RFID) implementations in terms of their costs and benefits. We consider the supply chain comprised of the manufacturer, distributor, retailer, and the consumer. We classify the transactions generated by different RFID tag reads and discuss implementations of the data networks connecting the tag readers at the retail store. Our models consider the cost of implementations including the cost of tag readers, the communication network cost and other infrastructure costs. The analytical models we propose consider the benefits of these implementations including automatic checkout at retail stores and reduced inventory costs due to efficient shelf replenishment.**

***Index Terms*—Cost-benefit analysis, data communication networks, electronic product code (EPC), enterprise resource planning (ERP) systems, radio frequency identification (RFID), supply chain information systems.**

I. Introduction

Several organizations including Wal-Mart, Tesco, and Proctor & Gamble (P&G) are currently testing and deploying radio frequency identification (RFID) technology in their supply chains. In addition, the Department of Defense (DoD) has mandated that its suppliers tag their products at the pallet level using RFID tags. Most companies are keenly following the great debate that RFID has generated in terms of the technology, potential business value, consumer concerns, and its overall impact on the business supply chain.

A cornerstone of RFID systems is a product's electronic product code (EPC). EPC is a number that is assigned to and that uniquely identifies a pallet, case, or an individual item of a product. It is a version of the barcode that can encode much more detailed information. An EPC is comprised of the company code, the product code, and the unique serial number for each product. EPCs can be either 96 or 128 bits. Even with a 96-bit EPC, 200 billion items can be assigned unique numbers for a given product. This expanded capacity for information allows many more potential uses, such as storing more production-related information and measuring the environmental conditions in which the item resides.

EPC is encoded into a microchip that is commonly referred to as a tag (or RFID tag). The EPC data can be activated and read using radio frequency readers, commonly referred to as RFID readers. One key advantage of the RFID technology is that RFID readers, unlike the barcode readers, do not require "line-of-sight" for reading the tags. RFID tags can store a significantly larger amount of information compared to barcodes, and the stored information can be changed, dynamically if needed, at different steps in the supply chain [1].

There are two types of RFID tags: active tags and passive tags. Passive tags do not contain any power source and are activated by the inductive power from the tag reader. On the other hand, active tags contain a power source and are capable of transmitting their tag data on a continuous basis. While business supply chains are focused mostly on the passive tags, defense industry is interested in the active tag technology. Passive tags, sometimes referred to as SmartLabels, can last more than a decade. But the range of transmission for passive tags can be relatively short (up to 20 ft) and may require high-powered readers. On the other hand, active tags can transmit over relatively long ranges (up to 300 ft). In this paper, we consider only the passive tags.

The potential advantages of RFID technology in the supply chain are numerous. RFID technology has the ability to provide up-to-the-minute information on sales of items, and thus can give an accurate picture of the inventory levels. This accuracy may lead to reduction in inventory levels, thus causing a reduction in inventory costs. RFID technology at the pallet level has the potential to automate the distribution of goods in the supply chain between manufacturing plants, warehouses, and retail stores of different organizations, which in turn, may reduce labor costs. Reading RFID tags allows companies to identify all items, thus cutting down losses from lost/misplaced inventory.

The process of reading the tags by an RFID reader in a retail store is depicted in Fig. 1. In a retail store, RFID tag information is generated based on events such as a product leaving a shelf or a product being checked-out by a customer at a (perhaps automatic) checkout counter; such implementations have been widely deployed in Europe. Fig. 1 indicates a tag reader deployed in a shelf; this tag reader is responsible for reading the RFID tags of items on the shelf. Items read by the tag reader

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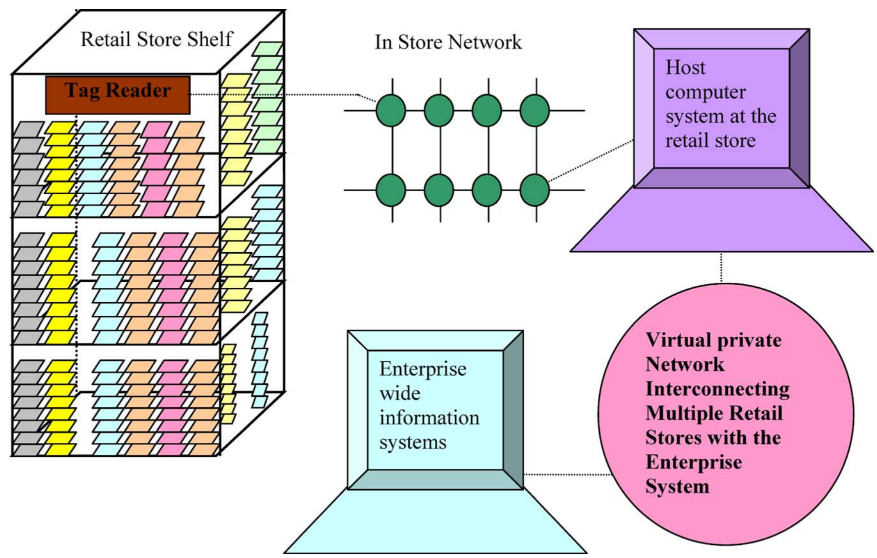

Fig. 1. RFID infrastructure in a retail store.

or other events (such as checkouts) generate messages for the host system (a.k.a. central transaction server) shown in Fig. 1. The host system, when it processes these messages, in turn, may generate messages for other partners in the supply chain. In addition, the host system may send some of the RFID transaction data to the enterprise system of the retailer. The host system is connected to the enterprise information systems via a virtual private network.

While there has been extensive research on the design of RFID tags and readers and issues such as the reliability of tag reads, there has been relatively little research on cost-benefit models for RFID implementations. In this paper, the main research thrust is arriving at cost models for RFID implementations by considering various factors such as the tag reader costs and the infrastructure costs including the communication network required for RFID implementations. We consider the supply chain comprised of the manufacturer, distributor, retailer, and the consumer. We classify the transactions generated by different RFID tag reads and discuss implementations of the tag readers and the data networks connecting the tag readers at the retail store. The analytical models we propose consider the benefits of these implementations including automatic checkout at retail stores and reduced inventory costs due to efficient shelf replenishment.

The rest of this paper is organized as follows. Section II discusses relevant literature on RFID tags and applications. Section III provides a discussion of the transactions generated by RFID tags in the supply chain. Section IV describes detailed RFID implementation plans for retail stores. For conducting the cost-benefit analysis, first, we need to identify and quantify the costs associated with RFID implementations. These costs can be infrastructure costs that are incurred once to purchase the hardware and the software for the initial installation. In addition, the operational or maintenance costs, which recur every year, must be analyzed. Section V discusses the cost for the RFID implementations for the retail stores in terms of the tag readers, the data communication networks and the enterprise information systems. Section VI describes a model for estimating the operational costs of RFID implementations in retail stores for the shelf replenishment operation. Benefits of RFID usage include automatic shelf replenishment, reduced losses due to shoplifting and automated checkout and point-of-sale transactions. Section VII presents the formula quantifying the benefits of RFID implementations for the retailer and compares the benefits with costs of implementation. Section VIII presents a numerical example of the costs and benefits for a hypothetical retail store. Section IX concludes this paper with directions for future research.

II. Literature Survey

RFID technology including the design of tags and the frequency/distance ranges in which the readers operate have been described in many articles [2]–[4]. Applications of RFID tags for many industries including retailing, healthcare, and restaurant industries have been discussed [1], [4]–[6], [8], [9].

IBM and A. T. Kearney's report prepared for Grocery Manufacturers of America (GMA) presents research on RFID implementations in the consumer products industry [6]. A report prepared by A. T. Kearney and K. Salmon, associates for GMA, discusses how implementation of EPCs can benefit each partner in the supply chain [1]. However, as implementations and extended processes are examined, GMA has also found that the benefits of RFID may be more substantial in some product categories and supply chain partners than others [6], [7]. Further, numerous studies at MIT's Auto-ID Center have demonstrated RFID applications that result in substantial gains in efficiency and effectiveness of logistics processes, but have also identified situations where the technology needs to advance to provide more than marginal benefits.

Clarke and Kipp discuss the technical details of how tag readers obtain data from the RFID tags [2]. Physical markup language (PML) has been designed for describing the product information referred to by an RFID tag [10]. The tag data simply contains a code, and this data is translated by an object naming

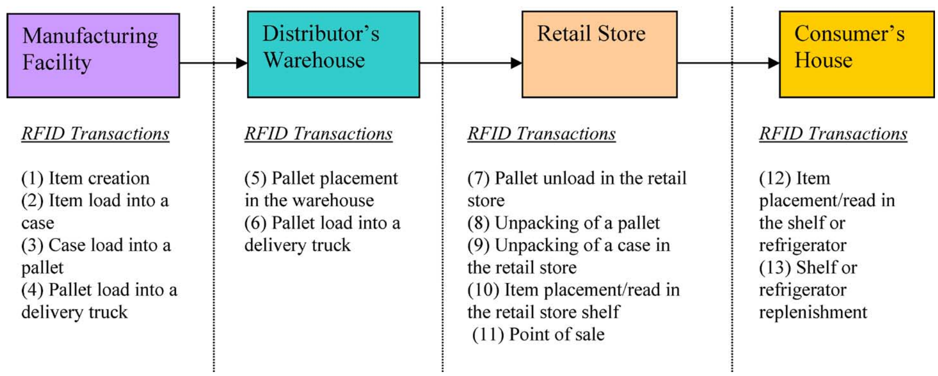

Fig. 2. Transition of an item from the manufacturer to the consumer in the supply chain and the relevant RFID transactions.

server (ONS) to product information, which is described using PML. Savant devices which obtain information from the tag readers and process this information for error correction and for maintaining event information have been discussed in [11]. Gaukler *et al.* discuss the impact of item-level RFID in a retail supply chain [12]. They formulate the problem of optimizing different RFID transactions based on service levels. Chalasani and Sounderpandian categorize different types of transactions that may arise in a retail store from RFID tag readings [13]. Chalasani and Boppana present data models for storing the data generated by RFID tag reads [14]. They also present techniques to optimize RFID data and discuss system architectures that enable RFID applications such as product recall and automatic shelf replenishment. Traub [15] envisions an enterprise architecture in which RFID middleware layer plays a key role. The middleware layer known as application level events (ALE) interface receives tag information from RFID tag readers and forwards this information, after consolidation and pruning, to different applications [15]. Chalasani *et al.* propose building intelligence into the tag readers so that they can achieve automatic identification of misplaced items and automatic generation of shelf replenishment alerts [16]. Hassan and Chatterjee [17] discuss a taxonomy of various currently available RFID systems. They describe different technologies behind RFID tags and tag readers; they also indicate protocols for security in RFID systems and protocols coordinating multiple simultaneous tag reads. RFID applications are numerous and range from business supply chains to healthcare systems to defense applications. Wang *et al.* [18] discuss application of RFID in a Taiwan hospital and discuss the general infrastructure support for RFID applications that resulted from their project. Ohkubo *et al.* discuss privacy issues related to RFID tags and present an overview of the current solutions on RFID privacy issues [19]. Eckfeldt discusses the benefits and risks of RFID technologies from a consumer perspective [20]. Garfinkel *et al.* describe the problems related to RFID privacy issues and give an overview of solutions [21]. Rieback *et al.* discuss how RFID tags, especially read-write tags, can propagate viruses through enterprise systems [22]. Juels provides a thorough literature survey of security and privacy issues related to RFID technology [30]. However, no research has been reported on the cost benefit models for RFID implementations. In Section III, we discuss RFID transactions generated at different locations in the supply chain by events related to products and inventory movement.

III. RFID Transactions

Passive RFID tags, in spite of their limited computational power, cost significantly less compared to their active counterparts. Active RFID tags are bulky and integrating them into retails products is difficult in their current form. Because of these reasons, passive tags are the most commonly used tags in retail applications. In this paper, we only assume passive tags. For the purposes of this paper, we assume the supply chain is comprised of the manufacturer, distributor, retailer, and the consumer. As an item with an RFID tag moves from one location to another location in the supply chain, it may be read at several different locations in the supply chain. We define an RFID transaction to be an event that corresponds to the reading of an RFID tag by an RFID reader. Each *RFID transaction* generates data including the RFID tag (EPC), the reader ID, and other relevant pieces of information.

The transition of an item with an RFID tag from the manufacturer to the consumer is depicted in Fig. 2. In this paper, we assume that the RFID tags are applied at the item, case, and pallet level. For some items, this hierarchy—items in cases and cases in pallets—may not be applicable. However, the discussion in this paper can be readily extended to other hierarchies. As an item is manufactured, an RFID tag is placed on the item, which generates the item creation RFID transaction at the manufacturing facility. Placing an item into a case, placing the case into a pallet as well as loading a pallet into a delivery truck generate different RFID transactions at the manufacturing facility. At the distributor's warehouse, placing the pallet into a warehouse shelf and loading the pallet onto a delivery truck (to be delivered to the retail store) generate RFID transactions. In a retail store, events such as shelf replenishment, movement of an item from one shelf to another (possibly because of item misplacement), and sale of an item generate RFID transactions. At the consumer's home, a futuristic model suggests that the consumer's refrigerator (or the storage area if the item does not need to be refrigerated) will be equipped with an RFID tag reader; this results in RFID transactions being generated when an item is placed in the refrigerator and when an item is taken out of the refrigerator, these events possibly triggering a refrigerator replenishment RFID transaction.

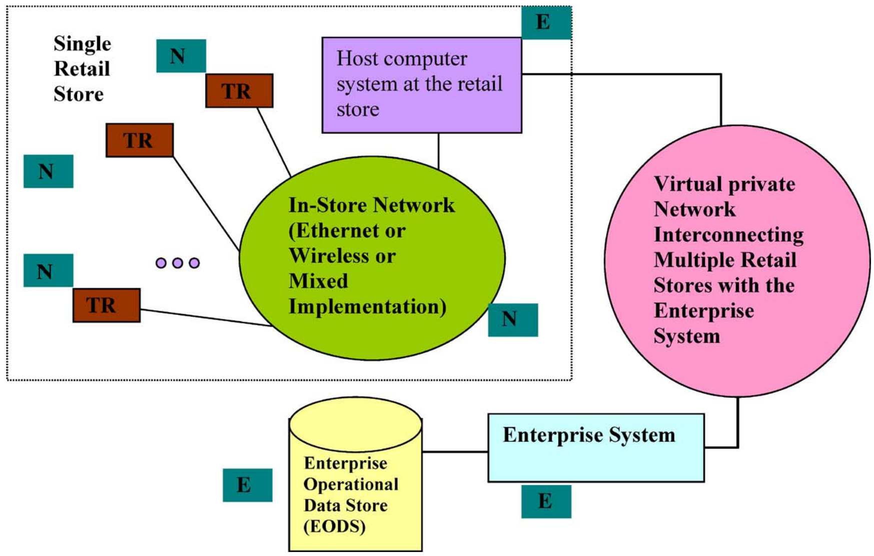

Fig. 3. Infrastructure for interconnecting tag readers to the host system in a retail store.

Fig. 2 presents a model for understanding the flow of events in the supply chain by summarizing the various transactions. However, for the rest of this paper, we focus on retail store implementations. In addition, we assume that tag readers can read multiple tags at the same time based on the capabilities of the reader. Multiple simultaneous tag reads can be accomplished using the technologies outlined in [26]. In the retail store, pallet unloading and unpacking of pallets [transactions (7) and (8) in Fig. 2] take place in the storage area of the retail store. Storage areas in the retail store will be equipped with RFID tag readers to record these events. Unpacking of cases may take place in the storage area as well. However, for items that are sold as a case, cases may be placed directly on retail store shelves. In this paper, we assume that only items are placed in retail store shelves. If cases are placed in store shelves, we assume that only the cases have an RFID tag and the items contained in the case do not have RFID tags. Transactions 10 and 11 (indicated in Fig. 2) in the retail store are of particular interest to unlock the benefits of RFID implementations. These transactions are further subdivided into transaction types in Section VI, where we present a model for the operational costs of RFID implementations.

To support the RFID transactions indicated in Fig. 2, infrastructure—in terms of hardware and software—is required. In this paper, we discuss the hardware and software infrastructure and the associated costs for the retail store implementation of RFID technology.

IV. RFID Infrastructure in a Retail Store

For the retail store, a typical RFID implementation requires the infrastructure shown in Fig. 3.

At the retail store, most of the infrastructure shown in Fig. 3 is necessitated by RFID implementations. RFID implementations require the tag readers and the communication network that connects the tag readers and the host system. However, the host system may exist on its own even when RFID technology is not implemented. Similarly, the virtual private network (VPN), the enterprise system, and the enterprise operational data store (EODS) are needed regardless of RFID technology. Entities such as the host system at the retail store, the EODS and the enterprise system may need to be enhanced because of RFID implementations; this is further elaborated in Section IV-A when we consider the cost of such implementations. In Fig. 3, infrastructure items that are newly added because of RFID implementations are labeled with N while the infrastructure items that need to be enhanced to accommodate RFID technology is indicated with an E. An infrastructure item without any label is required in a similar capacity regardless of whether RFID technology is used or not.

A. Technologies for Retail Store Tag Reader Networks

In this section, we discuss different technologies for interconnecting tag readers in the retail store. These technologies are divided into wired networks, wireless networks, and mixed networks (wired + wireless).

Wired Networks: The standard Ethernet network using category 5 100-Base TX cables can provide a high-speed network for tag readers. With the recent Power over Ethernet (PoE) Standard, IEEE 802.3af [23], the tag readers can also be powered by the Ethernet connection. This technology reduces the number of wires while obviating the need for frequent charging or replacing batteries in tag readers. So it is not difficult to have substantial computing and communication capacity in smart tag readers that are connected to a wired network. In particular, this also points to the feasibility of implementing light weight security mechanisms to cope with altering of data and falsifying of information by hackers. The primary disadvantage, however, is wiring the store shelves with a CAT 5 cable and the extra cost of the Ethernet switches. If the PoE option is used, then the equipment cost can increase by as much as 25%. Furthermore, this type of implementation is inflexible in the sense that if the aisles in a store are rearranged or temporary aisles are created, the networking cost can be substantial. Thus, the initial cost of a wired network is high, but the long term benefits are quite substantial for a fixed network.

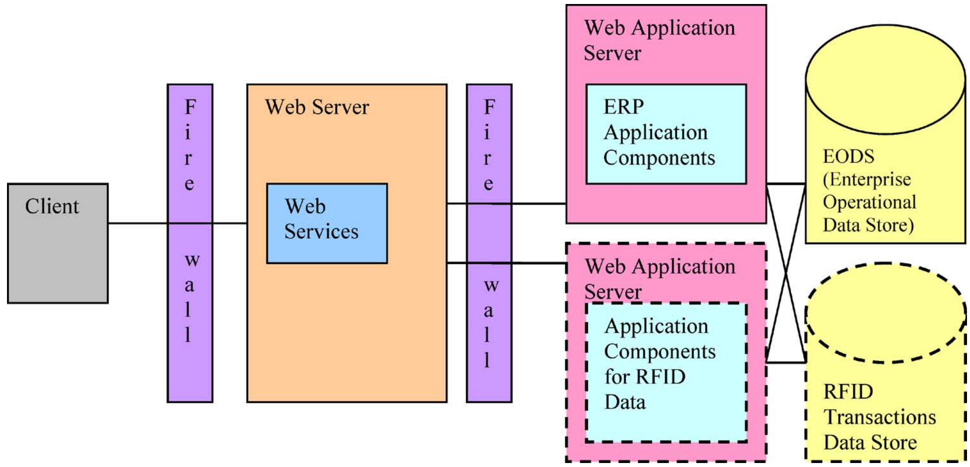

Fig. 4. Enterprise architecture to store and process RFID related transactions.

Wireless Networks: There are several wireless technologies such as Wi-Fi [24] and Bluetooth [25] that work in the free radio spectrum at 900 MHz, 2.4 GHz, and 5.8 GHz. Wi-Fi is designed to work for distances up to 300 m with distributed access to the wireless channel. The data transmission rates can be high, up to 55 Mb/s. Bluetooth, on the other hand, is designed for small-scale point control networks, in which a single device acts as a master and coordinates all communication activity within its range. Bluetooth covers distances up to 10 m with 1–2 Mb/s data rates. Given the current advances and adaptation trends, the Wi-Fi is likely to be the dominating and economical wireless technology for tag reader communication. The advantages and tradeoffs of wireless networks have been studied by Madni [27] and Ramamurthy *et al.* [28], [29].

The primary advantage of a wireless network is that it can be set up with low initial cost. In particular, wiring the shelves for network connection is avoided. By using ad hoc networking concepts in which networks are formed without any infrastructure network, the Ethernet switches such as those used for the wired network are avoided. For true wireless and flexible implementation, however, the tag readers should be battery powered. These battery-powered tag readers require substantial battery power and need to be recharged periodically. Thus, the operational cost of a wireless network can be higher than that of a wired network. A wireless network is susceptible to external interferences such as signals emitted by cell phones and radio-controlled toys. Furthermore, wireless networks are more prone to hacker attacks. On the other hand, a wireless network provides completely flexible implementation that adapts to the store needs without any additional cost.

Mixed Wired and Wireless Network: Combining wired and wireless network technologies to interconnect tag readers provides the benefits of wired network robustness and low maintenance costs with the flexibility of wireless network for adapting to changing needs. In this type of network, all tag readers have wireless capability to communicate among themselves. In addition, a small fraction of the tag readers have Ethernet connections. The Ethernet offers limited infrastructure support and improves the reliability of the wireless network. The wireless network among tag readers may be formed using ad hoc networking techniques. The tag readers with only wireless connectivity are completely mobile, while the nodes with both Ethernet and wireless connectivity are stationary.

B. Enhancements to EODS and Enterprise Systems

Fig. 4 shows an information system architecture at the enterprise level (for the retailer) that incorporates processing modules for RFID transactions. This enterprise-level architecture should not be considered a geographically centralized architecture. Different components of this architecture shown in Fig. 4 may reside at different locations, for example, the ERP processing module may be located in New York, while the RFID processing module may be located in Chicago. However, the individual pieces of data required for processing are not decentralized in this architecture. This enterprise-level architecture has the following advantages.

Consistent, Integrated View of Data: At any given time, all the RFID data is available to any application at the enterprise level.

Fast Access to Data: When the data is distributed throughout the supply chain, to obtain relevant pieces of information for applications such as product recall requires a significant amount of time. On the other hand, an enterprise-level data architecture provides information on items, warehouses, and the customers who purchased a recalled item very quickly.

Ease of Extension From the Existing Architectures: Already companies have collectively spent billions of dollars in implementing ERP architectures. To implement decentralized middleware devices that hold RFID and related data, cost of the infrastructure may increase substantially. Middleware devices that process RFID transactions, depending on their functionality are expected to cost thousands of dollars. Implementing such middleware devices to process RFID transactions, in our view, adds additional cost to the already expensive ERP implementations, thus reducing the return on company's investment. On the other hand, the architecture shown in Fig. 4 works with and extends the existing ERP architectures with nominal increases in cost.

In Fig. 4, the components indicated in dashed lines are required for RFID implementations. The other components exist in the enterprise architecture regardless of whether RFID technology is deployed or not.

V. Models of RFID Implementation Costs

A. Cost Models for Networks of Tag Readers

The cost of a network is modeled using the formula $(F+V)*R$, where F is the fixed, initial cost of implementation per year (amortized over the life of the reader), V is the annual maintenance cost per reader, and R is the number of tag readers installed. We use subscripts eth, wifi, and mix to denote the fixed and variable costs for completely wired, completely wireless, and mixed networks, respectively. For a completely wired network, the fixed cost consists of wiring the shelves and Ethernet switches. It can be estimated as $F_{\mathrm{line}}*R+F_{\mathrm{switch}}*R/k$, where F_{line} is cost of the Ethernet connection for each tag reader and F_{switch} is the cost of Ethernet switches, each with k ports. The annual maintenance cost V_{eth} consists of primarily rewiring the Ethernet and power lines to accommodate relocation of shelves and set up of temporary shelves. So the cost of implementing and maintaining a completely wired network with the cost of a tag reader (F_{tag}) added is

$$\mathrm{Cost}_{\mathrm{eth}} = (F_{\mathrm{tag}}+F_{\mathrm{line}})*R+F_{\mathrm{switch}}*R/k+V_{\mathrm{eth}}*R. \quad (1)$$

The cost of a completely wireless network is calculated as follows. The fixed cost is negligible. The variable cost, which denotes personnel cost in checking and charging and replacing batteries in tag readers, is proportional to the number of readers, R. So, the cost of a completely wireless network with the cost of tag readers added is

$$\mathrm{Cost}_{\mathrm{wifi}} = F_{\mathrm{tag}}*R+V_{\mathrm{wifi}}*R. \quad (2)$$

Comparing the annual costs for the two methods, Ethernet implementation is more cost effective if

$$\mathrm{Cost}_{\mathrm{eth}} < \mathrm{Cost}_{\mathrm{wifi}}. \quad (3)$$

If V_{wifi} is considered negligible since it can be folded into the regular cost of restocking shelves and checking shelves for normal maintenance, then the completely wireless network is cost economical even if there are no changes in the network topology for a long duration (that is, $V_{\mathrm{eth}} \approx 0$). If shelves are relocated or temporary shelves are created continually, then a completely wired network will never be economical compared to a wireless network since V_{eth} is likely to be significant. However, the performance of a completely wireless network may be lacking. A mixed network can be used to improve the performance significantly. The cost of a mixed network with w of the nodes wired is given by

$$\begin{aligned}\mathrm{Cost}_{\mathrm{mix}} = {} & F_{\mathrm{tag}}*R+F_{\mathrm{line}}*w \\ & +F_{\mathrm{switch}}*w/k+V_{\mathrm{wifi}}*(R-w). \quad (4)\end{aligned}$$

If the topology changes involve $(R-w)$ or fewer nodes, the fixed cost of a mixed network remains constant.

B. Cost of Enhancing the Enterprise Systems

To estimate the cost of RFID implementations, we also need to include the cost of changing the enterprise systems to accommodate RFID transactions. These costs range from hundreds of thousands of dollars to millions of dollars. In this paper, we assume that the fixed cost for enhancing the enterprise systems per year (amortized over the life of the reader) is indicated by E. Hence, the total infrastructure cost of retail store implementations is given by the following formula:

$$\text{Total infrastructure cost} = E + S*\mathrm{Cost}_{\mathrm{mix}} \quad (5)$$

where S is the total number of stores of the retailer. The previous formula also assumes a mixed network implementation [see (4) for the cost of the mixed network].

VI. Operational Costs of RFID for Shelf Replenishment

In this section, we will examine the operational (variable) costs of RFID for shelf replenishment. Without RFID, the typical practice is to have store clerks walk through the aisles periodically and look for items that need replenishment. At times, customer complaints about an item missing on the shelves can also trigger replenishment. With RFID, replenishment alerts can be automated. When the inventory level of an item in a particular shelf location falls below a predetermined minimum level it may be detected by a RFID tag reader and an alert message can be sent to the store clerks. The minimum inventory level corresponds to the reorder point in traditional economic order quantity (EOQ) models. A store clerk then replenishes the shelf inventory by moving a predetermined number of the item from the backroom to the shelf. This predetermined quantity is the EOQ in traditional models. Automation can reduce the cost by reducing the number of store clerks needed and by minimizing the probability of "stock outs" that occur when a customer looks for an item but it is not there on the shelf. To conduct a cost benefit analysis, we first compute the data processing costs. We assume that RFID is also used for point of sale (POS) applications and some benefits are realized in POS. In addition, RFIS can also be used to check against shoplifting, and we assume some benefits there as well.

A. Estimating the Shelf Replenishment Processing Load

When the data from a tag reader is processed, it may or may not entail a transaction. The transactions can be classified into two broad categories: POS transactions, and the shelf-inventory-replenishment (SIR) transactions. POS transactions are triggered by the purchase of items by customers, while SIR transactions are generated by frequent readings of the RFID tag readers on the shelves. SIR transactions can further be classified into the following subcategories.

Type SIR1: One or more items have left the shelf space since the last reading. This type has the following subcategories.

Type SIR11: The number of items on the shelf has fallen below the reorder point. In this case, a shelf replenishment order needs to be generated.

Type SIR12: The number of items on the shelf is above the reorder point.

Type SIR13: One or more misplaced items have been removed from this shelf space.

Type SIR2: One or more items that do not belong in that space are found in the space. These items need to be removed and placed on the correct shelf.

Type SIR3: One or more items have been added to the shelf space after the last reading.

Type SIR4: No change after the last reading.

We will use the following notations.

l	number of retail locations;
n_i	number of items at location i;
n	total number of distinct items at all locations;
f_{ij}^{POS}	frequency of tag reads of transaction type POS for item j in location i;
f_j^{SIR}	frequency of tag reads of transaction type SIR for item j;
t_{ij}^{POS}	processing time required for a POS reading of item j in location i;
t_j^{POS}	processing time required for a POS reading of item j at the central location;
p_j^{TYPE}	probability that an SIR reading of item j is of a particular TYPE;
t_i^{TYPE}	processing time required for an SIR reading of item j, where TYPE may be any of the subcategories under SIR;
r_j	reorder placement rate at the central location for item j (r_j will indeed be equal to the demand rate of item j divided by its order quantity);
t_j^R	processing time for reordering from the central location for item j.

We shall compute the POS load rates first.

$$\text{The POS load rate at location } i = \sum_{j=i}^{n_i} f_{ij}^{\mathrm{POS}} t_{ij}^{\mathrm{POS}}. \qquad (6)$$

The total POS load rate at the central location is the sum of POS reading load and reordering load. Thus, we get

$$\text{Total POS load rate at the central location} = \sum_{i=1}^{l}\sum_{j=i}^{n_i} f_{ij}^{\mathrm{POS}} t_j^{\mathrm{POS}} + \sum_{j=1}^{n} r_j t_j^R. \qquad (7)$$

Next, we shall compute the SIR load rates. The SIR loads include the processing times required for the following types of SIR readings: SIR11, SIR12, SIR13, SIR2, SIR3, SIR4. We shall assume the corresponding probabilities of occurrence of these types as shown in (8) at bottom of the page.

We note that p_j^{SIR11} is nothing but the shelf replenishment rate of item j and p_j^{SIR2} is the misplacement rate on the shelf space meant for item j.

The previous formulas can help information system designers estimate the load rate for RFID installation in retail stores. An important parameter in the previous expressions is the frequency of SIR-type readings denoted by f_{ij}^{SIR}. This is a decision left to the information system designers and it is an interesting optimization problem. A service level-based attempt to optimize this frequency can be found in [12]. Whatever optimal value is decided upon, it must be used in the previously shown load rate formula. Note that the probabilities depend on the frequency of readings. Assessing these probabilities, therefore, require a detailed discussion between the technical implementation team members and the store managers.

Next, we examine the cost benefit analysis of using RFID for shelf replenishment. A parameter needed in Section VII is the variable cost of RFID and the load rate computed in this section will help in its estimation.

VII. Cost Benefit Analysis of RFID for Shelf Replenishment

Consider a retailer who replenishes the inventory on the shelves using the inventory from a backroom. We shall assume that the backroom supply is always available. Assume that the current non-RFID method of replenishing the shelves involves an annual fixed cost F and a variable cost v so that the total cost is $F + vm$, where m is the total number of replenishments in a year. There is always the question about which costs are fixed and which costs are variable. We are assuming that fixed costs are those that do not change within the range of possible values for m and that the variable cost is linear in m. We also assume the v is constant for all items.

It is well-known that the EOQ for a particular item j is proportional to the square root of its ordering cost. Thus, the order quantity before RFID installation is proportional to $\sqrt{v}$. Let the fixed and variable costs be, respectively, F_{RFID} and v_{RFID} after RFID installation. F_{RFID} is derived from (5) in Section V, assuming that we implement a mixed network to connect the tag readers. Similarly, v_{RFID} can be estimated from the processing load rate computed in using (7) and (8) in Section VI. The new EOQ, denoted by $\mathrm{EOQ}_{\mathrm{RFID}}$ will then be proportional to $\sqrt{v_{\mathrm{RFID}}}$. That is

$$\mathrm{EOQ}_{\mathrm{RFID}} = \mathrm{EOQ}\sqrt{v_{\mathrm{RFID}}/v} \qquad (9)$$

$$\text{Total SIR load rate at location } i = \sum_{j=1}^{n_i} f_j^{\mathrm{SIR}} \sum_{\mathrm{TYPE}\in\{\mathrm{SIR11,SIR12,SIR13,SIR2,SIR3,SIR4}\}} p_j^{\mathrm{TYPE}} t_j^{\mathrm{TYPE}} \qquad (8)$$

which means that the number of units of a particular item brought to the shelf for replenishment will reduce by a factor of $\sqrt{v_{\rm RFID}/v}$ due to increased efficiency obtained from RFID installation. We next consider the dollar benefit of this reduction. It is also well-known that the sum of carrying cost and ordering cost over a year for a particular item is proportional to the square root of its ordering cost. The carrying cost here is the cost of the shelf space occupied by the item. If TIC_j is the total annual inventory cost (including shelf replenishment ordering cost and the opportunity costs of shelf space used) for item j, then

$$\mathrm{TIC}_{\mathrm{RFIDj}} = \mathrm{TIC}_j \sqrt{v_{\mathrm{RFID}}/v}. \tag{10}$$

This implies the summation of TIC_j over all the items j, denoted by TIC, will also reduce by the same factor. Thus

$$\mathrm{TIC}_{\mathrm{RFID}} = \mathrm{TIC}\sqrt{v_{\mathrm{RFID}}/v}. \tag{11}$$

This formula is easy to use because it easier to estimate TIC of all items together than individually. It must be noted that TIC includes all costs incurred to keep the shelf replenishment going, and the opportunity cost of shelf space. The opportunity cost refers to what can be done with any shelf space available, such as the profit that can be realized by using the space to sell other products. Indeed, a significant benefit of RFID is expected to come from the amount of shelf space that is saved due to reduction in the quantity of an item that needs to be kept on the shelves. Because RFID will bring in additional efficiency, the on-the-shelf quantity of an item can be smaller.

The total system cost TSC includes the fixed cost F and the inventory cost TIC. In other words $\mathrm{TSC} = F + \mathrm{TIC}$. After RIFD installation, we have

$$\begin{aligned}\mathrm{TSC}_{\mathrm{RFID}} &= F_{\mathrm{RFID}} + \mathrm{TIC}_{\mathrm{RFID}} \\ &= F_{\mathrm{RFID}} + \mathrm{TIC}\sqrt{v_{\mathrm{RFID}}/v}.\end{aligned} \tag{12}$$

There are two other benefits derived from RFID: reduction in losses due to shoplifting and reduction in checkout costs. RFID can reduce the amount of shoplifting and thus may bring significant monetary savings. Using RFID can reduce the time required for checkout, and thereby reduce the number of checkout counters and clerks needed. Let B_{SL} be the benefit due to reduction in shoplifting from RFID and B_{POS} be the reduction in the cost of checkout due to RFID.

Putting the costs and benefits together, we can say that using RFID for shelf replenishment will be beneficial if

$$F_{\mathrm{RFID}} + \mathrm{TIC}\sqrt{v_{\mathrm{RFID}}/v} B_{\mathrm{SL}}.B_{\mathrm{POS}} + F + \mathrm{TIC}$$

or, if

$$F_{\mathrm{RFID}} < F.B_{\mathrm{SL}}.B_{\mathrm{POS}} + \mathrm{TIC}(1 - \sqrt{v_{\mathrm{RFID}}/v}). \tag{13}$$

A numerical example of the previous method applied to a hypothetical retail store is described in Section VIII.

VIII. Numerical Example of Cost Benefit Analysis

Suppose a retail store uses part-time employees to replenish the shelves. The fixed cost is found to be, say, \$312 000 US dollars per year and the variable cost is \$0.75 per replenishment. The fixed cost may be estimated through a regression of the costs against the number of shelf replenishments. But this regression is possible only if the relevant historic data are available. Another way to estimate the fixed and variable costs is to estimate the total cost at the maximum expected number of replenishments per year and the total cost at the minimum number. A straight line may be fit between these two estimates to find the fixed and variable costs. The variable costs are typically the wages of part-time employees who are hired depending on the workload and the cost of consumables.

The company may find that RFID implementation has \$750 000 fixed cost (per year) and a low variable cost of \$0.10 per replenishment. The fixed cost would comprise the amortized cost of computer hardware, RFID related equipment, RFID tags, salaries of full-time employees and the wages of (fewer) part-time employees. The formulas presented in Section VI for estimating the loads can help to estimate the cost of computer hardware. The variable cost will be the cost of, once again, the consumables.

The use of RFID tags can reduce the number of shoplifting cases that go undetected otherwise. Suppose the use of RFID reduces the loss due to shoplifting by \$3650 per year (\$10/day). Another area of substantial savings from the use of RFID is the savings at POS terminals where the checkout will be faster. As a result, the store will need fewer checkout counters and fewer cashiers. Let the estimated savings in POS be \$24 000 annually.

The Cost Accounting Department can estimate the annual total cost of carrying and ordering inventories from the books fairly accurately. The annual carrying cost includes the cost of the shelf space which would be considerably large. It includes rent, utility, and maintenance cost of the area in which the shelves are kept. Suppose the total inventory cost (TIC) is \$980 000 per year.

We now have all the data and can compare the costs and benefits according to condition (13). In other words, we shall check if

$$F_{\mathrm{RFID}} < F + B_{\mathrm{SL}} + B_{\mathrm{POS}} + \mathrm{TIC} * \sqrt{1 - v_{\mathrm{RFID}}/v}.$$

In our example, this calculation works out to checking if

$$\begin{aligned}\$750\,000 < \$312\,000 + \$3650 + \$24\,000 \\ + \$980\,000 \times \sqrt{1 - 0.10/0.75}.\end{aligned}$$

This reduces to checking if $\$750\,000 < \$961\,805$.

Since the inequality is true, we declare that the RIFD installation is beneficial. Furthermore, it is expected to save $\$961\,805 - \$750\,000 = \$211\,805$ annually.

The previous example illustrates the benefits of RFID implementations. The exact number on the costs and expenses of RFID implementations varies depending on the implementation. However, the main thrust of this paper is the analytical models that managers can use to determine whether an RFID implementation is beneficial for their organization. The example of this section serves to illustrate the application of the models and is not intended as an argument either in favor or against RFID implementations.

IX. Conclusion

The literature on RFID applications has thus far focused on mostly logistics, an area in which RFID has proven to be beneficial. In this paper, we have attempted to examine whether RFID implementations in retail stores will also be beneficial. We first described and classified the various transactions that are generated by RFID tag reads in the supply chain. Then, we discussed how RFID technology can be implemented in a retail store. Specifically, we provided different designs to interconnect the tag readers in a retail store. These designs range from completely wired networks to completely wireless networks. We also suggested how mixed networks, which combine the wired and wireless technologies, can be used to interconnect RFID tag readers.

Next, we looked at the fixed costs of RFID implementations. These costs consisted of the cost of the readers and the networks that interconnect them. We then turned our attention to the variable costs. As a first step, we have provided mathematical models to estimate the processing load generated by RFID transactions. Following this, we have provided a mathematical model to estimate the reduction in the inventory costs by virtue of increased efficiency in shelf replenishment using RFID technology. Some additional benefits of RFID technology are reduced losses due to shoplifting and reduced cost of POS system. Putting them all together, (13) tells us when an RFID implementation is beneficial. It can give an estimate of the monetary benefit as well.

Future directions for research include extending these models to the manufacturer and the distributor. The infrastructure models for the manufacturer and the distributor are very similar to the models for the retailer. However, the manufacturer cost of implementation includes the cost of the tags as well. Another direction for future research includes estimating and analyzing other hidden costs associated with RFID implementations including employee training and possible reorganization of business units caused by RFID technology. Evaluations of intangible benefits, such as improvement in customer satisfaction and employee morale, are good topics for future research. Consumer concerns on privacy with RFID tags and security issues related to RFID implementations are additional topics that warrant further research.

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