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A cost-effective RFID encoding method for inventory identification

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In supply chain management, identifying the contents of an incoming package is a necessary process during inventory control. If each item in the package has its barcode, this job can be done by manually scanning the barcodes of thousands of items in the package. However, it is too impractical for today's inventory control. The identification should be done automatically and quickly (e.g., within 100 ms). If each item is RFID-tagged, this inventory control issue can be solved smoothly. Nevertheless, for small-scale participants, such kind of identification can be prohibitively expensive. A time-efficient and cost-effective method is thus called for. In this paper, we first discuss the inventory control issue, that is, verifying the items of an incoming package, emerging in supply chain management. The issue is not that easy to resolve, because the whole verifying process must be done economically, quickly, and automatically. To shorten the identification process, we propose an efficient method that compresses all items' keys (that is, barcodes) into a unique identifier (e.g., RFID) for an incoming package. The proposed method can support time-limited applications, achieve better global data sharing, and coexist with traditional barcodes. Moreover, it is well suited to small-sized or financially limited enterprises, and can be used to keep track of mediocre items as well as high-priced items. Finally, we conclude by discussing its technical, economical, and time feasibilities.

Key words: Barcode, RFID, multiplicity, supply chain management, ubiquitous computing.

INTRODUCTION

Supply Chain Management (SCM) (Benisch et al., 2009; Collins et al., 2009; Kiekintveld et al., 2009; Sardinha et al., 2009; Wu and Chuang, 2009) was first introduced by Oliver and Webber in 1982 (Oliver and Webber, 1982). It is defined as a serial of processes of planning, implementing, and controlling the operations of a supply chain (Wikipedia, 2009; Oliver and Webber, 1982); and it aims to achieve greater distribution efficiency, better inventory accuracy, and less labor intension (Aanza AutoID Group, 2004). A supply chain can be viewed as a distribution network together with its participants such as supplier, manufacturer, shipper, distributor, and customer. On the other hand, some up-to-date technologies and concepts can be adopted in SCM for benefiting all participants from the upstream to the downstream. Therefore, we require integrating their needs and those new technologies in a more efficient way. Traditional processes and facilities such as conceptual designs and physical equipments need some adjustments. Accordingly, the work of upgrading or redesigning will beget new issues in today's SCM.

In this paper, we concentrate on resolving an inventory control issue in SCM: Receiving identification (Bose and Pal, 2005; Keith et al., 2002; Wamba et al., 2006), that is, to provide identification for items in an incoming shipment. Shipped items can be packed, up to each participant's decision, in unit of case, pallet, or cargo container. Along a distribution network, each participant may attach his/her own tag or serial number to a shipment and this tag or serial number is recognized by him/her only. Suppose that the Internet is unavailable or the manifest is too detailed to transmit in a time-constrained application. Consequently, a downstream participant cannot determine what items are inside the shipment after reading the outside single serial number tagged by an upstream participant. From the viewpoint of management information system, it is a waste to manually check all items or to wait for a detailed list for a long time. All the participants' encoding standards should be integrated into a sharable single one and can be operated offline. If so, a united and sharable shipment identification method can actually benefit all participants. In addition, the miscount or mis-pick rate caused by any participant will be minimized greatly. Fortunately, today some technologies can help deal with this issue and reach the above goals.

Consider the following receiving identification example in a three-staged supply chain: At the first stage, a supplier produces various items ordered by multiple customers; The next stage is to send the items to a deliver; At the third stage, the items are finally brought to these customers. Note that there might be a potential bottleneck in the supply chain. Suppose the deliver receives a huge amount of packages simultaneously. Then, to determine the exact contents of each package time-efficiently and cost-effectively will become a thorny issue. Therefore, a more efficient receiving identification method is called for.

Barcoding is somewhat out-of-date and has been used in SCM for years (Aanza AutoID Group, 2004; Bendavid et al., 2006), but it can still provide some solution to the inventory control issue. Its strengths and drawbacks are discussed as follows: This technology is known for low cost, well-defined standards, global deployment, and can be preprinted on each item. However, several inherent shortcomings make it uncompetitive. For example, barcodes need to be visible (e.g., read by direct line-of-sight infra-red rays) and be very close to a hand-held reader. Furthermore, barcodes cannot support simultaneous item identification (that is, a reader cannot scan multiple barcodes simultaneously (Bose and Pal, 2005; Su et al., 2010)), cannot be re-written, and cannot store plenary information (e.g., a manifest of all shipped items). Consequently, all of these drawbacks deter us from resolving this issue by only using this technology.

Radio Frequency Identification (RFID) (Au and Kauffman, 2008; Dahlberg et al., 2008; Hassinen et al., 2008; Lim, 2008; Yoon and Kim, 2008) is an automatic identification technology and seems to be a better answer to this issue (Aanza AutoID Group, 2004; OGCIO, 2006; Bendavid et al., 2006; Bose and Pal, 2005; Keith et al., 2002; Niederman et al., 2007; Wamba et al., 2006; Smart Code Corp, 2009). It uses radio waves to capture data from RFID tags. Today the RFID technology is widely deployed in SCM (e.g., Wal-Mart) to increase checkup speed and inventory accuracy. Early error detection or exception handling becomes more possible and easier. Moreover, it needs fewer manual operations, offers faster and more reliable identification by enabling simultaneous reading of hundreds of items per read, and provides more information by a tag, e.g., 128 bits. RFID tags can be read slightly away (e.g., 3 feet) from a reader and are not necessarily visible to the reader (that is, obstacles may exist between the tag and the reader). As a result, we consider applying this technology to the inventory control.

However, there are still several challenges in integrating the RFID technology into today's SCM. They are listed below.

1. The cost of RFID tags is still much higher than that of barcodes [e.g., 50 cents-$50 vs. 0 - 1 cents (Su et al., 2010; HowStuffWorks, 2010; Barcoding, 2010; Barcode Discount, 2010; Nationwide Barcode, 2010; ISB, 2004)]. Although this technology has evolved from active tags to passive ones (that is, not battery-operated and less expensive), it is still not affordable for every participant. Moreover, RFID tags are usually used in a supply chain to track high-priced items (Bose and Pal, 2005). Therefore, tagging each item in a package is too expensive to carry out.
2. There are too many participants involved in the reengineering of an integrated information system. It is difficult to reach an agreement to the same extent for all of them. There might be different opinions on the introduction of RFID technology.
3. Some items, such as metal-made or liquid products, cannot be RFID-tagged. This is because these materials may cause deflection and refraction when reading RFID tags (Aanza AutoID Group, 2004; Niederman et al., 2007).
4. Without the Internet, a downstream participant cannot tell what items are inside a package after reading an RFID tag attached outside by a supplier. That is, the database of the supplier had better be accessible to shippers or retailers.

In this paper, we propose an eclectic method to deal with this issue. We consider both RFID and barcoding as the two complementary technologies. Taking advantage of barcode's low prices and RFID's reliability and automation, we can provide a better and faster shipment identification method than what is in use currently. This method is primarily done by a collision-free hash function which assigns a small-sized identifier to each package. This identifier is uniquely determined by the package's contents. This uniqueness makes all participants be able to immediately identify the contents of a package at its arrival without the need of unpacking the package, even in an off-line environment.

Seven contributions are made in this paper. First, the proposed method can support time-limited applications (Su et al., 2010). The verification of all items in a package can be done automatically and simultaneously. Second, the contents of a package can be easily identified by all related participants in a supply chain. Therefore, we can achieve better global data sharing across organizational boundaries. Third, the RFID technology can coexist with traditional barcodes. Namely, this technology can be phased in over time and the cost and risk of using the RFID technology can surely be lowered down to an acceptable level. Fourth, the proposed method can work in a ubiquitous environment even if the wired or wireless network is off-line. Fifth, to some extent, we can achieve item-level privacy preserving (Kerschbaum et al., 2010; Nohara and Inoue, 2010). Because we need not to unpack a box to identify its contents, irrelevant people will not exactly know what are inside the box. Sixth, the method can support planograms, that is, retail items can be organized in advance according to layout plans (Chaves et al., 2010). All desired items can be packed by an upstream participant and then delivered by some midstream participants. Finally, downstream participants unpack their own packages and put items to the right positions of shelves in their selling points. Seventh, compared with previous work (Jea and Wang, 2008), we consider associating a quantity (or multiplicity) with each item. For items in a package, they may have different quantities. This additive consideration makes the proposed method more practicable. Therefore, the method can be applied to tracking mediocre items, e.g., books or clothes, as well as high-priced items.

PROBLEM FORMULATION

In this paper, we consider simple linear barcodes [e.g., UPC (Wikipedia, 2010)] and passive RFID only. This is because they are in common use and their implementation costs are relatively low. Therefore, we can extend the proposed method to most situations. In light of this, some special barcode formats [e.g., 2D barcode (Wikipedia, 2010)] and active RFID standards are not considered here.

Before formulating the RFID encoding problem, we need a simple notation to denote the contents of a package. Therefore, we employ the concept of multiset (Liu, 1985) and denote each package by a multiset. The notation is described as follows:

Definition 1

A multiset is a collection of items that are not necessarily distinct and the multiplicity of an item is the number of times the item appears in the multiset. Then a multiset S can be denoted by $S=\{n_x \times d_x,\ n_y \times d_y,\ \ldots,\ n_z \times d_z\}$ and the number of item types in S is denoted by $|S|$, where n_x, n_y, $n_z > 0$ are the multiplicities of items d_x, d_y, d_x, respectively.

Now the RFID encoding problem in a ubiquitous environment is described as follows. A supplier offers N types of merchandise items. Let $B = \{1, 2, \ldots, N\}$ denote the barcode set of the N item types. There are many customers and each of them can order his/her designated items. Therefore, we assume that each participant knows about the manifest (the list of all items he/she ordered earlier) in advance. Suppose there are m kinds of orders in a single shipment. For the i-th kind of order, we denote it by a multiset and the desired items will be packed into a package, that is $p_i=\{n_{i,1} \times d_{i,1},\ n_{i,2} \times d_{i,2},\ \ldots,\ n_{i,|p_i|} \times d_{i,|p_i|}\}$, where $d_{i,1}$, $d_{i,2}$, …, $d_{i,|p_i|} \in B$. Under the above assumptions, the problem to solve is assigning a small-sized identifier (that is, RFID tag) to each package such that all the package-related participants in a supply chain can identify what items are inside the package at anytime anywhere. In other words, the process of examining an incoming package needs to be done automatically by a one-time tag reading, regardless of how many items in the package. As for the customers ordering the same kind of package (that is, their desired items are identical), we assume that the addressees' names are different. Thus no customer will mistake other's package.

In the problem, we need to examine an incoming package cost-effectively and time-efficiently. Unpacking the package and scanning each item's barcode surely ensures a correct inventory. However, it is too time-consuming to meet our needs. Someone may think of pasting an aggregate barcode (that is, for all items) up on each package, but it still does not work. First, barcodes do not support automatic inventory control and manual operations are therefore inevitable. Second, each barcode cannot hold vast amounts of data, e.g., up to 32 digits or 20 characters (ComputerWise, 2010; OMRON, 2010). Even so, some outdated hardware and software cannot get with it. Third, barcodes cannot be re-written. It means we need more new barcodes and more labor when dividing a package into several sub-packages or merging several packages into a larger package. On the other hand, it seems feasible to attach each single item an RFID tag and to pack them into a package. It surely achieves an efficient and correct inventory. However, it costs too much. Therefore, we need to develop a cost-effective method that ensures a correct inventory without the need of checking items individually and manually.

RFID ENCODING

Here we state the main idea of how to generate an all-in-one package identifier. In other words, all participants can determine if this package is the correct one that contains all their desired items after reading a single identifier (that is, RFID tag). After all, listing all items' barcodes on the outer packing case is neither space-effective nor time-efficient. Therefore, we propose an algorithm for generating small-sized identifiers and illustrate the main idea with an example.

An all-in-one package identifier

We need to assign an all-in-one identifier to each kind of package. However, simple bitmap-based identifiers cannot meet our needs (that is, must be small-sized).

Consider the following simple example. Assume that there is only one available item for each item type, that is, the multiplicities of items in a package are all 1. In theory, there are different kinds of packages (except the empty one).

$$C_1^N + C_2^N + ... + C_N^N = (2^N\text{-}1) \qquad (1)$$

The most apparent way is to number these packages from 1 to (2^N-1) by using (2^N-1) *N*-bit binary numbers. However, we cannot use such (2^N-1) serial numbers as the *m* identifiers, since it is a waste. Imagine that both a supplier and a customer use a 16-byte unsigned integer, that is, 128 bits, to store an identifier. Each bit signifies an item and the supplier can thus sell only N = 128 items at most. Moreover, if a supplier can offer multiple items for each item type, the problem will become more complicated. Therefore, we have to design another type of space-economic identifier.

The main idea is to transform multiple item keys (that is, barcodes) into a single identifier. Here we propose a collision-free hash function that can generate a unique real-number identifier for each multiset (or package). We define a hash function originated from the concept of moments (Hogg and Craig, 1995). Moments of different orders are usually of different meanings. For instance, the first moment indicates mean, and the second one indicates variance if the mean is zero, and so forth. We do not refer the moments in integer order. Instead, we extend the idea from integer to real number for guaranteeing the uniqueness of all identifiers. Thus we are able to assign an identifier to each kind of package.

In the following definition, we define a hash function, $A_i(x)$, to generate a space-economic identifier for the *i*-th kind of package. Here a package is denoted by a multiset. For each package p_i, in a shipment, we use $A_i(x)$ to signify it.

Definition 2

A package is denoted by a multiset. For each package p_i={$n_{i,1}\times d_{i,1}$, $n_{i,2}\times d_{i,2}$, …, $n_{i,|p_i|}\times d_{i,|p_i|}$} and all $x\in(0, 1)$, let

$$A_i(x) = \tfrac{1}{n_i}\sum_{k=1}^{|p_i|}\left(n_{i,k}\cdot d_{i,k}^{1+x}\right) \qquad (2)$$

be the hash function for p_i, where n_i = $n_{i,1}$+$n_{i,2}$+…+ $n_{i,|p_i|}$ is the total number of items in p_i.

Now we show that $A_i(x)$ is collision-free and we can use it as a unique identifier for the *i*-th package or the *i*-th multiset. That is, there exists a small positive real number δ such that all kinds of packages in a single shipment can be discriminated by $A_i(\delta)$, for all i =1, 2, …, *m*. The results are shown in Lemma 1, Lemma 2, and Theorem 1 below.

Lemma 1

$A_u(x) = A_v(x)$ for all $x\in[a, b]$ implies that p_u=p_v, where 0<*a*<*b*<1.

Proof: Note that the hash function $A_i(x) = \frac{1}{n_i}\sum_{k=1}^{|p_i|} d_{i,k}^{1+x}$ is a continuous and differentiable function for *I* = 1, 2, …, *m*. Thus, for $A_u(x)$ and $A_v(x)$, we can find their Taylor's series (Johnson et al., 1988) and the equation

$$A_u(x) - A_v(x) = 0 \qquad (3)$$

can be rewritten as

$$\sum_{k=0}^{\infty} a_{uk}(x-a)^k - \sum_{k=0}^{\infty} a_{vk}(x-a)^k = 0 \,. \qquad (4)$$

Let $b_k = a_{uk}\text{-}a_{vk}$ for all *k*. Then Equation (4) becomes

$$\sum_{k=0}^{\infty} b_k(x-a)^k = 0 \,. \qquad (5)$$

Since $A_u(a) = A_v(a)$, b_0=a_{u0}-a_{v0}=0. Note that $A'_u(a) = A'_v(a)$. If not, $A_u(x)$ and $A_v(x)$ will differ at some *x*>*a*. It contradicts that $A_u(x) = A_v(x)$ for all $x\in[a, b]$. Therefore, b_1=a_{u1}-a_{v1}=0. Similarly, we can infer that b_k=0 for all *k*. That is, a_{uk}-a_{vk}=0 for all *k*. Since the hash functions $A_u(x)$ and $A_v(x)$ are made up of the barcodes of the *finite* items in p_u and p_v respectively, it means that p_u and p_v are exactly the same as each other. The proof is complete.

Lemma 2

For any ε > 0 and any distinct p_u, p_v with $A_u(0) = A_v(0)$, there exists a small positive real number δ such that

$$0 < | A_u(\delta) - A_v(\delta) | < \varepsilon/2 \,. \qquad (6)$$

Proof: First, we show there exists δ_1 > 0 such that $0 < | A_u(\delta_1) - A_v(\delta_1) |$ holds. For any *i*, $A_i(x)$ is a continuous and differentiable function. Therefore, $A_u(x)$

and $A_v(x)$ are also continuous and differentiable at $x = 0$. The barcodes of the items in p_u and p_v need to be at odds for at least one item, because p_u and p_v are distinct packages. Hence, we can find a positive real numbers δ_1 such that $0 < | A_u(\delta) - A_v(\delta) |$ holds, since $A_u(x) - A_v(x) \neq 0$ for some $x \in (0, 1)$. If not, by Lemma 1, $A_u(x)$ and $A_v(x)$ are identical, Namely, p_u and p_v are identical. It is a contradiction. Therefore, there are two cases. The first one is that $A_u(x) - A_v(x) \neq 0$ for all $x \in (0, 1)$. Thus, we can set $\delta_1 = 0.5$. The second one is that $A_u(x) - A_v(x) = 0$ for some $x \in (0, 1)$. Let x_0 be the minimal solution between 0 and 1. Therefore, we set $\delta_1 = (x_0 - 0)/2$ and δ_1 is found.

Second, we show that there exists $\delta_2 > 0$ such that $| A_u(\delta_2) - A_v(\delta_2) | < \varepsilon/2$ holds. If $A'_u(0) - A'_v(0) = 0$, we set $\delta_2 = \varepsilon/4$. Otherwise, we set $\delta_2 = \varepsilon/(4\,| A'_u(0) - A'_v(0) |)$ and δ_2 is found. Finally, let $\delta = Min\{\delta_1, \delta_2\}$. δ is found. The proof is complete.

In the following theorem, we show that it is possible to assign each package p_i a unique identifier for $i = 1, 2, \ldots, m$, where m is the total number of packages in a shipment. Note that N is the number of item types and assume that there are at most n items in a package, that is, $n_i \leq n$ for all i. In theory, there are

$$C_1^N + C_2^{N+1} + C_3^{N+2} + \ldots + C_n^{N+n-1} \tag{7}$$

possible different packages. That is, m might be as large as ($C_1^N + C_2^{N+1} + C_3^{N+2} + \ldots + C_n^{N+n-1}$). Although m might be a large number, we can still ensure the uniqueness of all identifiers.

Theorem 1

There exists a small positive real number δ such that $A_i(\delta) \neq A_j(\delta)$ for all $i \neq j$, where $i, j \in \{1, 2, \ldots, m\}$ and m is the number of the kinds of packages.

Proof: Assume there are K pairs of distinct packages p_{a_k} and p_{b_k} with $A_{a_k}(0) = A_{b_k}(0)$, for $k = 1, 2, \ldots, K$. For all $i, j \in \{1, 2, \ldots, m\}$, let the minimal non-zero distance between $A_i(0)$ and $A_j(0)$ be ε. First, we need to separate the K pairs of function values at $x = \delta$. Second, we must guarantee that if $A_i(x)$ and $A_j(x)$ can be discriminated at $x = 0$, the merit should be retained at $x = \delta$ as well.

First, we show the existence of δ for the K pairs of p_{a_k} and p_{b_k} with $A_{a_k}(0) = A_{b_k}(0)$. By Lemma 2, we can find δ_k such that the following inequalities hold, for each $k = 1, 2, \ldots, K$.

$$0 < | A_{a_1}(\delta_1) - A_{b_1}(\delta_1) | < \varepsilon/2 \tag{8.1}$$

$$0 < | A_{a_2}(\delta_2) - A_{b_2}(\delta_2) | < \varepsilon/2 \tag{8.2}$$

$$\cdots$$

$$0 < | A_{a_K}(\delta_K) - A_{b_K}(\delta_K) | < \varepsilon/2 \tag{8.K}$$

Second, we show the inequality $A_i(x) \neq A_j(x)$ holds at $x = \delta$ for all p_u and p_v with $A_u(0) \neq A_v(0)$. That is, we need to make sure that each of them will not change intensely at $x = 0$ and satisfy

$$0 < | A_i(\delta) - A_i(0) | < \varepsilon/2 \,. \tag{8.K+1}$$

Let

$$A'_r(0) = Max\{A'_1(0),\ A'_2(0),\ \ldots,\ A'_m(0)\}. \tag{9}$$

Since $A_r(x)$ is of greatest slope at $x = 0$ and it is a strictly increasing function, we can find a small positive real number $\delta_{K+1} < \varepsilon/(2A'_r(0))$ such that Inequality (8.K+1) holds.

Finally, let $\delta = Min\{\delta_1, \delta_2, \ldots, \delta_{K+1}\}$. Note that $A_r(x)$ is of greatest slope at $x = 0$ and its function value just can increase the amount of $\varepsilon/2$ at $x = \delta$ at most. In addition, all other function values have relative distances ε at $x = 0$ at least. Hence, $A_r(\delta)$ will not be identical to any other hash function values at $x = \delta$. Now the most radically-changing $A_r(x)$ will not be identical to others at $x = \delta$, much less the remaining relatively-stable ones $A_i(x)$, for all $i \neq r$. So δ is found. The proof is complete.

We illustrate an example of RFID encoding in Table 1 and Figure 1. Suppose there are 20 types of merchandise items and 6 orders (that is, 6 packages). Assume the barcode d_j is j, for $j=1, 2, \ldots, 20$. Here we set $\delta = 0.01$ and make the supplier and customers aware of this setting. This can be done by tagging an extra RFID for storing δ, so no advanced commutation or physical contact is needed. The relationships of those packages in Table 1 are depicted in Figure 1. For example, packages

Table 1. An example of RFID encoding.

Package in a shipment	ID $A_i(\delta)$
p_1 = {4}	4.0558379
p_2 = {1, 4, 4}	3.0372253
p_3 = {4, 6, 15, 15, 20, 20, 20, 20}	15.4275840
p_4 = {1, 4, 4, 4, 7}	4.0610123
p_5 = {12}	12.3019245
p_6 = {10, 14}	12.3036582

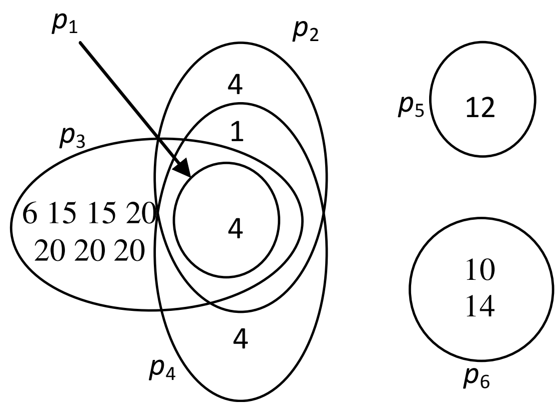

Figure 1. The corresponding graph of Table 1.

p_1, p_2, p_3, and p_4 have some items in common, whereas packages p_5 and p_6 do not.

Each multiset (e.g., p_3) is signified by a real number (e.g., 15.4275840). Upon reading the identifier 15.4275840 tagged on the package p_3, the customer ordering p_3 can easily identify what items are inside (that is, items 4, 6, 15, 15, 20, 20, 20, 20) without the need of manually scanning barcode item by item. Note that p_5 and p_6 are two packages with similar identifiers. If some identifiers are too close to be discriminated, we need a higher precision. In general, double precision (16 bytes) is a proper choice. Let us imagine that, if the proposed method is not used, the incoming package p_3 needs to be unpacked and then all its items' barcodes or RFID tags need to be scanned item by item. Both of them are impractical. The reasons are as follows: The former (barcode reading) is very time-consuming and labor-intensive; and the latter incurs very expensive cost because all items need to be RFID-tagged.

For a single shipment, in fact, there might be many eligible δ's that can generate a unique RFID identifier for each package. Note that the ultimate goal is to assign each package a unique identifier, and Theorem 1 ensures that there exists a small real number $\delta > 0$ such that all A_i (δ)'s are distinct. However, due to the limitation of floating-point notation, we may encounter a real-world quantization problem that a very small δ cannot be expressed by a 16-byte storage format. Therefore, we can use several δ's to achieve the same goal. That is, for a shipment, the values of δ's for all A_i (δ)'s (or all packages) are not necessarily identical. The following corollary shows that we can assign each package in a shipment a unique identifier by using different δ's. However, a different δ stands for one more RFID tag. Consequently, some extra cost is incurred if we use two or more different δ's for the packages in a shipment.

Corollary 1

There exists m small positive real numbers δ_i's such that $A_i(\delta_i) \neq A_j(\delta_j)$ for all $i \neq j$, where $i, j \in \{1, 2, \ldots, m\}$ and m is the number of the kinds of packages.

Proof: It follows directly Theorem 1. By Theorem 1, there exists a single δ that can make all $A_i(\delta)$'s are distinct. For A_1 (δ), we can replace δ with some $\delta_1 > 0$ and do not make A_1 (δ_1) collide with other A_i (δ)'s. Similarly, we can replace all δ's of A_i (δ)'s with different δ_i's for i = 2, 3, …, m. Therefore, using different δ's still can achieve different A_i (δ)'s for the packages in a shipment. The proof is complete.

Algorithm for package identifier assignment

We realize the abovementioned idea by a detailed algorithm shown in Figure 2. In this algorithm, we show how a supplier finds an appropriate value for δ. Note that this algorithm is executed by the most upstream participant (that is, supplier) only. All the other participants are merely informed of what δ is. The value of δ can be stored in a re-written RFID tag. Then all participants can identify the contents of a package after reading δ even though the Internet is unavailable.

Figure 2 shows the procedure of generating unique identifiers. Step 1: Sets the initial value of δ, the iteration counter k, and the flag DONE. In Step 3, all initial A_i (δ)'s are obtained. Step 4 checks if there exists any pair of packages unable to be discriminated at $x = \delta$. If no such packages exist, Step 5 sets *DONE* = True and Step 10 returns δ, iteration number k, and all identifiers A_i (δ)'s. Otherwise, Step 7 sets $\delta = \delta/2$ and repeats the procedure again. In the eighth step, if by any chance an underflow error occurs, a more precise precision is required. In general, δ = 0.001 is a proper setting, and a double-precision (that is, 16-byte) number is enough to signify the package identifier in this RFID encoding problem. Consider two similar packages $p_i = \{1, 2,\ldots, N\}-\{1\}$ and $p_j = \{1, 2,\ldots, N\}-\{2\}$ for N = 1,000,000. Their identifier difference, $A_i(\delta) - A_j(\delta) = (2^{1+\delta}-1^{1+\delta})/(N-1)$, is 1.00138677 × 10^{-6} for δ = 0.001. Clearly, we are still able to discriminate the difference between the two intractable identifiers. Therefore, we empirically set δ = 0.001 for most situations.

Algorithm *IdAssign*($p_1, p_2, \ldots, p_m$)

INPUT: m kinds of packages $p_1, p_2, \ldots, p_m$.

OUTPUT: δ, the iteration number k, and the identifiers $A_i(\delta)$ for i =1, 2, …, m.

Step 1 Set δ=0.001, k=0, and *DONE*=False.

Step 2 While not *DONE* do Steps 3-9.

Step 3 For each p_i do compute its $A_i(\delta)$ by Definition 1.

Step 4 For all $A_i(\delta)$'s do check if they are all distinct.

Step 5 If they are all distinct then set *DONE*=True;

Step 6 else execute Steps 7-8.

Step 7 Set δ=δ/2.

Step 8 If an underflow error occurs then output 'Consider a better precision!' and stop.

Step 9 Set k=k+1.

Step 10 Output δ, k, $A_i(\delta)$ for i=1, 2, …, m.

Figure 2. Encoding algorithm for generating package identifiers.

The time complexity of the algorithm in Figure 2 is analyzed as follows. Let the average number of items in a package be $\bar{n}$. Because the number of bits of a floating number is always fixed, Step 7 can be executed for k_0 times at most or otherwise an underflow error will occur, where k_0 is a constant. Therefore, the time complexity of this encoding algorithm is $O(m\bar{n})$.

CASE STUDY AND EVALUATION

Here, the proposed method in Section 3 is applied to two different scenarios of inventory identification. First, the encoding method is applied to the inventory identification of some mediocre items such as books or clothes. Tagging each item with an RFID is impracticable. After all, each participant cares about his/her own wholesale only. Second, participants have to keep track of every valuable or important item, e.g., blood bags or jewelry. Every step and every item in the shipping process need to be recorded and monitored. In this scenario, it is worthwhile tagging each item with a unique identifier. Finally, we evaluate this encoding method from different viewpoints of technical, economic, and time feasibilities.

Inventory identification of mediocre items

In the first scenario, a package may contain multiple items of identical barcodes. For example, books having identical ISBN and packed into a package are allowed. When such a package arrives, an automatic and offline inventory identification should be done by using two or more RFID tags (the fewer, the better). Compared with past research (Jea and Wang, 2008), the proposed method has taken the quantity or multiplicity of an item in a package into consideration. Thus, the encoding method can support participants in tracking ordinary merchandise items as well as high-priced items.

Figure 3 shows how we pack several packages into a larger package by using different δ's. Consider a shipper receives two packages p_6 and p_7 from two different suppliers, where p_6 uses δ = 0.001 and p_7 uses δ = 0.0005. Note that the identifiers of p_6 and p_7 in a shipment are different. Therefore, the shipper will not mistake others' packages. Here both p_6 and p_7 contain sub-packages and each sub-package has its own RFID (e.g., p_1 is tagged with RFID 3.0036622). No sooner had the shipper read δ from an RFID reader than he/she calculated the supposed identifiers of p_6 and p_7 by a hand-held devise (e.g., PDA). If the calculated identifiers are the same as the ones tagged on p_6 and p_7, it means that the contents of p_6 and p_7 are correct (that is, all items in $p_1, p_2, \ldots, p_5$ are his/her desired items). Therefore, without unpacking p_6 and p_7, the shipper can examine an incoming shipment correctly and quickly (even in an offline environment). This property is guaranteed by Theorem 1 or Corollary 1. After receiving the two packages, the shipper can pack them into a larger package (that is, p_8) for later transportation and set δ = 0.001. Finally, each package is tagged with a unique identifier (e.g., ID_8 = 10.2526683).

Figure 4 shows how we unpack a large package and repack its contents into several smaller sub-packages. When a shipment arrives, a downstream participant may need to repack it. In Figure 4, the shipper reorganizes p_8 into three sub-packages. For example, the shipper can choose another δ = 0.001; and p_1 and p_4 are packed into p_9 with ID_9 = 10.1370794. Now the original ID_1 and ID_4 can be revoked, since ID_9 can signify all items in p_1 and p_4. It means that the proposed encoding method consumes fewer RFID tags. If some package requires no repacking, e.g., p_5, we can leave it untouched and use its original RFID and δ. Note that the final resultant sub-packages are tagged with different ID's. Therefore, each retailer will not mistake others' packages.

Inventory identification of high-priced items

In the second scenario, a package may contain multiple high-priced items. Each item has its own RFID or barcode. For example, a blood bag should be monitored from the moment of blood donation to the completion of transfusion. When such a package arrives,

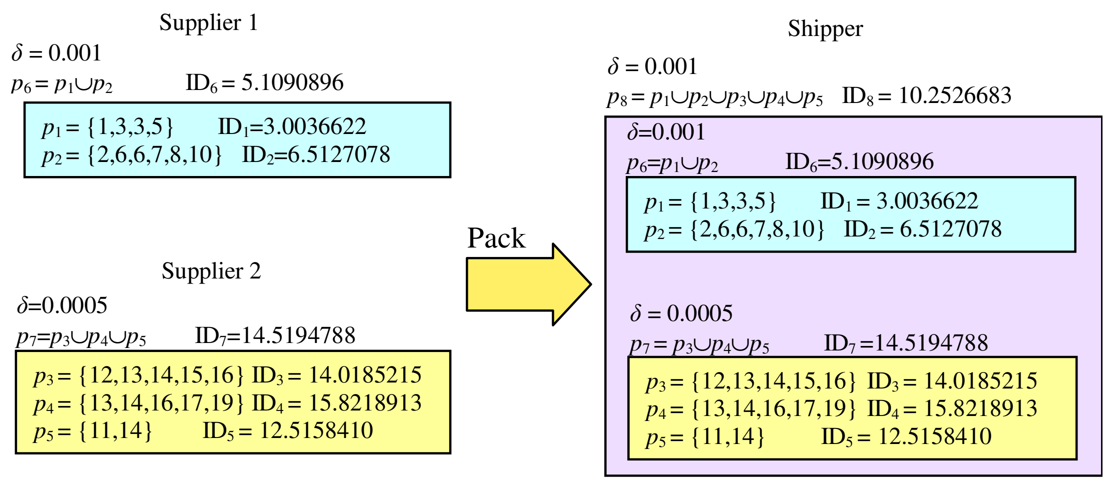

Figure 3. An example of packing two packages into a larger package.

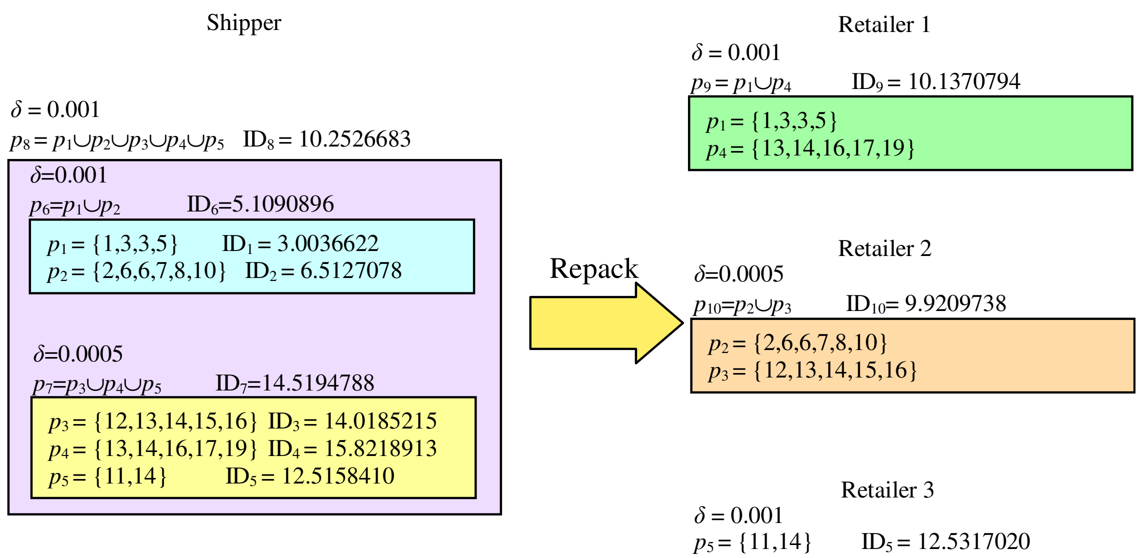

Figure 4. An example of repacking a package into three smaller packages.

receiving identification can be done without the need of scanning RFID tags or barcodes item by item.

Figure 5 shows how we keep track of the shipping process of important items. A shipper receives two packages p_6, p_7 from different sources and will send them to a receiver. First, the two packages can be packed into a large package p_8 with ID_8 = 11.0284140. That is, an extra RFID tag is required here. When p_8 arrives, the receiver can identify the contents of p_8 by reading ID_8 and need not to unpack p_8 right away. Therefore, the receiver can unpack it later if there is an urgent need (e.g., transfusion). Here we assume that a receiver/buyer needs to know his/her own manifest (that is, the list of items he/she ordered earlier) in advance.

Figure 6 shows that the lattice-like relationship between any two participants for the two scenarios. As long as there are no duplicate identifiers in a single shipment (that is, from participant i to participant i+1), each participant can pack, unpack, or repack his/her received packages in hand. Therefore, each participant can choose his/her own δ arbitrarily, use very few identifiers to signify all items in a shipment, and recycle the RFID tags in the previous shipment [e.g., an RFID tag on a crate (Barcoding, 2010)]. Note that an individual buyer can just damage the barcode label on a single item (e.g., food wrapper). Therefore, crate- or pallet-level RFID tag recycling is easily achieved.

As shown in Figures 3 - 6, it is clear that the proposed encoding method is very space-economic, cost-efficient, and easy to realize. First, the method is technically feasible. Each RFID tag is generated by scanning multiple barcodes and Theorem 1 or Corollary 1 guarantees that there are no identical RFID's in a shipment. Therefore, without unpacking an incoming package, a participant can identify the contents by reading the outside RFID tag. It means that the proposed method can achieve correct inventory identification. Second, it is economically viable. No matter how many items are in a package, we can still generate a small-sized identifier for the package. It represents that we need not to tag every item with an RFID. The cost is therefore reduced. Moreover, RFID tags in the method can be reused (e.g., ID_{10} in Figure 4) or revoked (e.g., ID_3 and ID_4 in Figure 4) for other purpose later. The cost can thus be saved more. Third, it is time-feasible. Participants

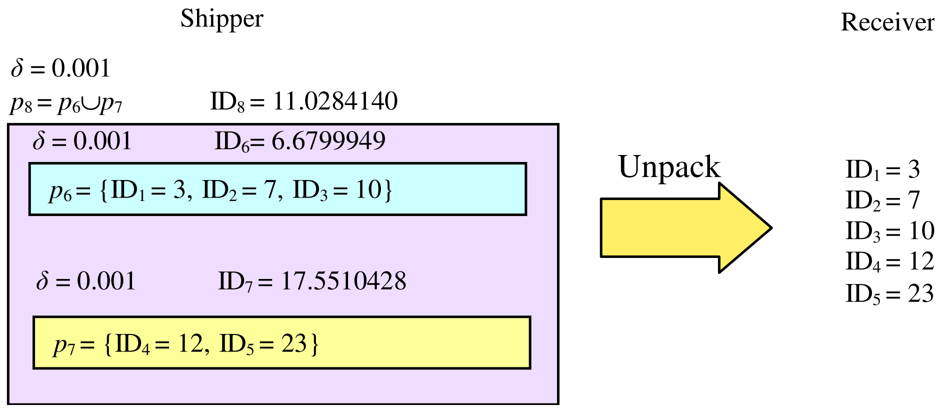

Figure 5. An example of receiving identification of high-priced items.

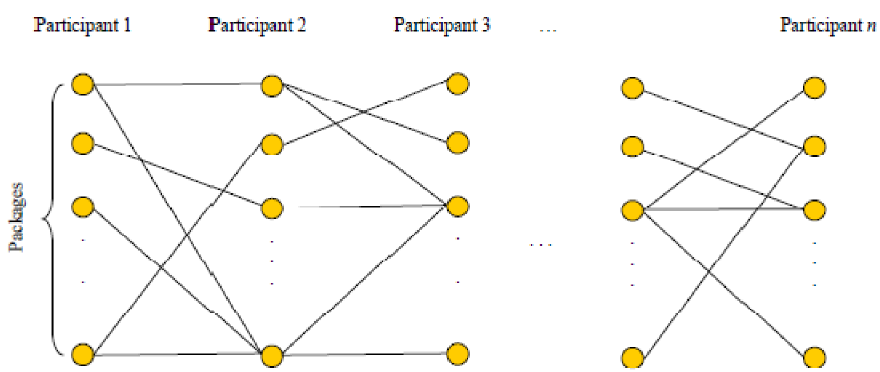

Figure 6. Hierarchy of a supply chain.

in a supply chain can avoid unnecessary unpacking, e.g., there is no need for unpacking p_6 in Figure 3. Hence, receiving identification can be finished in a flash. Moreover, the RFID technology can be phased in over time and the risk of using this technology can surely be reduced. It means that we earn more time to introduce the new technology into our daily use. In sum, each participant can complete receiving identification quickly and economically by using the proposed RFID encoding method.

EXPERIMENTAL RESULTS

Here, the experimental results from a synthetic dataset and a real-life dataset, respectively is shown. In both datasets, the proposed method works well and engenders no collision among all identifiers.

First, we conduct the code generating experiment on the "T10I4D100K" dataset which was generated by a generator from IBM (Goethals B, 2010). There are 100,000 transactions. A transaction contains 10.1 items on average; and these item barcodes are numbered between 0 and 999. We first assign each transaction a unique transaction-level identifier. Then, we repack these transactions into 10-, 50-, 100-, 150-, or 200-transaction packages as we wish; and we tag each package with a package-level RFID. There is still no collision. That is, the proposed method works well in both transaction and package levels.

Second, we choose a well-known real-life dataset "retail" (Goethals B, 2010). In this dataset, we have 88,162 transactions and a transaction contains 10.3 items on average; the maximal number of items in a transaction is 76. Moreover, these item barcodes range from 0 to 16,469. We apply the same method to the second dataset; both transaction- and package-level identifiers can be determined and assigned. In sum, these results validate that the proposed method can deal with not only synthetic datasets but also real-life datasets.

Conclusion

In this paper we propose an RFID encoding method to assign a small-sized identifier (that is, an RFID tag) to each package. Using these small-sized identifiers, all participants can easily identify their own shipments (even in an offline environment) and hence both shipping and receiving errors can be detected earlier. The cost and risk of implementing an RFID-enabled supply chain can be lowered down by phasing in the proposed method in the earlier transition stage, especially for some small-sized or financially limited enterprises. An RFID tag can also signify the compressed information of an item, a box, a crate, a pallet, or even a cargo container as we wish. Likewise, all items, crates, or packages can be packed in advance according to planograms (Chaves et al., 2010) that specify which item should be placed at which location on which shelf in a store. Besides, reading an RFID tag without the need of unpacking a box, so irrelevant people will not exactly know what are inside the box. Item-level privacy can thus be preserved. Moreover, traditional barcodes and new RFID tags now can coexist well in the proposed method. It offers each participant a great level of flexibility regarding the use of RFID tags. On the other hand, we extend the theoretical basis of previous work (Jea and Wang, 2008) by considering the possibility of associating each item in a package with a quantity. This consideration makes the proposed encoding method more feasible to keep track of mediocre items. Due to the improved trust and collaboration among all participants, the interoperability of inter-organizational information systems can be improved inch by inch, faster global data sharing and synchronization can be carried out, and better participant-to-participant supply chain visibility can be achieved, too.

Today the RFID technology is applied to many fields and it outperforms traditional technologies such as barcodes in several aspects; nevertheless, its implementation cost still daunts most of participants in a supply chain. In the transition stage, we need to bridge the gap between the new technology and the existent ones. By doing so, the substitution for existing technologies can thus go more smoothly. In the near future, we hope to design a more cost-effective RFID encoding method that can help us use fewer RFID tags and make more profits.

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