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TRENDS IN INDOOR AND OUTDOOR VISIBILITY IN SUPPLY CHAINS

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Summary

The business value of RFID, other wireless sensor technologies, and distributed application services for supply chain planning and execution are convincing and have been documented by several studies. These technologies enable and support real-time operational visibility and intelligence in supply chains. Application developers, systems integrators and hardware manufacturers continue to develop new products and services even as end-user uptake of RFID and related technologies is not growing as quickly as earlier predicted. In a recent survey of a representative sample of British companies across industries and sectors, we found that the adoption obstacles include challenges in configuring and managing devices, deriving business intelligence from RFID events, absence of uniform standards (or the presence of multiple standards), the availability of a diversity of medium access control protocols, and intricacies of linking RFID events with the enterprise back-end (ERP systems, warehouse management systems, etc.), the perceived cost of adoption (especially at the item level), lack of industry or customer mandates, and the assumption that the available technologies have not yet matured. Evolving standards, technologies and procedures have the potential to lower, or even eliminate, the barriers to adoption in the near term. This paper highlights some of our findings from extensive case studies of existing infrastructure for identification and location of items both indoor and outdoor of the supply chain. The paper also describes our ongoing project in which we are using system dynamics to build event-based decision models for supply chains. The devices considered in our study and in this paper include not only RFID but wireless sensors and generic visibility information sources.

1 Introduction

There are mainly two ways to boost the competitiveness and market survivability of a supply chain: closer integration of the organizations involved and their functional units, and enhanced coordination of materials, information and financial flows within the network. Both of these are geared towards enhancing customer experience and satisfying the customer more than the competition is able to match. Customer service has three facets: pre-transaction, inside-transaction, and post-transaction.

The integration of the organizational units that make up the supply chain rests on several building blocks, the principal ones of which include choice of partners, network organization and inter-firm collaboration, and leadership (Stadtler, 2005; Stadtler and Kilger, 2008). The coordination of supply chain flows is of particular importance because controlling supply chains at both operational and strategic levels is a challenging task, even for experienced supply chain managers. Partners in a supply chain are often neither part of a monolithic hierarchy nor are they loosely coupled by market relations. Hence control mechanisms are always needed, and often these mechanisms combine tools of market and hierarchical relationships. Specialized, transaction-specific, assets tend to lead to higher transaction costs, but, as Dyer (1997) found in his extensive study of the auto industry, this is not universally true. According to transaction cost economics theory, durable relationships and hierarchies prevail when and where the opportunity cost of markets and short-term contracts outweighs that of durable contracts or of integration. And if the cost of enforcing contracts surpasses that resulting from inefficiencies associated with integration, hierarchies will be preferred. Transaction costs include search costs, contracting costs, monitoring costs, and enforcement costs (Williamson 1985, 1991; Dyer, 1997). We would not delve into transaction cost theories here, since this article is supposed to focus on the applications of identification and location technologies to supply chain management.

The coordination of the organizational units that make up the supply chain rests on several pillars, including use of information and communication technologies, process orientation, and advanced planning. The use of identification and location data is especially important in the realization of these pillars. Mobile computing, the Internet and related technologies nowadays permit the accumulation of an almost infinite amount of detailed data concerning instant exchange of sales data, demand and production forecasts, customer orders, etc., across the global supply chain at a relatively low cost. The speed of information exchange can significantly reduce production and customer service lead times and hence the so-called bullwhip effects (demand amplification from the end customer towards the upstream of the supply chain) in supply networks. Communication links in the supply chain are either business-to-business (B2B) or business-to-customer (B2C).

In supply chain management, the availability of near real-time information can help reduce stock-outs and increase sales; improve stock, promotion and sales analysis; reduce labour costs associated with inventory reconciliation and management; increase overall system throughput; increase customer satisfaction and hence reduce annual mark-downs; reduce backdoor shrinkages; reduce losses from changes in the ambient environmental conditions when transporting goods; reduce security issues associated with low cost sourcing from across the world; accelerate custom clearance at ports; speed up ship loading; etc.

Technologies and applications that currently support inventory tracking and visibility include: linear and matrix barcodes, Internet tools (including electronic data interchange) for business-to-business transaction, and dashboard inventory reporting. All these tools, however, are limited in supporting agile, real-time inventory tracking and visibility. RFID and wireless sensor network based inventory tracking and visibility have proved to be far superior in discharging supply-wide visibility. Besides current technology adopters, world-class retailers are either currently trialling or planning to use RFID-based end-to-end inventory intelligence tools (Aberdeen Group, 2011).

End-to-end visibility is needed not only in the transfer of materials, goods and services from one site to another (Landers et al., 2000; Gainnopoulos, 2003; Kärkkäinen and Holmström, 2002; Kärkkäinen et al., 2004), but also in, for instance, manufacturing, retail shop-floor, and library operations (van Leeuwen and Norrie 1997; McFarlane et al., 2003; Thiesse and Fleisch, 2008). In this paper we refer to the former as *outdoor visibility*, while we call the latter *indoor visibility*. The identification, location, navigation, spatial data and telecommunication tools needed for the two types of visibility sometimes overlap but often they are different, much like the needed data accuracy and integrity differ in the two application scenarios. The RFID technology is often used in both types of visibility with different requirements and application modes. The same can be said of, for example, location and map/spatial data.

Many technologies have been introduced in the past decade for both indoor and outdoor visibility. This paper surveys the current state of the art in materializing end-to-end visibility in supply chains. In general, visibility does cost money (especially the needed initial investment in hardware and software components, the often necessary accompanying business process reengineering, communication and computational overheads, and system maintenance). However, the benefits often outweigh the costs, particularly if project options are decided after a thorough analysis of the business value of investment. For example, the Boeing 747 series airplane is made of 4.5 million components, most of which are manufactured by 25,000 companies in 60 countries. The components have to be tracked from source (OEMs) to the point of assembly of the plane; and if recalls happen (due to defects or accidents), they would need to be traced back to the OEMs. Visibility also provides real-time intelligence on the manufacturing shop-floor. For instance, by overlaying multiple manufacturing SmartShelves, SmartBenches, SmartZones, and SmartCells on the existing manufacturing facility, the Omnitrol manufacturing solution introduces real-time visibility and quality control data to the production process.

Visibility requires giving an identity to a good or service, rather assume the good or service to belong to a lot or batch or order. The lot systems have been in use in manufacturing and distribution since the industrial revolution until recently when the planning and operational benefits of item-centric data models and operations became apparent. Constant or continuous visibility is, of course, costlier than continual (or frequent or recurrent) visibility and is often not necessary (even if possible). For example, if at a particular instance all that is needed about a shipment is to inform a distribution or consolidation centre the time of planned arrival of a consignment, then continuous visibility would not justify the cost or the need. Moreover, not every shipment or mobile asset would need regular monitoring. But in modern days it is rare to find cargos or moving assets that do not require monitoring of a particular form. Also to be decided is the required atomic level of identification: item-level or aggregate visibility.

This paper uses products from several technology vendors solely for the purposes of case studies. The interest and objectives of the paper are purely academic; the paper does not qualify or promote any product. Neither does it serve as a commercial medium for any manufacturer. Moreover, we do not guarantee the functionality, quality or reliability of the products mentioned in this paper. Because of space limitation some companies and products that were part of our case studies have not been included in this paper. Prominent among these are Omnitrol (www.omnitrol.com), Ekahau (www.ekahau.com), AGAIDI (www.agaidi.com), Intellident (www.intellident.co.uk), TracerPlus (www.tracerplus.com), Ubisense (www.ubisense.com), Rockwell Automation (www.rockwellautomation.com), and Arira Design's Smart HDK (Arira Design, 2010). Technologies and products from these vendors offer a significant value proposition for supply chain managers. The application areas of the technologies from these vendors range beyond supply chain management to library logistics, hospital management, document management, food safety, network security, etc.

The Arira Design Smart HDK is an elegant web-based sensor solution that implements DASH7 (ISO 18000-7) standards and integrates low power microcontrollers with MEMS sensors (accelerometer, gyro and pressure), light sensor, temperature sensor, GPS and wireless connectivity (active RFID, WiFi, Bluetooth, GSM/GPRS). Multi-sensor integration to support supply chain execution has been a desideratum in the past decade.

2 Event-based planning and operation

Supply chain planning is usually undertaken using the hierarchical planning system (HPS), for which a modular structure is provided in the form of the supply chain planning matrix (SCP-M) in Figure 1. HPS needs a careful and representative modular structure, the allocation of planning tasks to the modules, and the pattern of information flows between the various modules. Normally, HPS uses a rolling horizon, on which complex synchronizations of the planning intervals and horizons on the different levels are assumed or materialized. However, event-oriented planning simplifies the use (and strengthens the outcome) of HPS; it also increases the flexibility and scalability of planning. A necessary requirement for event-oriented planning is a communication system that enables the forwarding of alerts on event to the relevant planning level and assignments. And the outcome of one planning brief can generate alerts for other plans and supply chain operations. Event-based planning and action is today aided by identification, location and communication technologies. There can be no real-time intelligence and operations in supply chain management without real-time or low-latency information about the locations, contexts and statuses of the resources of the supply chain. In short, there can be no ubiquitous intelligence without the corresponding ubiquitous identification and knowledge of location.

The supply chain planning matrix offers a means to visualize the various typical tasks in the supply chain in the two dimensions of planning horizon and supply chain processes. In Figure 1 the long-term tasks are shown in a single box to exemplify the all-inclusive nature of strategic planning in supply chains. The other boxes represent supply chain activities but do not exactly match the planning modules of an HPS; the latter might contain only some of the elements of a box. For example, on the short-term timescale, the planning tasks can be subdivided according to factory sites, shop-floors, or product groups. Planning tasks may also span several of the smaller boxes in Figure 1. The supply chain matrix is also at the core of most of the supply chain advanced planning systems from software vendors like SAP AG, i2 Technologies, Oracle, PeopleSoft, and JD Edwards.

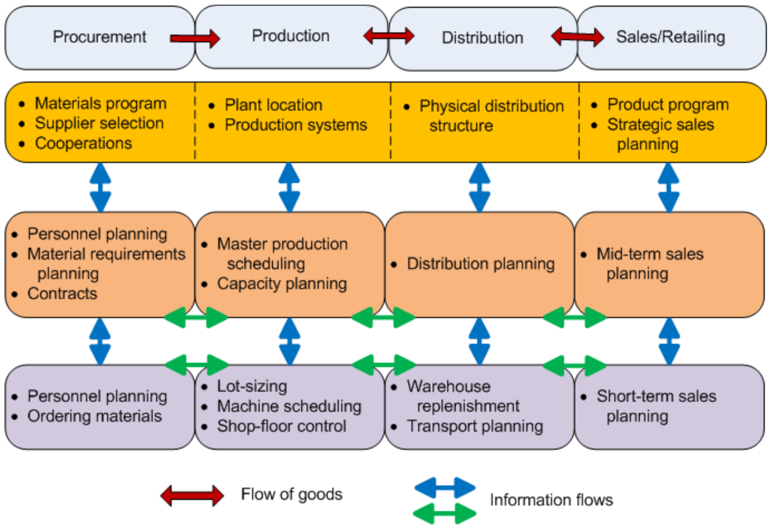

Figure 1: The supply chain planning matrix (after Stadtler and Kilger, 2008)

The existence of real-time identification, location and inventory status information rendered obsolete many former logistics algorithms that were designed to operate in batch mode. One can quickly gain an impression of the value of visibility and the event-based features that it enables in supply chain management by realizing that Tesco (the largest retailer in the UK) has the following cost budget in its supply chain: supplier delivery to Tesco distribution centre (18 per cent), Tesco's distribution centre operations and delivery to store (28 per cent), store replenishment (46 per cent), and supplier replenishment systems (8 per cent). It is evident that nearly one-half of supply chain cost at Tesco is incurred in stores. However, it is not feasible to reduce the in-store costs without spending time and money on improving the upstream and downstream operations. Tesco was able to reduce the costs across the supply chain by integrating external manufacturing and distribution processes with its own internal processes, while at the same improving on customer experience and beating its competitors. The Tesco transport system (www.tesco.co.uk) and the Tesco information system provide some excellent examples of some of the steps taken by Tesco in recent years to optimize its internal processes and collaboration with its suppliers and customers.

Recently we conducted a case study of the delivery systems of Sainsbury's, one of the major retailers in the UK. Sainsbury's capitalizes on tightly integrating Paragon's Routing and Scheduling Optimiser and Fleet Controller with Isotrak's Active Transport Management System to introduce unprecedented levels of certainty and control into its complex product distribution network (www.paragonrouting.com). The system has increased driver

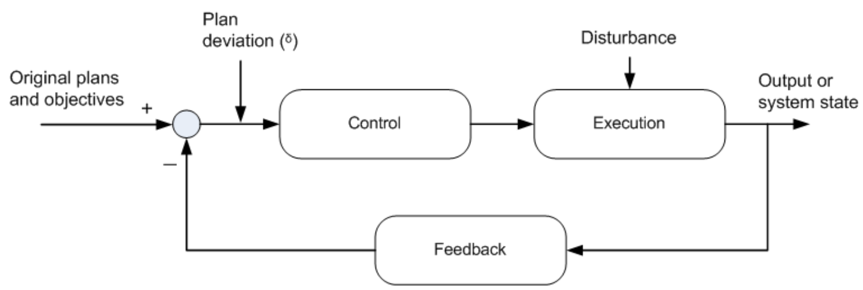

Figure 2: A control system formalism for visibility-enabled supply chain event-oriented planning and execution

productivity by 8%, reduced empty running by 12%, cut store turnaround times by 15%, and increased on-time delivery levels by 17%. Thanks to the new visibility enabled system, Sainsbury's trucks now make 2,000 fewer empty vehicle journeys per week.

2.1 A control system model for event-based supply chain execution

There is an ongoing effort in our University to represent and study the dynamics of events in supply chains using the control system model and real-time visibility data. System dynamics, as found in other phenomena and disciplines, can be applied to supply chain event handling. Real-time end-to-end visibility is needed for event-oriented supply chain planning and execution (see Figure 2). The major considerations regarding Figure 2 relate to:

a) The observation of system state, i.e., the selection of parameters to be monitored (e.g., vehicle position, speed, on-board inventory classification, the physical state of the inventory ─ temperature, humidity, pressure, shock tolerance parameters). Changes in the system state may trigger intervention by system managers or the supply chain control and command centre.

b) The type of interventions to be staged by managers (local plan adjustments versus global replanning). Global replanning may yield theoretically optimal or near-optimal solutions, but they often imply significant changes to the original plans and schedules. Global replanning also entails serious computational burdens for the central planning infrastructure, and considerable communications overheads (since all the distributed assets would need to be informed of the updated plans and schedules). Local replanning may yield more cost effective solutions with minimal distortions to the overall initial plans. However, it is not always easy or cost effective to decompose some system dynamics problems using objective functions that aim at only local optimization. See, e.g., Ghiani et al. (2003) for some related transportation problems.

c) The selection of the system functional objectives. This has significant effects on choice of appropriate intervention schemes. Objective functions usually involve one or more of the following: minimizing deviation from the original plan (locally or globally), minimizing the cost of deviation from original schedules, and minimizing the commercial risks associated with non-conformance (e.g., for supply chain managers, loss of reputation or custom).

The challenges associated with decision making in this regard include modelling the real-time replanning problem and developing suitable solution approaches. Two major factors come into play: problem complexity and computational overheads. Complexity has to be curtailed in order to produce solutions that are cost effective and that can be implemented in real-time. Model complexity can be reduced by disaggregating the problem into simpler, more tractable parts that can be solved independently, mostly by linear methods. The solutions of the decomposed problem are then aggregated to yield the solution of the global or higher-order problem. Approaches similar to the hierarchical method to complex problems are adopted by our research unit. An important consideration in the hierarchical approaches is the 'goodness of fit' of piecemeal solutions. The need to achieve a reasonable goodness of fit determines the choice of the problem partition scheme (Ghiani et al., 2003; Nagy and Salhi, 2007; Zeimpekis et al., 2007; Yao and Dresner, 2008).

Important questions in the solution algorithms include: the number of stages in the supply chain; simultaneous consideration of inbound and outbound deliveries; deterministic vs. stochastic supply and demand models; fleet size, factory, warehousing and retail locations and capacities; planning horizons; time windows; single vs. multiple objective functions; source and integrity of data; and solution approaches. Even apparently simple practical optimization problems in supply chain management are notoriously difficult to solve; they are mostly NP-hard and, therefore, cannot be solved optimally in finite times. Approximate solutions are possible, and they go by various names, including heuristics and meta-heuristics tabu search schemes. Exact solutions are usually by the branch-and-bound scheme, in which the minimum k-tree approach is often called upon. The availability of real-time (or even near real-time) tracking data does simplify and strengthen local heuristic solutions.

Supply chains employ numerous employees to undertake rules-based tasks efficiently, correctly and without errors. However, individuals do deviate from rules and commit errors that cascade down the supply chain with multiplier effects. Errors become apparent only after an asset is found to be missing, misplaced, or information is found to be incorrect or unavailable. End-to-end visibility, if employed correctly, has the ability to ensure that individual staffers correctly undertake rules-based activities and not deviate from processes. Staff can be made to accurately monitor activities and ensure that any errors or process deviations within the operations are immediately indicated for rectification.

This empowers organizations to efficiently and flexibly employ *management by system* and *management by exception* to implement much less error prone processes by complete visibility of operators, assets, products and services. This also ensures that the data and information employed for decision making are accurate and timely. Organizations are thus able to confidently upscale the adoption of automated processes and decision making, thereby boosting their competitiveness whilst reducing reliance on compliant staff. Automated processes can be developed to push event alerts to managers and end-users. However, for this to cost effectively materialize, applications need to be based on features that permit easy configuration of rule-driven events and alerts to automate business processes. Event logs and response requests can be configured in the system to ensure that the responsible staffers react to the alerts in a timely and pre-planned manner.

In the conventional process chain, data and information often trail behind the movement of assets through the forward and reverse process chains. The operator is often seen to deviate from the process: he/she may think and act in the direction opposite to that of asset movement. In the conventional process chain the operator manipulates asset, processes, and possibly the entire system. Such a manipulated process chain can be corrected by the availability of location and status information on assets and personnel. The asset and data can be made to progress through the forward and reverse process loops in tandem. In a visibility enabled process chain the asset, process and personnel are all controlled by the system.

2.2 Additional benefits of end-to-end visibility

In the following Sections 2.2.1 to 2.2.3 we discuss three more broad application categories for intersystem end-to-end visibility in supply chains, the three not being entirely mutually exclusive.

2.2.1 Improved asset capacity utilization and management

Enhanced asset capacity utilization and management by real-time resource positioning, routing and dispatch is known to be a source of significant cost savings for supply chain operators. This category of applications includes the optimal use and management of warehouses, distribution centres, truck fleets, train wagons, ships, shipping containers, etc. To this category belong concepts such as intermodal vehicle routing and dispatch, merge-in-transit, cross-docking, inventory on the move, virtual warehousing, and empty shipping container repositioning (Landers et al., 2000; Ala-Risku et al., 2003; Fung et al., 2005; Song and Carter, 2009; Dong and Song, 2009; Chen and Zeng, 2010). In terms of problem formulation and solution, many of these concepts have some common features.

The vehicle routing problem is perhaps the best well known and its modern formulation involves determining in near real-time the optimal number, capacity, and location of facilities serving the demands of some customer segments, and finding the optimal set of vehicle

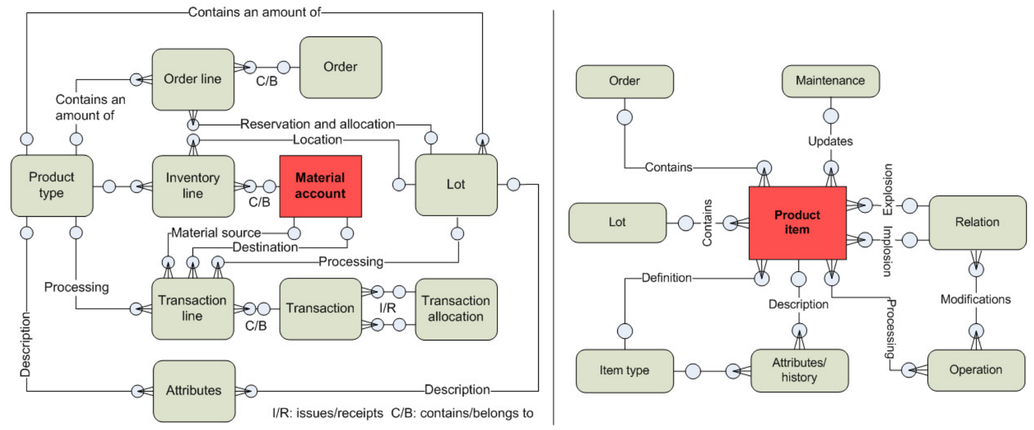

Figure 3: Material account model vs. item-centric data model in logistics

schedules and routes to attend to those needs in a dynamic fashion. Merge-in-transit (or full-set delivery) coordinates multiple less-than-truck loads, possibly on different transport carriers, that may be delivered at the same set of destinations. Virtual warehousing and inventory on the move consider moving inventory, whilst still in transit, as part of supply chain inventory that may be treated and called in like stationary inventory. They exploit knowledge of position and geospatial databases to design adaptive algorithms that adjust dynamically, based on real-time profiles, capacities and needs of customers, suppliers, and orders.

2.2.2 Enhanced supply chain agility and efficiency

Supply chain agility, just-in-time manufacturing and distribution, and lean operations all benefit from item-centric tracking and tracing. In order to achieve efficiency through economies of scale, classical manufacturing used the lot or batch system for material control and utilization (Figure 3). The batch operation logic, despite its shortcomings, is still the bases of some modern enterprise information systems. Such batch models do not inherently support the linking of handling data to individual material units, thereby making material-unit-level and product-level traceability an add-on feature rather than a fundamental operation logic of the production and distribution system. Lot tracing, which can be implemented in a lot system to improve visibility and control, has intrinsic drawbacks, which emanate from three main sources: physical lot integrity, data collection, and lot-process linking. The increasing complexity of manufacturing systems, customization and globalization all make it harder to maintain lot integrity: the traced lots become smaller as the variety of products increases, which in turn increases the need for lot splitting and joining. On the manufacturing shop-floor, the lot-based system of control makes it a cumbersome exercise to even mildly change product types and line configurations.

But perhaps more relevant to end-to-end visibility are the facts that the lot-based information model can result in loss of unique product information when transferring material and finished goods between supply chain partner organizations. This difficulty is caused by the use of quality classes, product mixing through lot delivery, and aggregation of products information. It does lead to rejection of good material or finished product when a part of the lot fails to meet specification. Moreover, operations can become disconnected from events, i.e., unresponsive to real-world circumstances, resulting in stock-outs, excess inventory, higher labour costs, sub-optimal asset utilization, and loss of competitive advantage.

Figure 3 compares the batch or lot model with the item-centric model of resources and products in the manufacturing supply chain. The diagram is highly simplified to aid clarity.

2.2.3 Security and control of assets and products

The objectives of the activities that may lie in this section may include the needs in Sections 2.2.1 and 2.2.2, but they are often mainly directed at securing sensitive cargos in transit or restricting the movement of the cargo or asset to a particular geographic location or area (also called geo-fencing or geo-auditing). The transport of especially hazardous materials belongs to this category, and so does shipping container security. The movement of military assets and pharmaceuticals are particularly subject to this type of control. To ensure the privacy of the data communicated to the telematics server, appropriate security protocols must be used. For these applications the communication modes for real-time visibility data require session cryptography.

3. Identification, ranging and positioning outdoors and indoors

In supply chain management, object and personnel identification and location can be obtained by RFID and by technologies that are not related to RFID. A target can be given an identity and then localized anywhere and at any time by any wireless or target-based technology. Examples of target-based non-wireless technologies include localization by dead-reckoning, inertial methods, and feature-matching. There are, however, huge accuracy and reliability challenges in deploying non-wireless technologies indoors.

Visibility in terms of both identification and localization can be achieved economically both indoors and outdoors by RFID systems. RFID readers or interrogators located at checkpoints can easily pick up RFID tags in their range. In this case, localization is obtained by the proximity method described in Section 3.1. But beside RFID, there are many other wireless methods of obtaining visibility indoors and outdoors. We briefly discuss these methods in Section 3.1.

The global positioning system (GPS) of location determination is perhaps the most widely known location determination technology, but GPS and other global navigation satellite systems (GNSS) perform poorly indoors because they were originally designed for outdoor, and not indoor, applications. They have encountered huge challenges with signal attenuation and interference indoors, mainly because of the weakness of ranging signals from satellites by the time the signals reach the earth. Unaided GNSS-based methods give errors in the range of 30 to 500 meters. Attempts to improve GNSS performance indoors and outdoors through various forms of assistance data (in the form of network-based pseudo-range corrections, the provision of approximate time and position from location servers, increased receiver sensitivity, etc.) have yielded results with errors in the range of 10 to 300 meters, and have in some cases proved expensive to implement. Assisted GNSS can reduce the time to first fix (TTFF) of position to 2 seconds by supplying current ephemeris and accurate time over a communications connection, but TTFF is not the only issue to be considered in selecting a positioning system. New modernized GPS signals, such as L5, provide enhanced signal penetration and accuracy indoors, but the attainable accuracy depends on the type (design and materials) of buildings. Moreover, in spite of the emerging enhanced GNSS signals, more than four visible satellites will continue to be needed for indoor location. GNSS also requires a dedicated chipset in the client device, and this demands the installation of GNSS circuitry, which adds to the cost and complexity of the user device.

Cellular telephony network-based systems yield results with errors in the range of 50 to 1000 meters, making them inappropriate for indoor applications. To obtain positions, cell-based systems typically use time-difference of arrival (TDOA), enhanced observed time difference of arrival (EOTD), received signal strength (RSS), triangulation, etc.

Low-cost micro-electromechanical systems (MEMS) inertial navigation systems (INS) have been used outdoors to obtain positioning accuracies of less than 100 meters. MEMS-INS systems have widespread applications, ranging from pedestrian navigation, in-car navigation, ballistic missiles to space applications. They have small footprint, low weight, and are power efficient. Consumer-grade INS is inexpensive but has poor error characteristics. Tactical or navigation grade INS is necessary for many applications beyond mass market. The main impediment to using low-cost MEMS-INS indoors is the time-dependent and relatively rapid growth of sensor drifts (especially gyroscope drift) as compared with the short distances found indoors. Dead-reckoning systems (using low-cost magnetic compasses and rotary encoders for direction measurement and accelerometers for distances) have also faced immense challenges in delivering the desired levels of accuracy, integrity and availability indoors. Magnetic compass directions are usually of low accuracy, and indoor materials and electronics may induce spurious magnetic fields that will interfere with compass measurements.

Map and feature matching algorithms have proved indispensable for outdoor pedestrian and vehicle navigation. However, indoors they require pre-prepared, detailed, and regularly updated three-dimensional representations of building interiors. These techniques determine the user’s location by comparing the features of the environment with database entries. Feature matching systems need initialization with an approximate position so as to determine the region of the database where to commence the search. Limiting the database search area naturally reduces the computational burden and the number of instances in which there are more than one match between the measured features and the database. To be able to determine the relative positions of the measured features, most implementations also require a velocity solution, usually from an INS or other dead-reckoning sensor. Feature matching is thus not an independent navigation technique. Furthermore, all feature matching techniques may suffer erroneous fixes due either to the age of the database or, where there are multiple matches, selecting the incorrect ground equivalent. The inherent integrated nature of feature matching does however help in some difficult situations. This class of methods may be appropriate for emergency responses, despite their inherent costs.

3.1 Wireless standards for short range distance and location determination

The main aim of this section is to review the wireless identification and location technologies that are currently available for supply chain visibility. These technologies are best suited for indoor applications, given their relatively short propagation ranges. However, WiFi has been used for identification and location over entire cities (LaMarca et al., 2004; Sohn et al., 2006) and UHF RFID has been deployed by SaviTrak for global tracking of cargos (see Section 5.2). RFID has also been proposed for integration with the intelligent highway infrastructure (Hsu et al., 2007).

Location information can be obtained both indoors and outdoors by WiFi and UHF RFID. Because of the relatively higher costs of WiFi scanners, WiFi systems tend to be more expensive than RFID. In a combined system, both UHF RFID and WiFi could be used for target identification and location and WiFi for communication. WiFi (the IEEE 802.11 family of standards) is widely available in many cities and buildings and RFID is a reliable, affordable and extensively deployed identification technology. Wi-Fi, the wireless version of a common wired Ethernet network, was intended as a replacement for cabling for general local area network access in work areas. This category of applications is sometimes called wireless local area networks (WLAN).

The OpenTag, DASH7, RFID standards and products continue to evolve and offer a significant potential over UHF RFID for object identification, data communication and location determination (www.dash7.org). DASH7 is based on an international standard (the ISO 18000-7 standard); the 433MHz frequency on which DASH7 is based is less crowded than other frequency ranges; it can be made to accommodate multi-hop, sensor networks, security, IPv6, and other features (communication between the tags is possible, and the tags can actually be thin devices); infrastructure costs are lower; direct tracking is possible and reliable; it is mandated by the US Department of Defense and allied militaries, thereby improving the chances of its ultimate wide adoption; its range is scalable (10-2000 meters); and its open source distribution allows for maximum proliferation of platform support (Norair, 2009; Agaidi, 2010).

Bluetooth is another possibility for target identification and location but it has a low scanning rate. This is not a problem for locating stationary targets because in this case the scanning rate is not important and Bluetooth is often integrated in office equipment like printers and fax machines.

ZigBee belongs to the same family of short-range low data rate standards for wireless personal area networks (WPAN) as Bluetooth. However, unlike Bluetooth, ZigBee is based on the IEEE 802.15.4 standard and was intended primarily for monitoring and for control applications that require very low power consumption from a battery source and low price. Range coverage of ZigBee is usually limited to between 20 and 30 meters, although ranging to 64 meters in free space is claimed by Texas Instruments (2006). The most suitable method for distance measurement and location determination by ZigBee is that based on signal strength indication (Azenha and Carvalho, 2007, 2008).

Ultra-wideband (UWB) communication is suitable for ranging and location. In the time-of-flight (TOF) ranging systems, the accuracy of time measurement determines the accuracy of the outcome. But the accuracy of timing is a direct function of signal bandwidth. In order to achieve an accuracy of 1 metre, the short range systems used indoors require pulse widths or rise times of several nanoseconds, and bandwidths of hundreds of megahertz, with equivalent clock rates. The same or similar degree of time resolution is needed to distinguish between line-of-sight and multipath signals. Multipath is a particularly troublesome issue indoors, where signal reflections are possible from many sources. Normally, better distance accuracy can be obtained by averaging, such as found for spread spectrum systems, but a higher performance ultimately depends on signal bandwidth. That is why UWB signals seem particularly appropriate for ranging and location, especially indoors.

According to the US Federal Communications Commission (FCC), UWB bandwidth must be within the band from 3.1 to 10.6 GHz, where average power density is -41.3 dBm/MHz. There is also a limit on the peak level of the emissions, equal to 0 dBm EIRP (equivalent isotropic radiated power), contained within a 50 MHz bandwidth centred on the frequency at which the highest radiated emission occurs. In the European Community, the bands 3.4 to 4.2 GHz and 4.2 to 4.8 GHz can be used with the -41.3 dBm/MHz upper limit for the average power density, provided appropriate mitigation techniques are applied. These techniques must limit the duty cycle to a maximum of 5 percent per second and 0.5 percent per hour, as well as restrict single transmission time to a of maximum 5 milliseconds (Commission of the European Communities, 2007).

IEEE 802.15.3 is a medium access control (MAC) and physical layer (PHY) standard for high-rate (11 to 55 Mbit/s) wireless personal area networks (WPANs). The ZigBee family of standards (IEEE 802.15.4) specified four different physical layers (PHYs), three of which utilized direct-sequence spread spectrum (DSSS), and one which used parallel-sequence spread spectrum (PSSS). IEEE 802.15.4a specifies two additional PHYs using UWB and chirp spread spectrum (CSS). The UWB PHY is designated to frequencies in three ranges: below 1 GHz, between 3 and 5 GHz, and between 6 and 10 GHz. The CSS PHY is designated to the 2450 MHz ISM band. Direct sequence UWB is spectrally efficient, can support precision ranging, and is very robust even at low transmission powers. The chirp spread spectrum PHY was added to the standard because CSS supports communications to devices moving at high speeds and at longer ranges than any of the other PHYs in the IEEE 802.15.4 standard. Both new PHYs added scalability to data rates, longer ranges, and lower power consumption into the standard, thus meeting the intent of the IEEE 802.15 standard to stress very low cost communications.

In the IEEE 802.15.4a standard, distance measurement is based on time of flight with timestamp precision to a fraction of chirp duration (around 2 nanoseconds). IEEE 802.15.4a includes specific commands (or primitives) for providing distance parameters to upper protocol layers. An accurate time measurement suitable for two-way distance measurement (i.e., TDOA location system) can be achieved by correlating a locally generated sequence with the received signal.

Direct sequence UWB and multi-band orthogonal frequency division multiplexing (OFDM) UWB competed to serve as the PHY for IEEE 802.15.3a and IEEE 802.15.4a. IEEE 802.15.3a was an attempt to provide a higher speed UWB PHY enhancement to IEEE 802.15.3 for applications which involve imaging and multimedia. The members of the task group were not able to come to agreement between two ultra-wideband PHY technology proposals, multiband orthogonal frequency division multiplexing (OFDM) and direct sequence UWB (DS-UWB), and the standard was abandoned in January 2006.

The direct sequence UWB, which was promoted by the ZigBee Alliance, was eventually adopted for IEEE 802.15.4a. Multiband OFDM UWB was adopted by the WiMedia Alliance, which published ECMA-368. ECMA-368 specifies a medium access control (MAC) sublayer and a physical layer (PHY) for high rate wireless personal area network (WPAN). As mentioned above, it is based on a multiband OFDM technique (ECMA, 2008). ECMA368 includes functions to enable and support ranging measurements between devices by means of two-way time transfer techniques. The accuracy of ranging is specified to be 60 centimeters or better. Time stamps are taken from a 32-bit counter that is clocked at 4224 MHz, with options for clocking at 2112, 1056, and 528 MHz. A timing reference point is defined in the specification as the instant when the timing counter is read. It is the instant in the packet preamble at the end of a synchronization sequence when the position of data symbols is accurately known.

Similar to most other wireless methods of indoor positioning, UWB location systems have proprietary scanners installed throughout the facility that continuously monitor UWB radio transceivers attached to clients. As mentioned above, UWB systems operate using radio signals having very wide bandwidth, and position calculations are made based on time-of-arrival techniques instead of signal strength. This leads to fairly good location accuracy. By reading the time of arrival of a beacon signal from a specific UWB radio transceiver from three or more scanners, for instance, the position of the target can be estimated. The use of UWB signals considerably shrinks signal interference and multipath propagation, which makes the coexistence with other types of networks tolerable. The issue, however, is that UWB makes use of technologies that are not consistent with standards in use by most corporations and establishments. Therefore, UWB hardware is expensive to purchase and scale in applications. Furthermore, the public use of UWB is still under consideration by the licensing authorities, which makes the future of UWB technology rather uncertain. UWB tags generally transmit several beacons each second, which makes batteries last approximately one year. Beacon rates are usually adaptable, but, as with all sensor network-based solutions, the optimum battery life is difficult to establish and battery replacement can be expensive.

The IEEE 802.15.5 standard has no inherent location function, but its other provisions make it an attractive future candidate for ranging and positioning. It provides the architectural framework that enables WPAN devices to support interoperable, stable, and scalable wireless mesh networking. This standard is made up of two parts: low-rate WPAN mesh and high-rate WPAN mesh networks. The low-rate mesh is built on IEEE 802.15.4 MAC, while the high rate mesh utilizes IEEE 802.15.3/3b MAC. The common elements of the two meshes include network initialization, addressing, and multihop unicasting. Furthermore, the low-rate mesh supports functions such as multicasting, reliable broadcasting, portability support, trace route and energy saving function; and the high rate mesh supports multihop time-guaranteed service.

RuBee (the IEEE 1902.1 standard) is a two-way, active wireless protocol designed for high security asset visibility applications in harsh or reinforced environments. It uses long wave magnetic signals to send and receive short (128 byte) data packets in a local or regional network. The protocol is similar to the IEEE 802 family of protocols (WiFi, IEEE 802.11; WPAN, IEEE 802.15.4; and Bluetooth, IEEE 802.15.1), in that RuBee is networked by using on-demand, peer-to-peer, active radiating transceivers. But RuBee uses a low frequency (131 kHz) carrier, implying that it is relatively slow (1,200 baud) compared to other packet-based network data standards. The low operating frequency provides RuBee with the advantages of ultra low power consumption (battery life measured in many years) and normal operation near steel and liquids. These features make it undemanding to deploy sensors, controls, or even actuators and indicators. Since RuBee uses long wavelengths and operates in the near field, it is possible to concurrently transmit and receive from many adjacent antennas without interference, provided the signals are synchronized. That makes it possible to enhance bandwidth and remove any angle dependence normally associated with other RF systems.

Unlike RF, RuBee uses magnetic photons: it has no reflections and is not blocked by steel or liquids and, therefore, is volumetric (not line-of-sight). That makes RuBee robust for visibility and security applications in harsh environments. It also implies that RuBee has no tempest target or eavesdropping risks in secure facilities. RuBee is the only wireless technology to ever be approved for use in secure facilities by the U.S. Department of Energy. RuBee tags may be detected with high sensitivity through doors, even if the asset is hidden in steel brief cases, as well as in vehicles (through gates using antennas burred in roads).

RuBee is often mistaken for RFID, but it does not work like passive or active RFID, and has a protocol more in common with WiFi and ZigBee. All passive and active RFID protocols use backscattered transmission mode. In contrast, RuBee is similar to WiFi and ZigBee, in that it is peer-to-peer, a networked transceiver that actually transmits a data signal on demand. But it is much slower (6-8 two-way packets per second) than WiFi and ZigBee. The main difference between RuBee and WiFi or ZigBee is that RuBee works in the long wavelength band using the magnetic field, whereas WiFi, Bluetooth, Delta7, and ZigBee operate in the VHF, UHF or SHF bands and with the electric field. The low transmission rate of RuBee makes it an unlikely candidate for real-time location applications.

The indoor messaging system (IMES) by GNSS Technologies of Japan (Manandhar and Hideyuki, 2011) is a proximity-based (no range calculations involved) three-dimensional location method that can be implemented in any client device that has an imbedded GPS/GNSS receiver without additional hardware modification. IMES beacons transmit three-dimensional positions and unique floor identity numbers (floor IDs) on the same frequency as GPS. They replace the ephemeris and clock data in the navigation message of GPS with the latitude, longitude, height and floor ID of a required location. A single transmitter is sufficient to obtain a location indoors from IMES, since the beacon's position itself is what is directly communicated to the receiver. The main issue with IMES is that the technology is yet to mature and, more importantly, questions have been raised about its possible interference with GPS signals. The system shares a common frequency as GPS L1 band (1575.42 MHz). To reduce the chances of interference with GPS signals, the IMES transmitter's effective isotropic radiated power (EIRP) is controlled to a maximum of -110 dBm at a distance of 3 meters from the transmitter (Manandhar and Hideyuki, 2011).

Like RFID, an infrared (IR) location system determines position of a target based on proximity (i.e., the presence of the target close to an emitter or a receiver). Each target being tracked includes a proprietary emitter that periodically transmits an IR beacon containing a unique number. In most conditions, infrared light is invisible to the human eye, so humans cannot see the signals. Specialized IR receivers placed throughout the facility detect the beacons and determine the approximate position of the target from the known location of the IR receiver. An IR system is practically immune to interference, largely because most other wireless communication systems operate in the RF spectrum far below the frequencies of light. Owing to the fact that IR signals do not penetrate non-transparent materials, such as walls and ceilings, an IR tracking system must often have several receivers in each room to avoid losing track of objects as they pass by building corners and behind office partitions. The orientation of the IR tag to the IR reader can also cause problems if, for example, the tracked target itself blocks the line of sight from the IR tag to the reader. This, in addition to the proprietary nature of IR systems, does contribute to the cost and complexity of the overall solution. Furthermore, scaling these proprietary solutions can be very expensive, thereby making real-time tracking impractical.

There are four geometric possibilities for calculating position coordinates from wireless signals:

a) *Proximity method*: In this method the location or position of a target node is inferred from that of a reference transmitter or receiver without additional ranging calculations, or from those of the surrounding reference nodes with some computation. RFID, IR, and IMES all use this technique. RFID and IR, however, can use some of the methods described in (b) to (d) below. Exact target coordinates are not obtainable by this method. It is, therefore, not suitable for tracking applications. However, it is suited to localizing large scale sensor networks. Many proximity-based approaches to location estimation from more than one reference node have been proposed. Within this class of methods, range-free location estimation schemes include the centroid algorithm, DV-hop scheme, and area-based approximate point-in-triangulation test (APIT) algorithm (He et al., 2005). Centroid localization algorithm broadcasts all possible reference nodes's location information to all other nearby target nodes. The target nodes use the location information from surrounding reference nodes to estimate their coordinates.

b) *Distance-angle scheme*: This is used when both direction finding and distance measurement capability are available. Only one fixed terminal is required to find the relative position of the target from the fixed terminal. The direction antenna may be located at the fixed station or at the target (as is the case in the very high frequency omnidirectional ranging (VOR) navigation system. If the fixed terminal estimates distance by receiver signal strength, the perimeter line may not be a circle but a constant signal strength contour derived from a mapping of the signal path loss in the region of the terminal.

c) *Triangulation*: When the coordinates of two fixed terminals are known with reference to a given coordinate system, directional antennas can be used at the fixed stations to find the location of a target by the intersection of the two lines of sight or signal directions. One advantage of this method is that target direction can be found without any time synchronization or restrictions of the type of signal modulation used, or of the protocol of the transmitted signals. The accuracy of the solution depends mainly on the directivity of the antennas. Unfortunately, directional antennas are significantly larger than omnidirectional antennas, and for automated location, electronically steered antennas are usually needed for direction finding.

d) *Distance-distance schemes*: In the time of arrival (TOA) and time-difference of arrival (TDOA) methods, directional antennas are not used at all and location is found by distance trilateration only. Distance can also be estimated using received signal strength (RSS) data or time-of-flight measurements. Time-based systems require fairly accurate clock synchronization between the transmitting and the receiving terminals. A minimum of two terminals are required for two-dimensional positioning; three or more are needed for three-dimensional location. In the *unilateral* localization scheme, the fixed stations are the transmitting beacons and the target is the receiver. In the *multilateral* system, the fixed terminals are the receivers and the target is the transmitter.

The time of arrival is hardly used on its own for finding locations, except for outdoor exploratory activities. It requires accurate and synchronized clocks to be maintained at all the participating stations. The receiver has to know the exact time the signal was transmitted by the sender. The TDOA system avoids these disadvantages; all it needs is a signal that has a recognizable unambiguous starting point. The input to the location algorithm is not the actual time of flight of the signal from the target to the fixed stations but the time difference in the reception of the starting marker at several base stations. One time difference (e.g., the difference in time between the receipts by two fixed stations of the signal sent by a target) is not enough to obtain the location of the target. TDOA thus requires one more base station than TOA. The clocks of the base stations must be synchronized, but not that of the target. Loran-C uses unilateral TDOA (in which the target finds its location from transmissions from fixed stations), while cellular network-based systems use multilateration (where time difference data is collected by the fixed stations from target transmissions).

3.2 Identification and location by RFID

UHF RFID is currently the most widely used wireless technology for assuring supply chain visibility. Active UHF RFID tags have onboard voltage supply and in many cases significant memory and chip capacities, unlike passive tags that rely on the reader for power and timing pulse and data. The transmission range of an RFID system depends on the frequency of operation and on whether or not the tag is passive or active. Depending on the operating frequency, passive UHF tags normally have a maximum range of about 15 meters, while active tags might be able to communicate with the reader at distances of up to 100 meters. All long range systems operate using electromagnetic waves in the UHF and microwave range, with backscatter (the most common) or surface acoustic wave transponders as the operating principle (Finkenzeller, 1999).

Location can be determined from RFID by three different approaches. The first is the proximity method, in which the position of the tagged item is inferred from that of the reader. The second approach uses the strength of received signals (RSS). The third approach is referred to as finger printing and is an advanced form of the second approach. It uses an *a priori* prepared map of signal strengths around and within the area of deployment of the system.

The proximity approach to location determination by RFID is the most commonly used

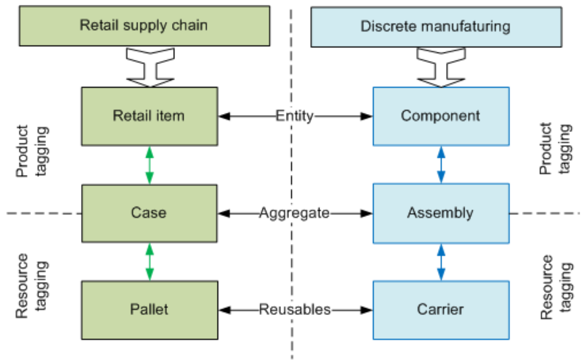

Figure 4: Item-level vs. aggregate-level object models

method for supply chain visibility. It has also been proposed to be an integral part of the intelligent roadside infrastructure (Chon et al., 2004; Hsu et al., 2007). It simply requires the establishment of a series of readers (or tags in the case of intelligent roadside infrastructure) at checkpoints within the intended area of deployment of the system. As the tagged asset or personnel passes by the interrogator, it is identified by the interrogator and its location and status are transmitted by the interrogator to a central back-end database. Normally, a middleware is required between the interrogator and the back-end database, to filter out erroneous measurements and to apply some preliminary mapping to the data before it is finally processed and documented. Instead of readers fixed to some specific locations in the area of operation or building, mobile, handheld readers could also be used. In this latter scenario, a means has to be incorporated for finding the changing locations of the handheld reader, but this is not always necessary (as the required location accuracy of proximity methods is usually low): often it is only required to know the room, wagon, yard or port at which a product or item is located at a particular time. Using RFID as a product identifier allows for a unique serialization of the product. This implies that inventory parts no longer have to be bundled together at the Stock-Keeping-Unit (SKU) level, but rather are uniquely identifiable as individuals, such that identical parts with different manufacturing dates, lots, production runs, or otherwise can be distinguished.

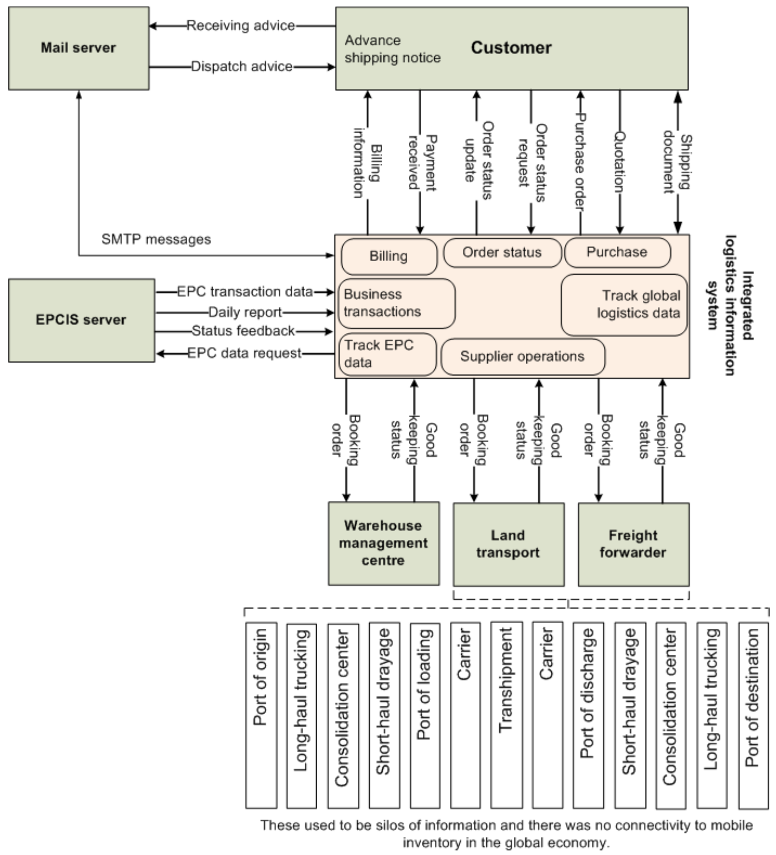

Figure 5: Information flow across visibility-enabled supply chain

The main challenges with using RFID are that radio waves bounce off metal and are absorbed by water at ultrahigh frequencies. For instance, the human body makes a very good shield against RFID signals because it contains so much saltwater. Interference from metal also disrupts the RFID signal and especially poses a challenge to RFID-enabled supply chain management, an area of operations normally packed with metal, liquids and environments considered harsh to RFID technology. Metal causes eddy currents in the vicinity of the RFID reader antennae which absorb RF energy, thus reducing the overall effectiveness of the RFID field. These eddy currents also create their own magnetic field that is perpendicular to the metal surface. This perpendicular magnetic field tends to cancel out the reader field. These challenges are, however, being vigorously addressed by RFID scientists and manufacturers (Bolotnyy, 2008).

4 Item-level vs. aggregate-level entity models

A fundamental decision that must be made in object-modelling of items for end-to-end visibility in supply chains is the level of tagging or traceability to be adopted, i.e., deciding between item-level and aggregate-level object or entity models. It is certainly not economical to tag every item irrespective of the economic value of the item, since the costs associated with tagging an item and ensuring end-to-end visibility may far outweigh the economic benefits of doing so. The object data and description model (Figure 4) adopted is thus a matter of economics. A cost vs. benefit analysis of tagging is, therefore, always necessary. Where item-level model is not economically viable, the aggregate object data model must be considered as an alternative.

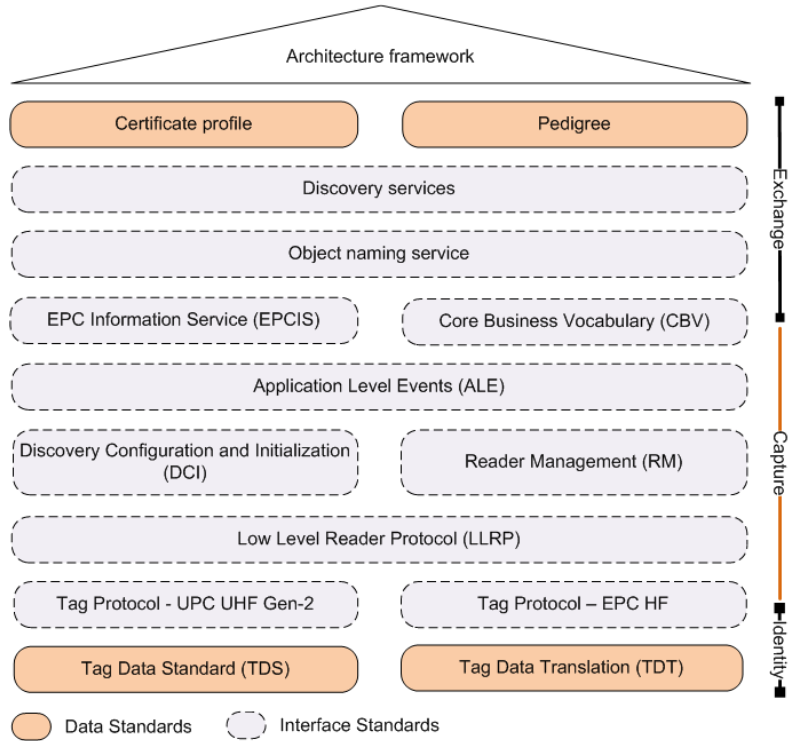

Figure 6: EPCglobal architecture framework

5 Models and products for end-to-end visibility in supply chains

There are many generic and proprietary schemes and products for achieving end-to-end visibility in supply chains. In Sections 5.1 to 5.3 we review some of the best known models and products. Figure 5 depicts the nature of enhanced information flow across the supply chain resulting from the schemes and technologies indicated in sections 5.1 to 5.3.

5.1 The EPCglobal network

EPCglobal Inc, created by EAN International and the Uniform Code Council, is an open, worldwide, not-for-profit, consortium of supply chain partners working to encourage and direct the global adoption of the EPCglobal Network. The EPCglobal network is a neutral entity that leverages RFID and the Internet to collect and communicate real-time data and create visibility about individual products as they transit supply chains. It provides a lineage of products movement that can be accessed by authorized parties. It uses firewalls, encoding, and other safe measures to guarantee the security of the transmitted information. The EPCglobal network also provides RFID-related standards for data generation and transmission. The architecture framework for EPCglobal's standards is shown in Figure 6 and the EPCglobal network is depicted in Figure 7 (EPCglobal, 2004a,b, 2010).

The EPCglobal network securely connects servers containing information related to products identified by the electronic product numbers (EPC). The servers are called EPC Information Services (EPCIS) and are linked via a set of network services. Each participant in the EPCglobal network stores relevant information relating to specific electronic product code (EPC) numbers in their own EPCIS servers. In some circumstances, local databases provide the information that is needed by the EPCglobal member. In situations where local databases cannot provide the required information, inquiries trigger searches in the electronic registries

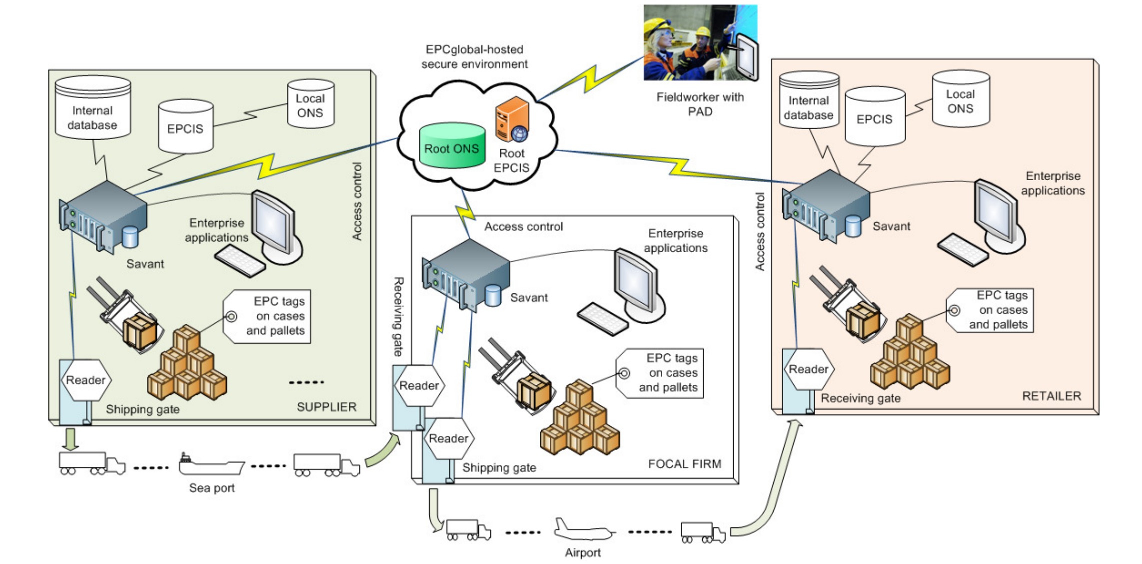

Figure 7: The EPCglobal network (the addition of mobile worker is by this paper)

of business partners via the EPCglobal network. The EPCglobal network provides a global network model and infrastructure support for identifying, locating and managing inventory in the global multi-supply chain by RFID (EPCglobal, 2004a,b; Shih et al., 2005). Palletized items of merchandize are tagged with RFID transponders whose details (product identities) are read by the interrogators located within the premises of the manufacturer enterprise. The records are then securely transmitted via the Internet to the EPCglobal net and to the receiver enterprise. As soon as the vehicle loading is accomplished, to complete the bill of lading (BOL) the cargo in the vehicles may be scanned by the onboard RFID readers. The data are then shared, by secure transmission through the Internet, between the logistics service provider (the carrier), the shipper, the receiver, and the EPCglobal net.

In the model of Figure 7, we have added the mobile worker. The premise is that while out in the field, the mobile worker can use an SMTP-enabled personal digital assistant (PDA) to access information from EPCglobal and from enterprise databases. When there is no connection, the mobile worker can still perform critical tasks using the limited database and computing capacity on the PDA, and later (when there is a connection) transfer the information onto enterprise servers.

5.2 The SaviTrak system

The SaviTrak system is owned and operated by Savi Networks (www.savinetworks.com). For the purpose of illustration we abstract the SaviTrak system in Figure 8. Our discussion of the SaviTrak network is based on this abstraction. The system provides a network infrastructure for sharing location information within and across supply chains, similar to what was proposed by Kärkkäinen et al. (2003). In the figure, location-enabled products act as information carriers between supply chain partners. Software components located at different places in the supply network can communicate using web services. Web services significantly abridge the creation of interactions between software components on different and remote computers. In the past this was achieved by technologies such as remote procedure calls (RPC), CORBA, Java RMI, Jini, DCOM, Microsoft RPC, and.NET Remoting.

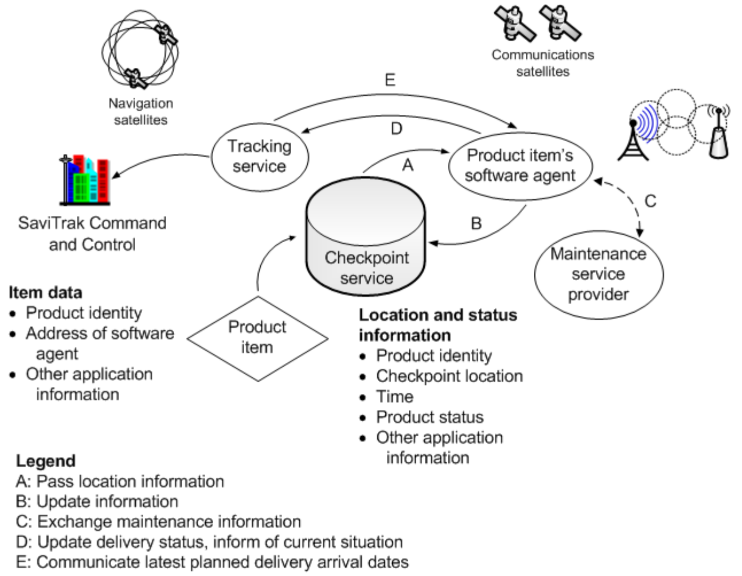

Figure 8: An abstraction of SaviTrak

Savi Networks (www.savinetworks.com) has built and deployed a global GPS, RFID, and sensor-based information network infrastructure called SaviTrak in all major ports and terminals of the world. Outside the geographies covered by the SaviTrak network of RFID and sensor checkpoints, assisted-GPS is used to locate cargo and cellular or satellite technology is used for communications. The SaviTrak system monitors and issues alerts concerning tampering or forced-entry of containers, shipments moving into incorrect zones or being improperly located, shipment's physical states (temperature, humidity, light or shock) exceeding environmental thresholds, shipments deviating from intended workflows and other user-defined exceptions. The operational environments involve customs authorities around the world, major international shippers, terminal operators, and third-party logistics service providers throughout Asia and between Asia, the United States, the Middle East and Europe. To date the SaviTrak networks covers most of the major ocean transportation ports and terminals and rail heads in Europe, North America, Australia, China, and along the Mediterranean coast. SaviTrak boasts of over 4,000 sensor checkpoints in more than 50 countries. For in-transit visibility between checkpoints, SaviTrak accepts feeds from onboard RFID readers, GPS units and mobile satellite communication modems attached to a power source such as a truck cab, ocean vessel or rail engine.

As the goods make their way to the receiver from the shipper (see Figure 7), the status of the cargo can be monitored onboard the vehicles and the information transmitted in near real-time to all the parties that have an interest in the cargo. Since the vehicles are continually tracked throughout their journeys by the carrier (or a contractor) using assisted-GPS, the locations of the in-transit goods can always be inferred from those of the vehicles irrespective of the stage of the journey. During transhipment, at all major sea and land ports that have installed RFID reader infrastructure, the tags on the goods can be scanned and the results transmitted to all the partners with stake in the cargo and to EPCglobal databases. At sensor checkpoints, the locations of the goods are inferred from those of the RFID readers.

The SaviTrak scheme offers a dependable procedure for transporting and delivering cargo across the global supply chain. It guarantees affordable continual end-to-end visibility, including real-time electronic map displays of trucks and ships in transit. It may also be used to identify bottlenecks in the transport system and appropriate remedies pursued. SaviTrak is

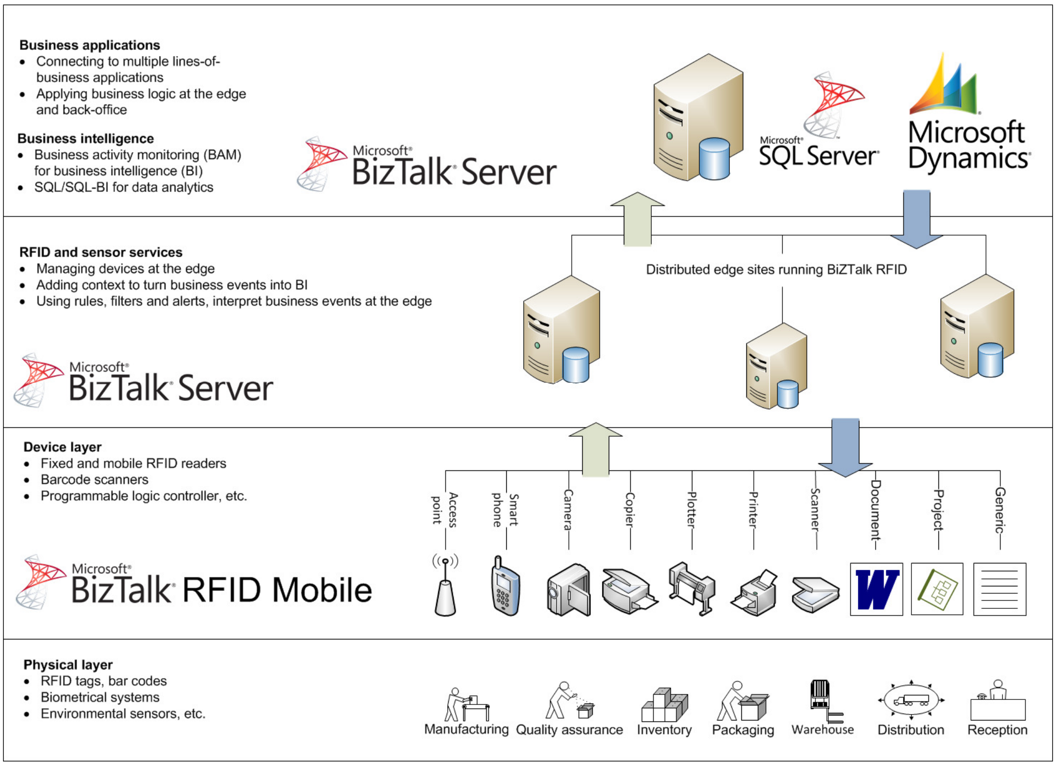

Figure 9: Microsoft BizTalk RFID logical stack (the extended sensor structure is by this paper)

built on an open technology platform and provides real-time intelligence on the global location, security and condition of inventory transported by container shipments through its integration with a tag device that includes GPS, cellular, and active UHF RFID with sensor technologies. SaviTrak uses a robust tag device and cellular roaming agreements in over 150 countries to provide global visibility and mobile connectivity to in-transit inventories of its customers. The multi-wireless tag device, which clamps onto a shipping container door, receives assisted-GPS location information at user-configurable time intervals. Sensors embedded in the tag detect and record security breaches of the container doors as well as changes of temperature, light and humidity inside the container. The device then communicates the information to either active RFID, cellular or satellite communications networks using GPRS.

5.3 Microsoft BizTalk

The Microsoft BizTalk RFID is built on the Microsoft .NET architecture and has both Server RFID and Mobile RFID. Microsoft BizTalk Server RFID enables users to speedily and effectively build and deploy RFID solutions through clear decoupling of design and deployment activities; agile and flexible process architecture with plug-in components for event handlers and workflow at the frontline of the enterprise; rich managed application programming interfaces (APIs) and tools for process lifecycle management; scalable event handling infrastructure with hooks to standards that support RFID and sensor technology; and legacy integration with BizTalk Server for end-to-end solutions for all supply-side, buy-side and internal processes.

Microsoft BizTalk RFID Mobile is an extension of the Microsoft BizTalk Server RFID platform to thin mobile clients. BizTalk RFID Mobile is an extensible platform for

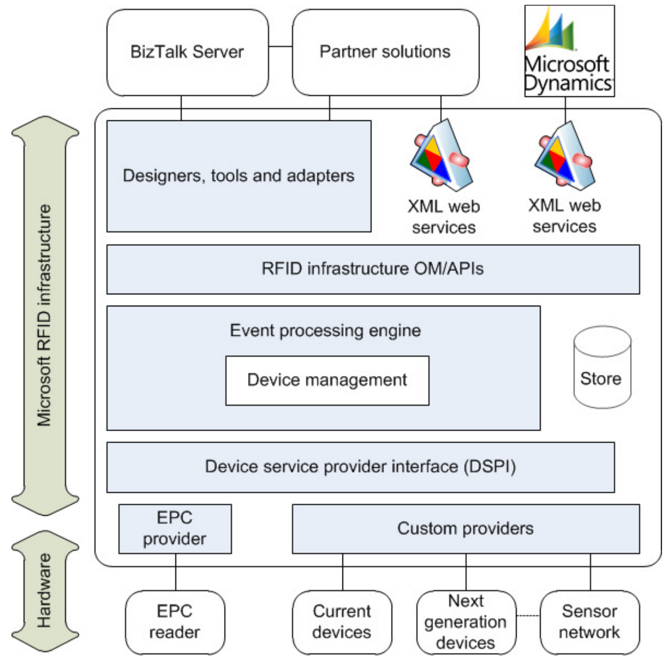

Figure 10: The inside of Microsoft BizTalk

developing, deploying and managing sensor applications (RFID, barcode, WiFi) on mobile devices.

Figures 9 and 10 show the logical layers of Microsoft BizTalk. The device service provider interface layer is made up of an extensible, general-purpose application programming interfaces (APIs) that enable software developers to create specialized interfaces that permit RFID devices to function harmoniously in the Windows OS environment. In order to allow for effortless integration of "software devices" (ie, the specialized interfaces that permit RFID devices to function seamlessly), Microsoft provides the platform, specifications and test packages by way of an RFID software development kit (SDK).

The engine and runtime layer uses event handlers and business logic to enable applications to filter, aggregate and map raw sensor data into business-centric information and intelligence. The event-processing engine is agnostic of sensor type and the sensor's communication protocol. The engine allows application developers to create and manage logical sensor processes and events independent of the underlying peripheral device type. The engine defines command sets for specific peripheral device types. The presence of "unknown" as one of the device types means that, in principle, the engine can interface with almost any device, but the standard is highly pragmatic and meets most commercial needs.

The central part of the processing engine is the "event processing pipeline". The event execution pipeline processes events either synchronously or asynchronously. It provides a means to process and execute RFID events by grouping readers into logical associations. The RFID Object Model (OM) provides a mechanism for creating event processing pipelines or trees of extremely simple or complex profiles. The event processing engine also contains the event handler, an extensible component that allows distributed RFID events to be processed on the chosen business logic. The engine and runtime layer also contains the device management block.

Another layer of Microsoft BizTalk RFID is the OM/API layer. The OM and APIs are meant to assist developers in designing, deploying and managing RFID and sensor solutions. The Object Model includes the device management module, process design and deployment, event tracking and health check. It provides the APIs to rapidly construct and deploy RFID processes.

The Microsoft BizTalk RFID server also has a "designers, tools, and adapters" layer. Designers consist of an array of tools to help developers compose different strands of business processes, while adapters assist in integrating real-time RFID events with Microsoft BizTalk RFID server and line-of-business applications.

5.5 Conclusions

Identification, location, navigation and geospatial data are nowadays at the core of technologies deployed to improve the efficiency and security of global trade. The data can be combined with reliable wireless shipment monitoring to provide shippers, logistics service providers, and terminal operators with easily accessible, accurate and actionable information. The information is used as a source of supply chain intelligence to identify and attend to both operational and systemic, longer term, issues. It is to be expected that the role of real-time inventory information on the supply chain's competitiveness will grow in the coming years. Technology is an enabler of both business efficiency and responsiveness.

In end-to-end visibility, object identity and location are normally required to be available 90 to 95% of the time and at 95% confidence level (i.e., 2-sigma level), with relatively high needs on solution integrity, continuity, and system availability. However, absolute position accuracy requirements rarely go beyond determining the room or the shelf on which an object lies.

One constructive model that we are developing in our University is a service that traces the progress of a product through the supply chain and transmits this information to the various enterprise resource planning (ERP) systems of the supply chain partners, as well as pass instructions from the ERP systems back to the product itself in a purely dynamic fashion. This is a key aspect of the event-driven control model described in Section 2.1.

In this paper, the costs of the various technologies reviewed, decision modelling issues and the actual integration of visibility information (front-end) with enterprise information systems (back-end) have been unavoidably left out of the discussion.

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