# Performance Review of RFID in the Supply Chain

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**Abstract.** Radio Frequency Identification (RFID) technology provides manufacturers, retailers, and suppliers with the tools to efficiently collect, manage, distribute, and store information on inventory, business processes, and security controls. The growth of RFID in the supply chain has been spurred by mandate compliance from global retailers such as Wal-Mart and Target. Despite the intrinsic advantages of the technology, factors such as lack of standardization, interoperability, cost and performance issues have slowed the pace of adoption. This paper will provide a quantitative content analysis on the performance and reliability of RFID in the supply chain based on literature reviews. The factors that will be examined include tag location, tag orientation sensitivity, read range, and interference from metal and water. The reliability of RFID system is a paramount factor that may determine the technology's ultimate adoption and diffusion. The paper will provide practitioners with insights to the issues affecting RFID implementation.

## 1 Introduction

The supply chain is a complex multi-stage process, which involves everything from the procurement of raw materials used to develop products, and their delivery to customers via warehouses and distribution centers [1]. For many years, the supply chain has used barcode for item identification. However, based on the limitations of barcode, Radio Frequency Identification is an emerging technology slated to complement or replace traditional barcode technology to identify, track and trace items automatically in the supply chain [2]. The technology provides the opportunity to redesign traditional warehouse packaging and shipping activities for a business-business vendor managed inventory system cost effectively to combat global competition [3]. It must be noted that the focus on RFID was primarily in closed- loop environment, that is, the use of the technology to manage internal tracking. However, the interest has switched to open-loop system where tags are used throughout the entire supply chain. Players in the supply chain will experience greater visibility and accountability from the technology in an open-loop system.

As a result, interest in the adoption of RFID in the supply chain heightened in 2003 when Wal-Mart mandated its largest 100 suppliers to place RFID tags on shipped items at the pallet level by 2005 [4,5]. Other companies including US Department of Defense (DOD), Target, Best Buy, Albertson's, Tesco, and Metro issued

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mandate compliance to suppliers. The mandates were announced by retailers that were interested in reaping the intrinsic benefits of the RFID technology. The benefits of RFID in the supply chain include reduction in shrinkage, improved stock management, reduction in labor costs and illegal duplication and manufacture of high value product, and enhanced visibility along the value chain [7].

Despite the advantages of the technology, it has been argued that mandates lack credibility with barriers still affecting widespread adoption, including lack of standardization, interoperability, cost and performance issues. While this paper will examine the aforementioned issues, the review of literature will focus on the operational issues affecting the performance of RFID in the supply chain. The reliability of RFID system in the supply chain is a paramount factor that may determine the technology's ultimate adoption and diffusion. A number of pilot programs and testing have been carried out under a variety of operating environments to determine the performance requirements, physical characteristics and limitations to achieve a near 100% read range. However there are variables that affect this goal which include tag location, tag orientation sensitivity, read range, and interference from metal and water. The outline of the paper will be presented as follow: Section 2 will provide a brief overview of the RFID technology; Section 3 will discuss players in the RFID Value Chain; Section 4 will report experimental results from various researchers with the intent to better understand the supply chain environment and increase the performance level of tags and readers. Section 5 will provide a conclusion.

## 2 Overview of RFID System

RFID is a sensor-based technology consisting of three key elements: RFID tags (transponders), RFID readers (transceivers), and a data collection, distribution, and management system (middleware) that has the ability to identify or scan information with increased speed and accuracy [8].

A tag consists of an antenna and a small silicon chip that contains a radio receiver, a radio modulator for sending a response back to the reader, control logic, some amount of memory, and a power system [9]. Tags attached to an object stores data including product identification, expiration, warranty, handling and storage instruction and service history [2]. Furthermore, tags have the capability to monitor temperatures, bacteria levels and a provide tamper evidence, regardless of the product position in the supply chain [7].

Tags can be classified based on the power source, namely passive, semi-passive and active. Passive tags gain electric power through an inductive field generated by a reader, while active tags are powered internally with batteries [10]. The range of a passive tag varies from a few centimeters to a meter, while active tags can achieve very high ranges of 15 meters or more [10]. In the supply chain, passive tags are used because they are cheaper, small, light, and have longer shelf life [11].

RFID readers can be categorized as handheld, mobile mounted and fixed [12]. In a typical production facility, reader portal areas are normally located at critical locations in the production or logistical chain where these product "events" can be tracked and counted to ensure an accurate inventory and tracking [13]. Fixed reader applications include conveyor belt, portal or doorway reading, shrink-wrap stations and pallet assembly stations [14]

The frequency of an RFID system defines the relationship between the tag and reader, and impacts both the transmission range and speed. RFID frequencies are categorized as Low frequency (125 - 134 KHz), High-frequency (13.56 MHz), Ultra-high frequency (860 - 930 MHz) and microwave (2.45 GHz) [15, 16]. Ultra High Frequency (UHF) is the typically frequency recommended for distribution and logistics applications, and is used in the supply chain as it supports greater read range (distance) between the tag and reader, fast data transfer rate and can perform concurrent read of at most 100 items [17]. However UHF systems have problems penetrating water or metals compared to lower frequency ranges [3].

## 3 RFID Value Chain

For definition purposes, the supply chain is the network of retailers, distributors, transporters, storage facilities and suppliers that participate in the sale, delivery and production of a particular product. In the supply chain, the process begins at the manufacturer or retailers where tags are affixed to all products at the case and pallet level and subsequently tracked. The RFID value chain consists of chip makers, system providers (tag/reader manufacturer) and integrators/consultancies. The actions of the players in the RFID value chain are dependent on the standardization bodies that govern RFID communication in the supply chain. It is posited that an evaluation of the RFID supply chain should include an outlook of the aforementioned players from standardization bodies to RFID vendors to end users (manufacturers to consumers). This section will explore each player and their roles.

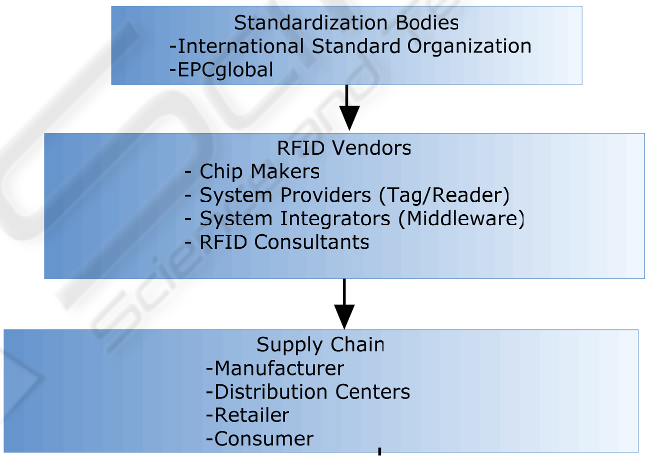


**Fig. 1.** RFID Value Chain.

### 3.1 Standardization Bodies

In order to achieve large scale RFID usage in the retail supply chain, that is, 'open loop', RFID technology needs to be standardized. Standards cover identification (coding of unique item identifier), data and system protocol (middleware of the system), air interface (wireless communication between the reader and the tag), application support, testing, and compliance governing RFID operations [18]. There are currently two standardization bodies in the supply chain, EPCglobal [19] and International Standard Organization (ISO) 18000 series 6 [8]. ISO is deemed as the most respected worldwide standards organization and has been in existence for a number of years. EPC, formed by the Auto-ID center in 1999, argued that the air interface protocol used by ISO was too complex and would increase the cost of tags unnecessarily [20]. As a result, all important air interfaces between both bodies were incompatible [17].

Players in the supply value chain are either EPC or ISO compliant. Interestingly, the two main drivers that issued mandates, Wal-Mart and Department of Defense (DOD), used different standardization bodies. Wal-Mart had decided to use the EPC standard; however the DOD wanted to use the EPC for general purposes while using the ISO standard for air interface [21]. This was impractical as both standardization bodies were not compatible. The interoperability became further problematic with the different classes of tag used by EPC. The Class 0 tag used a different protocol from the Class 1 tag, which meant that end users had to buy multiprotocol readers to read both Class 1 and Class 0 tags [20]. In addition, neither class tags 0 or 1 were compatible with ISO [20].

These inconsistencies caused players in the market (manufacturers and retailers) to become reluctant to invest in the technology as the lack of compatible standards would require constant changes and reinvestment. Standardization is essential to allow any reader to communicate with similar RFID tags at the same frequency regardless of the manufacturer of either [22]. As a result, convergence of both standardization bodies was achieved in 2006 with EPCglobal UHF Generation 2 Protocol endorsed by International Standard Organization (ISO). This action indeed paved the way for a truly global supply chain [23]. However, there are implications for early adopters of this technology as the aim for standardization may require complete change of tag types which will be costly. An example of such is seen in a recent document by DOD which explicitly stated that only acceptable are EPC Class 1 passive RFID tags that meet the Generation 2 specification will be accepted [24].

Another major concern in achieving a global supply chain is the different frequencies band operational under the UHF spectrum which impact international trade. For example, passive UHF tags operate in the 902 MHz to 928 MHz range in the United States and Canada, 862 MHz to 870 MHz range in Europe, and 952 to 954 MHz in Japan [25]. While some may argue that international agreements are afar off, it is suggested that the new Generation 2 standard will allow multiple applications of RFID, operating in the UHF band of the electromagnetic spectrum, to use the same RFID technology without conflict and on a global basis [26]. This is so as Gen 2 tags users have several options which include choosing a tag that operates across the widest possible range of the UHF spectrum (860-960 MHz) [26] .This action will in due course enable the use of tags that span internationally in the global supply chain.

### 3.2 RFID Vendors

RFID vendors play an integral role in the widespread adoption and diffusion as they provide the equipment (tag and reader) that will dictate performance, but also has the added role of distinguishing brands with quality and versatility. The RFID market is crowded, with numerous players including chip makers, transponder/reader manufacturers, system integrators or consultancies, all of whom offer different, and generally proprietary, products and services [27]. RFID vendors have also taken action towards standardization. In an article [28], it was reported that approximately 20 vendors are considering establishing a patent pool that will have patents related to UHF RFID systems based on EPC and ISO standards. It was highlighted that simplifying the Intellectual Property licensing process and limiting royalties on products will allow more companies to join the market and speed adoption.

While reliability is a concern of end users, the cost is of paramount importance with the anticipated 5-cent tag [3].However RFID vendors have argued that tag prices will not drop to 5 cents until 2008 [29]. An analyst from ABI research have suggested that companies need to start understanding RFID technology instead of playing "a waiting game" for tags that cost only 5 or 10 cents [30]. Chip makers, on the other hand, argue that a rush to achieve 5 cent tag can result in the degradation of capabilities and performance compared to higher price tag [31]. As a result, manufacturers are reducing tag prices by approximately 5 to 10% per year since 2000 while improving the technology [31]. However, it has reported that a vendor (SmartCode Corp) has created a historical milestone with the first 5 cent tag [32].

## 4 Performance of RFID in the Supply Chain

The performance and reliability of RFID in the supply chain will dictate the willingness of players to invest in the market. Despite the fact that RFID vendors have cited that their solution dictates quality, the use of the technology in the 'real world' setting has highlighted some factors that require further testing. This section will examine some of the benchmarks that have been used to examine performance of RFID in the supply chain. Performance is typically measured by the ability of the reader to correctly read all tags in its environment. Presently in the supply chain, typical reads are executed at the case or pallet level. It is posited by [33] that there are two fundamental properties of RFID performance: the fraction of times in which a tag responds, and the speed in which it responds. The former metric is estimated by the ratio of tag responses per requests, and the second is estimated by the number of responses per time. The factors that affect these metrics include tag location, tag orientation, read range (distance between the tag and reader antenna), and metal and water interference. These factors will be discussed in this section.

### 4.1 Tag Location

As many RFID pilot tests have indicated over the past year, tag-reader inaccuracies are a major challenge the new technology has faced, with one of the biggest challenges being tag placement for item, case and pallet tagging. It is important to note that RFID technology does not require direct line of sight (as with barcode) between the reader and tags, hence there are a host of potential tag placement options. Whilst this offers manufacturers a high level of flexibility in tag placement option, it may be problematic as tag performance is related to its location [34]. Determining the correct tag placement in the supply chain is time consuming and impractical due to the wide variety of goods (packaging) and environments in the supply chain. However, this process referred to as 'sweet spot' testing is deemed necessary as incorrectly placed tags will lead to poor reading results and inefficient pallet patterns [35].

Testing on proper tag location has reported different results. For example, at the pallet level, Tyco Fire and Security (RFID consultant) suggested that the number of tags placed is dependent on the type of pallet [36]. Recommendations noted that a one way pallet (that is, forks can enter the pallet from only one direction) could be tagged with one RFID device. However with four way pallets, the pallet had to be tagged on each side to ensure readability [36]. This has cost implications as it is suggests purchasing multiple tags for a single pallet. Other views on the locations of the tag have recommended tagging the stretch wrap on the pallet, without specifying the number of tags [36]. However [37] argued that the shrink-wrap can impact performance in terms of metal and water interference. Some RFID manufacturers recommend tagging the last carton, whilst others argued tagging the conveyance [36]. Hence there is no consistency on tag placement for pallet shipped items.

A study [37] argued that the tag location is dependent on the type of box used. The report related that full boxes allow the most area and flexibility to position the label, taking advantage of the internal air gaps. On the other hand, corrugated cardboard trays have far less space and provide little flexibility for tag placement. It was further recommended that styrofoam material creates the air gap effect in case packaging which complements proper reading of the tag.

As mentioned earlier, testing is exhaustive with a host of factors such as type of packaging and container (box). Software developers have created a solution that will help end users decide optimal tag placement [34, 38]. For example, Cape System Group has a RFID Tag Locator Software to improve speed of tag placement [34]. It is suggested that the software measures the performance of current tag-reader systems and generates interactive, color-coded models. Using these models, managers are better able to understand how the readers are interacting with the tags. The best tag-placement areas are then determined to increase scanning accuracy.

### 4.2 Tag Orientation Sensitivity

The radiation pattern of a RFID tag antenna determines the ability to read the tag in any orientation [33]. It has been argued that the location of tags (discussed in 4.1) in respect to the polarization of the reader's field can have a significant effect on the communication distance for both HF and UHF tags with reduced operating range of up to 50% [39]. In a study [33] on the orientation sensitivity of different tags, the tag antenna was rotated in free space at $20^0$ steps along the two perpendicular directions. The specified perpendicular directions were E-plane (horizontal) and H-plane for a dipole antenna. The test classified tags into two categories: the "long thin tags" (variant of dipole or slot antenna) and the "squarish tags" (dual dipole). The findings revealed that along the H-plane direction, all the tested tag antennas had circular patterns. However in the E-plane, the dual dipole tag performed equally well in all directions whereas the dipole tag performed differently with varying orientations. These findings were similar to that of [15] which noted that UHF tags are more sensitive to polarization due to the directional nature of the dipole fields. The study concluded that only a few tags available in the commercial market are orientation insensitive.

Another study [40] used a different methodology where the tag orientation test included tilting the tag circumferentially along three planes X-Y, Y-Z, and X-Z. The test indicated that tags placed parallel to the reader antenna yielded maximum read rates, with a decrease in read rate as the tag orientation changes. It was suggested that a method to overcome this problem is to develop a scan tunnel (large frame with RF antenna mounted on it) that can hold multiple antennas, perpendicular to each other. However this solution is deemed impractical and costly in a supply chain environment.

A third study [39] investigated tag orientation sensitivity with tag rotated at $0^0$, $30^0$, $60^0$ and $90^0$. It was concluded that tags positioned at $90^0$ experienced a decrease in operating range by 30%. The tag angle at $0^0$ had the greatest operating range. The studies mentioned used different methodologies to determine the effect of tag orientation sensitivity, however the results were consistent.

Regarding tag orientation, an issue highlighted by [41], [42], and [43] is polarization mismatch for reader and tag. The recommended polarization for a tag and reader differs. The polarization of the tag is usually linear because of pre-required small size of the tag. However, manufacturers normally recommend a circular polarized reader antenna for greater read range. This polarization mismatch may negatively affect performance of the RFID system and the use of a linear polarized reader may compromise read range. A recommended approach is to use many readers with a diversity of orientations relative to the read area, which is sequenced by performing multiple scans from different directions [44]. This is however an expensive option, a cost effective approach may be to employ a single reader with several switchable antennas that can be sequentially connected to the reader [44].

### 4.3 Read Range

Read range refers to the maximum distance at which RFID reader can detect signal from the tag. The literature articulates that read range is sensitive to tag orientation, tag location, and the propagation environment. The Friis formula is used to measure read range [41]

$$r = \frac{\lambda \cos \theta y}{4\pi} \sqrt{\frac{P_t G_t G_r (1 - s^2)}{P_{th}}} \qquad 0 \le s^2 \le 1$$

where, $G_r$ is the gain of the tag antenna, λ is the wavelength of the EM RF waves, $P^{th}$ is the minimum threshold power required to power an RFID tag, θy is the angle made by the tag with the reader plane, and $s^2$ is the power reflection coefficient, which is the ratio of reflected power to incident power by the tag. It has been argued by [33] that the read range claims by RFID vendors are unverified and fail to mention the deterioration of tag performance with distance. In a test by [2], the same sentiments were echoed with the range of the tags falling between 2 and 18 inches, as opposed to the specified range by vendors, which was 8 to 80 inches.

Another study [33] measured distance by examining response rate vs. attenuation, by using attenuation of power levels as a means to stimulate distances. The forward channel (reader to tag) and reverse channel (tag to reader) was attenuated at varying distances. The authors used the results from the findings to classify tags. It must be noted that class 1 tags were used from different commercial vendors, the results varied. Consequently, Class 1 tags were categorized as Class 1 “fast” and Class 1 “slow”. The findings reveal that Class 1 “fast” tags show a slightly different behavior in response rate from the Class 0 and Class 1 “slow” tags.

Researchers [40] have argued that read range is also dependent largely on the design of the antenna coil of an RFID tag. It was also highlighted by [40] that studies reveal that the orientation of the tag in the RF field affects its read range. It was argued that a perfectly parallel tag, relative to the base station antenna, yields maximum read range. On the other hand, a tag perpendicular to the base station antenna’s field has minimum to zero read range. With all these factors affecting read range, end users must examine the specification of the RFID system when choosing tags. In addition, the read range specified by the vendors may not reflect actual results in the environment that the system will be utilized.

### 4.4 Metal and Water Interference

A drawback to UHF systems is the inability to accurately read tags on objects with or surrounded by high water or metal content. Metals reflect electromagnetic (EM) waves and scatter them in all directions, which reduce the power needed by tags to respond [2]. Product contents such as liquids tend to weaken the RF signal by absorbing much of the energy so the reader has no signal to receive [33].

In the supply chain, most of the common products have forms of metal and water. As noted by [33] UHF frequencies band varies between different countries. The lack of standardization is problematic for the supply chain, as visibility can only be achieved if the tags operate well at UHF bands across all countries. In a study on metal interferences [33], experiment was carried out at 902 MHz, 915 MHz, 928 MHz and 955 MHz. The findings reveal that tags performance varied at different frequencies in the UHF range. This has implications on global trade as a tag sent from USA would be completely unreadable in Japan.

Besides the lack of harmonization in standardization, there are other factors affecting read rates of metal-based products. It has been suggested that UHF tags can have increased read range if there is a sufficient air gap between them and the metal surface [40] [45] (air gap insulate the tag from the disruptive properties of metal). It was further noted that this situation is unique to each particular application using UHF tags on metal surfaces and cannot have the same predictable results in all cases. There are differences in recommendation on the suitable air gap required between the item and the metal surface. In an experiment by [40] it was concluded that perfect (i.e.100 %) read-rate probabilities for tracking metal objects can be achieved with an air gap of at least 1.5 mm. Another study [46] contradicted the above, concluded that an air gap of 2.54 thicknesses will increase the read rate probabilities. However the experiment performed by [40] argued that air gaps over 2 mm will cause tags to bend or peel-off resulting in an unreliable RFID system. The use of air gap to increase performance also applies to liquid products [40]. A recent study [47] conducted with a cuboid case of bottles reported that interference was greater at the points which has the least air gap.

Another technique to increase read rate from metals is the placement of tags in front of a metal at a particular separation [48]. This causes constructive interference between the backscattered signal from the tag and the metal. The results from the study show that increase in performance is achieved at a separation of 4 cm. A recent study [48] suggested that a specialized tag with a metal ground plate of 5mm thickness to separate tag from the metal surface will enhance read rate.

An interesting report by [49], tests revealed that high humidity levels reduced the ability to successfully read tags by as much as 50 percent. The findings reveal that even after the boxes were seemingly dry, the reads were negatively impacted due to the absorptive nature of the cardboard. The above arguments suggested that interferences from metal and water will be problematic in the supply chain. Continuous testing is required to identify measures that can be applied to solve this problem.

## 5 Conclusion

Radio-frequency identification (RFID) as an emerging technology has generated enormous amount of interest in the supply chain arena. While the literature has mentioned the 5-cent price tag as the Holy Grail or catalyst for widespread adoption and diffusion of RFID, there are operational issues that must be considered. These include lack of harmonization in UHF bands, and factors affecting read rate of items transported in the supply chain at the pallet, case or item level. However, there is evidence that standardization bodies and RFID vendors have converged to create compatible standards to increase adoption. The analysis of the literature suggest that the demise of barcode is premature and deployment of RFID technology will gradually increase as RFID vendors and researchers perform test to achieve a near 100% read range as goods traverse along the supply chain.

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