Comprehensive Commercial RFID Review – Retail Focus

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***Abstract*—This paper explores the evolution and contemporary significance of Radio Frequency Identification (RFID) technology, focusing on its integration in the retail sector. It synthesizes theoretical foundations, practical insights, and future projections to provide a holistic understanding of RFID's implications for retailers, with a structured analysis of key components and case studies.**

***Index Terms*—RFIDs, RFID systems, asset management**

I. Introduction

Radio Frequency Identification (RFID) has been used since its apparent invention during World War II. During its formative years as a piece of technology, the variety of use cases and academic study was limited, until the 1970's, which brought about applications within military and train tracking [1]. Nowadays, the technology is seamlessly integrated into daily lives, with the industry on an upwards trajectory with the currently global market estimated at $11.3bn, with growth estimations being $40.9bn by 2032 [2]. The purpose of this paper is to provide a holistic overview of RFID technology at its simplest level which can be used by commercial entities as an introduction to the technology. There are few papers which combine the theoretical and commercial applications of RFID, with those usually being either retrospective or present in nature. This paper aims provide an overview of RFID technology and its normal systematic usage, as well as showcasing what this could mean for retailers, with a culmination of various studies and use cases of successful and unsuccessful RFID usage. This paper shall also look to the future, providing indications of what is to come within the RFID world, to attempt to broaden horizons and expectations of RFID technology. The paper is structured as follows. Section II shall build upon the foundations of RFID, introducing a level understanding about the technology and its components, as well as its interactions within an RFID system. Section III shall introduce some commercial benefits with a focus on retail and benefits to retailers, using commercial reviews [3]. Further in this section, some alternative elements which retailers should consider shall be explored, bringing together potential pitfalls in an implementation process. In Section IV, these benefits shall be supported by short case studies of successful RFID use cases and implementation, such as the Metro-Group and Lululemon case studies, alongside an example of how implementation can go wrong. It is intended that throughout this paper, there shall be balance, with some pitfalls and areas to consider being proposed, providing a picture of the context behind an RFID implementation journey. In Section V, a case for the future of RFID shall be detailed, with new applications and approaches being highlighted [4], [5], showing RFID is not just a technology for the present, but has the potential to become a crucial element for retailers going forwards. Finally, Section VI, presents the conclusions of this paper.

II. RFID ARCHITECTURE

RFID uses radio waves to transfer information from electronic tags to a reader which identifies that specific tag from the information it contains. Because of the radio waves, the information transfer from the tag can be completed without a reader's line of sight, providing a benefit over traditional barcode scanning [6]. Furthermore, when compared to other Near Field Communication (NFC) technologies, the potential distance of data transfer is much larger, with RFID having a potential range of up to 100m [1]. The potential RFID range is largely dependent on the type of tag. Whilst there are different types of tags, there are similar components between all types. Each RFID tag contains three key components [7]:

i. Antenna – The transmission mechanism that converts the RFID reader's signal into radio waves. The efficiency of this in specific directions is known as the gain. The higher the gain, the longer the read range of the tag [8]. Antennas can be different shapes and sizes depending on their applications, which results in having different dipoles, which influence the electrical inductance through the tag, changing the frequency

at which the tags operate and resonate. Examples of different antennae can be seen in Figure 1.

ii. Microchip – Integration of memory and processing functions.

iii. Substrate - The material support to adhere tags to the desired surface.

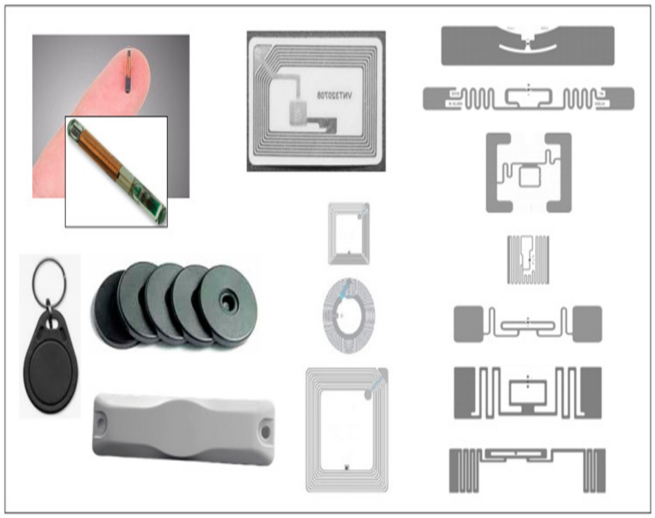

Fig. 1. Examples of different RFID tag types, including differing antenna types [1].

Within the microchip of the tag, there is an Electronic Product Code (EPC), which assigns a unique identity to the associated object relative to all other objects in the world [9]. Each item therefore becomes distinguishable from others, which differs from traditional barcodes or Universal Product Codes (UPC's) [10]. Herein lies a benefit of RFID; through the microchip transmits individual data from individual objects, including those within the same category. Therefore, a granularity of data becomes available from each product being uniquely identified, which provides industrial/commercial use cases for RFID across various sectors.

RFID uses passive, active, and semi-active tags. Whilst all hold data, however, it is the transfer mechanism that differs between their different types [1]:

i. Passive tags are dormant and battery-less and therefore require "activation" by a radio wave. The energy received by the antenna is converted into DC voltage to power the chip. The chip then transmits its EPC information via the tag's antenna back to the reader. Therefore, a passive tag requires no maintenance and has a long lifespan.

ii. Active tags are battery integrated. Therefore, can constantly transmit the stored information in their microchips. The extra capabilities the tag has, originating from the battery, comes with the caveat of routine battery changing and more maintenance.

iii. Semi-active tags also have an integrated battery, however, instead of the battery powering transmission, the battery powers the electronic circuit or sensor within the tag.

RFID uses different frequency ranges to communicate; the range of the tag depends on the frequency at which they operate. There are three main frequency types called: Low Frequency (LF) ranges from 125 to 134kHz, High Frequency (HF) at 13.56MHz, and Ultra High Frequency (UHF) from 433 to 960HMz. However, certain bands have been standardised to allow for operational efficiency [11]. These bands vary further by country/global region, meaning a single configuration of frequency does not satisfy entire markets. For example, UHF in the European Union sits around 865 to 868 MHz, whereas in North America, UHF ranges from 902 to 928 MHz [11], [12].

The combination of the tag type and the frequency they operate at, provides the basis for the applications of RFID technology in various marketplaces. However, one combination of tag type and frequency is not "better" than others, the potential implications of each element contribute to a specific capability which can be translated into industrial use-cases.

Table I provides a summary of the differing frequency types of RFID, along with the subsequent impacts on their associated read ranges, with the varying levels of cost, and potential applications of each type.

A summary of the pros and cons of each are also noted. From Table I, there are many tag types, each with differences in the memory capacities and capabilities of each microchip in each tag type. Typically, this memory is to store basic product information such as design information, manufacturing date, product location [13], [14]. Meanwhile, the different capabilities lead to differing application potential within each variant. Also important to note the better the overall performance of the tag, the more expensive they are, with the UHF Active tags being the most expensive due to the active battery. There are active LF and HF tags, however these are rarely operationally utilised.

A. CONVENTIONAL RFID SYSTEMS

The type of tag will be chosen based on the application. Having selected the appropriate tag for the use case requirements, a system must be designed around the tag to ensure an operational solution is created. RFID systems aim to capture data accurately and quickly from all RFID attached products. This is achieved by fine-tuning the setup of a tag, its frequency type and RFID reader selection. This can be a time consuming and resource intensive process due to the trial-and-error approach, which is required to fine-tune a system. This includes the hardware selection of an appropriate antenna within a tag, the appropriate readers capability and the systems interaction with software [15]. Figure 2 depicts a conventional RFID system and its interactions.

TABLE I
SUMMARY OF RFID TAG TYPES

	Types	OFR[a]	Range	Cost per Tag	Application	Pros and Cons
Low Frequency	Passive	125-134kHz	10cm	$0.75-$5	Car Key-Fob, Access Control	Very good around liquids and metals, Short range, Limited memory, High production costs
High Frequency	Passive	13.56MHz	30cm	$0.20-$10	Library Books, ID Cards, Near Field Communications	Larger memory options than LF, Short range, Low data transmission rate
Ultra-High Frequency	Active	433MHz	100m	$25-$50	Vehicle Tracking, Asset Tracking	Very long read range, Large memory, High data transmission rates, High per tag cost, Shipping restrictions, Complex software may be required
Ultra-High Frequency	Passive	860-960MHz	25m	$0.09-$20	Supply Chain Tracking, Asset Tracking	Long read range, Low cost per tag, Variety of tag sizes and shapes, High data transmission, High equipment costs, Moderate memory capacity, Interference from metals and liquids

[a]OFR: Operational Frequency Range.

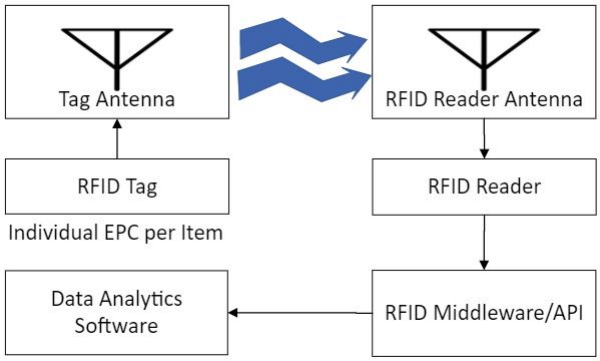

Fig. 2. RFID System Components.

The tag and reader form the hardware, whereas software must be integrated into the system. Software has been attributed as being critical to RFID application success [16]. The main software value is in middleware, which upon receiving the transmitted tag data from an RFID reader, processes the data and transmits the information to an analytical platform, where the true granularity of data which RFID provides can be understood and manipulated via data analysis. This middleware and final analytical software have the benefit of being able to scale the benefits of RFID across the required scope of application to be able to process large amounts of data, making and RFID system an attractive industrial proposition [15]. This systematic configuration allows for data to be available real-time to prospective users and therefore has widely become a key part in a variety of sectors with a variety of applications.

III. RFID BENEFITS IN RETAIL

Since the inception of RFID in commercial use cases, many different value propositions have arisen in a variety of industries. However, one of the most prominent industries to adopt RFID on a wide scale is retail. Within retail, RFID technology is used as a tool to revolutionize the way businesses operate, because of its broad impact on areas such as manufacturing, logistics, material handling, inventory tracking and management, safety and security, cashless payment, and customer service [17]. Other mentioned benefits to the retail sector include: better purchasing experience, fewer counterfeit items, faster product recalls, reduced out-of-stocks, fewer misplaced goods, lower prices mainly due to decreased supply chain costs and more efficient decision-making, more convenient and faster checkouts, more opportunity for consumer behavior research and more accurate targeting (e.g. more individualized offers and promotions), real-time information about the product and reduced labor requirements for backroom functions and thus more staff available for consumers [18]. Examples of benefits of RFID in different business processes within retail are tableted in Table II [19].

Beck in [3] conducted a case study review of ten apparel-led retail companies who had integrated RFID into their operations. Key indicators were considered across financial and operational performance. A summary of their findings is tabulated in Table III. Table III is an example of the potential realised benefits of RFID. All ten companies included in the review had successful implementations of RFID and realised the benefits which can flow. There are both operational and financial improvements. Arguably most importantly, the Return on Investment (ROI) figures show the technology becomes a worthwhile investment if done correctly. Anecdotally from the study, another benefit was increased staff satisfaction due to their working lives becoming easier. The ability to better understand consumer behaviour and consumption patterns provides retailers with further avenues to create a significant competitive advantage. RFID allows retailers to understanding this in real-time, the combination of which allows retailers to deliver adaptable best practice and create a more thorough and personalised customer experience in store [20]. Recent case studies and academic research has highlighted the data analytics element which RFID drives due to the Big Data which is generated. RFID implementation can lead to “enormous data volumes” which poses both challenges and opportunities to organisations [21]. The data analytics element has been categorised as the “least reported driver of RFID implementation” [22]. However, recent research has found firms should use Big Data analytics to improve decision making, alongside identifying new commercial opportunities

TABLE II
KEY BENEFITS OF RFID TECHNOLOGY FOR RETAILERS [19].

Business Process	Benefits
Inventory Control	Enable precise, real-time inventory counts, reduce out-of-stock situations, manage expiration dates, and reduce product dissipation (theft).
Manufacturing	Facilitate supply of raw materials, provide visibility of manufacturing process, and improve tracking of production processes.
Service	Improve checkout procedures with increased speed and accuracy, provide better customer service and improve customer satisfaction.
Transportation and Logistics	Limit disputes between manufacturers, suppliers, and retailers by tracking delivery quantities at each step of the logistics process. Allow supply chain shrinkage to be readily identifiable.
Recalls	Provide a fast and efficient means to recall products by pinpointing the location of recalled goods.

TABLE III
SUMMARY OF RFID BENEFITS TO 10 APPAREL RETAILERS [3].

Benefit	Description
Increase in Sales	Sales improvements of 1.5%-5.5%, delivering a potential increase of €1.4-€5.2bn.
Improved Inventory Accuracy	Improvement from 65%-75% to 93%-99%.
Stock Availability	SKU availability being 90%+.
Reduced Stock Holding	Stock reduction of 2%-13%.
Reduced Leakage	Shrinkage losses of 15%.
Reduced Staff Costs	Savings of 4% on staffing costs.
Return on Investment (ROI)	ROI had been achieved within 2/3 years via payback or pure ROI.

and reorganise resources [23], [24]. Therefore, businesses who are looking at RFID implementation for the more "traditional drivers", should consider the wider reaching applications and implications of the technology to see how to optimise other areas of the business.

RFID implementation has both internal and external consequences. The internal drivers mentioned above translate into external advantages. The added value of RFID brings a competitive advantage to organisations depending on how the insights generated from the data are utilised.

A. POTENTIAL NEGATIVES

As with all investment projects and technological adaptions, there are areas of concern which need to be assessed to decide if their impacts are project critical which has been investigated by researchers in [3], [21], [25]–[30]. A summary of their findings is tabulated in Table IV. Table IV shows some of the potential pitfalls which retailers may encounter and need to mitigate for, during an RFID journey. The majority of these, are both consequences of the technology, as well as limitations of RFID technology itself.

In addition to this, there are fundamental factors which need to be established and conducted throughout an RFID journey. The technological elements of RFID are not the most important factors, with the implementation steps of: Project Scoping, Analysis of the Existing System, System Design, Prototype testing, Implementation and Continuous Improvement being more important [31]. Of these, the elements of "understanding the potential and limitations of RFID technology" and "hardware/software selection" and "defining the project objectives" being the most important elements.

IV. COMMERCIAL CASE STUDIES

There are numerous case studies which highlight the effects of RFID on retailers, ranging from those who were early adopters, to those who are taking advantage of the falling tag prices and the improved components of an RFID system, with hardware and software interactions becoming smoother. A few of some key case studies are highlighted below:

A. THE METRO-GROUP

The Metro-Group's journey into RFID started through the creation of an IT subsidiary of the parent company called Improving the Retailer Industry Performance Through RFID Technology [32]. This initially started by tagging products, cases and pallets from certain partnered retailers, within a distribution centre. An item tracking system both in warehouses and shop floors were used to monitor the movement of stock within the business [33].

The benefits for Metro Group were easily founded. The main benefits surrounded effective inventory management including streamlining operations, saving time and resources through precise stock monitoring and faster replenishment orders while minimising errors. There were also improvements in stock availability by promptly identifying store needs and reducing 'out-of-stock' scenarios. Overall, Metro Group saved 14% in warehousing manpower costs, increased inventory availability by 11%, and reduced acquisition and loss by 18% [25].

B. WAL-MART

Wal-Mart began their RFID journey in 2004 by conducting a Pilot Trial on receiving products in a Distribution Centre (DC) in Texas, with 8 suppliers being included in the trial [34]. Such was the success of the trial, by 2006, RFID was supporting 500 stores and 5 DC's. Overall, the commercial benefits which Wal-Mart realised included a 19% increase in sales and an out-of-stock reduction of 16%, comparing RFID enabled stores, to non-RFID enabled stores [34].

C. LULULEMON

Lululemon rolled out RFID technology in 2014, with the primary objective of elevating the customer experience. After

TABLE IV
POTENTIAL NEGATIVES OF RFID TECHNOLOGY

Topic	Description
Tag Reliability	Maintaining tag adherence throughout entire product journey, leading to some products being "untagged", leading to reduced positive impacts [3]. This is due to overall accuracy reducing, thereby reducing the viability of the data produce by the system, leading to un-optimised commercial decisions.
Financial Constraints	RFID implementation can exacerbate financial difficulties due to the initial investment and recurring overhead of the hardware and software. A particular example is Beijing Zhaijisong Express Co., Ltd., who refused to adopt RFID due to tag prices being too high and affecting profitability [25].
Metal and Liquid Interference	Metals detune and reflect radio waves, whilst liquids can absorb waves, causing reduced read range and poor performance [26], [27]. This is important for fixture types for some use-cases.
System Communication	Difficult Integration of new software into legacy systems, leading to extra required resources, increased implementation time, and even a potential fail point of the project [3].
Mixed Supply Chains	There will be multiple information flows if not every item within a portfolio is tagged, which causes difficult integration [3].
Tag-Tag Proximity Interference	When there are large volumes of tags in proximity, detection rates decrease. However, this can be mitigated for by completing scans closer to the tagged objects and completing a "longer scan" [28].
Correct Usage of Data Analytics	Building in the capabilities following the Big Data introduction from RFID is "not a trivial task", which requires changes to managerial and organisational capabilities [21], [29].
Tag Performance vs Usability	A limitation of RFID technology is the base hardware reads every tag in the proximity, including those from "other companies". Therefore, complex software and middleware are required to ensure only correct tags are read, starting from "business level", down to individual products [30].

successful Pilot Trials, an RFID solution was globally rolled out to 300 stores in a year [35]. Estimates suggest the tags Lululemon utilise cost $0.05 per. However, Jonathan Aitken, Lululemon IT Director, estimated the RFID deployment returned its investment in a single season, mainly due to being able to satisfy customer product requirements [36]. Overall, Lululemon estimate accurate RFID data has led to commercial benefits of an 8% revenue increase and stock accuracy of up to 98%, alongside high staff satisfaction with RFID [37].

D. PUMA

Recently, sports and apparel manufacturer integrated RFID into their operation and supply chain. Puma are early in their RFID journey, with a 2-year conceptualization phase into 2019, wherein a flagship store in New York showcased stock being RFID enabled, as well as having RFID smart mirrors and shelving [38]. For their requirements, Puma used UHF RFID technology to power their innovation. Additionally, following a successful trial, in 2022, Puma rolled out RFID into another 135 stores in North America, which had the benefits of a 2% uplift in replenishment and a 2% uplift in sales. [39].

E. JP PENNEY

JP Penney are one of the few cases, where a negative impact of RFID has been recognized. In Q3 2013, JP Penney noted a poor RFID implementation cost them $28 million. The estimated reason for this was the systematic implementation was rushed, with a verbalized requirement to have all merchandise tagged in one year, to facilitate self-help checkout systems. This led to suppliers quitting using the Electronic Article Surveillance (EAS) tags and switching to RFID, with some being adhered to by the supplier, and others adhered to in-store. When the RFID implementation was cancelled due to inadequate cash, suppliers were not notified, leading to many items having no RFID or EAS tag. Stock leakages throughout the supply chain, as well as high theft levels, led to a poor financial performance [40].

The above case-studies detail high profile businesses RFID implementation, which have had largely positive outcomes. The journeys for each of these businesses have included lengthy planning processes with trial-and-error approaches to fine tune their system which has led to positive results. In the case of JP Penney, there was no clear vision, plan or set guides to the implementation which led to the failure of implementation.

V. FUTURE OF RFID IN COMMERCIAL USE

RFID in recent years has experienced a growth in usage, which has coincided with a development in the technology. This is not just from a performance improvement perspective, but also with the costs associated with the technology reducing, as the average cost of an RFID tag has fallen to around 4 cents, with the prices of readers also falling 50% in recent years [41]. This has made RFID more accessible and provided a continual growth in application due to financial viability improving.

Within the retail space, there are numerous new applications and designs of tag which are being created to expand the capabilities of RFID. A sample of these are detailed below:

A. CHIPLESS RFID

Chipless RFID has been an area of interest for some time, with its emergency as being a potential disruptor across numerous sectors. As a form of printable electronics, chipless technology enables internet-connected electronics to be manufactured as thin, flexible inlays, which can be adhered directly to products [4]. As aforementioned, within each RFID tag is a microchip, which acts as the data computational storage. This is normally a silicon-based product, with the antenna's being made from copper or aluminium [42]. These elements form the main cost behind RFID tags and can prove to be implementation killers for some businesses, as well as reducing the potential number of mass-market applications, as the benefits of the technology are outweighed by the recurring

and fixes overheads of the technology. Through removal of the current silicon-mounted chip, but maintaining the functionality of a traditional RFID system, the costs are reduced and therefore the potential use-cases increase.

B. NANOMATERIALS

Another form of chipless RFID is being established through nanomaterials. Nanomaterials have the benefit of maximising the surface area they are implemented on, allowing for greater reactivity, and achieving high sensitivity as sensors [5]. Furthermore, in comparison to traditional metallic RFID tags, they are lighter, smaller, and cheaper. The types of nanomaterial, which are being used include polymers; which are cheap and conductive, metal nanoparticles; which are being mainly used in inkjet printing which can replace microchips, and carbon nanostructures; which are also being used to replace microchips [5]. When applying this to retail environments, an application in monitoring food spoilage has been proven, using a conductive nanoparticle biosensor to detect changes in ammonia in milk [43]. This research has the potential to translate to other food groups, providing a more accurate method of detecting food spoilage, leading to reduced stock wastage.

C. RFID ROBOTICS

Within warehousing and stock management, robots are being used to a greater extent as the advancements in robotics grow. Autonomous robots within warehousing are now being used to locate and grasp items, having integrated AI machine learning capabilities [44]. Relating to RFID, a RFID robot is usually UHF enabled with multiple antennas, acting as a mobile reader to detect RFID enabled products [45]. Operationally robots will search and scan RIFD tags using a pre-programmed map or a self-generated map for inventory. Items which fall within the reading range and set parameters of the robot can be uniquely identified [46].

D. VOICE ACTIVATED RFID SYSTEMS

With accessibility of retail becoming an ever increasingly key concept for retailers, development in technology can play a part in helping physical retail ensure as many customers can be serviced from a diverse spectrum of people and abilities. An advancement in this area is highlighted by a potential new use case of RFID, which is voice activated. This allows for visually impaired customers to be able to find the items they want within a physical retail environment [47]. The system operates using a gadget, which comprises of a transmitter and receiver, a speech recogniser and RFID tags. A visually impaired customer speaks the item of they wish to find, with the gadget's antenna activating, and the item locator function of RFID and the enabled gadget guides the customer to the item.

Based on these highlighted examples of future applications of RFID, there is huge potential for the technology to become widely adapted into a plethora of scenarios and use cases. Despite RFID technology existing in commercial spaces for many years, with some of the barriers to entry such as the cost of hardware reducing, RFID will become more accessible to all businesses. Traditionally the well documented success stories are of large retailers who have the financial resources to implement RFID how they require. However, smaller retailers shall also be able to capitalise upon the benefits of RFID, hopefully moving towards a better commercial landscape for all.

VI. CONCLUSIONS

This paper serves as an overview of RFID technology, covering elements from the base elements of what RFID is and how it works, to how systems can be designed and the ramifications of those systems for commercial demands. It has been proven to have positive benefits for retailers across both operational and financial metrics. This was supported not only with just literature, but also commercial reports from case studies showing how impactful RFID can be. Finally, with RFID technology growing and markets expanding, the examples of new innovative use cases show RFID has a current and certainly, a bright future within retail.

However, throughout this paper, elements have been proposed which retailers need to take into consideration when looking to implement RFID. The planning process is one of the most important steps and the initial fact finding about the capabilities and limitations of the technology, alongside clear vision planning is important. Particular elements of technological limitation have been noted and a consequence of poor implementation has been noted with the JP Penney case study.

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