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Outlooks for UHF RFID-Based Autonomous Retails and Factories

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ABSTRACT

Radio-frequency identification (RFID) in the ultra-high-frequency (UHF) band with passive tags was envisioned for logistic purposes to track a large number of tagged items. However, the present designs of hardware and air protocols still fall short of the required functionality to deploy in large autonomous facilities such as retail shops and assembly factories. This paper presents the evidences of the current RFID limitations, and illustrates the possible paths towards future adoption in large-scale logistic applications.

1. INTRODUCTION

1.1 RFID adoption in large facilities

Today's radio-frequency identification (RFID) systems [1], [2] have many unique merits for logistic control: A fully functional electronic production code (EPC) Gen 2 air protocol out of the efforts of Walmart and MIT Auto-ID lab for tag multiplexing; passive UHF tags less than $0.1 with roll-to-roll production; reader cost between $50 - $2,000 depending on the range and performance [3]. When tags are well separated spatially, we have mature industrial implementation in airport luggage handling [4] and EasyPass in highway tolling [5]. The scaling of the number of tags in the capture zone is presently a direct tradeoff with the mean sampling time due to the time-division based Aloha anti-collision protocol in EPC [6].

Before COVID-19 pandemic, Amazon Go [7] and Alibaba Go [8] opened their autonomous retail stores as pilot studies. Both chose image-based systems instead of RFID, even though arguably RFID was originally designed for such logistic purposes. For example, Amazon Go is a giant system by profuse imaging, sensor fusion and AI, with hundreds of cameras, scales on every shelf and Bluetooth beacons in a 1,500 ft^2 shop. The cost is high, and the imaging system is only linearly scalable to the size of the store. The backend computation was also expected to be excessive and hard to scale with the store size. Although small-scale demonstration of RFID had made occasional news [9], broad adoption in large supply chain and autonomous operations remain elusive.

On a related note, for autonomous driving, Elon Musk announced that Tesla has abandoned the radar approach to switch to an all-vision system [10], similar to the way people drive. Radar and Lidar technology were not in favor. From private conversations, many companies on logistics have also expressed about their view on RFID for autonomous retails and manufacturing facilities: "RFID is no longer in our company's portfolio." "RFID seems to oversell its potentials." "Walmart tried RFID. It was not competitive."

Why did RF approaches fall from industry adoption in autonomous logistics and driving? Radar and RF used to be the pride technology in the 20th century that enabled victory in wars, made radio and TV networks, and revolutionize our daily life with mobile phones and wireless networks. Are RF and radar for logistics no longer favorable in the 21st century against imaging? Although it is possible that Amazon, Tesla and Walmart made wrong choices in technology, but these big companies were definitely making well informed decision.

For an RFID-based autonomous retail, we will need item-level ID and 3D locating of every tag to connect to the logistic system. The item sampling time can be between 0.2 – 1 s, and location accuracy around 5 cm. To cover the large floor space, multiple readers are required. At a glance, these specifications seem to be achievable in current RFID systems. What is missing though? Why did Amazon Go choose imaging? RFID developers need to take notice in order to turn the tide around.

1.2 The market perspectives

For RFID industry to grow in the next 10 years, we will need to find new, large applications in addition to luggage and toll controls. With integration to the existing networks, RFID has the potential to enable real-time flow of product data to the entire business ecosystem. The present global RFID market, mostly for a relatively small number of tags in the capture volume, is about $10B - $14B in 2020 and estimated around $40B in 2030 [11][12]. The broad spread in the 2030 forecast is a result of different estimates of the compound annual growth rate (CAGR) from 9.6% - 13.2%. In comparison, autonomous retail is estimated at $229B in 2026 [13]and factory automation at $351B in 2027 [14], both of which provide ample room for RFID industry to grow with successful adoption. In addition, RFID may carve out some portion in digital twinning in AR/VR at $155B in 2030 [15] and smart buildings at $122B in 2026 [16]. Without penetrating to new applications in large-scale logistics, RFID industry may see stagnant development and growth.

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1.3 Cameras vs. RFID

If RFID cannot be applied to item-level control in autonomous facilities, imaging would likely be the default choice, similar to the plan behind Amazon Go. Imaging has seen impressive growth in ability and significant reduction in hardware and computation cost. It is arguably the nature's choice, although imaging is expensive to scale up and can be obstructed by common materials. RF on the other hand is human's own invention [17], and can provide ID, ranging and data with penetration to many common materials except metals and water. A common observation is that even imaging has fundamental limits, it can be the preferred choice, as "seeing is believing". RF is quite the opposite, after adoption, it would be driven to perfection, but before adoption, a lot of hesitance and barriers in regulation and deployment.

The paper will start from the investigation on current limitations of RFID systems for large-scale autonomous facilities. We will then point out specific challenges and potential solutions. Two challenges will be addressed specifically: Read yields and real-time locating. We will then briefly summarize the other related challenges, and then finally arrive at the conclusion on the importance of holistic approaches. This paper is not meant to offer full solutions, but point out what direction of innovation are needed for RFID to be applied to autonomous retails and factories.

2. RFID IN LARGE FACILITIES

2.1 The present RFID technology

We will offer a quick summary on UHF RFID technology [2] for audience with less exposure to the current system. The reader sends both power and commands to passive tags. The tag modulates its backscattering with a switch on the antenna providing a tag-specific digital ID code and signal differentiation from ambient reflection and transmitter (Tx) leakage, as the subcarrier band by tag modulation will not happen for pure Tx signals even though walls, furniture and floors have large radar cross section (RCS). When the operational range is limited by the tag energy scavenging following the r^{-2} scaling, the system is limited by the *tag sensitivity*. Alternatively, when the range is limited by the reader receiver (Rx) to demodulate the tag ID successfully and follow the r^{-4} relation, the system would be limited by the *reader sensitivity*. To mitigate collision from multiple tags in the capture volume, an Aloha-based TDMA (time division multiple access) is used by the simple tag circuits in EPC Gen 2, which also assumes only one reader at a time is operating in a given capture volume.

2.2 Wish list and showstoppers

Now we will take a look at the specific challenges for RFID in large autonomous facilities. A possible scenario of an autonomous retail is illustrated in Fig. 1, where the space has four readers to cover the entire area. Each reader has a pair of Tx and Rx. In the present RFID system, the four reader has to follow a time multiplexing scheme directed by another network protocol. In the ideal situation, each Tx can be demodulated by all Rx and can simultaneously operate, as shown by the channels labeled by $h_{i,\{DL;UL\}}$, where i is the reader number and DL and UL denote the downlink (reader-to-tag) and uplink (tag-to-reader), respectively. Each item on the shelf has one or more passive RFID tags. The shopping carts and shoppers are also tagged. A comparable implementation can be modified for the autonomous assembly factories, with the addition of tags on robotic arms for the purpose of positioning instead of logistics.

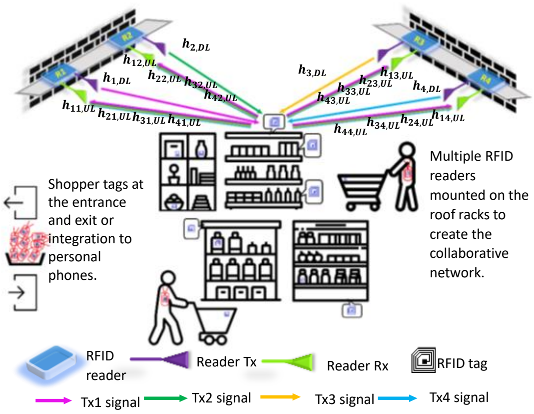

Fig. 1 Illustration of an autonomous retail by RFID. Four readers with respective Tx and Rx cover the large space. The items on sale, the carts and the shoppers are assumed to be tagged.

Table I shows the major requirements and the present commercial RFID capabilities for autonomous facility adoption. Table I is for representative purposes, and may have missed some system requirements and practical considerations.

Table I. Requirements for autonomous facility logistics and present commercial RFID capabilities.

Requirements	Needed	Present
Read yield in a clutter space	> 99.999%	80% – 99%
Affordable in large facilities	1 reader/500 ft^2; Cost effective	Reader-to-reader collision by TDMA
Many tags in proximity	< 1 cm apart; Overlapping tags	> 5 cm apart
3D tag localization	< 5 cm at 99% CDF	~ 20 cm at 50% CDF
Functions of tags	Tiers for tracking, landmarks, and inventory	Tag based on classes/cost, not functions
ID space in regional Gold Standard GS-1	Universal meaning with privacy and security	Unregulated
Security	Cost-effective layers of security in protocols	Low standard security level in EPC

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First and foremost, for logistic functions, the read yield of the passive tags within the autonomous facilities needs to be higher than 99.999%, i.e., only one item can be missed in 10^5 to 10^6 items. Surely even higher read yield will be appreciated in many applications, but quality control (QC) will be harder to be validated during the product testing stage. For cluttered items, the present RFID tags can be detuned and shadowed by nearby stronger tags, which made the read yield in the range of 80% - 99%, except in conveyor-belt systems.

The line-of-sight (LoS) read range, if tag sensitivity limited, is often around 6 m – 10 m or 20 ft – 30 ft, set by the Tx maximum power at 36 dBm and tag wakeup sensitivity around –20 dBm. Therefore, approximately one reader is needed for every 500 ft^2 space, with tolerance given to some mild blockage and off-center deployment of the reader. Larger facility will need multiple readers for adequate coverage. However, the present EPC does not prescribe how multiple readers can work collaboratively, except through external control of time division, similar to the multiple antennas connected to one reader. Time-division readers will then incur a direct compromise to the tag sampling rate. When two readers are on simultaneously, no reader-to-reader collision (R2RC) is regulated which will make the tags in the joint capture volume suffer read failure.

As the RFID system operates around the 900 MHz ISM (industrial, scientific and manufacturing) band depending on the region, the tag antenna can be seriously detuned when another tag antenna is in the proximity of 1/6 of wavelength or approximately 5 cm. Due to the random shelfing items in the autonomous facility, it is difficult to guarantee 5 cm separation for all tags, and detuned tags that are at the edge of the capture volume will become unreadable. For 3D tag localization, the tag has to be successfully read by at least 4 different reader Rx antennas with known locations. More Rx antennas can enhance the 3D locating reliability. For most retail applications, tag location within 5 cm for more than 99% of tags will be acceptable. However, most present RFID systems can only achieve ~ 20 cm accuracy at 50% cumulative distribution function (CDF) [18], unless moving readers on known tracks are used to increase the synthetic aperture [19].

The EPC tags are designed according to various classes by their capabilities in the air protocol, built-in battery, code length and sensing. For autonomous facilities, it would be beneficial that tags can be additionally assigned different functionalities such as inventory tags with unknown ID, tracking tags with known ID and unknown location, and landmark tags with known ID and location. The most important function for inventory tags is unambiguous recognition for a very large number of tags, and the sampling rate can be relatively low. The most important function for tracking tags is accurate 3D locating with a high sampling rate, but the number of tracking tags can be small. In comparison, the number of landmark tags can be large, but the sampling rate can be low for only calibration or tagless object detection [20][21] purposes.

For each limitation of the present RFID system, the suggestions in the literature abounds. Table II gives a few examples, but far away from a comprehensive list. The purpose is to show that most present revisions over the conventional EPC Gen 2 RFID system did not have a holistic solution for the requirements in Table I, and hence their adoption to autonomous facilities will take much more integration efforts.

Table II. Methods in the literature to remedy conventional RFID limitations.

Ideas	Applications	Concerns
Chipless RFID [22]	Few tags in the capture volume	Air protocol for tag multiplexing, cost
Harmonic RFID [23][24]	Precision locating	New readers; dual-band tag antennas
Semi-active and active RFID [2]	Extended reading range	Cost, low-term maintenance and recycling
Other frequency bands [25][26]	2.4/5.8/28/60 GHz; mmID	Less than 1 μW scavenged at 5 m
SAR/iSAR locating [19][27]	High aperture and precision	Motion assumption
Cellular network for power [28]	LoS from cell tower	Coverage for 10 μW at tag
Ambient energy scavenging [29]	Thermoelectric; solar	More ambient requirements
Non-TDMA air protocols [30][31]	Reader/tag CDMA	Initial polling; tag cost by logic gates
Digital twinning [32]	Augmented reality/ virtual reality	Insufficient power to support sensors
ID interpretation rules [33]	Universal with security	Regulation consent

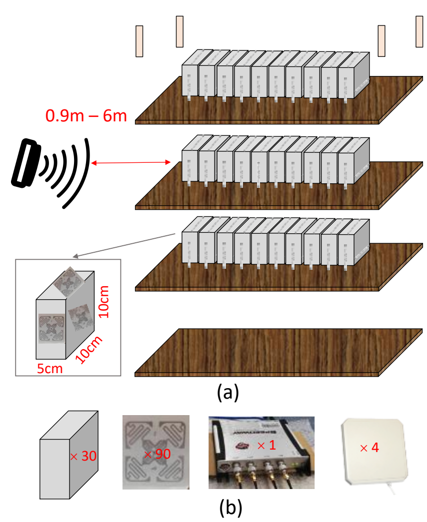

Fig. 2. An illustrative system for read yield limitation. (a) The RFID system schematic; (b) The reader, reader antennas, tags and boxes used in the experiment.

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3. READ YIELD AND LOCATING

In this section, we will illustrate the critical limitation of read yields for cluttered tags in the present RFID systems, and then make observation on possible solution. We will treat locating reliability as an extension to read yield. If a tag cannot be read by 4 Rx antennas with correct ID, its location can at best be ambiguous.

3.1 Read yield and ranging of cluttered tags

A simple illustration for the cluttered tag scenario in a shelfing arrangement is shown in Fig. 2. The system here may not be representative for common autonomous facility applications, but should be reasonable to illustrate the current limitation. We will use 90 tags (Impinj 18000-6c), pasted on three orthogonal sides of 30 paper boxes of 10 cm by 5 cm by 5 cm. The tag antenna is circularly polarized. The paper boxes are scattered randomly on typical metal shelves with 10 boxes on each tier. When two tags are in close proximity, the antennas will be detuned. The shelf will be approximately 0.9 m – 6 m away from the reader. The 3 tags on one box can enable the study of the effect of tag orientation. The reader is Impinj Speedway R420 with 4 Laird 9 dBi patch antennas.

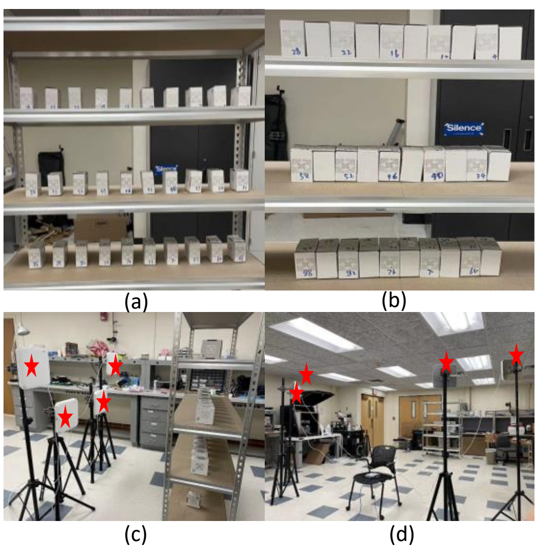

Fig. 3. Different case studies of read yields for cluttered tags: (a) Well separated tags for the baseline; (b) Half of the tags detuned due to touching other tags; (c) (d) Different reader antenna arrangements. Red star markers represent the positions of reader receivers.

There are three groups of experiments for read yield testing, as illustrated in Fig. 3: (a) The boxes and the tags were well separated and the tags are in different orientations; (b) The boxes are packed together with about half of the tags on the large side touching each other, detuning the tag antenna; (c) Four reader antennas were arranged in a coplanar array, on the ceiling, or more diversified positions.

For well separated tags operated from 0.9 m to 5.9 m, if we just need to identify their ID, then they can all be read at any distance tested, as shown in Fig. 4(a). When we require all four antennas have to successfully read the tag for localization, then only up to 4.7 m can all tags be read, although with some large delays, as shown in Fig. 4(b). For 5.9 m, about 10% of tags can never be read due to misalignment of the main lobe of specific antennas. This teaches us that the read yield is not only a function of distance, but can also be different for each antenna position. As shown in Fig. 5(a), for tags that are touching other tags, all tags can be read only at 0.9m. At 5.9m, about 40% of tags are detuned and cannot be read by any antenna. For locating by 4 antennas in Fig. 5(b), more tags were lost, as you can only locate a tag if all four antennas can correctly identify the tag. Tag ID provides the signal differentiation to retrieve the information for RSSI and phase, which implies that located tags will be a subset of recognized tags.

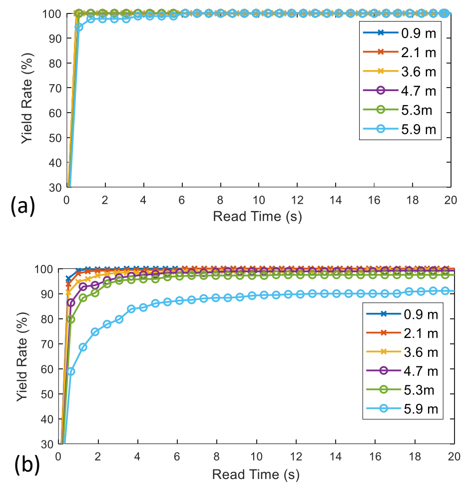

Fig. 4. Read yield testing for well separated tags: (a) For identification, tags at all distances of 0.9 m to 5.9 m can be read; (b) For locating and read by 4 readers, only tags within 4.7 m can be located.

The ranging for those tags that were identified by the antennas were derived from phases after resolving the

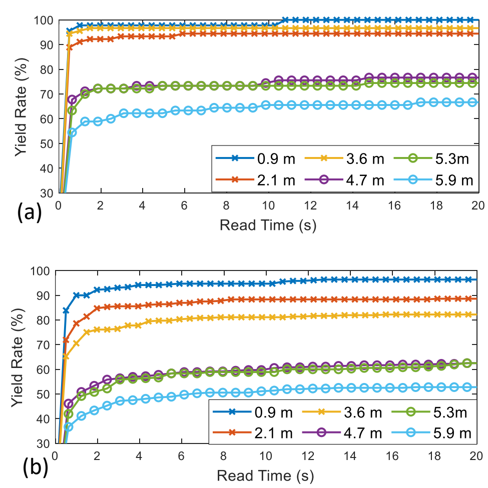

Fig. 5. Read yield testing when half of tags are touching other tags: (a) For identification, only at 0.9 m can all tags be read; (b) For locating and read by 4 readers, about 5% of tags fail at 0.9 m and about 50% fail at 5.9 m.

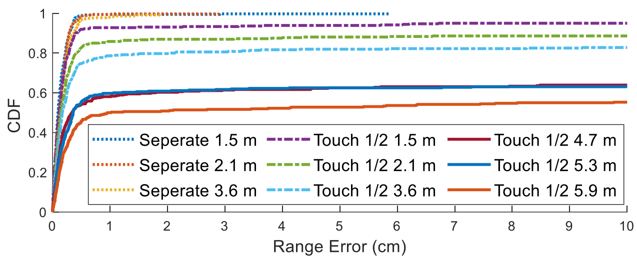

Fig. 6. CDF of ranging errors for cases in Figs. 4 and 5. For well-separated tags, all tags can be ranged with small errors by 4 Rx antennas when the distance is smaller than 3.6 m. For cluttered-tag scenarios, detuning will cause the percentage of tags that can be recognized and ranged to decrease with increasing tag-to-reader distance, but the precision for correctly recognized tags does not drop significantly.

wavelength ambiguity in a phase-static ambient (no moving persons or robots) [34]. For 3D locating derived from trilateration of tag-to-reader ranging, further dilution of precision would happen due to the reader antenna placement. We can see in Fig. 6 all separate tags closer than 3.6 m were read and ranged with small errors, tags can be reasonably ranged as long as they can be read by four antennas, although the yield drops gradually with increasing tag-to-reader distance. We can conclude that the main limitation of RFID locating in the cluttered tag condition is that the system needs very high read yield rates.

In the cluttered tag scenario, if we can make up the link budget of 5.9m to be like that in 0.9 m, then in the tag sensitivity limit cases, the read yield can be significantly improved. However, for r^{-2} scaling, this is about 16 dB, which is difficult to achieve by the brute force of pushing Tx power to 52 dBm or adding 16 dBi gain to the Tx antenna gain. Beam steering for effective antenna gain can make up the required 16 dBi as in the cellular 5G cases of the 24 GHz band [35], but the cost will be the sweeping time delay for inventory tags without known location and the possible concerns from FCC (Federal Communications Commission) regulation in the ISM band.

3.2 Reading tags with reader spatial diversity

Another possibility to improve read yields is the spatial diversity of readers, i.e., reader antennas are diversely distributed in the capture volume. Mathematically speaking, arbitrary room layout would require spatial diversity for reliable observation and locating, especially when unknown obstruction is a serious concern. If we can create many observation channels, then we can select the ones that have higher SNR for read yields or more Rician channels with LoS dominance for locating [36]. How can we have more channels in a cost-effective way instead of relying on adding more readers in an incremental manner? Increasing the number of readers and antennas by brute force will likely incur high cost in hardware and deployment, which can be prohibitive for large facilities.

We will first take a look at the spatial diversity effect in the present system of four reader antennas. For this study, all antennas will remain to be around 5.9 m away from the shelf. The previous experiment was done with planar arrangement with forward looking antennas (Position 1), and here we created three additional scenarios of spatial diversity as shown in Fig. 7. Diversity 1: Putting antennas close to the ceiling with nonplanar positions; Diversity 2: Nonplanar positions with height variation; Diversity 3: Antennas on the two sides of the shelf. The three reader diversity

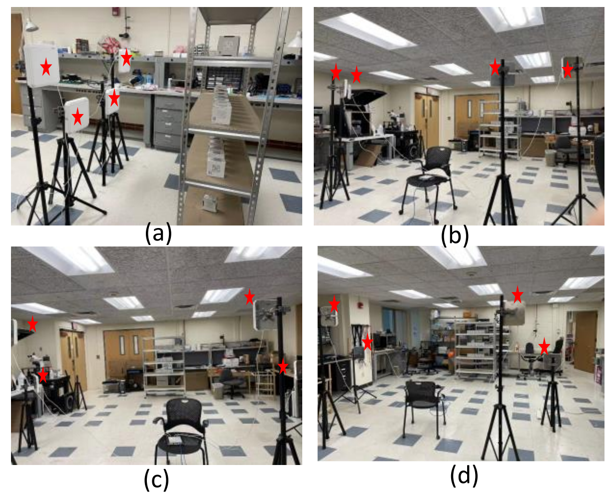

Fig. 7. Four reader antenna deployment scenarios to test the effect of spatial diversity on read yields and ranging: (a) Position 1: Planar forward looking (previous results); (b) Diversity 1: All close to the ceiling but nonplanar; (c) Diversity 2: Nonplanar with height difference; Diversity 3: Antennas on the two sides of the shelf including (c) and (d).

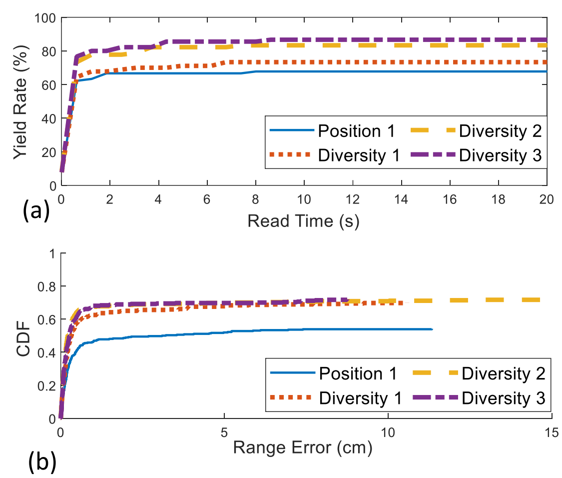

Fig. 8. Effects of spatial diversity on (a) Read yields; (b) Ranging.

arrangements have increasing volume for the tetrahedral formed by the 4 antennas and hence higher spatial diversity. We can see that the spatial diversity, even when reader antennas are on one at a time, can enhance both the read yield and ranging CDF in Fig. 8, and also (not shown) reduce the dilution of 3D locating accuracy, which is well established in the literature [37] and will not be the focus here.

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However, the improved read yield is still far away from enough, as our goal is 99.999%!

4. COLLABORATIVE READERS

As the tag sensitivity will limit the operating range, multiple readers to cover a large cluttered facility are a must for reliable operations anyway. It is fair to assume that the multiple readers can be collaboratively integrated with another local area network (LAN) such as WiFi and cellular for reader coordination, data integration, and baseband synchronization. The RFID reader-to-tag multiplexing will still need the specific air protocols so that the tag can remain passive and low cost.

4.1 Protocols for multiple readers

In addition to the conventional TDMA scheme, multiple readers can be simultaneously operated through frequency-division multiple access (FDMA) and code-division multiple access (CDMA). For reader TDMA, though only one reader Tx is active in a given time slot, multiple reader Rx can receive the tag backscattering information to increase spatial diversity of observation, in particular for tag locating. For scenarios limited by tag sensitivity, additive Tx reverberation, particularly in the Rayleigh limit of multi-path dominance [38], cannot be employed to enhance the read yield. The transceiver complexity can remain low for both readers and tags, although the overall tag sampling rate will decrease according to the time division.

Simplistic reader FDMA is however problematic, as the tag in the backscattering mode without its own local oscillator (LO) for channel selection can suffer reader confusion and R2RC. In-band interference and desensitization in the FDMA scheme can also increase the transceiver complexity by higher channel isolation requirements. The tag charge pump in the energy harvesting unit can be weakened as well due to the low-frequency beat tones by multiple carrier frequencies.

An interesting proposal to increase the spatial diversity effectively is to employ multi-static N reader Tx/Rx operating at the same time by collaborative CDMA to create N^2 MIMO channels represented by $h_{i,\{DL;UL\}}$ in Fig. 1 [39]. Here each reader Tx has a preset orthogonal code through coordination in the higher LAN layer and can be correctly demodulated by all Rx. This collaborative reader CDMA scheme can not only greatly increase the spatial diversity, but also resolve the R2RC problem, which was not resolved in EPC Gen 2 even for the simplest Tag-Talk-Only (TTO) protocol where the tag response was not coordinated by a specific reader [40]. The collaborative read CDMA has all readers transmit at the same time, and the tag backscattering will contain the reader CDMA code to be identified at each Rx with the proper phase evaluation for ranging. We can create N^2 channels from N readers with multi-static spatial diversity. The preliminary result in a small capture volume also indicated that the read yield can be significantly enhanced beyond 99.999% in a cluttered environment by exploiting the anti-correlation effects in the read failure cases of individual channels, i.e., the read failure case in Channel 1 will be unlikely to be the same failure case in Channel 2 due to channel spatial diversity.

4.2 Alternative methods for spatial diversity

Additional methods to enhance the reader spatial diversity include moving reader antennas similar to synthetic aperture radar (SAR) [27], moving radiation patterns by antenna arrays [41], and meta-material antennas [42]. Besides increasing the read yield, the SAR or inverse SAR (iSAR) techniques can also boost the locating resolution and reliability. Although these radar-based techniques are well established in the 1970s and 1980s, they often will increase cost in hardware or deployment.

Another interesting option of multiple readers is to separate the Tx carriers to power tags and to collect the backscattering data, such as the Mojix STAR™ system [43]. For energy scavenging with monotone beacons, the power unit can be much simpler than the conventional RFID readers with resonance microwave cavity instead of high-linearity power amplifiers, and can thus be more profusely deployed without adding significant cost. For the data reader, the system will become reader sensitivity limited with a different scaling rule. However, similar to the harmonic back scattering, the tag will require a dual-band antenna, as the power and signal bands need to be well separated to avoid signal desensitization.

4.3 Types of tags in large facilities

In large autonomous facilities, the total number of tags can be well over 10,000 in total, and well over 1,000 for the capture volume of individual readers. The inventory, tracking and landmark tags have to be separated in their responses to the reader, as the sampling rate requirement can be hugely different. It is impractical to insist on high sampling rates for tags mainly used for inventory purposes that can cause severe channel congestion, as the number of inventory tags is expected to be huge. It is also less useful that tracking tags cannot have real-time guarantee. For landmark tags used for tagless object detection [20][21], both the sampling rate and the number of tags can be high, but all tag ID are known after the polling cycle and will remain static. Spatial diversity for both tags and readers is important for tagless object detection. It is therefore important to include such type considerations for tags in the protocol level, especially for the responses to multiple readers.

5. OTHER FACTORS

5.1 Locating and capture volume

Tag ranging can be derived from the received signal strength (RSSI) and the phase of the carrier at the reader Rx [23]. Differential ranging is often used to reduce the dependence

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on constant physical and phase offsets. RSSI-based methods include fingerprinting [44] and various learning algorithms [45], but often the computational cost is high. Phase-based methods have two main error sources caused by wavelength ambiguity and phase noises. Some degrees of LoS dominance in Rician channels have to be assumed, as the multi-path signal will not have a phase offset in proportion to the tag-to-reader distance. Unlike RSSI-based methods, phase-based methods cannot reliably estimate ranging in Rayleigh channels or capture volume that approximates the reverberation limits. Errors caused by wavelength ambiguity will be much larger than those from phase noises in most transceiver architectures [23]. When the capture volume is smaller than the wavelength in its largest form factors, wavelength ambiguity is not an issue and sub-millimeter precision can be achieved when the phase noise sources can be controlled through proper transceiver designs [46]. For present RFID systems, the backscattered signal at the reader Rx is separated from the Tx signal by the subcarrier injection during the tag ID modulation, and its phase signal is often dominated by the leakage Tx noise skirt, where the ranging error is usually around 3 – 10 cm.

For large facilities, wavelength ambiguity needs to be properly resolved to achieve sub-10 cm precision. The main mitigation for reliable wavelength integer estimation often relies on the spectral and spatial diversities of available channels [23], which also controls the error of 3D locating from 1D ranging. Spectral diversity or large effective bandwidth is less important when the capture volume is smaller than the wavelength. Additional techniques to evaluate the channel feasibility for locating estimation include angle-of-arrival (AoA) estimation in differential schemes and AoA variation estimation to determine the degree of LoS dominance [47]. In summary, spatial diversity of reader antennas is critical for many RFID specifications in logistic operations of large facilities.

5.2 Tag cost

The passive UHF RFID tag has the unique advantages of low cost with medium operating range, in comparison with near-field communication (NFC) and semi-active tags with built-in batteries [2]. Through roll-to-roll production, the current tag cost is around \$0.03 – \$0.08, depending on the technology choices and application specification. The overall cost is nearly equally divided to the tag chip, the substrate with the printed antenna, and the packaging and testing. Depending on the tag collision control of the air protocol, the tag chip has about 3,000 – 30,000 gate equivalents (GE) for implementing multiplexing protocols, and 128 – 1,024 bits of nonvolatile storage for tag ID, limited mostly by power consumption instead of the chip size, which is in turn mostly influenced by the packaging method [48]. Air protocols of TTO is significantly simpler and less power requirement than tag-talk first (TTF) and reader-talk first (RTF), which will show the tradeoffs among operational range, chip size, chip cost and sampling rates [40]. Various tag substrates to enable tags on liquid bottles and metals as well as laundry resistance have also been developed [49]. As the cost structure already approaches the Amdahl's law in cost distribution, further cost reduction can only be realized from reduction of all three main components. New proposals for tag circuits and wireless protocols will need to take the cost structure seriously to realize industrial adoption. The present low cost and overall revenue of manufacturing have actually become a barrier for participation from large companies seeking markets with large revenues. When the UHF tag can be adopted in new applications of autonomous retails and factories, the overall volume can significantly increase to draw in new major players.

5.3 Tag power scavenging

The radar cross section (RCS) of the tag antenna needs to remain nearly constant to maintain the scavenged power level of the passive tags, regardless of the frequency band. Higher operating frequency can use smaller antennas in proportion to the wavelength, but RCS governs the energy distribution in Frii's law, and the practical operational distance. The RF-to-DC efficiency is also difficult to improve as it is now limited by the fundamental nonlinearity of the diode. Impinging RF waves with voltage amplitude at the diode rectifier smaller than the thermal voltage will bound to have low efficiency in the cycle of pumping and stoppage of leaking [50]. By these arguments, extending the operational range of passive tags in large facilities will meet many fundamental challenges. Multiple collaborative readers seem to hold more promises for facility scaling.

5.4 Air protocol for tags and readers

Unlike EPC Gen 2 that has a focused design on the dedicated capture volume in a conveyor-belt like setting, the next RFID protocol for large autonomous facilities has to be reasonably efficient for > 5,000 tags and > 10 readers working in a collaborative manner. Air protocols are also constrained by the limited power and gate equivalents on the tag, whether it is based on Aloha or tree polling [2]. The backend integration of multiple reader data flows also needs further attention for various possible LANs, which is however beyond the scope of this paper.

5.5 Code space

The tag backscattering data format is not strictly regulated in EPC Gen 2. After collecting and verifying the word of 96 – 128 bits from the tag response, the tag word can be gibberish to unknown readers [33]. Code space is regulated by GS-1 in each country, and will be hard to come to universal agreement, even with the efforts of RAIN consortium [51]. With the advances of digital chips, it is probably more practical to sacrifice some code efficiency to achieve unambiguous universal interpretation of tag responses, such as dedicated length of bits that abides by the International Article Number used in bar codes [52]. The remaining item-level bits can be subject to individual reader interpretation, but the response will be understood universally in the category level.

6. CONCLUSION

This paper presents representative challenges and possible solution paths to enable RFID as an attractive option for logistic control in large autonomous facilities. The main conclusion of this paper would be the roadmaps to enhancing read yields > 99.999% in densely populated tags on shelves, multiple collaborative readers for a large space, and reliable location estimate. For RFID industry, if we can realize these specifications, the market opportunity is much larger than the present RFID market size. For academia, the new ideas will need more *holistic* considerations on read yield, cluttered tags, large space and 3D locating at the same time, so that RFID innovations can truly make an impact to the future autonomous facilities.

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