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Efficient tag detection in RFID systems

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ABSTRACT

Recent technological advances have motivated large-scale deployment of RFID systems. However, a number of critical design issues relating to efficient detection of tags remain unresolved. In this paper, we address three important problems associated with tag detection in RFID systems: (i) accurately detecting RFID tags in the presence of reader interference (*reader collision avoidance problem*); (ii) eliminating redundant tag reports by multiple readers (*optimal tag reporting problem*); and (iii) minimizing redundant reports from multiple readers by identifying a minimal set of readers that cover all tags present in the system (*optimal tag coverage problem*). The underlying difficulties associated with these problems arise from the lack of collision detection mechanisms, the potential inability of RFID readers to relay packets generated by other readers, and severe resource constraints on RFID tags. In this paper we present a randomized, distributed and localized Reader Collision Avoidance (RCA) algorithm and provide detailed probabilistic analysis to establish the accuracy and the efficiency of this algorithm. Then, we prove that the optimal tag coverage problem is NP-hard even with global knowledge of reader and tag locations. We develop a distributed and localized Redundant Reader Elimination (RRE) algorithm, that efficiently identifies redundant readers and avoids redundant reporting by multiple readers. In addition to rigorous analysis of performance and accuracy, we provide results from elaborate simulations for a wide range of system parameters, demonstrating the correctness and efficiency of the proposed algorithms under various scenarios.

1. Introduction

Radio Frequency Identifier (RFID) is an increasingly deployed technology for tagging and uniquely identifying objects. Unlike barcodes, RFID enables simultaneous detection of multiple, distant, and non-line-of-sight objects. There are hundreds of millions of RFID tags currently deployed; it is believed that this number will reach tens of billions within seven years [20]. The use of RFID systems is primarily motivated by their net savings, low deployment cost, and accuracy. As an example, Wal-Mart anticipates savings of billions of dollars from tagging pallets and individual products, while the International Air Transport Association (IATA) projects annual industry savings of $760 Million from RFID luggage tags [16]. Apparel vendor Gap documented an increase of accuracy from 85% to 99.9% when using RFID technology [5].

RFID systems have two types of components, RFID transponders (tags), placed on objects and RFID transceivers (tag readers). RFID tags store information using a small integrated circuit and communicate using an antenna. RFID readers are capable of reading the information stored on tags placed in their vicinity and communicate it to a host computer. Most tags are passive, *i.e.* they do not require battery power. Instead, passive tags use the energy of the reader's signal to fetch, process, and communicate stored data.

The past few years have witnessed tremendous advances in RFID technology beyond reduction in size and price of components. Notably, diverse solutions for wireless readers are now supported, including quarter-sized wireless readers [28] compatible with Crossbow [10] sensors, Bluetooth enabled readers [4], SD card reader/writers [32], and reader enabled phones [22]. These developments broaden the scope and utility of RFID systems, enabling their on-line deployment. On the other hand, convenient, remote ad hoc deployment of wireless readers poses several problems.

Reader collision avoidance: One problem, *reader collision* [12], occurs when co-located readers are simultaneously active. Specifically, reader collisions occur at tags situated in the vicinity of two or

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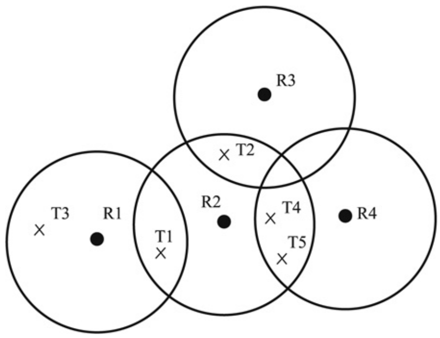

Fig. 1. Example reader and tag deployment. Readers are denoted by small dark circles and their RF interrogation zones by larger disks. Tags are denoted by small crosses. In this example, all the readers except R_1 are redundant, however, both R_1 and R_2 need to report their covered tags. Moreover, tag T_1 is redundantly covered by R_1 and R_2 and may be reported twice. RRE assigns tag T_1 to reader R_2, which will be the only reader reporting it.

more readers that simultaneously interrogate tags. Such tags may be unable to correctly decode reader queries, leading to undesirable behavior. Consider, for example, the reader and tag deployment in Fig. 1. In the figure, readers are represented by dots, tags are represented by crosses, and the interrogation zone of a reader is represented by circles centered around readers. If readers R_1 and R_2 interrogate tags at the same time, neither of them may detect tag T_1. This is because T_1 resides at the intersection of interrogation zones of the two readers, and consequently responds to both of their queries. This causes existing tag detection protocols to potentially report incorrect data, or to not terminate at all.

Current protocols for avoiding reader collisions are based either on time scheduling of reader transmissions, spatial isolation of readers or frequency assignment to readers, or a combination of these techniques. Solutions may either require a centralized entity or are completely decentralized.

Time division multiple access (TDMA) techniques are used when networked readers may be instructed to read at different times. The absence of global topology and reader and tag location information requires a distributed implementation of TDMA. An instance of a distributed TDMA solution is the Colorwave protocol of Waldrop et al. [31]. Colorwave attempts to assign a tag interrogation time slot to each reader in the network, such that no two readers whose transmissions interfere are assigned the same slot. To achieve this, Colorwave assumes that each reader knows the set of readers with whom it interferes, and can communicate with them. Note that Colorwave is independent of tag locations. For a given reader network instance, the Colorwave solution works for any tag deployment. However, building the interference set is a challenging problem in itself, as the interference range of wireless devices may well exceed their transmission range. In the worst case a reader may need to contact $O(n)$ other readers, where n is the reader network's size, in order to build its interference set. Moreover, the assumption of reader communication capabilities, restricts the applicability of the protocol to reader devices that can communicate. Even if readers have additional wireless interfaces (e.g., 802.11x, 802.15.4 or Bluetooth) their power requirements may significantly reduce the network's lifetime.[1]

Spatial isolation relies on predefined reader deployment, with antennae designed to read clearly delineated areas, coupled with the use of RF shielding materials to prevent other readers from detecting tags in the same area. The work of Zhou et al. [36], based on the Spatial Time Division Multiple Access (STDMA) protocol is an instance of a hybrid between spatial, temporal and frequency division mechanisms. In the case where the tag distribution is unknown, the authors attempt to solve the problem assigning readers to frequency channels in each time slot, such that each location of the deployment space is well-covered by some reader in one of the time slots. Then the authors extend and optimize their solution for the case where the tag distribution is known. This approach makes two important assumptions, which restrict its applicability. First, a planned deployment of readers is assumed, allowing deployers to perform RF site surveys to measure the location and interference patterns of readers. However, spatial isolation is difficult to implement in un-orchestrated, on-line reader deployment scenarios. Second, the existence of a central entity processing this information and providing a channel and slot assignment to each reader is assumed.

The frequency assignment solution for the reader collision problem consists of allocating different frequency channels to interfering readers, that can then be scheduled for reading tags simultaneously. Deolalikar et al. [11] proposed a graph theoretic approach for this problem. They made the observation that if the interference graph for a reader network can be converted into a bipartite graph, the frequency assignment is to simply assign one frequency to readers in one of the partitions and another frequency to the readers in the other partition. The authors show that the conversion of the interference graph can be achieved in a succession of steps, where each step can be either removing one edge or one vertex from the graph. They propose heuristics for choosing the best edges and vertices for removal, both based on a "correlation" metric. The correlation of two readers is defined to be the number of tags covered by both readers. This approach suffers thus from two problems, (i) it requires the existence of an interference graph and (ii) it requires the readers to read the tags, before being able to assign frequencies to readers, for reading the tags.

In this paper, we consider the *reader collision avoidance problem* in a more general setting, *i.e.*, assuming arbitrary tag distribution and reader deployment, and no communication among readers. We develop RCA, a randomized, distributed, and localized time division algorithm. RCA avoids reader collisions *with high probability*, allowing readers to accurately detect tags in their vicinity. RCA does not require inter-reader communication capabilities, rather, it relies on existing reader-to-tag communication capability. We prove that when the interrogation zones of ψ readers overlap, RCA requires at most $O(\log \psi)$ reader-to-tag retransmissions. We further show through extensive simulations that for realistic reader and tag deployments RCA generates very few retransmissions, while consistently discovering over 99.9% of all deployed tags.

Optimal tag reporting: Motivated by considerations of power at readers, as well as minimizing the overheads of multiple reader resolution, we consider the problem of minimizing redundant tag reports—the *optimal tag reporting problem*. Consider the scenario illustrated in Fig. 1. Here, if readers report all tags in their interrogation zone without any optimization, tags T_1, T_2, T_4, and T_5 are reported twice, generating nine tag reports for five tags. While duplicate tag reports will be eventually eliminated by the host system, the number and duration of wireless transmissions may be reduced by detecting and eliminating redundancy as early as possible, *i.e.*before any communication between the reader and the host system occurs.

Optimal tag coverage: We further introduce and study the related *optimal tag coverage problem*. This problem follows from the observation that a reader that covers only tags covered by other

[1] We have tested the 802.11b cards of Motorola A910 phones and found that even in idle mode they reduce the battery lifetime by more than 45%.

readers as well, is *redundant*.[2] Consequently, the number of readers that need to use their wireless interface can be minimized by identifying a minimal subset of readers in which no reader is redundant (with respect to the subset). This is the optimal tag coverage problem, as illustrated in Fig. 1. Observe that all readers except R_1 in this deployment are redundant. On the other hand, the minimum number of readers that need to report detected tags to ensure complete tag coverage is two, since no reader is redundant in the set $\{R_1, R_2\}$.

We first prove that even with centralized knowledge of tag distribution and reader deployment, the problem of finding the optimal number of readers that need to report tags is NP-hard. We then propose RRE, a decentralized and localized algorithm for the optimal tag coverage problem. Similar to RCA, RRE requires only basic reader-to-tag communication capabilities. Furthermore, we show that a side effect of RRE is to allow each tag to be reported by a single reader, effectively eliminating redundant tag reports, *i.e.*providing a solution to the optimal tag reporting problem.

Our simulation results show that the performance of RRE is close to that of a centralized greedy heuristic for the minimum set cover problem. We also show that, by ensuring that each tag is reported only once, RRE generates a significantly lower number of (redundant) tag reports. Specifically, RRE generates between 20% and 600% fewer tag reports than a protocol that does not eliminate redundancy.

This paper is organized as follows: we present background material, the RFID system model, and the problems addressed in this work in Section 2. In Section 3, we discuss related work. Section 4 describes a randomized querying technique for avoiding reader collisions, used in both RCA and RRE. The technique is described in the context of RCA. We prove the NP-hardness of the optimal tag coverage problem in Section 5 and present the details of our solution, RRE, in Section 6. Simulation results of both algorithms are presented in Section 7. We conclude our discussion in Section 8.

2. Preliminaries

We initiate our discussion with an overview of RFID systems and the capabilities of existing tags and readers. In Section 2.2, we briefly describe the tree walking algorithm for resolving tag collisions. In Section 2.3, we formally define the problems addressed in this paper. Finally, in Section 2.4, we describe the system model considered.

2.1. Overview of RFID systems

RFID tags contain limited memory resources for storing unique identification, and information relating to the objects with which they are associated (attached). They also contain an antenna, used for communication with readers. There are two kinds of tags: passive and active. Passive tags do not need batteries, but are powered by RF energy from the reader. In addition to the memory chip and antenna, active tags are equipped also with a battery and a transmitter, allowing them to initiate transmissions.

While active tags have a greater communication range and can operate autonomously, they are more expensive. The price efficiency of tags is the dominant factor determining their wide deployment. Most current RFID applications use only passive tags, thus, this paper focuses on passive tags. For most tags, the chip and antenna are mounted on a base and encapsulated with thermoplastic. Their length ranges from 1/16 inch to more than 6 inches. Tags can be paper thin or embedded into materials allowing them to withstand high temperatures and chemical environments. They can be flexible enough to be embedded within an adhesive label and run through a printer.

Most RFID systems use either the low frequency LF (125–134.2 kHz and 140–148.5 kHz), high frequency HF (13.56 MHz) or ultra high frequency domains UHF (860–960 MHz) for transmission. HF tags typically cost less and are better suited for tagging water or liquid-bearing objects because the longer wavelengths of HF systems are less susceptible to absorption. A UHF tag can be made to work in these conditions, but its effective read range is dramatically reduced. The ISO/IEC 15693 standard has enabled the global acceptance of 13.56 MHz RFID technology. Examples of HF tags include TI's Tag-It HF-1, Philips' I-Code SLI, Infineon's my-d SRF55VxxP or ST Microelectronics' LRI512. These tags have factory programmed 64 bit identifiers and between 112 and 1000 bytes of memory available for read/write operations.

Signals from RFID readers activate compatible tags within their interrogation zone. The interrogation zone is defined to be the area around a reader where tags can receive the reader's signal, process it and send back a response that can be correctly decoded by the reader. The information decoded by the reader is passed to host computing systems where it is further processed, according to the application. In addition to locating, activating, and receiving transmissions from RFID tags, RFID reader-writers also have the ability to send data back to read/write-capable tags in order to append or replace data.

Readers may themselves be fixed or portable. Fixed readers are usually attached to antennae that are designed to detect the tags within a specified area. These units typically collect data from products traveling through loading dock doors, conveyor belts, gates and doorways, or even cars on tollways. Portable, wireless readers can be moved to detect remote tags, in areas where wiring or antenna placement could be difficult. Readers with various wireless communication capabilities exist in today's market. SkyeTech's SkyeRead M1 [28] reader is compatible with Mica Motes [10] and IDBlue [4] is a handheld Bluetooth 13.56 MHz RFID reader, compatible with devices ranging from PDAs to PCs. Major cellular phone manufacturers provide phones with embedded RFID readers [22].

The size, portability, and price of such wireless readers motivates their deployment and organization into ad hoc networks. The network can not only detect tags but also relay tag reports of remote readers toward the host system. Several applications benefit from arbitrary deployments of reader networks, including supply chain management, warehouse management [18], baggage management in airports [2,16], and tracking participants at marathons [26]. In an arbitrary deployment the placement of readers does not follow pre-defined constraints so no assumptions about the location or interference patterns of readers can be made.

Reader networks are currently supported by a number of vendors. PGS Electronics [25] provides a complete solution for wireless RFID integration and Reva Systems [24] recently proposed a protocol called Simple Lightweight RFID Reader Protocol (SLRRP). SLRRP defines how readers convey configuration, control, status, and tag information between RFID reader network device managers and other readers in an IP-based network, either wired or wireless.

We consider two models of wireless reader network deployments, each with a different set of networking capabilities. While the results presented in this paper are not restricted to these models, we believe them to be of independent value.

The first model considers only the deployment of RFID readers that are equipped with cellular interfaces (e.g., RFID enabled

[2] In multi-hop wireless reader networks, redundant readers may still need to use their wireless interface to forward tags detected by other readers. In this case, however, eliminating duplicate tag reports is even more important, since redundancy may generate a large number of transmissions.

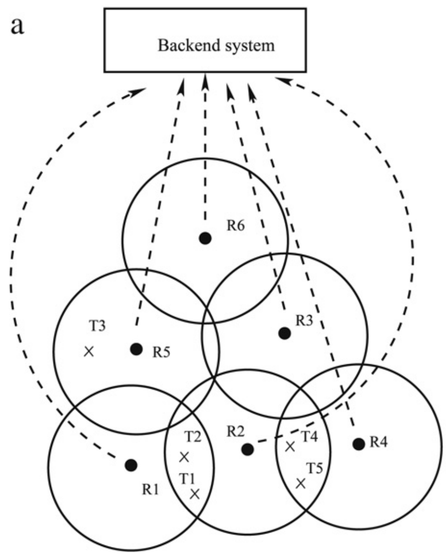

Fig. 2. Example of redundant tag reporting. Readers are denoted by small filled circles and their RF interrogation zones by larger disks. Dotted arrows represent cellular links and plain arrows represent reader-to-reader wireless links. Small rectangles represent tags. (a) Wireless readers may only communicate with the host system. If readers report tags directly to the host server, readers R_1 and R_4 can safely *not* transmit. If they do, the duplicate tag reports are eliminated by the host system. (b) The same reader and tag placement but wireless readers may now communicate with each other and with the host system. The root node R_6 needs to communicate with the host system. All other readers route their reported tags toward R_6. If R_1, R_2 and R_4 all communicate their detected tags, tags T_1, T_2, T_4 and T_5 are reported more than once. While the duplicate reports of T_4 and T_5 can be eliminated by reader R_3, duplicate reports of tags T_1 and T_2 will be forwarded by both readers R_3 and R_5 and the duplicates eliminated only by R_6. This generates 4 transmissions, instead of only 2.

cellphones) and is illustrated in Fig. 2(a). Such readers may locally detect tags and then report them to the host system using their cellular data link. Readers are assumed to be unable to communicate with each other, except through the host system. The second model considers the deployment of WLAN, Bluetooth, or 802.15.4 readers, that are able to locally communicate.[3] In this model, depicted in Fig. 2(b), only a subset of the readers communicate directly to the host, forming a backbone of the reader network. The other readers establish ad-hoc paths to backbone readers and forward tags reported by other readers. In this model, redundant tag reports may be more damaging than in the first model, since redundant tags may be propagated several hops before being eliminated (see Fig. 2(b) for an example).

2.2. Tree walking: An algorithm for detecting tags in the presence of collisions

RFID readers have the ability to accurately read (and report) data stored at multiple tags placed within their interrogation zone. Since readers broadcast their queries, multiple tags may end up responding simultaneously, leading to interference and inaccurate decoding of responses. This is known as the *tag collision problem*. Note that tag collision and reader collision are different problems.

Several techniques have been proposed to solve the tag collision problem. A popular solution, known as the tree walking algorithm (TWA) [27] is based on recursive traversal of the binary name tree of tag identifiers. The reader initially sends a broadcast query containing the "0" string. All tags in its interrogation zone whose identifier starts with a "0" bit reply. If a reply is received, or a tag collision is detected, the reader recurses on both subtrees of "0", rooted at "00" and "01". However, if no reply is received, the reader concludes the absence of "0"-prefixed tags in its interrogation zone and subsequently sends a "1" query. For a reader, the complexity of TWA is proportional to the number of tags present in its interrogation zone and to the length of the binary representation of tag identifiers.

While TWA was designed to accurately read tag identifiers, it can also be used to read arbitrary data stored on tags, as long as the data's bit length is the same across all tags.

2.3. Reader collision: Problem definition

The tag collision problem occurs when one reader simultaneously interrogates multiple tags. In large scale environments, such as retail spaces, the interrogation zone of a single reader may not cover all the tags. Furthermore, tags can be randomly placed or moving. In such cases, accurate detection of all tagged objects requires (possibly random) deployment of multiple readers. A good reader placement ensures that the entire tag deployment area is covered by the union of the interrogation zones of all readers. Complete coverage implies coverage redundancy, since regions may be covered by the interrogation zones of multiple readers.

Redundantly covered tags may be incorrectly detected or even escape detection if readers with overlapping interrogation zones simultaneously query tags (possibly part of the tree walking algorithm). This scenario, known as the reader collision problem [12], is due to reader signal interference occurring at tags. Avoiding reader collisions is an essential requirement for error-free operation of an RFID system. We now formally define this problem. In the following, we use $|s|$ to denote the bit length of binary string s and $|\mathcal{A}|$ to denote the cardinality of set $\mathcal{A}$.

Let $S = (\mathcal{R}, \mathcal{T}, C, \beta)$ denote an RFID system. We use $\mathcal{R}$ to represent the set of readers and $\mathcal{T}$ the set of tags. Let $\psi = |\mathcal{R}|$ be the number of readers and $\theta = |\mathcal{T}|$ be the number of tags in the system. $C : \mathcal{R} \to \mathcal{T}^*$ is the coverage function, such that for any $R \in \mathcal{R}$, $C(R) \subseteq \mathcal{T}$ denotes the set of tags that are within the interrogation zone of R. β is the bit length of tag identifiers. We denote the set of all binary strings of length at most β with B^β. We use the notation $s \trianglerighteq s'$ to denote that binary string s is a prefix of binary string s'. Note that we do not make any assumption on the interrogation zone radii of readers. We discretize time as the set $\mathcal{U}$ of successive time frames, where the length of a time frame is

[3] Many existing cellphones are equipped with Bluetooth and/or WLAN communication capabilities.