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Coverage-Based Placement in RFID Networks: An Overview

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***Abstract*—Radio Frequency IDentification (RFID) is a wireless technology that promises to facilitate many identification and tracking solutions. The placement problem, i.e. choosing the optimal locations for RFID readers, tags or both in a given RFID layout, is reviewed in this paper. Placement approaches are generally coverage-driven and vary according to the system's scopes and constraints. RFID coverage is associated with readers' interference, which requires applying redundancy elimination algorithms. In this paper, we propose a coverage-based categorization of RFID placement schemes based on the span of the readers' field. We also provide a comparative analysis of placement schemes based on their performance objectives, constraints, and potential applications. We finally discuss some open issues regarding RFID placement in terms of alternative objectives and systems' specifications.**

Keywords- RFID; placement; coverage; redundancy elimination

I. INTRODUCTION

Radio Frequency IDentification (RFID) is being rapidly adopted as one of the most affordable and scalable technologies of wireless identification, tracking and detection. An RFID system consists of a reader, a tag and the electromagnetic transmission between them. The reader is the active and more complex unit. Passive tags are powered by their associated readers. Each tag has an identification number and a memory that stores additional data such as manufacturer, product type, etc.

As in any wireless network, coverage in RFID systems is an optimization deployment problem that needs to be dealt with carefully. Placement of both tags and readers has a crucial effect on the performance of the system. The complexity and cost associated with an RFID system is directly related to the number of complex components (i.e. readers) being deployed. Each RFID reader has an electromagnetic interrogation zone. Overlaps between these zones cause reader-to-reader collisions. Alternatively, reader-to-tag collisions occur when interferences from nearby readers prevent tags from decoding interrogation signals from their intended readers.

Many RFID systems deploy redundant readers to guarantee area coverage. Rredundancy, however, is not a cost-effective approach. It has the side effect of creating significant interference among readers and consequently degrading the performance of the whole system. Nonetheless, overlaps among readers' zones represent an inevitable consequence of achieving full coverage. According to [1], only a maximum coverage of 90% of the intended area is achievable without any overlaps. Moreover, the number of tags within each reader's interrogation zone determines the interrogation delay of that reader. The overall interrogation delay of the system is determined by the longest delay associated with a single reader. Therefore, reducing overlaps and balancing the load of readers, in addition to reducing the delay and monetary cost of the system, are all considerable constraints for any efficient RFID coverage scheme.

RFID coverage may be achieved according to two scenarios, depending on the amount of available readers in a given setting: maximum coverage, or full coverage [2][3]. In maximum coverage, the number of available RFID readers is limited and cannot be increased. As a result, the main problem to be addressed here is to identify the best places for the available readers in a given setting to achieve the optimum weighted average of system coverage while avoiding reader collisions. In the full coverage scenario, the budget allocated for the RFID network is assumed to be sufficient to place a number of RFID readers to the level that 100% coverage of the sensed field can be achieved. As mentioned earlier, this is associated with collisions. Such a situation requires applying redundancy elimination algorithms to identify and deactivate redundant readers.

It is important to distinguish between coverage redundancy in wireless sensor networks (WSNs) and redundant reader elimination in RFID systems. Coverage in WSNs is defined in terms of optimizing coalitions of adjoining areas associated with sensors [4], whereas in RFID systems, coverage is defined in terms of discrete points (RFID tags) [1] and stems from the network's ability to accurately and efficiently read tags while minimally utilizing the available resources, such as number of readers and communication cost.

In the remainder of this paper, we will review the placement schemes for RFID tags and readers, in addition to outlining their common objectives and constraints. We introduce a distinct type of placement categorization depending on the extent of the coverage zone which would be either 3D (space), 2D (plane), 1D (linear) or point coverage. Then, we provide an overview of redundant reader elimination schemes. Finally, we compare the reader placement schemes in terms of their placement approaches, coverage and performance goals and constraints.

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II. PLACEMENT OBJECTIVES & CONSTRAINTS

Coverage is an essential objective for the efficiency of any RFID placement approach. The tasks of tracking and detecting tagged-objects are immediately dependent on efficient coverage schemes. Reader placement is an issue that raises a number of questions, such as: (i) how many readers are needed for providing complete coverage, (ii) where should the readers be placed, and (iii) how should the mobile readers move? [1]. Deciding on factors such as the number of readers or the distance between them is related to the type of tags (active or passive) and their distribution in the system.

Other placement factors are affected by the geographical area, expressed in the distribution of Signal Test Points (STPs), and the density of readers' in a given setting. RFID deployment is expected to increase as RFID is considered to be a pivotal component of the futuristic vision of an Internet of Things (IoT) [5]. This may shift the attention to optimization goals other than coverage, such as cost, tag reading time, load balancing and tag localization, among others. Important parameters related to RFID coverage also include relative antenna orientation, type of reader (static, multi-static or bi-static), type of reader's antenna (directional, omni-directional or array) and its polarization (linear or circular).

Accordingly, tag placement is particularly challenging in large-scaled RFID networks such as in buildings or city-sections. In large indoor environments, tag placement challenges include multipath, rare line-of-sight, absorption and reflection. A survey of several indoor localization algorithms is presented in [6]. These algorithms are classified into three groups: distance estimation, scene analysis, and proximity algorithms. In metropolitan settings, such as the case with vehicle tracking applications [7], the location of tags is of particular importance because the tag orientation could directly affect the accuracy of location-information received by the reader. Subsequently, Ultrawide bandwidth RFID [8] is viewed as a promising solution for next generation systems to overcome most of the limitations related to reduced area coverage and accurate localization. However, as argued in the next section, many of these limitations are currently viewed through the full coverage problem, which is directly affected by the positioning of the readers.

III. PLACEMENT & ELIMINATION SCHEMES

The placement problem, i.e. choosing the optimum locations for RFID readers, tags or both in a given RFID layout, has been widely studied. However, the majority of these studies have been focused on the reader placement. We provide in this section a brief description of placement approaches for RFID tags before elaborating on readers' placement and redundancy elimination schemes.

A. Tag Placement

Item-tagging is the core of any RFID application including inventory control and supply chain management [9]. RFID tags also provide tracking and positional accuracy that may surpass that of GPS especially in indoor settings [10]. Tag placement may be broadly classified into either dynamic or static. Examples of dynamic placement include tags assigned to individuals moving across a given workplace or a city-section, or transported items to be tracked by real-time inventory and supply chain management solutions. As for static tag placement, its applications include defining boundaries within buildings for security measures or to assist the disabled. In [11], for instance, an intelligent system is proposed to automatically suggest the tag placement locations and calculate the number of tags required for implementing an indoor navigation system for the visually-impaired. The reader, in this scenario, is carried by the visually-impaired person.

SpotON [12], on the other hand, is a tagging technology that was developed using RFID for 3D location sensing based on radio signal strength. In this approach, objects are located by homogenous sensor nodes without central control. The tags use received radio signal strength information as a sensor measure for estimating inter-tag distance.

B. Reader Placement

Extensive work has been reported on RFID reader placement. In general, there are two reader placement approaches: controlled (planned) and random (ad-hoc). Controlled reader placement is usually pursued for indoor [13] and city-scape applications [7]. Such approaches utilize algorithms to find an optimal placement of RFID readers in a 2D square-grid [13], a honey-grid [14] or in 3D set-cover space [15]. These placements are mostly coverage-based. We, hence, further propose a classification of coverage schemes depending on the extent of the readers' coverage zone as: 3D (space), 2D (plane), 1D (linear) or point coverage.

Our classification includes two broad methods: area-based and tag-based coverage. The former is similar to the full coverage problem in cellular and wireless sensor networks, while the latter assumes scenarios where tag locations are known and specifically targeted by readers. Examples of such tag-based scenarios include defining street routes or room boundaries (linear coverage) and tags embedded inside door key-cards for access control applications (point coverage).

RFIDcover [1] is a coverage planning tool that is able to find an optimal layout of readers required to guarantee complete coverage for a given application scenario. It is distinctive in proposing a set of mobile readers with a zig-zag mobility model to guarantee coverage for each tag for a defined time period. In addition, RFIDcover adopts two performance constraints: Deployment cost and Tag Reading Time (TRT) to select the placement and movement pattern that is optimal for both. In [2], an asset tracking system for hospitals is proposed. Readers are deployed in a 2D square-grid where the distance between neighboring readers is determined by the radii of their interrogation zones. The objective here is to achieve full coverage and minimum time search through defining a criticality index to aid locating the most critical health care assets faster. The assets are affixed with active tags so that in emergency situations these assets can be located quickly. The full-coverage genetic approach proposed in [3] defines a set of constraints for optimal reader placement including complex propagation environment, and uplink-signal, where in each RTP, the backscatter signals reflected by tags must be received by a reader. It takes into consideration factors such as antenna transmission gain and the radio wave propagation model.

Another scheme based on designing a square-grid is proposed in [13]. The authors assume a typical high frequency RFID system with slow data transfer rate from the passive tag to reader for tracking applications. Also, a circular reader coverage zone is assumed, which eliminates the effect of the reader's orientation. The authors argue that square grid networks require the optimal number of readers while guaranteeing coverage and accurate accuracy. The scheme in [14] takes a different turn by adopting a honey grid in which the readers are deployed in asymmetric rings of different sizes and are co-centered at the centre of the interrogation zone. When rings are numbered based on their radii, the i^{tch} ring contains 6*i* readers. Similar to the regular grid approach, max coverage is claimed to be achieved and after deployment, readers not covering any tags can be turned off. However, this comes at the cost of large number of readers, significant readers' collisions and unfair load distribution.

LANDMARC [16] is an active RFID calibrated positioning system in which tags are used to serve as reference points. This approach requires a high level of deployment since its accuracy is determined by the number of readers required, the placement of these readers, and the power level of each reader. The proposal in [17] takes into account tags and readers orientation to find an optimal number of readers, their locations out of a set of pre-fixed locations and their antennas orientation to maximize readability. It deals with orientations and polarizations issues using Friis' equation. This proposal aims at maximizing the size of the powering region in order to maximize reading accuracy. The scheme, however, is not generic. It is only being proposed for portal accuracy in supply chain management scenarios. Furthermore, like other schemes in the literature, it considers only placement without load balancing.

Alternatively, the work in [15] proposes a generic 3D set-cover planned placement scheme which guarantees maximal coverage using few readers and with fair work-load balancing amongst the readers. Assuming the locations of passive tags to be known, a set-cover approximation algorithm is applied to find the minimum size set of readers such that each tag element is covered by at least one reader. In [18], the Misplaced Tag Pinpointing (MTP) problem is targeted. This approach aims to detect and pinpoint passive or active tags attached to misplaced inventory items in a large warehouse, retailing store or an airport. Here, the readers are deployed at known positions to provide a position reference for placing tags. The authors assume an inventory item list in accordance with all present items is maintained on a backend server that executes the MTP protocol. The target is to design protocols to time-efficiently and energy-efficiently collect information for detecting and pinpointing misplaced tags. This is achieved through using reader vectors and requesting responses from partial tags. The intuition is that misplaced tags in a category must exist when separate clusters of readers cover tags in this category.

The random placement approach, on the other hand, is generally applied for item-level tagging applications [10] and typically invoke a redundancy elimination algorithms to turn off readers that are not granted access to any tag in the vicinity in order to avoid collisions and to improve the system's lifetime and performance.

C. Redundant Reader Elimination

The redundant reader elimination problem is known to be NP-hard. It is defined as follows [19]:

Given a set of RFID tags and a set of RFID readers covering all tags, find the minimum cardinality subset of RFID readers that cover all the tags.

Numerous schemes have been proposed in the literature for redundant reader elimination problem [19]-[22]. The main motivation is to reduce overlapping among readers coverage regions in order to minimize collisions.

One of the earliest schemes to tackle this problem in RFID was introduced in [19] as RRE. This scheme initiates with each reader broadcasting its identity and tags count. The tags count of each reader is to be stored by each tag receiving the broadcasted query within the corresponding interrogation zone. Access to a particular tag is granted to a reader that has the maximum tags count. Readers which are not granted access to any tag are marked redundant and, hence, are eliminated.

Tags in the RRE scheme suffer from significant communication overheads and are required to perform frequent memory read and write operations. To overcome the situation, the Layered Elimination Optimization (LEO) and Layered Elimination Optimization with Redundant Reader Elimination (LEO+RRE) schemes introduce the "first-read first-own" principle [20]. Here, readers compete to write their identities into tag memories. Firs reader to succeed is granted access to that tag. In addition, the "first-arrive first-serve" approach was introduced where the time delay readers encounter to read a tag is used to find a reader granted access to that tag. A reader queries and writes its identity to the tags it covers and is successful if and only if no other readers have done so. The reader without any tags is eliminated as a redundancy.

In [21], the authors proposed a Two-step Redundant Reader Elimination (TRRE) based scheme, which is fairly similar to the LEO scheme. In TRRE, a reader sends out its query packet, embedded with its own identity, to all tags it covers. The tag responds either with a *NULL*, which implies the reader has been granted the ownership, or with an identity, which is different from the query's embedded identity, which implies the tags ownership has already been assigned to another reader. A reader without any tag's ownership is marked as redundant.

A Neighbor and Tag Estimation (NTE) algorithm is introduced in [22]. It is a heuristic greedy algorithm to find the minimum subset of RFID readers that cover all the tags. When a reader has a large number of neighboring readers, tags covered by it have a high probability of being also covered by other readers in the neighborhood of that reader. Thus, for each active reader R_i, the algorithm assigns a weight based on the ratio of active tags covered by R_i to the number of active neighboring readers. At the beginning of the each iteration, weights of active readers are calculated and then a reader with the maximum weight is deactivated and all its tags deactivated, as well. Any reader with a weight of 0 is considered to be redundant and deactivated. This process continues until all tags are inactive, at which point all remaining active readers are considered to be redundant.

TABLE 1. COMPARATIVE SUMMARY OF PLANNED READER PLACEMENT SCHEMES

Paper	*Placement Type*	*Placement Topology*	*Coverage Space*	*Coverage Method*	*Tag Type*	*Objectives*	*Constraints*	*Application*
[1]	Mobile	Zig-zag mobility model	1D	Tag-based	Passive	Full coverage	Deployment cost (optimal number of readers) and Tag Reading Time (TRT)	Retail inventory tracking
[2]	Static	Square grid	2D	Area-based	Active	Full coverage	Minimal time search	Asset tracking in hospitals
[3]	Static	--	2D	Area-based	Passive	Full coverage	Minimum reader count and minimum interference	--
[7]	Static	City-scape	1D	Tag-based	Passive	Tracking	Real-time reporting	Vehicular networks
[13]	Static	Square grid	2D	Area-based	Passive	Tracking and positioning	Coverage	Indoor tracking
[14]	Static	Hexagonal grid	2D	Area-based	--	Minimize collisions	--	--
[15]	Static	--	3D	Area-based	Passive	Full coverage	Load balancing	Generic
[16]	Static	Octagonal grid	2D	Area-based	Active	Accurate positioning	Interrogation zone range	Indoor location sensing
[17]	Static	--	3D	Tag-based	Passive	Maximize powering region	Antenna orientation and polarization	Supply chain management
[18]	Static	Grid	2D	Tag-based	Passive/ Active	Accurate positioning	Execution time and number of tag responses	Misplaced tags pinpointing in airports

We add that a different redundancy elimination approach was briefly mentioned in [13]. Here, a master reader is assigned to be used for timing control to set the particular client readers in a grid network. Hence, in each time slot, only one reader can communicate with tags in the interrogation zone, thus overcoming the interference problem.

IV. COMPARITVE ANALYSIS

Table 1 contains a comparative summary of the placement proposals according to the coverage classifications and methods defined in the previous section. We propose a coverage-space classification for placement schemes depending on the extent of the readers' coverage zone: 3D (space), 2D (plane), 1D (linear) or point coverage. This includes two broad coverage methods: area-based and tag-based coverage. All the placement proposals listed in Table 1 were planned schemes. None adopts a random reader deployment approach. Hence, the type placement was observed to be either static, with fixed readers' locations, or mobile, with readers changing their location according to a predetermined mobility pattern.

It is apparent from Table 1 that most of the placement approaches assume a 2D (plane) coverage space. Note that when this topology is restricted by a fixed path, such as a street layout or a building boundary, we classify it as a 1D (linear) placement. Yet, none of the planned approaches fall under our point coverage class. This is justified since placing a single point reader is a task that does not require a sophisticated level of planning.

The placement objectives specified by each proposal in Table 1 vary according to its intended application. We notice that full coverage is the dominant objective for placement schemes. Similarly, most of the approaches adopt the area-based coverage method. The second most common objective according to Table 1 is tag-tracking, which is, correspondingly, directly associated to efficient coverage.

Likewise, the constraints of each placement approach differ according to the application as well. There is no correlation between the constraints and the placement type. Another observation is related to the mobility of the readers. Except for the placement scheme in [1], all the schemes adopt static placement approaches. This, in our opinion, raises concerns regarding the level of attention paid to a wide set of RFID applications that promise to utilize mobile readers.

V. OPEN ISSUES

It is clear from our overview that achieving full coverage is the dominant objective for RFID placement approaches. Consequently, addressing coverage incorporates tackling challenges related to minimizing readers' interference and their count in the system. Some of the reviewed schemes explicitly mentioned these as placement constraints. We argue that any full coverage placement approach should also be compared to other approaches in terms of the number of readers per coverage area, since this is a crucial metric in determining the overall cost of the system.

Another interesting observation from our overview is related to the type of tags assumed with coverage schemes. As a matter of fact, tags in most RFID application proposals are assumed to be passive which puts a limit on the readers' interrogation zone. We comprehend that most of the coverage schemes assume passive tags for reasons related to reducing the system's power consumption and cost minimization. We, however, note that deploying active tags may simultaneously and considerably lower the count of readers, which typically drive the cost component of the RFID system. In addition, Ultra-wideband active tags could communicate with readers over distances much greater than passive tags do. Hence, deployment of active tags may actually reduce reader collisions by avoiding the behaviour of passive tags that gather energy from the carrier signal from readers and *backscatter* their replies. Thus, it would be interesting to compare the performances of variants of a given placement approach while deploying different types of tags with respect to cost and power efficiency metrics.

Finally, we notice that load balancing was a minor concern for the majority of placement schemes we reviewed. In fact, distribution of tags in a given layout may be unbalanced and some readers would be overwhelmed by covering more tags in the system. This could lead to exceptionally long reading delays or even reading bottlenecks at some segments of the system. Load balance, hence, should be tackled as a primary objective by placement schemes. Similarly, the aforementioned placement schemes seldom address concerns related to the antennas orientation, reading rate or the mobility models of tags. Such factors represent important objectives or constraints that are influential to the performance measures of RFID applications.

VI. CONCLUSION

In this paper, we provide a comparative overview of RFID placement schemes based on their coverage approaches and performance objectives. We present a coverage-based categorization of placement schemes that is dependent on the extent of the readers' coverage zone identifying 3D (space), 2D (plane), 1D (linear) and point coverage placements. In our comparative analysis, we apply our coverage-based classification to the predominant placement schemes in the literature, in addition to comparing these schemes in terms of objectives and constraints. We notice that coverage is the most influential objective in placement schemes. Most of the schemes, as well, assume passive tags in static settings. Thus, we point toward the opportunities of proposing placement schemes that discover alternative settings such as systems with active tags, and discuss alternative system characteristics such as antenna types, reading and range variances, and alternative objectives such as connectivity and load balancing.

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