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Set-Cover Approximation Algorithms for Load-aware Readers Placement in RFID Networks

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***Abstract*—Radio Frequency Identification (RFID) is an emerging wireless technology that poses new fundamental challenges. Coverage in RFID networks, which is one of these challenges, is the ability to accurately read a set of RFID tags. Accurate coverage is of utmost importance in RFID networks as missing some tags may result in missing important events and, for some RFID applications, losing asset and revenue. In this paper, we address an optimization problem related to the deployment of RFID readers to cover a set of RFID tags with the objectives of minimizing the number of readers, reducing overlapping among readers coverage, and balancing the load.**

We propose a set-cover based approximation algorithm for RFID coverage with the minimum number of readers. We extend this algorithm to consider the objective of reducing overlapping and interference among readers interrogation ranges. And finally, we give a load balancing algorithm that evenly distributes the load among different readers. Comprehensive experiments that study the performance of our algorithms are presented.

***Keywords*— RFID, approximation algorithms, load balancing, readers placement, set cover**

I. Introduction

The emerging technology of Radio Frequency Identification (RFID) turns objects into a mobile network of nodes, which can then be used to track objects, trigger events, and take certain actions. An RFID system is composed of one or more RFID readers, a set of tags, and middleware. RFID systems demand accurate coverage as well as acceptable operating performance. Having accurate coverage is crucial for many RFID applications. In a self-checkout counter at a department store, for instance, missing a tag is simply a loss of revenue. Several factors influence coverage in RFID networks; some of these factors are density of tags, size of the interrogation area, number of deployed readers, and overlapping among readers [1].

The complexity and monetary costs associated with an RFID system strongly depend on the number of readers being deployed to interrogate tags. Similar to any wireless network, coverage in RFID systems is an optimization deployment problem that needs to be dealt with carefully. While deploying too many readers may guarantee full coverage, it has the side effect of significant interference among readers, which results in more reader-to-reader collisions and, hence, a lower performance for the whole system. Furthermore, the number of tags within each reader's interrogation zone determines the interrogation delay of that reader, and the overall interrogation delay of the whole system is determined by the longest delay associated with a single reader. Therefore, reducing overlapping and balancing the load of readers are essential to any coverage scheme in RFID systems.

Several maximal RFID coverage schemes have been proposed in the literature. These schemes can be broadly classified as planned and ad-hoc. In the planned approach, algorithms are designed to find an optimal placement of RFID readers in a grid [2]–[4], a honey grid [5], or at a predetermined set of locations [6]. While these schemes are able to achieve maximal coverage, that comes at the cost of a large pool of RFID readers and, hence, results in the previously mentioned problems associated with having too many readers. In the ad-hoc approach, readers are to be deployed randomly and an algorithm is to be executed afterwards to turn-off some redundant readers [7]. In most of these schemes, in order to eliminate redundancy or to manage the load, some state information is maintained within each tag [7]–[9]. Such an ad-hoc approach is generally applied for item-level tagging applications which is not the focus of this paper. Our objective is to have planned deployment schemes which guarantee maximal coverage using a reasonably small number of readers and with a fair workload distribution amongst readers. Furthermore, we do not require tags to maintain any state information.

In this paper, we address the coverage problem in RFID networks and propose a set-cover based approximation algorithm for it. We present an algorithm that gives the approximate minimum number of readers and their locations to cover a set of tags. By reducing the number of readers, not only is the overall network cost reduced, but the overall system performance is improved also by reducing interference and overlapping among readers coverage regions and, hence, having less collisions among readers. Furthermore, we also enhance the overall system reading rates by achieving a near-optimal load balancing amongst the deployed readers; by minimizing the maximum delay encountered by a single reader we minimize the overall delay of the system. We evaluate the proposed algorithms via comprehensive simulations and we compare them with other schemes available currently in the literature. The simulation results validate that the proposed approximation algorithm is effective in minimizing the number of readers, reducing their overlapping regions, and maintaining a good load balance.

The remainder of the paper is organized as follows. Section II surveys previous work related to RFID readers placement. Section III outlines the adopted model and its underlying assumptions. Section IV describes the proposed readers placement algorithm. Section V presents simulated experiments and analyzes the obtained results. Finally, section VI concludes our work.

II. BACKGROUND

Existing schemes handle coverage and deployment issues for RFID networks in two approaches: planned and ad-hoc.

In the planned approach, algorithms are designed to find optimal placement of readers in terms of maximal coverage and minimum number of readers, and under some constraints on where readers can be placed [2]–[6], [10], [11]. In the optimal grid coverage approach [2], readers are deployed in a grid where the distance between two neighboring readers is determined by the interrogation range of readers. After deployment, readers which are not covering any tag can be turned off. Another similar approach is the honey grid in which readers are deployed in rings, of different sizes, centered at the center of the interrogation zone [5]. When rings are numbered based on their radii, the i^{th} ring contains $6i$ readers. Similar to the regular grid approach, after deployment, readers which are not covering any tag can be turned off. It has been proven that both schemes provide maximal possible coverage. However, that comes at the cost of having a large number of readers, significant readers collisions, and unfair load distribution. Our proposed scheme achieves full coverage of tags, yet with minimal overlapping and a better load balancing. Some reader deployment schemes that take into account tags and readers orientation have been proposed [6]. The scheme proposed in [6] finds an optimal number of readers, their locations out of a set of pre-fixed locations, and their antennas orientation to maximize readability. 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 placement only without load balancing. Our proposed scheme is generic as it can be easily adopted for various RFID applications.

In the ad-hoc approaches, algorithms are devised to find redundant readers in a given deployment strategy [7]–[9]. In the RRE scheme [7], each reader broadcasts a message carrying its own identity and its tag count, which is the number of tags within its region. Each tag stores the identity of the reader having the maximum tag count it received. Access to a particular tag is granted to the reader covering that tag with the maximum tag count (i.e., the reader whose identity is stored in the tag). Readers which are not granted access to any tag are marked redundant and are turned off. The RRE scheme has a lot of communication overhead as it requires frequent write operations to the tag. To mitigate this overhead, the LEO and the LEO+RRE algorithms introduce the concept of "first-read first-own" principle: an RFID reader only write its own identity into a tag memory [9]. The reader which manages to singulate the tag and write its identity first is granted access to that tag. In case of the LEO+RRE algorithm [9], upon completion of LEO execution, the RRE algorithm is then used to further eliminate any redundant readers. Various other redundant reader elimination schemes have been proposed in the literature and they try to make enhancements upon the RRE and LEO schemes [8], [12]. A load balancing scheme utilizing tag storage space has also been proposed in [13]. The basic idea is that each reader writes its tag count into a tag memory space, and the tag picks and responses back to the reader with the lowest load. Various other middleware-based load balancing schemes have also been proposed in the literature [14]. All of the aforementioned schemes are generally adopted for item-level tagging or Internet of things in which thousands of small readers are deployed in an ad-hoc manner over geographically large areas and with the main focus of reducing energy consumptions of already deployed readers. Our research objective is to have a planned, pre-operation deployment strategy which guarantees maximal coverage, uses a small number of readers, and also achieves a good performance through load balancing and less overlapping among readers.

III. ASSUMPTIONS AND DEFINITIONS

We consider an RFID system of n passive tags and multiple readers. The transmission range of a passive tag t_i is modeled as a sphere of radius r_i, i.e., tag t_i can be interrogated by an RFID reader if and only if the distance between the tag and the reader is at most r_i. Tags are assumed to be placed in a 3D space modeled as a rectangular cuboid, and readers are to be placed on particular sides of the rectangular cuboid. Figure 1 illustrates this environment. The problem can be defined as follows. Given the number of tags and their 3D locations, find a minimum number of RFID readers and their exact locations such that all tags are covered. While the locations of tags are assumed to be known, we show later how to accommodate fluctuations in tags locations.

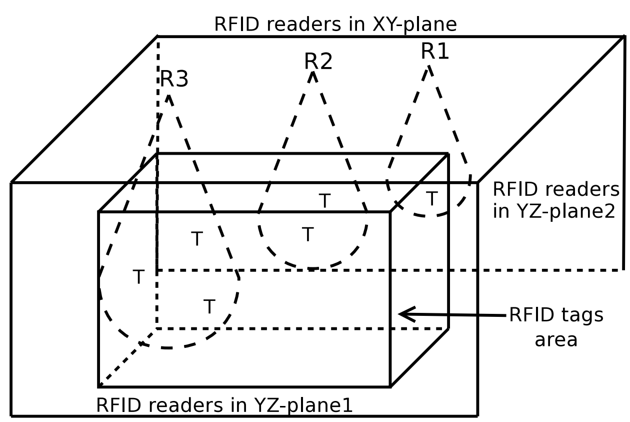


Fig. 1. 3D Coverage in RFID Networks.

In the presentation of our algorithms, we use the following notations:

- $T = \{t_1, t_2, \ldots, t_n\}$ is the set of tags.

- p_i is a point representing the location of a tag t_i; $p_i.x$, $p_i.y$, and $p_i.z$ are the $x-$, $y-$, and $z-$ coordinates, respectively.
- r_i is the transmission range of a tag t_i.
- $|S|$ is the cardinality of a set S.
- $|p, q|$ is the Euclidean distance between two points p and q.
- For any point q in the 3D space, $Cover(q)$ is the set of all tags that have q within their transmission ranges (i.e., $Cover(q) = \{t_i : |p_i, q| \leq r_i\}$).

Our algorithms are based on an approximation algorithm for the set covering problem which is known to be NP-hard [15]. For the sake of completeness, we give a formal definition for the set covering problem as follows:

An instance of the set covering problem consists of a set $\mathcal{C}$ of a finite number of elements and a set $\mathcal{F}$ whose elements are subsets of $\mathcal{C}$ with the condition that each element $c \in \mathcal{C}$ belongs to at least one subset $f \in \mathcal{F}$; when $c \in f$, f is said to cover c. The problem is to find a minimum size set $\mathcal{G} \subseteq \mathcal{F}$ such that each element in $\mathcal{C}$ is covered by at least one element in $\mathcal{G}$ [15].

IV. RFID READERS DEPLOYMENT ALGORITHM

In this section we present our algorithm for RFID readers deployment in a rectangular cuboid. We first describe an algorithm that provides full coverage, we then show how to modify that algorithm for the purpose of reducing overlapping among readers, and finally we give a scheme that uses our algorithm to give load-balancing deployment strategies.

A. Providing coverage

In order to provide full coverage, each tag must have at least one RFID reader placed within its transmission range. And since RFID readers are to be placed only on the sides of the rectangular cuboid, we need to find the intersection of the transmission spheres of tags and the planes representing the sides of the rectangular cuboid. If a sphere intersects with a plane, their intersection will be a circle on that plane. For example, the intersection of a sphere centered at the point (a, b, c) with a radius of r and the plane $z = 0$ is a circle centered at the point $(a, b, 0)$ with a radius of $\sqrt{r^2 - c^2}$, if $r^2 - c^2 \geq 0$. Let us call those circles *side circles*. Each tag will have at most one side circle on each side, and in order to cover a particular tag t_i, at least one reader must be placed within one of the side circles that belong to that tag.

To minimize the number of readers needed to cover all tags, readers should be placed in areas where several side circles, belonging to several tags, overlap. Instead of looking for regions where side circles overlap, it suffices to focus on *intersection points*, which are the points where the boundaries of side circles intersect. These intersection points can be considered as representatives to all possible overlapping regions (for more details on this, see our earlier work in [16]). Thereby, locations of RFID readers will be limited to intersection points and, hence, the problem becomes a discrete optimization problem. Moreover, an instance of the RFID reader deployment problem can be reduced to an instance of the set covering problem in which $\mathcal{C} = T$ (i.e., the set of tags) and $\mathcal{F} = \{Cover(q) : q \text{ is an intersection point}\}$.

Therefore, the greedy approximation algorithm for the set covering problem can be used to solve the RFID readers deployment problem; and for the sake of completeness, the greedy approximation algorithm is shown in Algorithm 1 [15].

Algorithm 1: The greedy set covering algorithm

Set Cover($\mathcal{C}$,$\mathcal{F}$)
$U = \mathcal{C}$;
$V = \phi$;
while $U \neq \phi$ **do**
  Find a set $S \in \mathcal{F}$ that maximizes $U \cap S$;
  $U = U - S$;
  $V = V \cup \{S\}$;
end
return V;

This greedy algorithm is known to have an approximation ratio of $\ln |C| + 1$ and can be implemented in $O(|C||\mathcal{F}| \text{ MIN}(|C|, |\mathcal{F}|))$ time.

B. Reducing overlapping among readers

Overlapping among RFID readers causes reader-to-reader interference which results in collisions at the readers and, hence, an additional delay to the interrogation process. The general set covering problem does not take overlapping among subsets into account; the sole objective therein is to minimize the number of subsets covering all elements. For example, let $\mathcal{C} = \{1, 2, 3, 4, 5\}$ and $\mathcal{F} = \{\{1, 2, 3\}, \{2, 3, 4\}, \{1, 2, 5\}, \{4\}, \{5\}\}$. The greedy algorithm may pick the set $\{\{1, 2, 3\}, \{2, 3, 4\}, \{1, 2, 5\}\}$ to cover all elements with a minimum number of subsets, which is an optimal solution for this instance of the set covering problem. However, another optimal solution with no overlapping is $\{\{1, 2, 3\}, \{4\}, \{5\}\}$, which is much more suitable for readers deployment in RFID networks. In this subsection, we modify the earlier described greedy set covering algorithm (Algorithm 1) to make solutions with less overlapping preferred.

The greedy set covering algorithm constructs the set of covering subsets incrementally; at each stage, it picks the subset that covers the maximum number of uncovered elements until all elements are covered. That can be viewed as giving each remaining subset a *weight* equal to the number of uncovered elements it covers, and picking the one with the maximum weight. We can calculate the weight of subsets in a different way that gives credit to those subsets that do not cover many covered elements. Let U be the set of uncovered elements and $weight(S)$ be the weight of a subset S. According to the general greedy algorithm, $weight(S) = |U \cap S|$. We can modify the general algorithm so that among subsets covering the maximum number of uncovered elements, it picks the one that covers the minimum number of already covered elements. This can be done using the following weight formula: $weight(S) = |U \cap S| - \alpha(|S| - |U \cap S|), 0 < \alpha \leq 1/n$. The greedy algorithm for set covering with less overlapping is shown in Algorithm 2.

Algorithm 2: Weighted set covering algorithm to minimize overlapping amongst subsets

Weighted Set Covering($\mathcal{C}$,$\mathcal{F}$,α)
$Z = \mathcal{F}$;
$U = \mathcal{C}$;
$V = \phi$;
while $U \neq \phi$ **do**
    foreach *subset* $S \in Z$ **do**
        $Weight(S) = |U \cap S| - \alpha(|S| - |U \cap S|)$;
    end
    Find a set $S \in Z$ that maximizes $Weight(S)$;
    if $Weight(S) \leq 0$ **then**
        /* This means that the set C can not be covered by subsets in $\mathcal{F}$ */
        return ϕ and exit;
    end
    $U = U - S$;
    $Z = Z - \{S\}$;
    $V = V \cup \{S\}$;
end
return V;

It is obvious that when $0 \leq \alpha \leq 1/n$, the approximation ratio of $\ln \mathcal{C} + 1$ holds for the weighted set covering algorithm. This is because both the weighted set covering algorithm and the general set covering algorithm picks the same subset at each stage except when there is a tie (i.e., several subsets covers the same maximum number of uncovered elements). When there is such a tie, the weighted set covering algorithm picks a subset that covers the minimum number of already covered elements. However, the approximation ratio of the general greedy algorithm holds regardless of how ties are dealt with.

C. Load balancing

The algorithms we have discussed so far aim at reducing the total number of RFID readers and reducing overlapping among different readers. However, the issue of load balancing is not considered. Therefore, we may get solutions in which readers have significant variations in their workloads (i.e., the number of tags they cover), which lowers the performance[1] of the whole system. This is because each RFID reader is associated with a subset of tags and readers interrogate their tags in parallel. Thus, the overall performance is determined by the reader with the maximum workload because it will be the last to finish. For example, a system with two RFID readers each covers 50 tags is much better than a system with two readers one covers 90 tags and one covers 10 tags.

[1]The performance herein is defined as the time needed to interrogate all tags.

In this subsection we present a method that distributes the load evenly among RFID readers for the sake of improving the overall performance of the system. The main idea is to put a constraint on the maximum number of tags β, which are covered by a single reader. However, the objective of minimizing the number of readers and that of minimizing β conflict with each other; the minimum possible value of β is 1, which means that each reader covers a single tag; and the minimum number of readers may be one reader covering all tags, which results in the maximum value for β. This can be dealt with either by putting a constraint on β and finding the minimum number of readers meeting that constraint, or by putting a constrain on the maximum number of readers R and finding the minimum value of β meeting that constraint. The former option is straight forward and can be done by excluding intersection points whose coverage exceeds β (i.e., when $|Cover(q)| > \beta$, $Cover(q)$ is excluded from $\mathcal{F}$). The latter option is less trivial. In fact, one may need to try all possible values of β and take the minimum value that meets the constraint of having at most R readers. That can be done more efficiently by doing a binary search over all possible values of β (i.e., $[1..\text{MAX}_{S \in \mathcal{F}}|S|]$). This method is illustrated in Algorithm 3. The overall computational complexity of this algorithm is $O(\log(\text{MAX}_{S \in \mathcal{F}}|S|)|C||\mathcal{F}| \text{ MIN}(|C|, |\mathcal{F}|))$.

Algorithm 3: RFID readers deployment algorithm with load balancing

Readers Deployment(T,α, R)
$C = T$;
$Q =$ the set of all intersection points;
$\mathcal{F} = \{Cover(q) : q \in Q\}$;
$\beta_{max} = \text{MAX}_{S \in \mathcal{F}}|S|$;
$\beta_{min} = 1$;
while $\beta_{max} > \beta_{min}$ **do**
    $\beta = \lfloor \frac{\beta_{max} + \beta_{min}}{2} \rfloor$;
    $Z = \{S : S \in \mathcal{F} \wedge |S| \leq \beta\}$;
    $V =$Set Cover($\mathcal{C}$,Z,α);
    if $0 < |V| \leq R$ **then**
        $\beta_{max} = \beta$;
    else
        $\beta_{min} = \beta + 1$;
    end
end
$Z = \{S : S \in \mathcal{F} \wedge |S| \leq \beta_{max}\}$;
$V =$Set Cover($\mathcal{C}$,Z,α);
if $0 < |V| \leq R$ **then**
    return V;
else
    return ϕ;
end

D. Displaced tags

While we assume that exact locations of tags are known, it is expected in practice to have some tags being displaced from their planned locations. However, this can be easily accommodated in our scheme; if we reduce the actual transmission ranges of tags by a value of r units, our scheme becomes resilient to any displacement of at most r units from the planned locations.

V. Performance evaluation

In this section, we evaluate the performance of the proposed algorithms as compared to that of other recently proposed schemes for readers deployment in RFID networks. We use the number of readers and the maximum load among readers as our evaluation criteria.

A. Simulation setup

We used an in-house developed software to simulate the RFID system. We compared our algorithms with two recent readers deployment schemes, namely the optimal grid coverage [2], [4]; and the honey grid coverage [5]. These two schemes were selected because of their relatively high performance as compared with other schemes in the literature. In the rest of this section, Algorithm 2 and Algorithm 3 are referred to as Approximate Set Cover (ASC) and Approximate Set Cover with Load Balancing (ASC-LB), respectively. The criteria we used for comparing different schemes are the number of readers and the maximum load assigned to a single reader (i.e., the maximum number of tags covered by a single reader). A lower number of readers implies a lower cost, less overlapping among readers, and, hence, less reader collisions. And a lower value for the maximum load amongst readers implies a higher overall reading rate. We evaluated the different schemes under different scenarios using different tags densities and various interrogation areas.

Our simulations are performed using the following settings. RFID readers have an interrogation range of $4-5$m and an interrogation area of $5\text{x}5\text{x}100\text{m}^3$. Tags are placed in a 3D space modeled as a rectangular cuboid, and readers are to be placed on particular sides of the rectangular cuboid, as illustrated in Figure 1. Locations of tags are generated randomly using a pseudo-random number generator. Values of the performance metrics are averaged over twenty different runs generated using distinct random seeds.

B. Simulation results

Fig. 2 shows a comparison between the different schemes according to the number of readers required to cover the same set of tags. Our ASC algorithm outperforms other algorithms; on average, the number of readers deployed by the honey grid algorithm is twice as that of the ASC algorithm. Both the optimal grid algorithm and the honey grid algorithm quickly reach the maximum allowable number of readers as tags density exceeds a certain threshold. On the other hand, such a saturation point comes much later when the ASC algorithm or the ASC-LB algorithm is being used. In highly dense environments, our algorithms and the optimal grid algorithm have a similar performance in terms of the number of readers. This is because after a sufficiently large number of tags, all

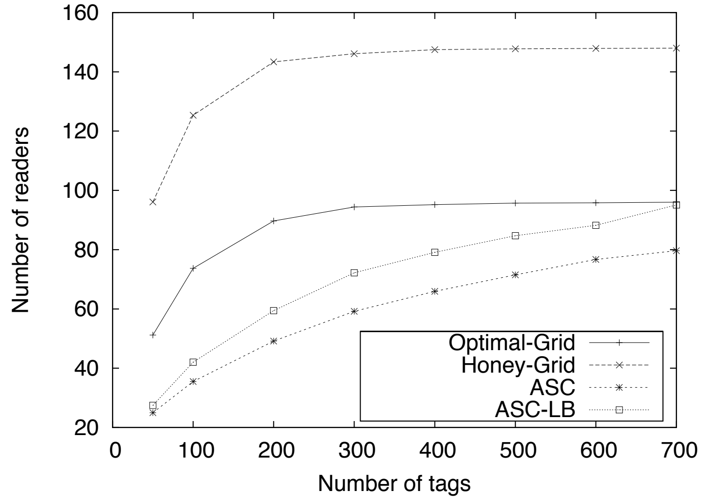


Fig. 2. Number of readers deployed by different schemes.

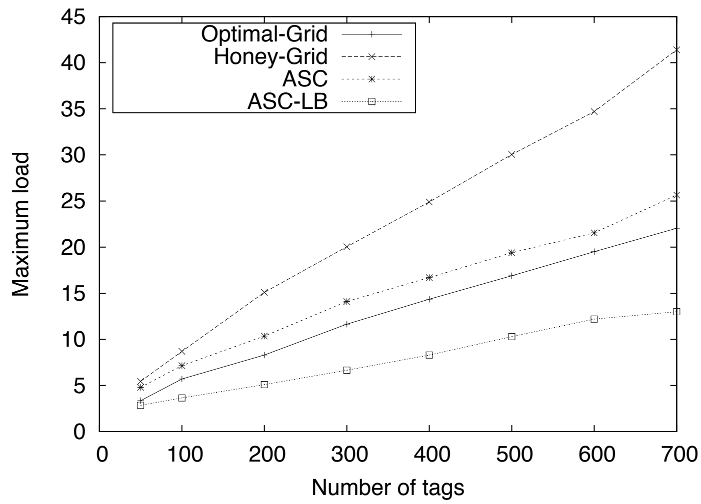


Fig. 3. Maximum load assigned to a single reader using different schemes.

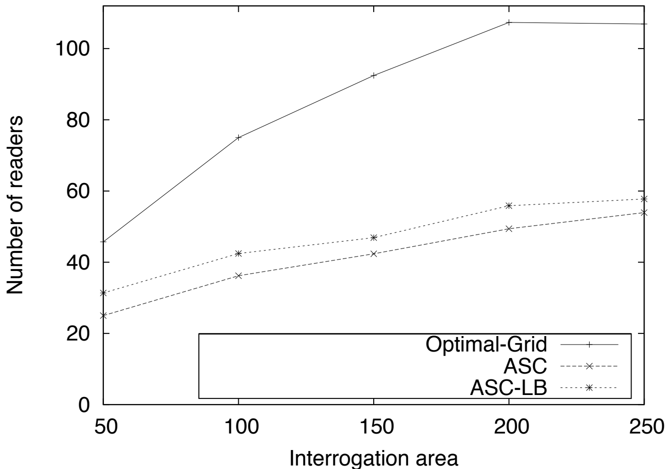
schemes require almost the same number of readers to achieve full coverage.

While the ASC algorithm deploys a minimal number of readers, it does not provide any guarantees regarding balancing the load among readers. Fig. 3 shows a comparison between the different algorithms in terms of the maximum load assigned to a single reader. As anticipated, since the ASC-LB is the only algorithm that considers load balancing, it outperforms other algorithms in terms of load balancing. The improvements achieved by the ASC-LB algorithm get more significant as the the number of tags grows.

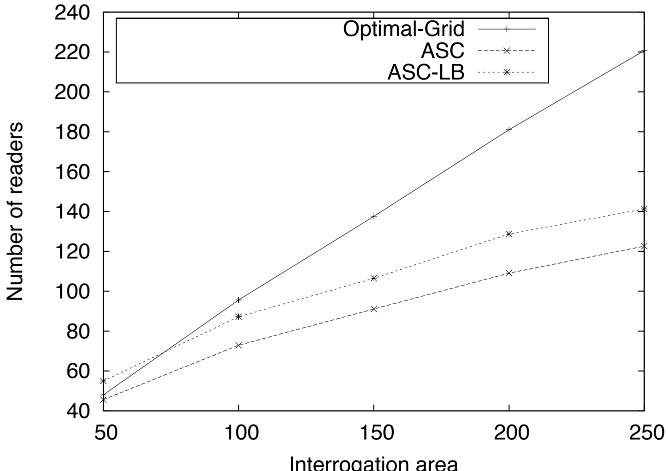
The results on different interrogation areas, in sparse (100 tags) and dense (500 tags) environments, are shown in Fig. 4. This shows that our algorithms scale very well to growing interrogation areas and tags densities.

VI. Conclusion

While RFID systems have a great potential to automate complex activities in major applications, several technical challenges need to be overcome in order for these systems



(a) 100 tags



(b) 500 tags

Fig. 4. Effect of growing tag densities and interrogation areas.

to deliver their promises. Deployment of RFID readers and coverage are two major challenges in RFID systems. Although several deployment schemes have been proposed in the literature, issues such as overlapping among readers and load balancing have not yet received enough attention. This paper addresses the readers deployment problem and proposes an algorithm that approximately determines the minimal number of readers and the location of each reader in a 3D space. We also extend our algorithm to guarantee less overlapping among readers and to provide a balanced distribution of load among them. The performance of our algorithms is compared with that of existing algorithms using simulations.

While this work assumes that RFID readers have a fixed transmission range, we plan to look into the problem of optimizing and/or dynamically controlling the transmission range of RFID readers to reduce overlapping and to balance the workload among readers.

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