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NOP: An Efficient Non-optimization-based Method for RFID Network Topology Design

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Abstract

For Radio Frequency IDentification (RFID) applications in Internet of Things, proper reader deployment is important because unguarded deployment may cause reader-to-tag or reader-to-reader interferences, incurring huge deployment cost. Current RFID topology designs are optimization-based whose heuristic search for optimal or sub-optimal solutions may take much complexity and whose improper utilization or concurrent consideration on the involved objectives may generate unfavorable results. To pursue more desirable reader deployment for RFID networks, this paper presents an efficient new topology design – ***NOP****.* ***NOP*** *involves a* ***N****on-****OP****timization practice to avoid the tediously long heuristic search in optimization-based methods and gives proper sequential considerations on involved objectives to avoid improper objective utilization. The conducted experimental evaluation shows that our* ***NOP*** *method can produce better reader deployment by reduced complexity. Specifically, it outperforms optimization-based methods, such as* ***GA****,* ***GAA*** *and* ***IGAA****, by yielding higher fitness values at less processing time and deployment cost.*

Keywords*: RFID (Radio Frequency IDentification) networks, Internet of Things (IoTs), topology design, optimization-based and non-optimization-based methods, reader deployment, experimental evaluation*

1. Introduction

The development of the Radio Frequency IDentification (RFID) technology [1-5] casts significant impacts on both the Internet and the real world. The technology has now become one of the principal building blocks of the thriving Internet of Things (IoTs) [6-10], which will soon dominate people’s daily life. Most RFID applications in IoTs need to use multiple readers to read the IDs of multiple tags which form the RFID network (for instance, a supermarket will need multiple readers to read the multiple items in an area). In such networks, a proper topology design is particularly important as it can maintain good system performance by ensuring efficient deployment of those to-be-deployed readers, including their positions and power levels. Unguarded or unplanned reader deployment – *e.g.*, readers are largely or randomly deployed – may incur tremendous deployment cost and jeopardize the performance of an RFID network. This is because when unplanned reader deployment generates over-crowded readers in the network, it can impact the success ratios of tag detection and cause reader-to-tag or reader-to-reader interferences [10-13]. Therefore, when setting up reader deployment for RFID networks, we must take all of the factors (the reader-to-tag and reader-to-reader interferences, success ratios of tag detection and deployment cost) into careful considerations.

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Established methods for RFID network topology designs are all optimization-based, utilizing such optimization techniques as the Genetic Algorithms (**GA**) [14], Genetic Annealing Algorithms (**GAA**) [15, 10] and Improved Genetic Annealing Algorithms (**IGAA**) [10]. Optimization-based methods usually take conspicuous complexity in the heuristic search for optimal or sub-optimal solutions. They may also turn over unfavorable results due to improper utilization or concurrent consideration of the six objectives (the overlapping of the reading areas, the number of useless readers, the number of redundant readers, the number of tags located in the overlap reading areas, the number of uncovered tags and the deployment cost [10, 14]) which are covered by the multi-objective fitness function.

To pursue desirable reader deployment for RFID networks and meanwhile remove the problems in optimization-based methods, this paper presents a new and efficient Non-OPtimization-based (**NOP**) topology design. The proposed **NOP** method is unique in that it adopts a non-optimization approach to avoid the tediously lengthy heuristic search of optimization-based methods and enacts a proper sequential consideration of the six objectives to replace the improper utilization or concurrent consideration in existing methods. **NOP** works out reader deployment in three phases: (1) the initial reader deployment – to find the best initial deployment of each reader, (2) the reader power increment – to cover more tags after initial deployment and (3) the reader power decrement – to further reduce the deployment cost without affecting the number of covered tags. Extended simulation runs are conducted to evaluate and compare the performance of the proposed **NOP** and the optimization-based methods **GA**, **GAA** and **IGAA**, specifically their performance in fitness values, processing time and the six objectives. The obtained results exhibit that our new method practically outperforms existing methods by turning up better fitness values at significantly reduced processing time and less deployment cost. That is, **NOP** is able to yield better reader deployment by reduced complexity.

2. Background Study

2.1. The Adopted Multi-Objective Fitness Function

To attain favorable RFID network topologies, existing optimization-based methods usually check possible RFID topology designs by a defined linear weighted multi-objective fitness function. The fitness function covers six objectives: the overlapping of the reading areas, the number of useless readers, the number of redundant readers, the number of tags located in the overlap reading areas, the number of uncovered tags and the deployment cost. Note that, in the last objective, we take the deployment cost in [10] to replace "the number of readers located out of the deployment area" in [14] (because it is practically unreasonable to deploy readers *out of* a pre-specified deployment area). Like [10], we also define each objective as $f_i = 1/(100+|\varepsilon_i|)$ in order to remove possible biased effects due to a certain objective, *i.e.*, to be more practical and reasonable. By doing so, we will attain the fitness = $\sum w_i * f_i$, f_i and w_i each representing objective i and its weight. The six objectives in the linear weighted multi-objective fitness function in [10] will be further illustrated in the following to assist future discussions.

1. The overlapping of the reading areas: As dense reader deployment tends to increase the overlapping of reading areas and cause reader-to-reader or reader-to-tag interferences, it is desirable to limit the overlapping of reading areas at deployment, as Figure 1 shows. Given that, in practice, keeping the reading areas of all readers in an RFID network from overlapping is infeasible, we can hence pre-set the limit of the overlapping ratio to be 25%, to help maintain good performance.

The objective can be defined as

$f_1 = 1/(100+|\varepsilon_1|)$

where ε_1 indicates extra overlapping (which exceeds the pre-set 25% limit).

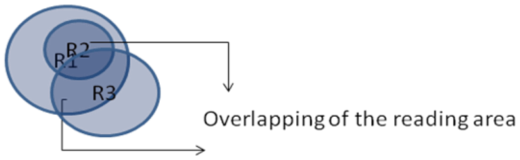

Figure 1. Overlapping of the Reading Areas

2. The number of useless readers: Useless readers, as Figure 2 shows, will cause extra cost and also reader-to-reader interference.

The objective is defined as

$f_2 = 1/(100+|\varepsilon_2|)$

in which ε_2 refers to the number of useless readers.

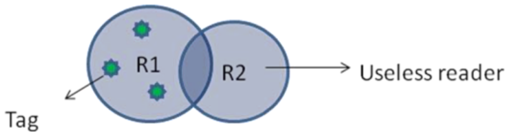

Figure 2. Useless Readers

3. The number of redundant readers: Figure 3 reveals that, besides extra cost, redundant readers may cause reader-to-reader and reader-to-tag interferences as well.

The objective is defined as

$f_3 = 1/(100+|\varepsilon_3|)$

where ε_3 is the number of redundant readers.

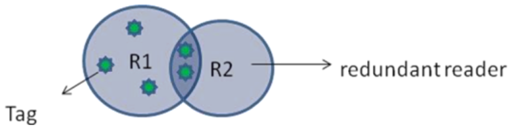

Figure 3. Redundant Readers

4. The number of tags located in the overlap reading areas: To avoid locating tags in the overlap reading area will be difficult or costly (*i.e.*, at substantial deployment cost). However, to reduce the probability of incurring reader-to-tag interference, we must pre-confine the number of tags in an overlap area upon deployment. Figure 4 displays that the number of tags allowed in an overlap area between two readers is set to 2.

The objective is defined as

$$f_4 = 1/(100+|\varepsilon_4|)$$

ε_4 indicating the number of tags located in overlap reading areas beyond the limit.

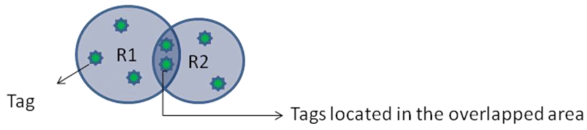

Figure 4. Tags Located in the Overlap Area

5. The number of uncovered tags: In Figure 5, assume a tag can be successfully identified when covered by a reading area. Then it will be favorable for all deployed readers to cover as many tags as possible.

This objective is defined as

$$f_5 = 1/(100+|\varepsilon_5|)$$

ε_5 indicating the number of uncovered tags which should be minimized.

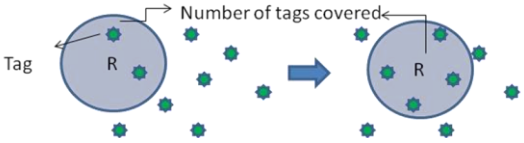

Figure 5. The Number of Tags Covered

6. The deployment cost: The cost objective function in existing literature considers only the total price (related to the total power) of deploying readers [16]. It may lead to biased reader deployment in multi-objective optimization. To avoid such biased effects, [10] define a more proper cost objective

$$f_6 = 1/(100+|\varepsilon_6|)$$

where

$$\varepsilon 6 = \sum_{i=1}^{n} \frac{\text{the coverage area of reader } i}{\text{the number of tags covered by reader } i}$$

(n = the number of deployed readers). The value of ε_6 indicates the average reader coverage area per tag. It is related to the density of covered tags: The smaller ε_6 is, the higher the density. That is, minimizing ε_6 can increase the covered tags and reduce the cost.

2.2. Optimization Techniques

As reader deployment may significantly affect the performance of RFID systems, a number of optimization-based approaches have been set up to pursue favorable RFID network topologies. To attain desirable reader deployment, these approaches involve popular optimization techniques – such as genetic algorithms (**GA**) [14], genetic annealing algorithms (**GAA**) [15, 10] or Improved Genetic Annealing Algorithms (**IGAA**) [10] – to optimize the above multi-objective fitness function. To assist understanding, we briefly introduce the involved optimization algorithms in the following.

1. The genetic algorithms (GA) [14]: **GA** [17] has three major operations: selection, crossover and mutation. It uses the selection process (selection and copying) to select better fitness values into the next generation, the crossover process to mix the species in order to produce a better next generation, and the mutation process to avoid the missing of excellent species. **GA** operates by the following steps.

Step1: Initialize the population size
Step2: Calculate the fitness value of each species according to the objective function
Step3: Go through the selection process according to the fitness values
Step4: Go through the crossover process to produce the next generation
Step5: Take the mutation process to avoid local optima

It will repeat steps 2 to 5 until convergence or reaching a stop condition.

2. The genetic annealing algorithms (GAA) [10]: GAA [15] is the hybrid practice of GA, SA (simulated annealing) [18] and GESA (guided evolutionary simulated annealing) [19]. It involves only one operation – the stir operation, and four parameters – the number of genes to be stirred (N), the decreased number of genes to be stirred (n), the number of stirs (M), and the decreased number of stirs (m). G = N/n = the number of generations. M decides the frequency of stirs; m decides the decreasing stir frequency in the stir operation. The stir operation is denoted by Stir(X, N), X representing any solution and N = the number of genes to be stirred. The operation works as follows.

(1) Randomly select N genes (characters) from an X.
(2) Change the values of the selected genes or their positions in the chromosomes.
(3) Completely stir the genes in the chromosomes to bring up all possible solutions scattering over the search space.

GAA operates by the following steps.

Step1: Set the four parameters N, n, M and m
Step2: Randomly generate a solution X
Step3: Generate a new solution Y after executing the stir operation for X
Step4: Select Y if F(Y) is better than F(X) or select X if otherwise

Repeat steps 3 and 4 M times. Then, decrease N by n and repeat steps 3 and 4 M = M-m times, until N becomes 0.

3. The improved genetic annealing algorithm (IGAA) [10]: **GAA** has two problems. It generates limited iterations and yields less search capability in the middle of iterations. For improvement, **IGAA** takes a proper decimal number n, 1>n>0, as the decreased number of genes to be stirred, to extend the number of iterations. For instance, with the initial number of stir genes N = 10 and n = 1, **GAA** will have at most 10 iterations, but when n = 1/20 (0.05), the number of iterations can be extended from 10 to 200. N, being an integer, will always decrease by 1 after 20 iterations. We can use notation (10,...,10), (9,..,9), …, (2,..,2), (1,..,1) to illustrate the value change of N, with each parenthesis indicating the value of N for 20 iterations. Note that the two problems in **GAA** are related in such a way that the solution for the first problem may worsen the second problem. That is, when a smaller n is taken to increase iterations, the stir operations will generate large-scale mutations which may degrade the search capability. To deal with the situation, **IGAA** decreases n by a different method: It moves from *constant* decrement to *cyclic* decrement to cut down possible large-scale mutations.

3. The Proposed NOP Method

When existing methods use optimization techniques to attain favorable topology designs for RFID networks, they face certain challenges. For instance, the heuristic search for optimal or sub-optimal solutions may incur significant complexity. Also, improper utilization or concurrent consideration of the six objectives (in the multi-objective fitness function) may lead to unfavorable results. We hence decide to pursue favorable RFID topology designs by a different approach, *i.e.*, by a **N**on-

OPtimization-based (**NOP**) method. In the following, we will illustrate how the proposed **NOP** method practices to attain desirable reader deployment, *i.e.*, to avoid the lengthy heuristic search and unfitting utilization or concurrent consideration on the six objectives in optimization-based methods.

NOP works in three phases.

(1) Initial reader deployment: to find the best initial deployment of each reader.

(2) Reader power increment: to cover more tags after initial deployment.

(3) Reader power decrement: to further reduce the deployment cost without affecting the number of covered tags.

Figure 6 depicts the flowchart of its practice.

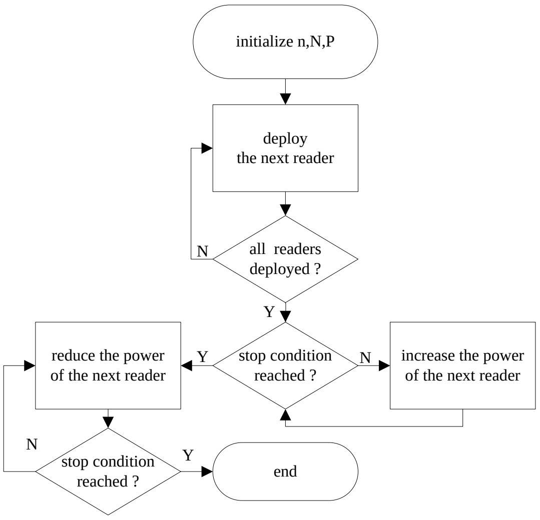

Figure 6. The Flowchart of our NOP Method

(1) initial reader deployment: In this phase, we record three items – possible reader positions (Pt[i]), covered tags (St[i]) and the number of covered tags (Ci) – to compare the deployment alternatives properly and, based on the result, to pursue desirable initial deployment of the preset number (N) of available readers – one by one. Pt[i], St[i] and Ci are respectively denoted below.

*Pt[i]=1 indicates the position in the ith tag (of the n tags) is not a possible reader position due to certain reasons (*e.g.*, the position has been occupied by another reader).

*St[i]=1 indicates the ith tag has been covered.

*Ci of a reader indicates the number of tags covered exclusively by this reader when it is deployed on the position of the ith tag.

We meanwhile use count to calculate the number of deployment failures for each reader in the initial deployment phase. When the count of a reader exceeds a preset threshold, we will decrease the power of the reader (P) to avoid possible deployment failures.

The steps for this phase:

Step 1: Initialize Pt[i], St[i] and the count for a reader.
Step 2: Calculate the reader's Ci for all n tag positons according to Pt[i] and St[i].
Step 3: Select Max Ci and check if such a deployment breaks the preset limits: at most 25% overlap reading area and 2 tags in the overlap reading area.
Step 4: If the deployment works, set Pt[i]=1 and {St[i]}=1; otherwise, set Pt[i]=1, count++ and perform power adjustment according to the count value.
Step 5: Loop again to Step 2 until the number of deployed readers reaches N.

The flowchart of the initial reader deployment phase is given in Figure 7.

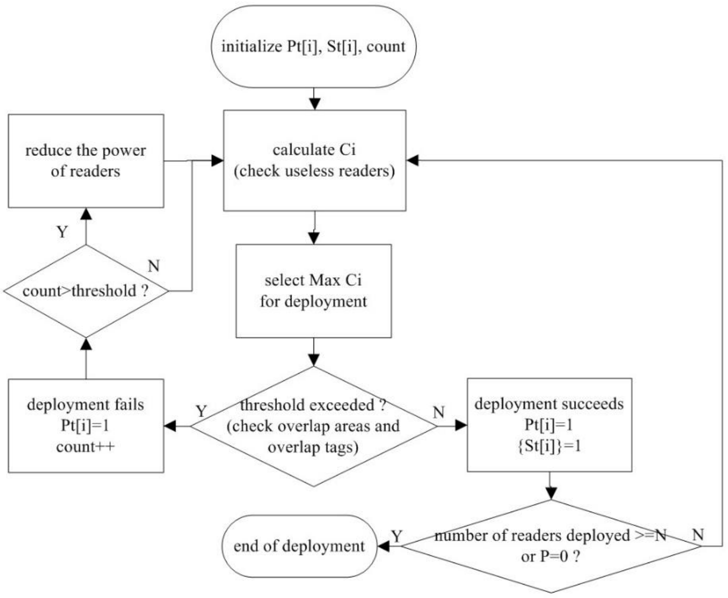

Figure 7. The Flowchart of Initial Reader Deployment

(2) reader power increment: In this phase, we maximize the power of each deployed reader to increase the covered tags for each reader and also the total covered tags in the network.

The steps for this phase:

Step 1: If the stop condition – when 90% of tags are covered – is not reached, go to the following steps.
Step 2: Calculate the reader's Ci for all n tag positons according to the increased power (P) of the reader and St[i].
Step 3: Select Max Ci and check if such a power increment breaks the preset limit.
Step 4: If the deployment succeeds, assign the new power to the reader and set {St[i]}=1; otherwise, keep the original topology.
Step 5: Return to Step 1.

Note that we define the stop condition as "when 90% of tags are covered" based on the fact that optimization methods can cover only less than 90% of tags after convergence [10]. The flowchart of the reader power increment phase is depicted in Figure 8.

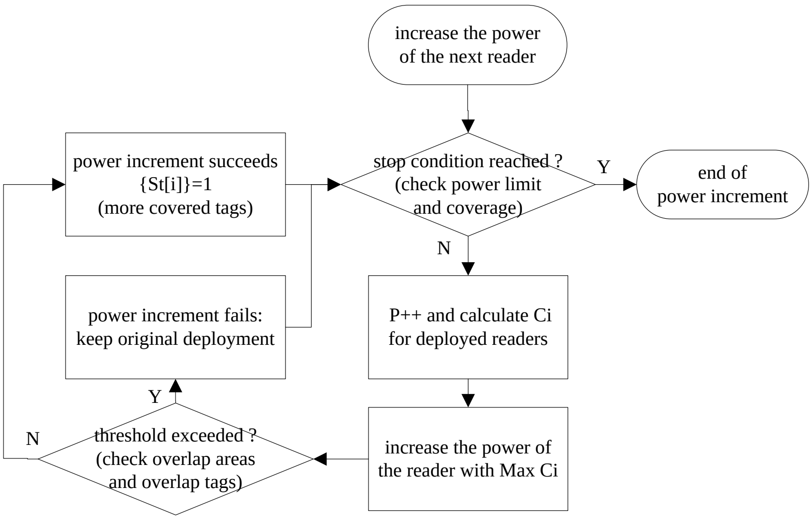

Figure 8. The Flowchart of Reader Power Increment

(3) reader power decrement: In this phase, we maintain the same tag coverage but will possibly decrease the power of each reader to save the deployment cost. We can practically detect and decide if a reader is useless or redundant by reducing its power until it covers no tags and yet the system maintains the same tag coverage. Such useless/redundant readers will then be removed from the system due to their negligible performance.

The steps of this phase:

Step1: Select the next reader.

Step2: Do power decrement.

Step3: Return to Step 2 if the number of covered tags is unchanged.

Step4: Replace the power of the reader by the new minimum power which maintains the original tag coverage. Loop again to Step1 until all readers finish the power decrement.

Figure 9 gives the flowchart of the reader power decrement phase.

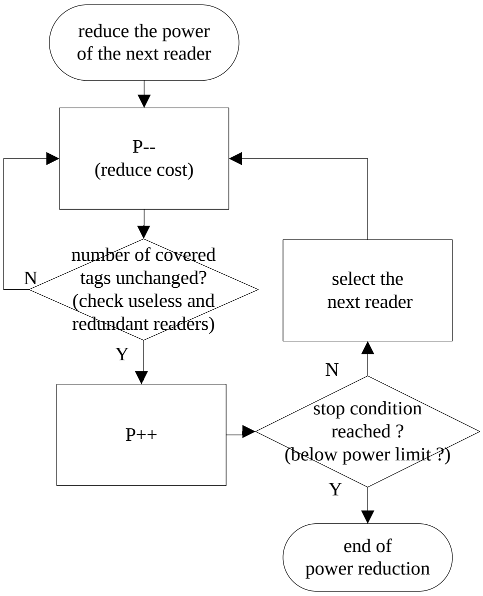

Figure 9. The Flowchart of Reader Power Decrement

Our **NOP** method takes sequential consideration on the six objectives of the multi-objective fitness function to avoid the improper utilization or concurrent consideration in optimization-based methods, as Table 1 displays.

Table 1. Our sequential consideration on the six objectives.

Objectives phase	initial reader deployment phase	reader power increment phase	reader power decrement phase
Overlapping of the reading area	✓	✓	
Number of useless readers	✓		✓
Number of Redundant readers			✓
Number of tags located in the overlap reading area	✓	✓	
Number of tags covered		✓	
Deployment cost			✓

4. Experimental Evaluation

Extended simulation runs are conducted to evaluate and compare the performance of our **NOP** method and existing optimization-based methods, including **GA**, **GAA** and **IGAA**. The performance measures of interest are *fitness values* and *processing time*. That is, the performance of the four methods will be compared in terms of *fitness values* and *processing time*. We also examine their performance in each of the six objectives, to prove the effect of our sequential considerations.

4.1. The Simulation Environment

In the simulation, we assume 30 tags are located in a 20m*20m tag area and 10 readers will be deployed to read the tags in a 32m*32m reading area. The pre-set limit in the initial reader deployment phase is, as mentioned, a 25% overlap reading area with 2 tags. The reader power increment phase will stop when 90% of the tags are covered (which is the stop condition) and the preset threshold for a reader's deployment failures (count) is 2. The performance of the three optimization methods and our **NOP** method is evaluated under the above environment by the same six objective functions. Note that we collect the results of the three optimization methods around 200 iterations because convergence normally takes place at the time [10].

4.2. Simulation Results

4.2.1. Fitness Values and Processing Time: Figure 10 depicts the obtained fitness values for the four methods. As we can see, our **NOP** yields better fitness values than **GA**, **GAA** and **IGAA**. This is because we enact proper sequential considerations of the objectives to avoid the improper utilization or concurrent consideration in optimization methods.

Figure 11 gives the processing time of the four methods. In contrast to the three optimization methods, our **NOP** significantly reduces the required processing time – mainly because our non-optimization-based practice can avoid the tediously long heuristic search in optimization-based methods.

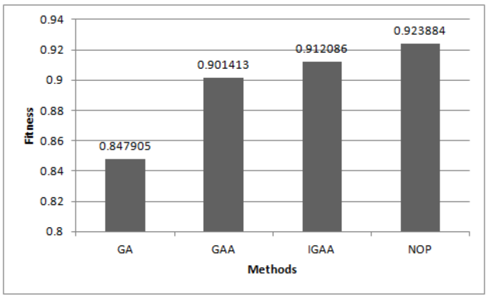

Figure 10. Fitness Values for the Methods

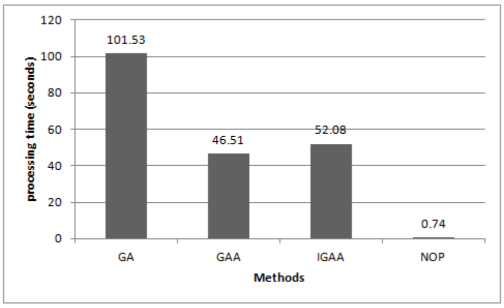

Figure 11. Processing Time for the Methods

4.2.2. The performance in the objectives: Besides examining the performance in fitness values and processing time, we also check how these methods perform in each of the six objectives. The main purpose is to demonstrate the difference between our sequential considerations on objectives and the improper objective utilization in the other methods. The obtained results for the six objectives are depicted in Figures 12-17 for further comparisons.

(1) Excessive overlapping

As mentioned in Sec. 2, the excessive overlapping of reading areas can cause reader-to-reader or reader-to-tag interferences. When the overlap area widens, such interferences will worsen and eventually jeopardize the overall system performance. To maintain good system performance, it is hence important to narrow down the overlap reading areas as much as possible. In Figure 12, our **NOP** algorithm is shown with 0 excessive overlapping of the reading areas, apparently outperforming the other methods. This is because **NOP** has a mechanism to check if a reader deployment breaks the preset limit – 25% overlap reading area (in Step 3 of its first phase). The mechanism will help it control the overlapping of reading areas in the allowed (25%) scope constantly.

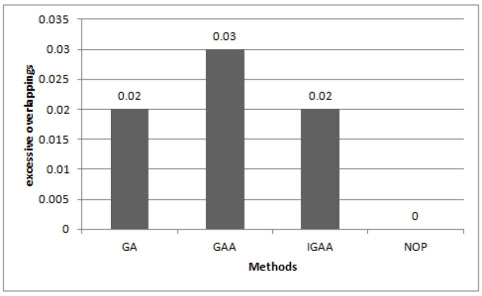

Figure 12. Excessive Overlapping

(2) Useless readers

As the flowchart of our initial reader deployment (in Figure 7) shows, the **NOP** algorithm can locate a potential useless reader by calculating the Ci of the reader. After calculation, it will not deploy a reader with Ci = 0 to the system, to avoid futile reader deployment. The result in Figure 13 is actually a strong support for the Ci calculation practice. As we can see, in contrast to **GA**, **GAA** and **IGAA**, **NOP** produces 0 useless readers.

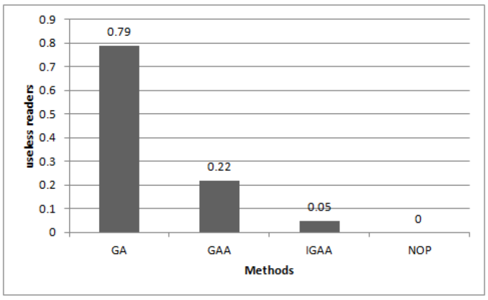

Figure 13. Useless Readers

(3) Redundant readers

Figure 14 gives the number of redundant readers for different methods. Recall that by calculating the Ci values of readers in the initial reader deployment phase, our **NOP** algorithm can locate possible useless readers and exclude them from getting into the RFID network. But useless readers may still appear in the power increment phase. We handle the problem in the power decrement phase. In the power decrement phase, we can practically detect a reader to be useless or redundant by reducing its power to such an extent that it covers no tags and the fact does not influence the tag coverage in the system. That is, when we reduce the power of a reader until it covers no tags but the system maintains the same tag coverage, we consider the reader to be useless or redundant and will remove it from the system. That explains why **NOP** produces 0 redundant readers in Figure 14.

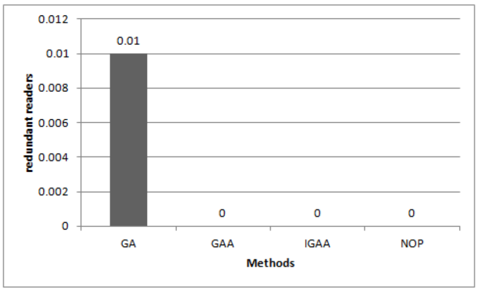

Figure 14. Redundant Readers

(4) Overlap reading areas with more than two tags

Figure 15 displays the number of overlap reading areas which cover more than two tags. The proposed **NOP** algorithm has preset a limit (in the initial reader deployment phase) which allows an overlap reading area to have at most two tags. Therefore, we see the result in Figure 15 is 0 for **NOP**.

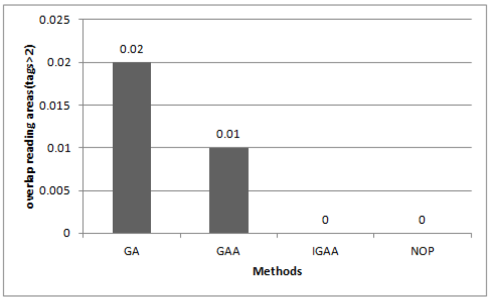

Figure 15. Overlap Reading Areas with

(5) Uncovered tags

Figure 16 plots the number of uncovered tags for each method. **NOP** gives the lowest value, *i.e.*, the smallest number of uncovered tags among all. This is because, in the reader power increment phase, **NOP** maximizes the power of deployed readers to increase the tag coverage of each reader and that of the whole network. The result in Figure 16 again pinpoints the superiority of our proper sequential considerations of objectives over the improper objective utilization in optimization-based methods.

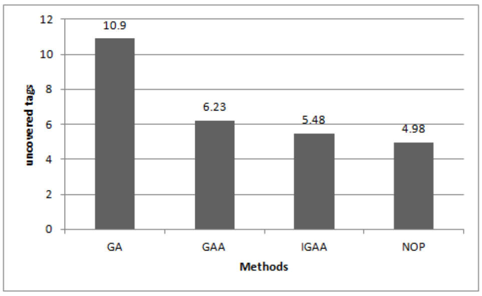

Figure 16. Uncovered Tags

(6) Deployment cost

Figure 17 exhibits the deployment cost of the four methods. It shows that **NOP** takes less deployment cost than the other methods. That is, **NOP** attains the above good performance at satisfactorily low deployment cost. The desirable cost performance can be traced back to the initial reader deployment and reader power decrement phases. In the initial reader deployment phase, **NOP** will properly check the deployment alternatives and use the obtained result to set up favorable initial deployment of available readers – one by one – under the initial power. It has attempted to pursue desirable initial deployment at the least cost in this phase. Then in the reader power decrement phase, **NOP** will maintain the same tag coverage but meanwhile possibly decrease the power of each reader, to save more deployment cost.

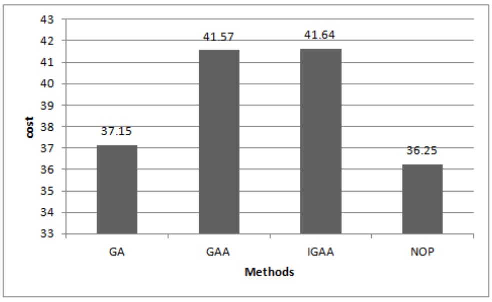

Figure 17. The Deployment Cost

5. Conclusions

In RFID networks, a proper reader deployment design is important as it can critically affect the overall network performance. Current RFID topology designs are basically optimization-based methods confronting certain key challenges, including the heuristic search for optimal or sub-optimal solutions may incur remarkable complexity and the improper utilization or concurrent consideration of objectives covered by the multi-objective fitness function may generate unfavorable results. To remove these negative impacts while attaining more desirable topology designs, we introduce an efficient non-optimization-based (**NOP**) new method in this paper.

The proposed **NOP** adopts a non-optimization approach to avoid the tediously lengthy heuristic search of optimization-based methods and enacts a proper sequential consideration of the six objectives to replace the improper utilization or concurrent consideration in existing methods. We work out better reader deployment by a three-phase practice: the initial reader deployment which helps find the best initial deployment of each reader, the reader power increment which helps us cover more tags after initial deployment and the reader power decrement which can further reduce the deployment cost without affecting the number of covered tags. Simulation results show that, our **NOP** constantly outperforms **GA**, **GAA** and **IGAA** in fitness values, processing time and each of the six objectives. That is, our non-optimization-based topology design can obtain more desirable reader deployment for RFID networks than optimization-based designs because we produce higher fitness values at less processing time and smaller deployment cost.

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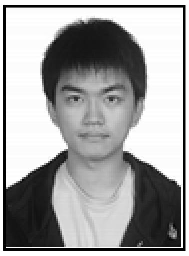

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