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Robust multi-objective optimization for solving the RFID network planning problem

Ait Lhadj Lamin S., Raghib A., Abou El Majd B.

LMSA Lab, FSR, Mohammed V University in Rabat, Morocco

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Radio-frequency identification (RFID) is a new technology used for identifying and tracking objects or people by radio-frequency waves to facilitate automated traceability and data collection. The RFID system consists of an electronic tag attached to an object, readers, and a middleware. In the latest real applications based on the RFID technology, the deployment of readers has become a central issue for RFID network planning by means of optimizing several objectives such as the coverage of tags, the number of readers, and the readers/tags interferences. In practice, the system is affected by uncertainty and uncontrollable environmental parameters. Therefore, the optimal solutions to the RFID network planning problem can be significantly reduced with uncontrollable variations in some parameters, such as the reader's transmitted power. In this work, we propose a robust multi-objective optimization approach to solve the deployment of RFID readers. In this way, we achieve robust optimal solutions that are insensitive to uncertainties in the optimization parameters.

Keywords: *RFID, RNP problem, robustness, multi-objective optimization, uncertainty.*

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1. Introduction

Radio Frequency IDentification (RFID) is an automated traceability and data collection technology where data is transferred between a reader and an electronic tag via radio frequency waves for track identification and material flow management. In practice, the RFID network planning is affected by uncertainty and uncontrollable environmental parameters. Therefore, the optimal solutions to the RFID network planning problem can be significantly reduced by uncontrollable variations in some parameters, such as the reader's transmitted power. This problem proved by the scientific community as an NP-HARD problem. In this case, finding an effective solution to this type of problem is a challenge. In reality, the RNP problem comprises two challenges: the first challenge of the problem is to determine the optimal number and positions of readers to reach a full coverage of all tags deployed in an space, and minimizing the tags/readers interference. The second challenge that a decision maker find in real applications while optimizing the RFID network planning problem is to achieve a robust optimal solutions that are insensitive to uncertainties.

In the literature, the RFID network planning problem has been studied by many researchers by several approaches in order to cover all tags with a minimum number of readers [1]. These approaches are often able to find a high performance of the optimal solutions. However, no research has been done under uncertainty. The deployment of the RFID system has firstly proposed by Guan et al., in [2], it's one of the fundamental problems in large-scale RFID networks. Several studies have been proposed, including many algorithms, and approaches to solve the deployment of RFID readers problem. Among the existing famous studies, H. Chen et al., suggested optimizing coverage of tags, interferences, load balance, and economic efficiency using a weighted sum approach to transform multiple objectives into a single objective optimization problem solved with different algorithms such as Genetic algorithm(GA), Particle Swarm Optimization(PSO) in [3], Multi-colony bacteria foraging optimization in [4], Multi-swarm Optimizer in [5], and self-adaptive bacterial foraging optimization [6], and the simulation results compare all these algorithms and show which is efficient for RNP. Moreover, H. Chen et al., solve the RNP problem using a multi-objective approach based on two algorithms: Multi-objective Evolutionary and Swarm Intelligence approaches in [7], and Hierarchical Artificial Bee Colony algorithm in [8] by optimizing the same proposed objectives. Besides these works, O. Botero et al., in [9] implemented a heuristic technique (GA) to solve the RNP problem and developed a software tool for deployment of RFID readers. In [10] Gong et al., used PSO algorithm based a tentative reader elimination operator to delete and recover the deployed readers during the search process and achieve an optimal deployment. Besides all these methods and approaches, there are exist also more studies as M. Tuba et al., formulated the problem by considering four objectives: Coverage, interferences, number of readers, and transmitted power. In [11] they presented an implementation of the firefly algorithm with a mono-objective approach and they show that it is efficient than cooperative multi-objective artificial bee colony algorithm (CMOABC), multi-objective artificial bee colony(MOABC), and non-dominated sorting genetic algorithm II (NSGA-II), and in [12] Tuba et al., solve the RNP problem using Hierarchical and Multi-objective approach. Also in [13] authors used Fireworks Algorithm to solve the problem and they obtained that this algorithm is efficient than GPSO and VNPSO. In [14] they presented an Artificial Bee Colony algorithm(ABC) hybridized with a heuristic for determining approximate number and locations of (RFID) readers. In spite of all these works, there are just a few studies that considered the uncontrollable parameters and uncertainty in RFID network planning as in [15] Raghib et al., and in [16] Zhao et al. by using robustness multi-objective optimization, they were able to find robust optimal solutions to RID network planning problem that are insensitive to uncertainties in the optimization parameters. Finally Tuba et al. [17] proposed a probabilistic model of coverage for solving the deployment of RFID readers.

This work is an extension of [15]. There is presented a robust multi-objective optimization approach to solve the RFID network planning problem based on non-dominated sorting genetic algorithm II (NSGAII). The benefits of our work are: we formulated the RNP problem such as a multi-objective optimization problem, and propose an effective approach to deal with the (RNP) with many attractive features: identifying the minimal number of readers and their best locations to ensure that all tags in the network are covered and minimizing tags and readers interference. Furthermore, the solutions are optimal and unaffected by uncertainty on the reader's transmitted power.

The rest of this work is organized as follows: Section 2 presents our methods, the RFID network planning formulation, and the proposed approach to deal with our problem. In section 3 we present the implementation of the proposed approach and discuss the numerical results. Finally, section 4 concludes and gives some perspectives.

2. Methods

2.1. RFID system

2.1.1. Components of RFID system

A basic RFID system consists of an electronic tags, RFID readers, and a middleware that allows the data flow to be integrated into the information system.

Figure 1 shows the basic components of the RFID system.

Fig. 1. Basic components of the RFID system.

An RFID tag consists of two main parts: The chip and the antenna, the chip is a small system that stores a series of numbers unique to that chip. It has the logic of telling itself what to do when it is in front of a reader, and the antenna allows the chip to receive the power and communicate. The RFID tag allowing data to be exchanged with the reader. These tags can then be incorporated into objects or be stuck on products. There are three types of tags: Active, passive, and semi-passive tags. In practice, we use usually tags passive as they're cheaper than tags active. The RFID reader is the element responsible for reading the tags and transmitting the information by middleware to the information systems, in order to use it by the real application [18]. It can take various forms depending on its intended use. Because it does not need to be in direct contact with the chip of tags, the most used reader is the fixed reader, but it can also take the portable form.

2.1.2. Communication process in an RFID network

The RFID reader reads a tag if it is in its interrogation zone, it activates by sending an electromagnetic wave and starts the communication, and it is connected to a host application that retrieves the information for processing. The reader-tag communication process is influenced by a number of elements and parameters to find the best power received at an antenna using the Friis transmission equation:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2.$$

Where G_t and G_r are the gains of a reader's and a tag's antenna respectively. P_r is the power at the receiving antenna, P_t is the transmitted power of the reader's antenna, λ is the wavelength, and d is the communication distance between these two antennas. In reality, the received signal is influenced by environmental noise (Metallic material, obstacles, etc) within the interrogation zone of the reader.

2.2. Multi-objective optimization

2.2.1. Multi-objective optimization

A multi-objective optimization problem has many different objective functions which are to be minimized or maximized, and it satisfies a number of constraints [19].

In general a multi-objective optimization problem (MOOP) can be defined as:

$$\begin{cases} \text{Min/Max} F(x,p) \quad x = (x_1, \ldots, x_n), \\ \text{such that:} \\ g_j(x) \leqslant 0 \quad j = 1, \ldots, J, \\ h_k(x) = 0 \quad k = 1, \ldots, K, \\ x_i^{(L)} \leqslant x_i \leqslant x_i^{(U)} \quad i = 1, \ldots, n. \end{cases}$$

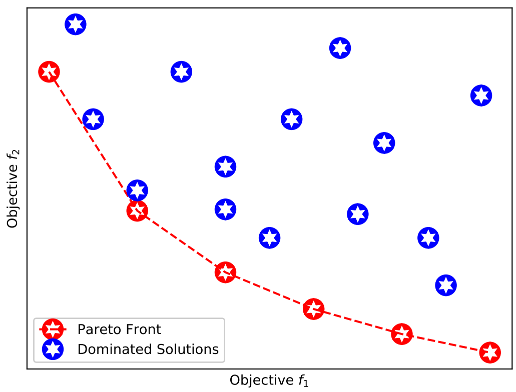

Fig. 2. Example of the Pareto–Front

Where F is the objective function, and the functions $(g_j)_{j=1}^{J}$ are the equality constraints, and $(h_k)_{k=1}^{K}$ are the inequality constraints, x is a vector of n decision variables, each decision variable x_i is between a lower bound $x_i^{(L)}$ and an upper bound $x_i^{(U)}$, and p is G-component design parameters.

Generally, multi-objective optimization problems have more than one solution in the feasible region [19]. It takes into account the trade-offs between the objective functions. Pareto set is the collection of those solutions [19].

Figure 2 shows an example of Pareto–Front of a multi-objective optimization problem.

2.2.2. Robust Multi-objective optimization

In general, there are two categories of optimization algorithms: deterministic and stochastic, with deterministic optimization all parameters are controllable but the optimal solutions with classical optimization are not always best suited in practice due to uncontrollable variations or errors in the mathematical model.

Many real engineering optimization problems have parameters with uncontrollable variations that can significantly affect the optimal solution's performance, then the main goal of optimization is to obtain a robust solution that is not just efficient but also robust. In literature, robust optimization is dealt with single-objective optimization problem in many studies such as in [20] and [21]. In this work, we focus on the multi-objective optimization problem because our problem of RFID network planning is a MOOP that we will show later. For multi-objective optimization, they are many approaches as in [22] Gunawan and Azarm suggested a robust multi-objective algorithm that measures the multi-objective sensitivity of a design alternative, and a deterministic approach using non-gradient to obtain robust Pareto optimal solutions based on parameter sensitivity estimation. In [19] Deb and Gupta presented two types of robust solution: in approach type I, they used the mean effective objective functions calculated by averaging the original objective function over perturbations, and in the type II approach they calculated the normalized difference in values between the perturbed function value and the original function. Also in [23] Kuroiwa and Lee dealt with uncertainties in multi-objective optimization problems by replacing the objective functions with their respective worst cases in all scenarios, thus obtaining a deterministic multi-objective optimization problem whose effective solutions are said to be robust. Authors Ehrgott et al., suggested interpreting the worst case of an objective vector as a set of efficient solutions of a multi-objective problem that is maximizing the objective function over a set of uncertainties in [24]. Besides all these approaches, Yu and Liu applied game theory to obtain robust solutions for problem in [25].

2.3. RFID network planning formulation

2.3.1. The proposed multi-objective approach for the RNP problem

In this part, we describe the different objectives, parameters, and variables considered for solving the RFID network planning problem. Our aim is to find simultaneously the optimal number of readers deployed in the network and their coordinates, such that all the tags of the whole space are covered, and minimizing interference.

The RFID network planning (RNP) process focuses on four main goals, which are formulated as follows: first, to reduce the cost of the RFID system, we must minimize the total number of readers and find their optimal positions. Second, the main objective function for the deployment of RFID readers is to cover all the tags in the whole space. Then we need to make sure that each tag throughout the network must be in the interrogation zone of at least one deployed reader to achieve full coverage. Finally minimizing tags and readers interference increases the efficiency of the RFID system. Figure 3 shows an example of the deployment. The red cross represents the deployment of readers, while red circles represent their interrogation range, and blue diamond nodes represent tags.

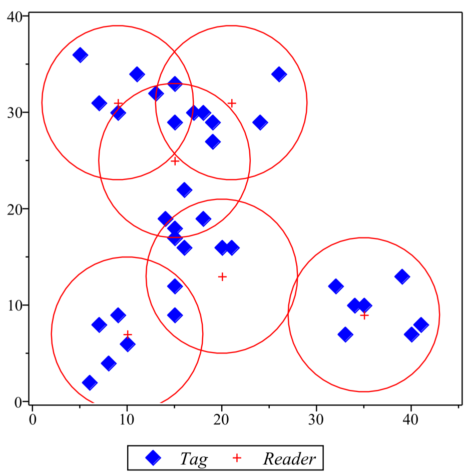

Fig. 3. Example of deployment of RFID readers.

In this work we will use the following notations:

- N_r: the total number of readers available in a network.
- N_t: the total number of the tags.
- Pr_i: the best received power of i^{th} tag.

The total number of deployed readers. The first objective function in the RFID network planning problem represents the number of deployed RFID readers, which is important to evaluate the performance of the deployment. To reduce the cost of deployment of the RFID readers we need to minimize the total number total of readers. This objective function can be defined as:

$$f_1 = \sum_{j=1}^{N_r} r_j,$$

where,

$$r_j = \begin{cases} 1, & \text{if the } j^{th} \text{ reader is deployed,} \\ 0, & \text{otherwise.} \end{cases}$$

In addition, our proposed approach finds the robust optimal position of each deployed and ensures that we can only place each reader in a certain space. For a rectangular zone with height H, width W, and depth D, this constraint is satisfied:

$$0 \leqslant x_j \leqslant H,\ 0 \leqslant y_j \leqslant W \quad \text{and} \quad 0 \leqslant z_j \leqslant D,\ \forall j = 1, \ldots, N_r.$$

Coverage of tags. The principal objective function for RFID network planning is to cover all the tags in the whole space. If the radio signal received at a tag is greater than a certain threshold P_d, the communication between reader and tag can be established, that's means the tag is covered. Therefore, for maximizing the coverage of tags we suggest minimizing the non-coverage of tags to achieve an optimal deployment of RFID readers, it can be formulated as follows:

$$f_2 = N_t - \sum_{i=1}^{N_t} y_{ji}.$$

Where,

$$y_{ji} = \begin{cases} 1, & \text{if } \exists!\ j = 1, \ldots, N_r \text{ such that } Pr_i \geqslant P_d \text{ and } r_j = 1, \\ 0, & \text{otherwise.} \end{cases}$$

Tags Interference. The tags interference occurs if many readers interrogate tags in the same space at the same time. It decreases the efficiency of the RFID system.

Figure 4 shows an example the interference of six tags covered by three RFID readers. The tags interference must be reduced by the following expression:

$$f_3 = \sum_{i=1}^{N_t} c_i,$$

where,

$$c_i = \begin{cases} 1, & \text{if } \sum_{j=1}^{N_r} y_{ji} \geqslant 2, \\ 0, & \text{otherwise.} \end{cases}$$

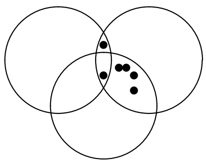

Fig. 4. Example of the interference of six tags covered by three RFID readers.

Readers Interference. The readers interference occur when the interrogation ranges of at least two deployed readers in the space overlap as we can see in Figure 4. It decreases also the efficiency of the RFID system. The readers interference must be reduced by the following expression:

$$f_4 = \sum_{j=1}^{N_r} cr_j,$$

where,

$$cr_j = \begin{cases} 1, & \text{if } \sum_{k=1, j\neq k}^{N_R} IntR_{jk} \geqslant 2, \\ 0, & \text{otherwise.} \end{cases}$$

And,

$$IntR_{jk} = \begin{cases} 1, & \text{if } \exists!\ k = 1, \ldots, N_r \text{ such that } dr_{jk} \leqslant (IR_j + IR_k) \text{ and } r_j * r_k = 1, \\ 0, & \text{otherwise,} \end{cases}$$

dr_{jk} is the distance between the j^{th}reader and the k^{th} reader. IR_j and IR_k are the interrogation range of the j^{th} reader and the j^{th} reader respectively.

2.3.2. The proposed robust approach for RNP

The goal of the robust optimization is to achieve a set of solutions that is Pareto optimum when the uncontrollable parameters exist, the robust solutions are insensitive to the variations of uncontrollable parameters. In this work we suggest to apply a robust approach [22] to deal with uncertainty and obtain an optimal deployment of readers in the network.

In a multi-objective optimization problem there is a noise or uncertainty, the parameter values can vary by a small amount $\mathbf{\Delta p}$, the goal is to reduce the sensitivity in objective values of optimum designs to these variations as much as possible.

The notations and terminologies used in this paper are defined as follows:

- $\mathbf{p_0}$ nominal p value: fixed value of $\mathbf{p}$ that is used to optimize the problem.
- $\Delta f_{i,0}$ positive variation in the $\mathbf{f_i}$ objective as determined by the designer.
- $\mathbf{R_0}$ threshold sensitivity.
- $\mathbf{\Delta p_0}$ range of threshold parameter variations to calculate $\mathbf{R_0}$ (determined by the designer).
- Parameter variation space: ($\mathbf{\Delta p} - \mathit{space}$): A $G - \mathit{dimensional}$; space in which the axes are the parameter variation ($\mathbf{\Delta p}$) values.
- Nominal Pareto set: Pareto set of optimization problem when $\mathbf{p} = \mathbf{p_0}$.
- Nominal $\mathbf{f}$ value: Objectives values of the design when $\mathbf{p} = \mathbf{p_0}$.

The robust approach is presented by Gunawan and Azarm [22], they proposed a sensitivity measure to multi-objective optimization problems.

Let $\mathbf{f}(\mathbf{x_0}, \mathbf{p_0})$ the objective values for the design $\mathbf{x_0}$ with robustness we want to measure, and $\mathbf{p_0}$ be the nominal parameter value. For an acceptable objectives variation range $\mathbf{\Delta f} = [\Delta f_{1,0}, \Delta f_{2,0}, \ldots, \Delta f_{M,0}]$, there is a set of $\mathbf{\Delta p}$ values such that the objective variation due to these $\mathbf{\Delta p}$ values falls within the ranges of $\mathbf{\Delta f_{i,0}}$ for all $i = 1, \ldots, M$. This set is known as the "sensitivity set of $\mathbf{x_0}$", it's defined mathematically by following expression, to account the negative values, we use the square for each Δf_i value.

$$S(x_0, p_0) = \left\{ \Delta p \in R^G \colon (\Delta f_i)^2 \leqslant (\Delta f_{i,0})^2, \forall i = 1, \ldots, M, \text{ and } \Delta f_i = f_i(x_0, p_0 + \Delta p) - f_i(x_0, p_0) \right\}.$$

The points in sensitivity set S form a region called the "sensitivity region", it can be used to calculate a design's sensitivity but the shape of a sensitivity region mostly be asymmetric. To account for this asymmetry, we measure the sensitivity of a design based on the size of its worst-case sensitivity region (WCSR), it's the smallest hypersphere within the sensitivity region that comes closest to touching the region at the origin, and we calculate the radius of the WCSR for a design x_0 by solving the below single-objective optimization problem with an equality constraint, and can be solved using any conventional optimization methods:

$$\begin{cases} \text{Min}_{\Delta p} R(\Delta p) = \left[\sum_{j=1}^{G} (\Delta p_j)^2 \right]^{\frac{1}{2}}, \\ \text{such that:} \\ \text{Max}_{i=1,\ldots,M} \left(\frac{|\Delta f_i|}{\Delta f_{i,0}} \right) - 1 = 0. \\ \text{Where} \\ \Delta f_i = f_i(x_0, p_0 + \Delta p) - f_i(x_0, p_0). \end{cases}$$

The approach consists to calculate the multi-objective robustness measure $R(x)$ of a design x_0 for the nominal value p_0 of the parameter p. We can reach the robust pareto by integrating an additional constraint $R(x)$ the robustness measure in the multi-objective optimization problem,

$$\begin{cases} \text{Min}_x[f_1(x,p_0), f_2(x,p_0), \dots, f_M(x,p_0)], \\ \text{such that:} \\ g_j(x,p_0) \leqslant 0 (j = 1,\dots,J), \\ h_k(x,p_0) = 0 (k = 1,\dots,K), \\ R(x) \geqslant R_0. \\ \text{Where} \\ R_0 = \left[\sum_{j=1}^{G}(\Delta p_j)^2\right]^{\frac{1}{2}}. \end{cases}$$

Where $R(x) \geqslant R_0$ is the sensitivity constraint, R_0 is a threshold sensitivity determined by the designer by defining a symmetric range of p_0 values and aggregating them using the Euclidean norm, and $R(x)$ is calculated by solving the above single-objective optimization problem.

In the optimization of RFID network planning described above, we take into account the variations of the environmental parameters. The transmitted power by readers to tags is influenced by many constraints of (noise, rain, energy, obstacle, etc.).

3. Results and discussion

Table 1. The parameters of RFID network.

Parameters	Value
Space height H	50.0 m
Space weight W	50.0 m
Space depth D	20.0 m
Number of available readers N_r	12
Maximum Iterations	25 000
Population Size	20
Length of Chromosome	10
Identification Threshold P_d	−80 db

In this section, six RNP scenarios, namely C30, R30, C50, R50,C100, and R100 which are deployed in the working space and contain 30, 50, and 100 tags are tested to assess and validate the effectiveness of the proposed method. The readers and the tags are placed in a 50 m×50 m×20 m working space. For the optimizer in this work, the NSGA-II algorithm is adopted for solving the RFID network planning problem since to provide many advantages. The NSGA-II algorithm is described in detail in [26]. Figure 5 shows a flowchart of the non-dominated sorting genetic algorithm II (NSGAII). In implementation of our proposed approach, we consider that there are uncertainty and uncontrollable parameters in the transmitted power of each deployed reader to tags (Pr_j). We selected an acceptable objective variation range for the sensitivity parameters $\Delta f_0 = [\Delta f_{1,0}; \triangle f_{2,0}; \Delta f_{3,0}; \Delta f_{4,0}] = [1; 5; 0; 0]$ and consider the uncontrollable transmitted power by the reader to tags variation $\Delta Pr_j = 5\% P_d$.

Table 1 shows parameters and their value using in the determinist and the robustness multi-objective optimization for RFID network planning using NSGA-II.

Table 2 presents the global results obtained from all six problems by using the NSGA-II algorithm. And the results are graphically supported in Figures 6–11 by a set of Pareto optimal solutions for the six problems according to two objectives (the total number of deployed readers and the coverage of tags).

It's clearly to observe that our proposed approach for RNP as a robust approach that always provides a set of Pareto optimum solutions that remain possible when varying the uncontrollable variations in transmitted power by redears to tags exist which facilitate the decision aiding for the designer. As we can see also in Pareto figures, our approach obtains always the optimal solutions and the robust, which facilitate the decision aiding by giving a global vision of all scenarios considering the transmitted power by readers parameter variation, the robust pareto obtained is inferior to the

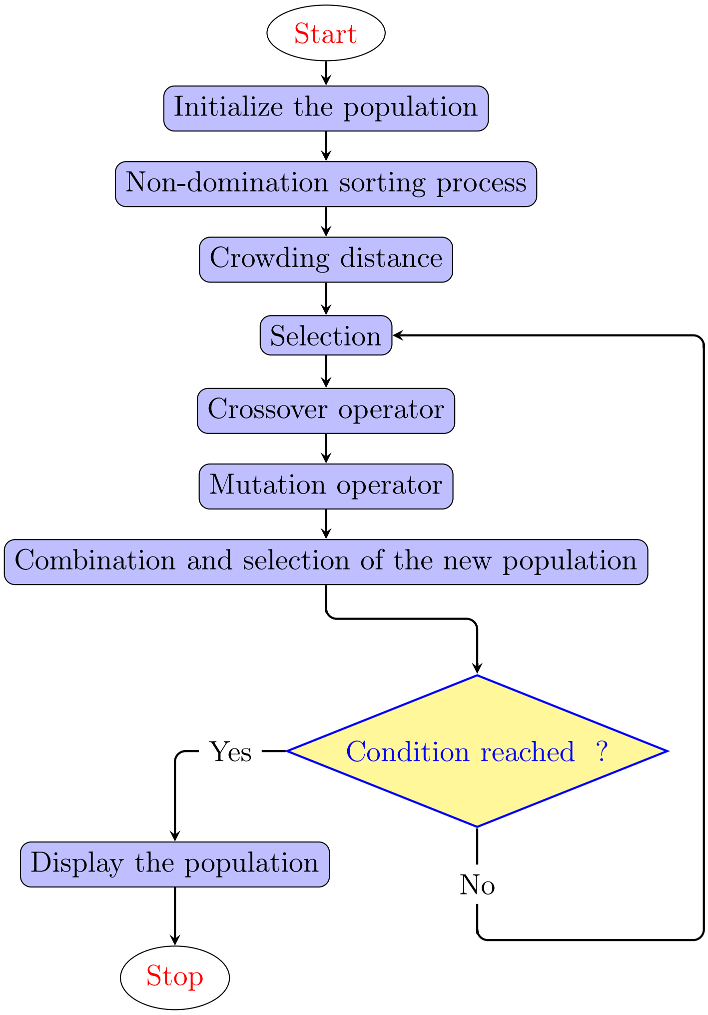

Fig. 5. Flowchart of the Non-dominated Sorting Genetic Algorithm II (NSGA-II).

Table 2. Results obtained by NSGA-II algorithm for C30, R30, C50, R50, C100, and R100.

Benchmarks	Coverage	Number of readers	Tags interference	Readers interference
C30	100%	3	0	0
R30	100%	7	1	0
C50	100%	5	0	2
R50	100%	8	4	0
C100	100%	5	3	2
R100	100%	9	5	0

optimal. As a result, some performance must be sacrificed in order to get a more robust solution to the RFID network planning problem.

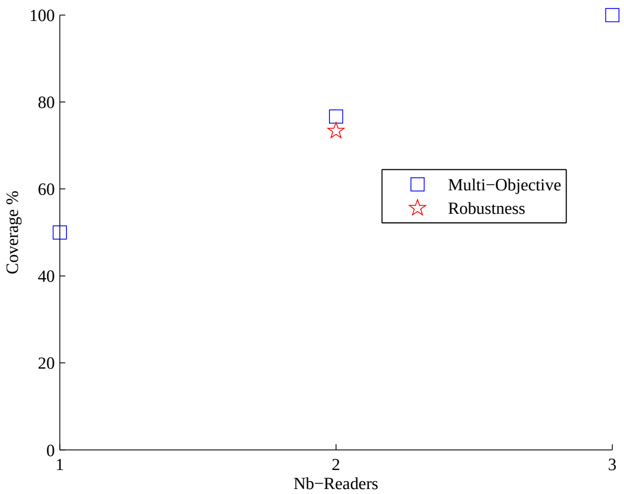

Fig. 6. Pareto–front obtained using the robust multi-Objective optimization approach for C30.

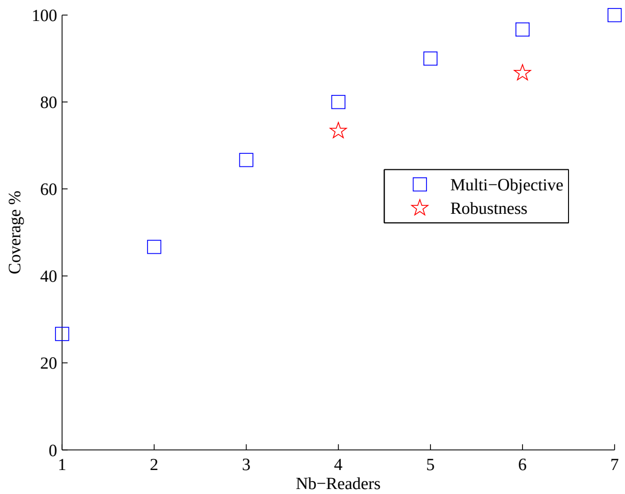

Fig. 7. Pareto–front obtained using the robust multi-Objective optimization approach for R30.

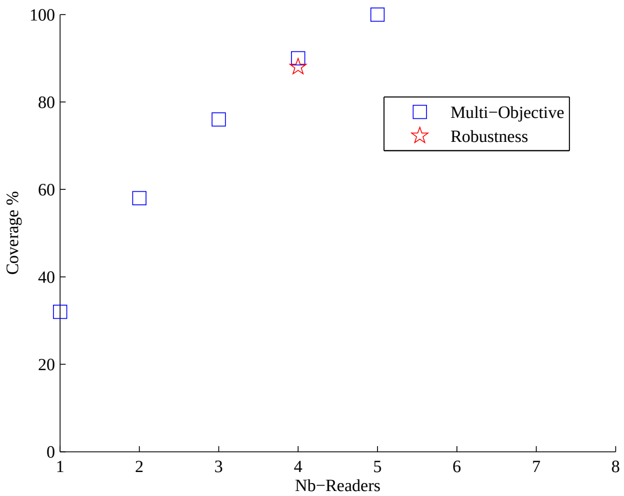

Fig. 8. Pareto–front obtained using the robust multi-Objective optimization approach for C50.

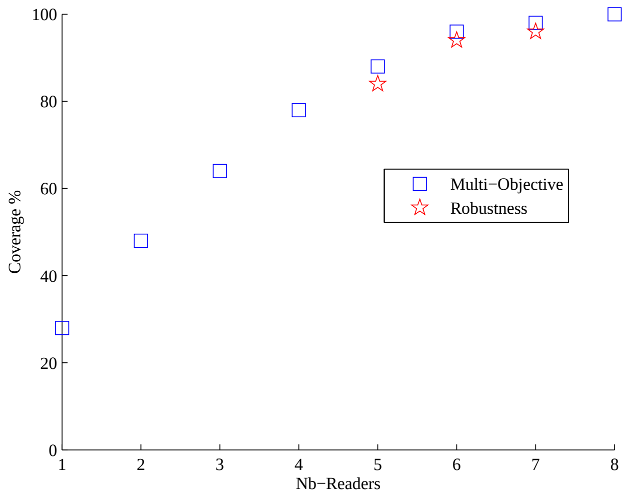

Fig. 9. Pareto–front obtained using the robust multi-Objective optimization approach for R50.

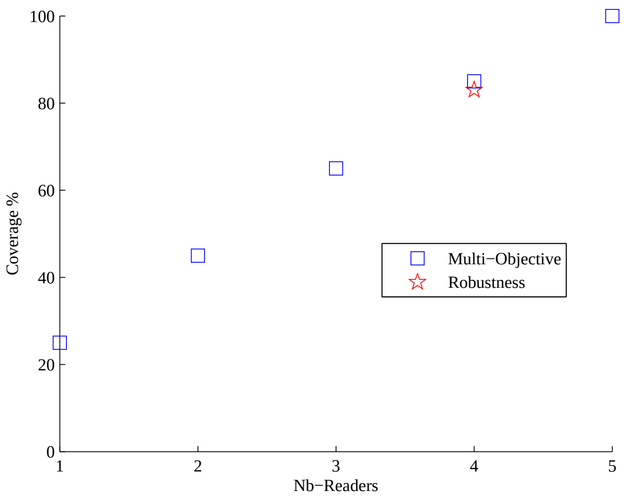

Fig. 10. Pareto–front obtained using the robust multi-Objective optimization approach for C100.

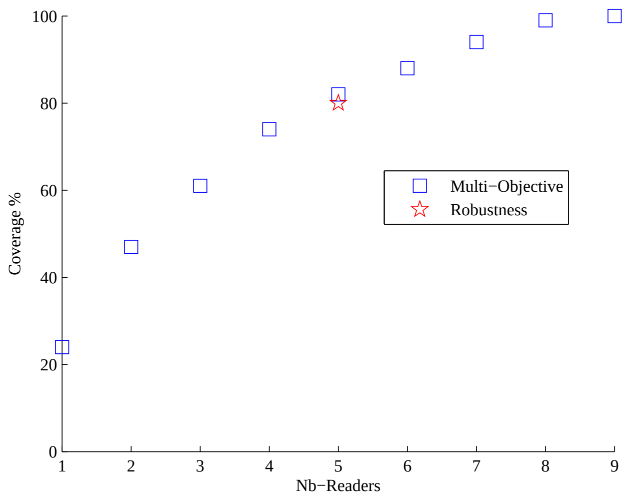

Fig. 11. Pareto–front obtained using the robust multi-Objective optimization approach for R100.

4. Conclusion

This work presented a new approach to solve RFID network planning under uncertainty and obtain an optimal solution of deployment readers problem for the multi-objective RFID network planning. The results obtained demonstrate clearly the efficiency and the robustness of the proposed approach by determining a minimal number of readers, and their optimal positions and locations, guaranteeing full coverage of all tags in the working space, with minimal tags and reader interference. As perspectives, we plan to apply the game theory as a new approach with the aim to achieve optimal deployment of RFID readers to deal with RFID network planning. In addition, we suggest applying the proposed approach for more complex benchmarks and real applications.

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Надійна багатоцільова оптимізація для вирішення задачі планування мережі РЧІ

Аіт Лгадж Ламін С., Рагіб А., Абоу Ель Маджд Б.

Лабораторія LMSA, FSR, Університет Мохаммеда V в Рабаті, Марокко

Радіочастотна ідентифікація (РЧІ) — це нова технологія, що використовується для ідентифікації та відстеження об'єктів або людей за допомогою радіочастотних хвиль з метою полегшення автоматизованого відстеження та збору даних. Система РЧІ складається з електронної бирки, прикріпленої до об'єкта, зчитувачів та програмного забезпечення. У найновіших реальних додатках, заснованих на технології РЧІ, розташування зчитувачів стало центральним питанням планування мережі РЧІ за рахунок оптимізації кількох цілей, таких як охоплення бирок, кількість зчитувачів та завад читачів/тегів. На практиці на систему впливають невизначеність та неконтрольовані параметри навколишнього середовища. Тому оптимальне розв'язування задачі планування мережі РЧІ можна значно звузити за рахунок неконтрольованих змін деяких параметрах, таких як передавана потужність зчитувача. У цій роботі пропонується надійний підхід багатоцільової оптимізації для вирішення задачі розміщення зчитувачів РЧІ. Таким чином, досягнено надійних оптимальних рішень, нечутливих до невизначеностей параметрів оптимізації.

Ключові слова: *РЧІ, задача планування радіомереж, надійність, багатоцільова оптимізація, невизначеність.*