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An RFID network design methodology for asset tracking in healthcare

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ABSTRACT

The purpose of this research is to provide decision makers with a methodology to optimize the design of a medical-asset tracking system constrained by a limited number of RFID readers. Using an enhanced formulation of the *maximal covering location problem* along with a new *criticality index analysis metric* (derived from the *severity*, *frequency* and *dwell time* of the critical medical assets) the optimal placement of the limited number of RFID readers is determined. The proposed methodology is implemented in a healthcare facility where the RFID system coverage has improved by 72% compared to the currently utilized expert/heuristic-based placement strategy.

1. Introduction

Effective and efficient tracking of medical assets in healthcare facilities could be achieved by means of Radio Frequency Identification (RFID) system implementation. However, RFID systems are fairly new, complex, and often prohibitively costly to implement. Therefore, most of the time adequate number of RFID readers are not obtained and properly placed in these facilities for appropriate coverage. Due to the managerial as well as cost related constraints, the number of readers may also be fixed and hence cannot be increased to improve the system performance (size of the total coverage field). In such a scenario, the best way to make use of the current system would be to optimize the RFID reader placement. This research proposes a methodology based on a maximal covering location optimization for optimal placement of limited number of RFID readers. The proposed methodology is validated in an actual healthcare facility where a significant increase in the RFID system coverage performance was observed.

1.1. Motivation

Recently the importance of the service industry has increased considerably as the economies in developed countries have expanded towards a service orientation while gradually shrinking on the manufacturing base [13]. Among all service industries, the healthcare sector is perceived to be the fastest growing and the most critical due to the fact that it deals with human life and any deficiency in this sector can cause inevitable and incurable results [10]. Because of the unpredictable service demand and the complex infrastructure of hospitals, quickly locating the critical assets (which ironically have high utilization numbers) has been one of the perpetual problems in the healthcare service industry [14]. Consider the case where an intensive care unit (ICU) nurse is using an *oxygen regulator* with a stable patient and is called up to help in an emergency case. She would have to immediately go and take care of the patient in dire need rather than taking the oxygen regulator to its regular storage location. If a consecutive event occurs where the same asset (i.e., oxygen regulator) is needed, it would be hard for another nurse or doctor to locate it in a timely manner because it is not in its regular location, but in the ICU room where it was previously left. Therefore, real-time tracking and information sharing of medical assets emerges as a vital issue. Lack of proper tracking of these critical assets would result in poor service quality, low patient satisfaction, customer churn, loss of revenue and, more tragically, loss of the life of a patient [10].

Radio frequency identification (RFID) technology has risen to prominence among auto-ID technologies, which can provide the infrastructure enablement needed to maximize real-time tracking and information sharing of assets to improve underlying service systems [12]. RFID can be used to identify, track, sort and/or detect a wide variety of objects by means of radio frequency transmission using a wireless identification technology that communicates data by means of radio waves. Communication takes place between a reader (a.k.a. interrogator) and a transponder (a.k.a. a tag) where data is encoded in a chip embedded into the tag. Tags that are integrated with an

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antenna and packaged into a finished label can be either active (powered by a battery) or passive (powered by the reader field) [11]. Because RFID does not require line-of-sight to identify an object and is capable of recognizing many objects at once, various fields have employed it. The top three fastest growing economic sectors (i.e., application areas) of RFID are predicted to be (a) retail services, (b) commercial services, and (c) healthcare services [26]. Furthermore, the increasing number of patents filed on innovative uses of RFID in healthcare shows the importance and enormous potential of this technology [1,23,27]. Due to the aforementioned unpredictable and complex nature of healthcare facilities, currently more medical assets are affixed with RFID tags to be able to track their real-time locations and, hence, achieve real-time tracking and information sharing via the backend application of RFID systems.

1.2. RFID in healthcare service sector

The application areas for RFID technology in the healthcare service sector are growing exponentially, and a representative list would include door security, patient ID, inventory management, medical file management, pharmaceutical security, high-heat and sterilization, high accessibility, scalability, availability, error reduction at point of care, medications management, and real-time asset and employee tracking [8]. Among these different possible usages of RFID systems in healthcare, active tracking of critical assets that are shared resources is likely to become the mainstream area of RFID uses in medical settings [9,19,29]. Medical asset tracking with RFID has vital importance due to the complicated and unpredictable nature of healthcare facilities since the location of the assets change arbitrarily and continuously [20]. Therefore, tracking mobile and highly critical medical equipment has become a priority for healthcare system performance. Many hospitals lose equipment worth hundreds of thousands of dollars each year and also spend precious time searching for temporarily lost assets for patient care; these assets include medical devices (such as infusion pumps, portable X-ray machines and patient monitoring devices) as well as other mobile assets (such as wheelchairs, stretchers and gurneys) [25]. Without an asset tracking system, the central supply staff in a hospital may spend hours each day performing a "round-up" [13] of equipment, which is a time consuming manual search of every department for unused equipment or equipment that requires servicing [13]. Additionally, many high-value assets go underutilized while hospitals continue to overspend on additional assets (purchased or rented) in order to increase the timeliness of their services [25].

The healthcare community now sees tremendous benefits in deploying RFID for item tracking (especially high-value mobile assets) and security along with maintaining the highest level of data integrity [21]. There are several obstacles in identifying and tracking objects and people within the hospital environment, which create difficulties in making real-time decisions [2] such as common usage of some assets by different departments, locating the assets in various local storages, locating healthcare providers, and following patients' recovery trends. In order to tackle these obstacles, Li et al. [16] proposed an integrated mobile healthcare service system to shorten the tracking time and increase the accuracy of positioning and identifying people with infection of SARS disease. Wu et al. [28] analyzed an RFID-based healthcare system that identifies the patient and compares drugs intake. This allows the healthcare providers to eradicate patient–drug mismatches, over dosages and drug errors. Booth et al. [3] pointed out other possible applications in the location of staff and patients, theft prevention, patient safety, incident audit trail, dynamic patient–equipment association, equipment status, and cost capture. Østbye et al. [20] specifically focused on a study that analyzes whether an RFID-based infrared system would increase equipment utilization and decrease personnel time spent on searching for the assets in a hospital. This study revealed that the proposed RFID-infrared integrated system improved the current control system's accuracy to detect various types of medical equipments in the healthcare facility where the case study was held.

By optimally placing RFID readers throughout the hospital, the search time for critical assets can be minimized and also fewer staff would be needed to perform the round-ups. Additionally, such a system enables a faster response to patient needs as equipment locations are known and are accessed more rapidly [13]. Thus, in emergency situations, RFID systems enable nurses to spend less time searching for equipment, while preventing materials managers from ordering excess amount of equipment [18]. Therefore, having an RFID-based asset tracking system in hospital settings is proven to be cost-effective and economically justifiable [4].

An important issue in the design of RFID systems is the placement of readers to achieve optimal system performance [4]. Guan et al. [7] conducted a study to identify optimum reader placement. The objective was to minimize the number of readers with the constraint that all RTPs (read test points in sensor field) should be covered and the interference level should be minimized. Similarly, Chakrabarty et al. [4] has also approached the same problem but from a slightly different direction; evaluating different types of readers, their objective was to identify the best combination of these reader types along with their required quantities to satisfy the objective of best possible sensor coverage.

1.3. Proposed method

The related research section reveals that there is a vacancy in literature to overcome the case where the RFID system has a fixed number of readers (due to budget-related or other acquisition-related issues). Therefore, the main assumption in this research study is that the number of RFID readers cannot be increased and the available number of RFID readers is less than what would be needed for full coverage of the complete field. Under such a scenario, rather than the minimization of the number of readers, the main optimization problem is to place scarce RFID readers so as to maximize the utility of the system (i.e., obtain the best sensor field coverage). In this paper, we propose a methodology to handle such a case.

Maximal covering location problem [22] is shown to be an effective approach to solving this type of location specification problems. Therefore, this paper focuses on optimal RFID reader placement to track crucial assets using an improved maximal covering location problem. The enhancement is achieved with a criticality index analysis and the system is implemented and tested at a healthcare facility. Crucial assets can be defined as expensive resources which are less in quantity. In case of emergency, it is vital for healthcare staff to easily and quickly locate them to avoid any serious harm to the patients or cause of deaths.

Fig. 1 summarizes the general framework of the proposed methodology. Given the specification of the problem as inputs (i.e., hospital floor plan, number of RFID readers and their read ranges, and expert knowledge), first, a severity analysis of the critical assets is to be performed. The severity analysis is performed using a knowledge acquisition method where a survey (including questions with a five-point Likert scale [17]) is conducted with the medical experts to incorporate their knowledge/information about the importance/urgency level of the medical assets in a variety of medical settings. Then, the whole floor plan of the healthcare facility is to be divided into squares as a representation of grid points. By performing the frequency and dwell time analyses for each square and combining them with severity analysis, the criticality index of each square is to be determined. At this point, an optimization model based on a modified extension of MCLP is to be formulated. Since the complexity of the problem is high due to the large number of alternatives/combinations to evaluate, there needs to be a meta-heuristic approach (e.g., genetic algorithm (GA) or simulated annealing) to solve this problem. By the

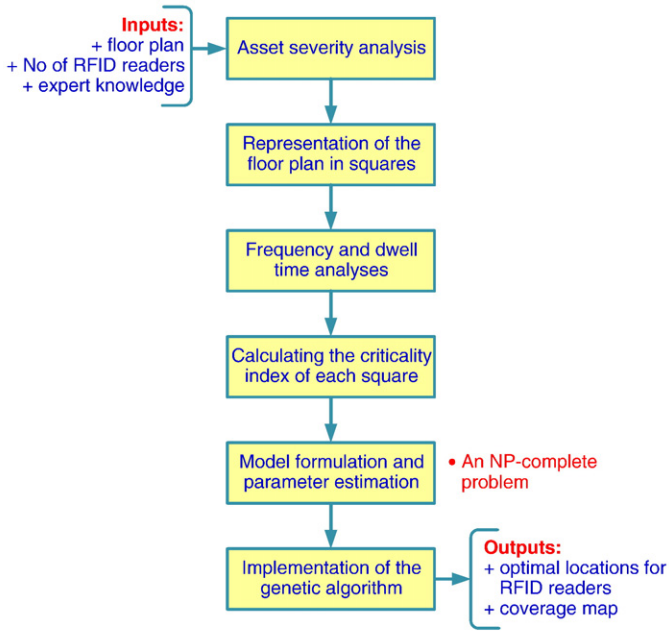

Fig. 1. The process flow of the proposed method.

utilization of a colored map of grid points, the initial solutions for the GA algorithm are generated, and subsequently (through an iterative process) the "optimal" solution to the RFID reader locations is obtained. Since GA is a heuristic, the optimal solution is not really the global optimum, rather, a good enough solution under the terminating conditions.

The rest of the paper is organized as follows. Section 2 presents the proposed optimization model for the RFID reader placement problem. Section 3 provides a case study (an actual implementation at a healthcare facility) to validate the proposed methodology. Therein a comparison of the proposed methodology with the existing heuristic method is also provided. Finally, Section 4 summarizes the findings and provides some concluding remarks.

2. A methodology for RFID network designs in healthcare facilities

2.1. Objective function and constraints

The first step in our proposed method is to divide the whole floor plan into small squares as seen in Fig. 2. The floor can be considered as a grid that contains n squares, commonly called *demand squares* (*DS*) in a generic MCLP problem.

As seen in Fig. 3, a *reader node* "A" in the circle is defined as a candidate place for the RFID reader which covers its surrounding demand squares based on its radius of reader range (RRR). Four demand squares are represented in Fig. 3, as a representative example. However, by dividing the floor plan into a different number of demand squares and considering various read ranges of RFID readers, the coverage of a reader node may vary. Here, there is a loss of information that stems from the fact that the floor plan is divided into square grids whereas the RFID reader coverage is defined as a circular area. However, according to our calculations, this loss was not found to be very significant and hence is ignored in the modeling. In order to evaluate the reader coverage achieved after positioning a reader on a particular reader node, it is necessary to evaluate the criticality index of the demand squares it covers. It is proposed here to evaluate the criticality index of these squares by integrating severity, frequency, and dwell time of all assets which visit that particular demand square.

The brief definitions of these three terms are as follows:

Severity (s_k) The importance level of asset k in emergency cases as evaluated by experts based on a five-point Likert scale.
Frequency (f_{ki}) Number of times asset k passes through demand square i in a day.
Dwell time ($(d_t)_{ki}$) Average of time that asset k spends in demand square i in a day.

The criticality index of demand square i which is represented by c_i is calculated using the following equation:

$$c_i = \sum_{k=1}^{L} f_{ki} * (d_t)_{ki} * s_k \quad (1)$$

where k is the type of assets; f_{ki} represents the frequency of asset k in square i per day; $(d_t)_{ki}$ indicates the dwell time of asset k spent in demand square i per day; and s_k indicates the severity of asset k.

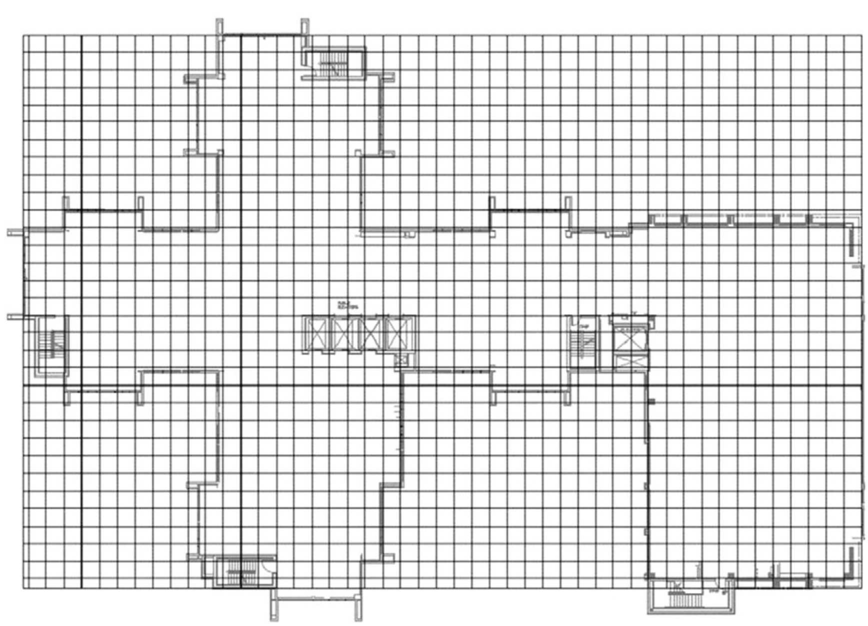

Fig. 2. A floor plan representation divided into grid of squares.

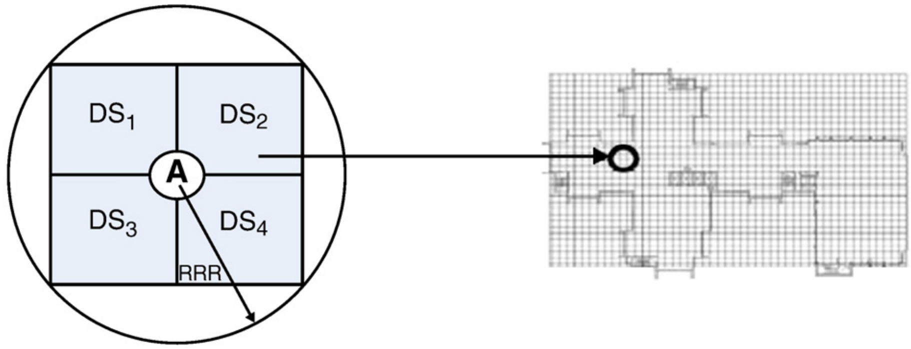

Fig. 3. Reader node and the demand squares it covers.

A greater criticality value of a demand square indicates (1) a higher frequency of assets visits that particular demand square (referring to frequency), (2) a larger amount of time spent in that demand square (referring to dwell time), and/or (3) the severer assets are being utilized/stored in this demand square (referring to severity of asset).

By considering Fig. 3, coverage of reader node A is given by the addition of the criticality indices of demand squares ($c_1, c_2, \ldots, c_t$) that it can cover based on its read range; namely the coverage will be $A = c_1 + c_2 + c_3 + \cdots + c_t$ under the assumption that one reader can cover t number of demand squares. For Fig. 3 particularly, this value would be $A = c_1 + c_2 + c_3 + c_4$ where c_1, c_2, c_3, and c_4 refer to criticality values of demand squares (DS_1, DS_2, DS_3, and DS_4, respectively). Reader coverage defined by A is obviously desired to be increased. However, if there are excessive number of RFID readers, their coverage areas would collide, which is called reader collision/ interference. Reader collision problems mainly occur in a dense reader environment where several readers try to interrogate tags at the same time in the same vicinity [15]. In the case of reader collision, the reading results can be unsatisfactory with coinciding read times, multiple read instances, and undesirable data integrity problems.

Having a fixed number of readers, p, our objective is to locate these p readers on m candidate reader nodes to maximize possible coverage on the service floor. To achieve this goal, the mathematical model is formulated as follows:

$$\text{Max } w_1 \left(\sum_{i=1}^{n} c_i {*} y_i \right) - w_2 \left(\sum_{i=1}^{n} \left(\sum_{j \in N_i} x_j \right) - y_i \right). \tag{2}$$

Subject to

$$m {*} y_i \geq \sum_{j \in N_i} x_j \geq y_i \quad \text{for } i = \{1, 2, \ldots, n\} \text{ where } N_i = \left\{ j \mid l_{ij} \leq s \right\} \tag{3}$$

$$\begin{aligned} &\sum_{j=1}^{m} x_j = p \\ &x_j = 0, 1 \qquad j = \{1,\ 2, \ldots, m\} \\ &y_i = 0, 1 \qquad i = \{1,\ 2, \ldots, n\} \end{aligned} \tag{4}$$

As defined by Eq. (1), c_i is the criticality index of each demand square in the grid; y_i is a binary variable whose value is "1" if demand square i is covered by at least one reader and "0" otherwise; n is the total number of demand squares and m is the total number of reader nodes (candidate places for readers); x_j is a binary decision variable whose value is "1" if a reader is located at reader node j, and "0" otherwise. Therefore, y_i is dependent on x_j. N_i is the set of reader nodes (j) that can cover demand square i. The distance between these reader nodes and demand square i "l_{ij}" should be less than the read range of the reader "s".

The objective function of this model (Eq. (2)) is to identify the optimal location of available readers by: (1) maximizing total covered criticality indices of demand squares by $z_1 = \sum_{i=1}^{n} c_i y_i$ and (2) minimizing the reader collision by $z_2 = \sum_{i=1}^{n} \left(\sum_{j \in N_i} x_j \right) - y_i$. The first objective ($z_1$) is straightforward. The rationale for the second objective (z_2) is as follows: If multiple readers cover the same demand square(s), reader collision will occur. In order to minimize this possibility of reader collision, z_2 will force the model to assign only one reader for the same demand square to be covered. These two objectives are formulated as a multi-objective function in which the weights of these two objectives are represented by w_1 and w_2, respectively (Eq. (2)).

By having at least one reader on one of the elements of $N_i (\sum_{j \in N_i} x_j \geq 1)$, demand square i will be covered ($y_i = 1$). On the other hand, demand square i will be an uncovered square ($y_i = 0$), if there is no reader on N_i reader nodes ($\sum_{j \in N_i} x_j = 0$). This constraint is formulated by Eq. (3). The constraint indicating that the total number of available readers is fixed at p is represented by Eq. (4). Fig. 4 illustrates the schematic representation of the optimization model.

2.2. Implementation of the proposed methodology by genetic algorithms

When there is a large number of demand nodes in the model, the total number of constraints increases drastically. Therefore, the proposed method can be classified as an NP-complete (or NP-hard) problem. It is not possible to find the global optimum solution of this

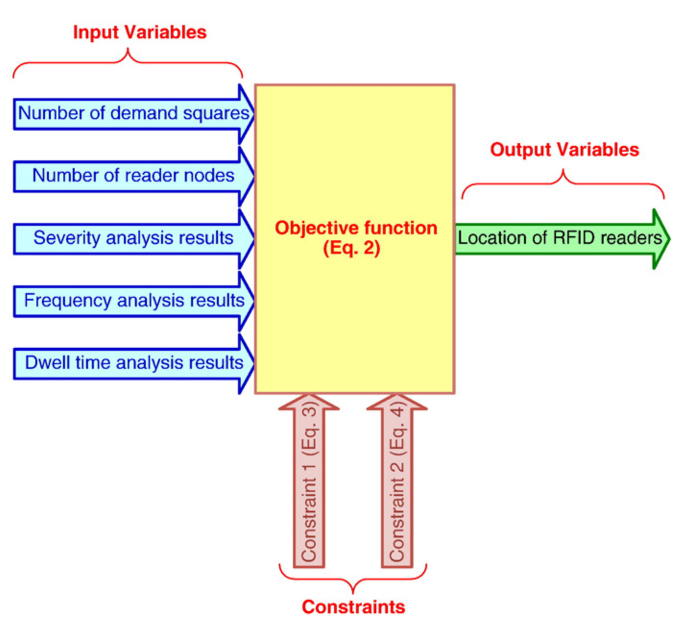

Fig. 4. Schematic representation of optimization model.

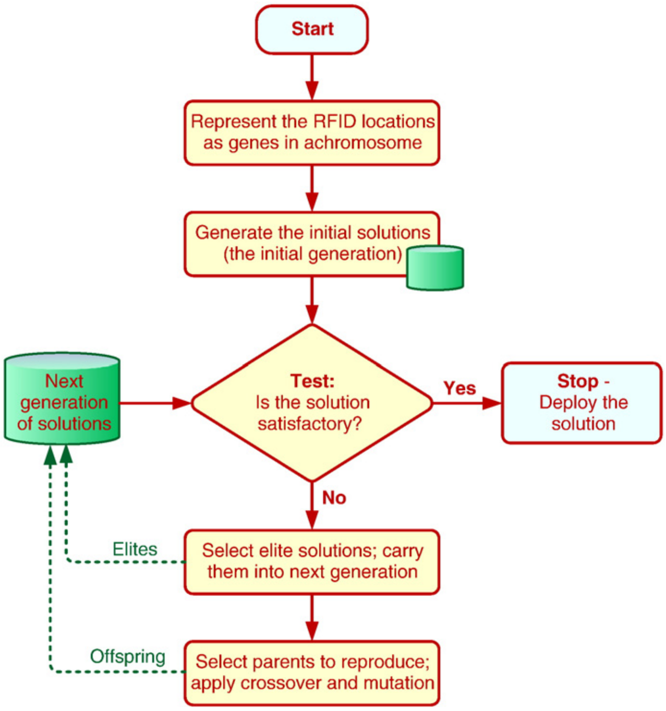

Fig. 5. Genetic algorithm-based solution development process.

problem using deterministic approaches (i.e., linear modeling). Hence, it is necessary to implement a meta-heuristic algorithm to overcome this issue and provide a suboptimal satisfying solution [24]. In this study, a genetic algorithm (GA) method is utilized. GA is a stochastic global search method which is a nature-inspired algorithm based on the process of natural biological evolution and is used to solve optimization problems [6]. The overall procedure using GA is illustrated in Fig. 5.

The fitness function of the GA algorithm is given by Eq. (2). Each chromosome consists of *p* genes where genes represent the places where the readers are to be allocated. Therefore, each chromosome represents a solution set which exhibits the places of the readers in the service floor. After representing the solution in terms of a chromosome consisting of *p* number of genes, the initial population of solutions is randomly generated. After evaluating the fitness of each potential solution in the population, the chromosomes are ranked based on their fitness values. The ones with the best values are migrated to the next generation of solutions and the remaining better ones are given higher probability to be used as parents of the subsequent populations. During the reproduction process, the randomly selected parents are pushed through the mutation and crossover operations. In deciding whether to perform a mutation and/or a crossover, two common variables are utilized: P_C (*probability of doing crossover*) and P_M (*probability of doing mutation*). These variables are evaluated using a random number generator. Parents that take part in the mutation and the crossover are randomly selected, giving higher possibility to the ones with better fitness values. The graphical representation of reproduction operators is shown in Figs. 6 and 7. In Fig. 6; numbers 90, 101, 20, 14, and 32 represent the places of the reader nodes. For crossover, two parents are selected randomly. As shown in Fig. 7, the crossover is performed using the *one-point crossover method* [5].

3. Case study

To validate the proposed methodology, a case study was performed at Stillwater Medical Center (SMC).

3.1. Introduction of the healthcare facility

SMC had an RFID system in place for three years to track the location of the certain medical assets. The assets which were important and/or difficult to find were affixed with active RFID tags so that in emergency situations these assets could be located quickly. However, SMC still faced problems with the ability to locate those assets on time. The reason for this was twofold: (1) There was limited number of RFID readers so full coverage of the floor cannot be achieved, and (2) The locations of these readers were not optimally determined. The readers were placed based on the experiences and estimation of the healthcare providers in SMC. The proposed methodology was used to maximize the coverage of the RFID system with this fixed number of readers.

To demonstrate our proposed method, the third floor of SMC (which was the busiest floor in the medical center) was used in the case study. As illustrated in Fig. 8, there were three departments on this floor: (1) Intensive Care Unit (ICU), (2) Respiratory, and (3) Nursing. The assets were stored in various storage places according to convenience and/or usage profiles of those assets. Knowing the location of these storage places was necessary for conducting the frequency and dwell time analyses.

3.2. RFID tracking system in use

The RFID system being used by SMC was provided by WhereNet Corporation®. The system consisted of the following components: (1) whereport, (2) location sensor, (3) backend application, and (4) tags.

3.2.1. Whereports

In this system RFID readers are called as whereports. When a tag is in the read range of a whereport, the tag is sensed and located by the whereport. The whereport creates a spherical magnetic field which interrogates the tag(s) within its sensing field. Typical read range at various positions with the combination of power requirement and power level settings are given in Table 1. In general, the wider the read range, the greater the required power. The usual practice is to keep the power range at level 4 which gives spherical read range of 7 ft.

3.2.2. Location sensors

Location sensors are the devices which receive the signal from the whereports and then transmit it to the backend application. These sensors communicate with the whereports in their surrounding area.

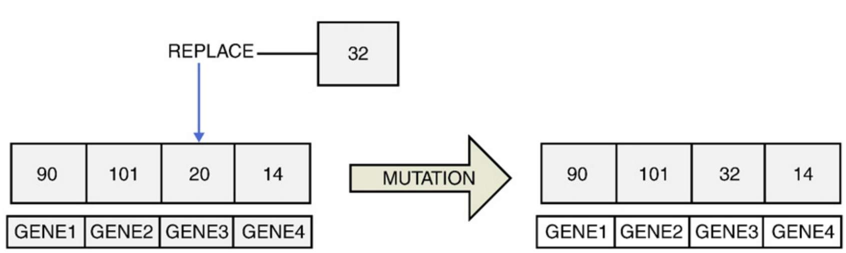

Fig. 6. A sample representation of mutation process.

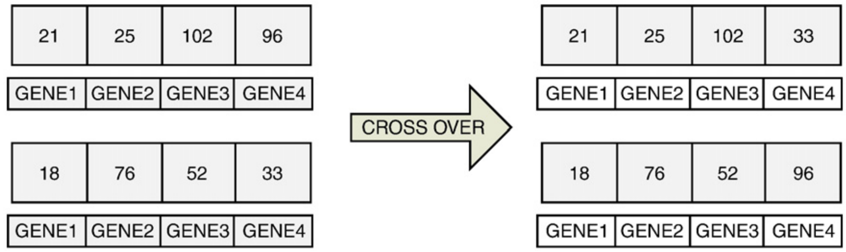

Fig. 7. A sample representation of crossover process.

The real-time locating system (RTLS) operates on 2.4 GHz RF, and the location sensor read range is approximately 350 ft.

3.2.3. Tags

The system uses active RFID tags. The positioning of these tags is such that they are unobstructed in relation to whereports at all directions. This enhances the signal exchange between the whereport and the tag.

3.2.4. Backend application

The system uses a GE IntelliMotion® backend database for recording tracking occurrences. This system is mainly used for collecting the data in real-time and visualizing the location of an asset at the time of need.

The present sensor distribution and coverage offered by these sensors are illustrated in Fig. 9. Since the location sensor offers coverage of about 350 ft in radius, whereas the whereports offer coverage of about 7 ft, the main problem of low RFID system performance stems from the poor positioning of the whereports rather than the location sensors.

3.3. Implementation of the RFID network design methodology

3.3.1. Severity analysis of assets

SMC had a number of medical assets which were insufficient in quantity, but in emergency situations it was important to locate them in a timely manner. These assets were already affixed with active RFID tags and all assets that were used on the third floor are listed in Table 2. A survey was conducted with various departments regarding the importance of each asset as defined in Section 2.1. The severity value indicates the degree of importance it has in helping rescue the life of a patient, which translates to the degree of importance placed on the ability to locate the asset in a timely manner. A five-point Likert scale, ranging from extremely important (=5) to mildly important (=1) (representing a descending order of importance level) was utilized in acquiring the expert opinions. The severity values for all assets evaluated by the SMC healthcare providers are summarized in Table 2. It also tabulates the number of assets used on the third floor of SMC. A change in these numbers would definitely affect the efforts spent in the time and motion analyses steps although they would not affect the computational complexity and scalability of our method. The only parameters affecting computational complexity and scalability are RFID reader range and grid points of the floors (demand squares).

3.3.2. Frequency and dwell time analyses

A time and motion study was conducted for the assets on the third floor to identify the path that each asset follows and the frequency of it passing through this path per day. These values were assigned as the frequency value, f_{ki}, number of times asset k passes through demand square i per day. Using a similar method to the frequency analysis, the dwell times for each asset was also obtained. The dwell time was calculated as the time that an asset spends in a demand square for a day.

3.3.3. Criticality index analysis and initial solution for GA

The criticality index of each demand square was calculated by Eq. (1). Fig. 10 is the diagram of the third floor which shows different

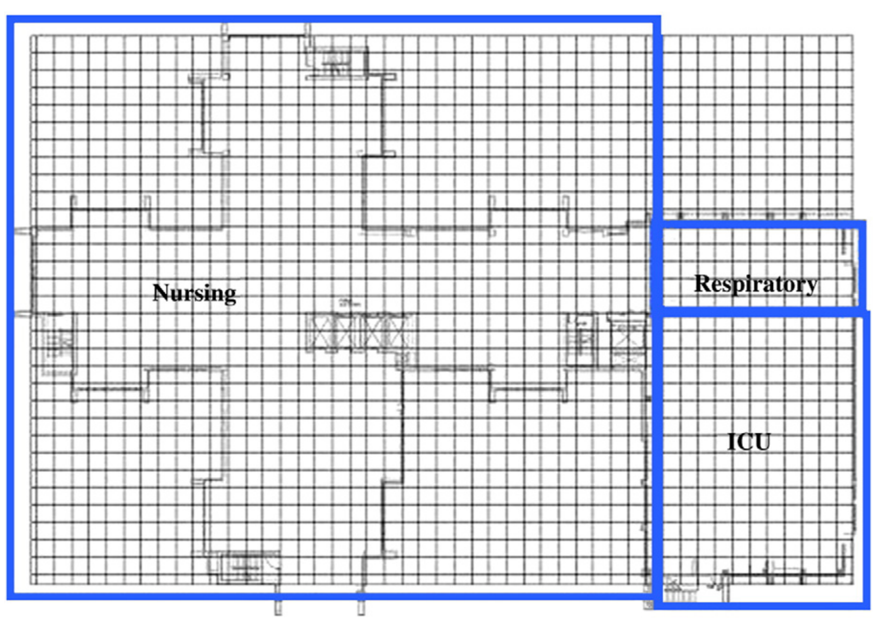

Fig. 8. Plan for the third floor of SMC with its departments.

Table 1
Various ranges of whereports.

Power level setting	Any orientation range	Good orientation range	Release range
1	3.5	4	6
2	5	6	9
3	6	7	11
4	7	8	13
5	8	9	15
6	9	10	17
7	13	16	24
8	15	20	30

Table 2
List of critical asset with owning departments and severity values.

Name of the asset	Owning department(s)	Severity values	Number of the asset in system
Bed warmer	ICU	1.50	2
CPM machine	ICU	2.67	6
Doppler	ICU	2.33	2
ECG/EKG machine	ICU	2.42	1
Heat therapy pump	Nursing	2.00	1
O_2 regulator	ICU, respiratory, nursing	5.00	47
PCA pump	ICU, nursing	3.67	21
Sequential compression pump	ICU, nursing	3.00	39
Vital sound monitor	ICU	2.33	7
Bi-PAP	Respiratory	2.58	4
Wheelchair	ICU, respiratory, nursing	3.83	43
Ventilator	Respiratory	1.67	5
Continuous pulse oxymetry (CPO)	Respiratory	3.67	19
IV pumps	ICU	2.67	21
Entreal feeding pump	ICU	2.00	2
Misttent	Respiratory	1.67	5
O_2 cylinder	ICU, respiratory, nursing	4.87	54

criticality index values of the demand squares with different colors, for example, red (dark-gray in black and white printing) corresponding to the highest criticality value and blue (light-gray in black and white printing) to the lowest. Since there were four readers to be used for this floor, the initial GA solution of the reader placement is also indicated in the colored map by the four circles (see Fig. 10).

A careful analysis of the colored map revealed that nodes in blue zones could potentially be eliminated since the criticality index values of these nodes are the lowest (making them unlikely candidates for reader placement location). An example of this elimination procedure is graphically represented in Fig. 11.

3.4. Results of the case study

After implementing the proposed methodology by using 100 replications with different population sizes and selection probabilities for the GA algorithm, the best solution is obtained and summarized in Table 3. In this case study, the weights in Eq. (2) are set as equal for both objectives (z_1 and z_2). The current locations of the readers provided 14% coverage of the demand squares and are represented in Fig. 10 with circles. The implementation of our methodology improved this performance metric to 24.05% and the proposed locations of the RFID readers are marked with circles in Fig. 12. The results as well as the RFID reader locations are compared in Table 3. The maximum coverage of the system proposed by our methodology provided 72% more coverage than the existing heuristic placement of the readers by assigning the four readers to nodes 72, 145, 137, 169, which validates the viability of the proposed method.

In the first sight, the performance of the proposed method could be perceived unsatisfactory with only 24.05% coverage. However, taking into account the fact that SMC currently has only four RFID readers (as shown with circles in Figs. 10 and 12) and the third floor of SMC is a rather large area inhabited with a large number of critical assets, the increase in the reader coverage (from 14% to 24.05%) is actually quite significant. The SMC decision makers agreed with this fact and decided to apply our solution to achieve more timeliness on tracking the critical assets.

Using the case study settings, we also investigated how the RFID reader placement and corresponding coverage levels would change if we change the definition of the criticality index. Since different preferences may result in different definitions of the criticality index, (for example, one might choose to use only the frequency as the

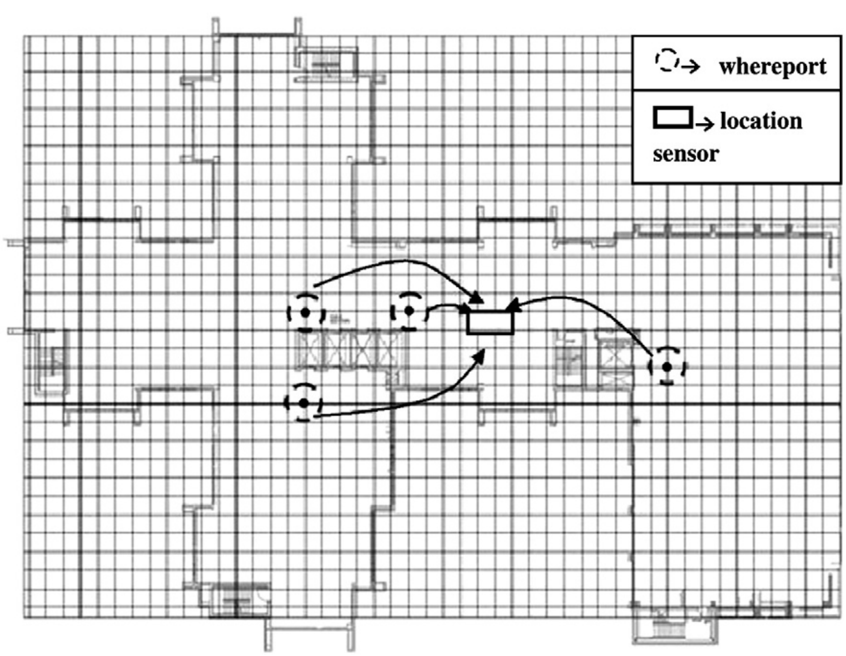

Fig. 9. Present whereport and location sensor placement in SMC.

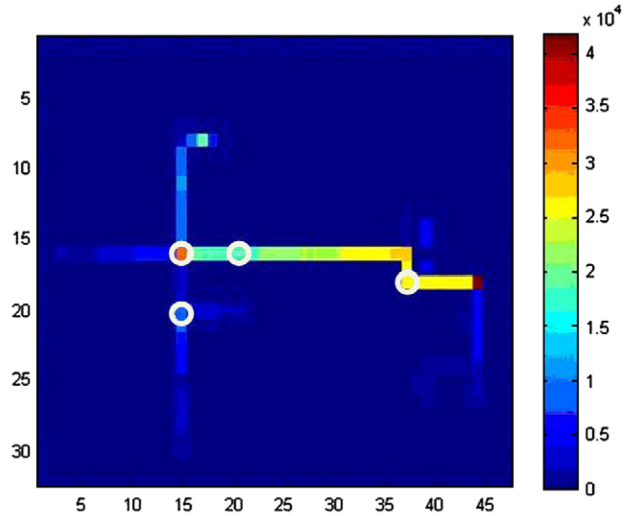

Fig. 10. Current placement of RFID readers (marked with white circles) in SMC.

determinative parameter of the criticality index, instead of the combination of severity, frequency, and dwell time), it would be a worthy effort to see how sensitive the placement and coverage of the readers are to these different definitions of the index. The results of all feasible definitions of the criticality index along with the current sensor field coverage of the RFID readers are summarized in Table 4.

As shown in Table 4, in addition to the Eq. (1), five other possible ways to define criticality index values are explored: (1) frequency only, (2) dwell time only, (3) both dwell time and severity values, (4) both frequency and severity value, and (5) both frequency and dwell time.

Based on the results presented in Table 4, our proposed RFID network design method outperforms the current heuristic placement of the RFID readers in all possible definitions of the criticality index. Improvements on the coverage of the sensor field are observed for all different types of the criticality index definitions. In particular, the improvement seems to be most (87%) when the criticality index is defined as the combination of frequency and dwell time of the assets $(c_i = \sum_{k=1}^{L} f_{ki}*(d_t)_{ki})$. Also the consideration of only frequency gave a high improvement with 81%. Both of these definitions in fact rely on the assumption that all the assets have the same severity value

Table 3
Summary results of the case study.

Comparison	Node 1	Node 2	Node 3	Node 4	Coverage
Current system solution	72	145	107	73	14.00%
Proposed method solution	72	145	137	169	24.05%

because they do not incorporate this parameter (s_k). However, for our case study this assumption and in turn these definitions of criticality index are not acceptable since the severity values for each medical asset are considerably varying as shown in Table 2. Yet, these definitions may be useful for other RFID settings where the assumption (that all assets are equally important) holds.

4. Summary and conclusion

In this paper, we provided a detailed description of a decision support system aimed to maximize the sensor field coverage by optimally placing the fixed number of RFID readers. The underlying methodology utilizes a new parameter called criticality index to better evaluate the demand squares to determine the optimal location of the readers for maximum coverage of the service floor. The methodology is validated by a case study at a healthcare facility. The case study results showed that compared to the existing heuristic placement of the RFID readers, the proposed methodology improved the coverage of RFID readers on the hospital floor by 72%. For the cases where the number of readers are fixed for some reason (such as limited budget for the RFID system deployment) and the service area is larger than what can be covered with the limited number of readers, the proposed methodology can be used to optimize the reader placement location and hence maximize the sensor field coverage.

There are two noteworthy points in the study: (1) although the proposed modified MCLP-based methodology is validated with only four RFID readers in the case study section, the problem can be applied to any number of readers. This would only require changing the parameter p in Eq. (4). The case study was focused on only four readers to prove that there is an improvement in the RFID reader coverage compared to the current RFID setting of the healthcare facility on hand. (2) Given that the required parameters in Section 2.1 can be obtained, the proposed methodology can be implemented in any RFID-related setting (e.g. production systems, retail shop floors, security areas, etc.). In this study, it is illustrated through a medical asset tracking example, but the methodology can be generalized to different asset tracking systems that utilize an RFID system. This is

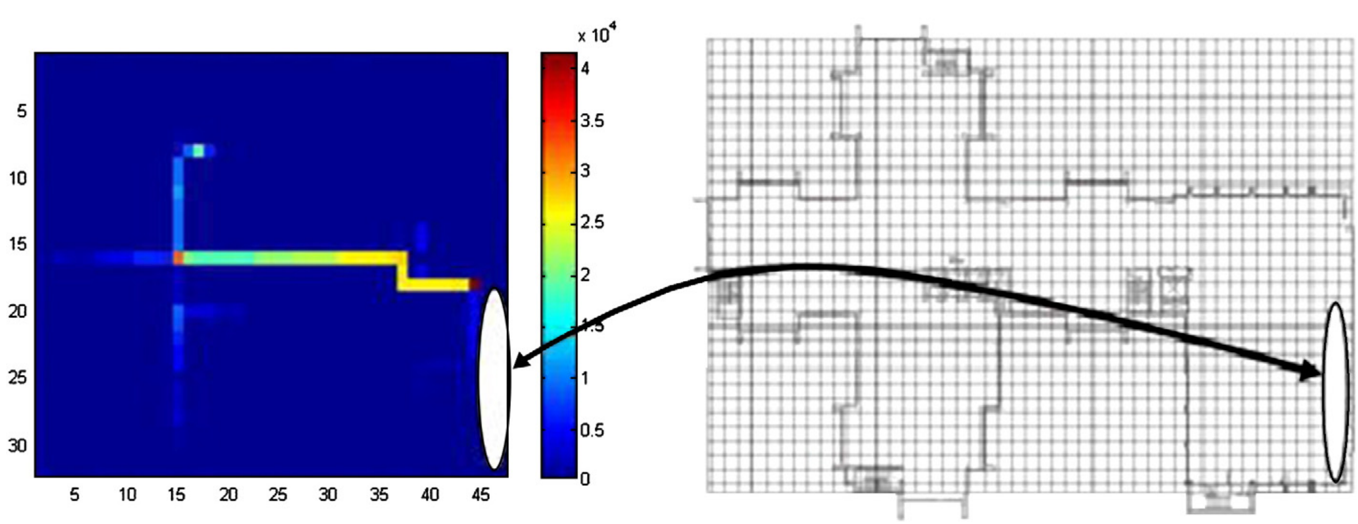

Fig. 11. Eliminating reader nodes with low criticality index values.

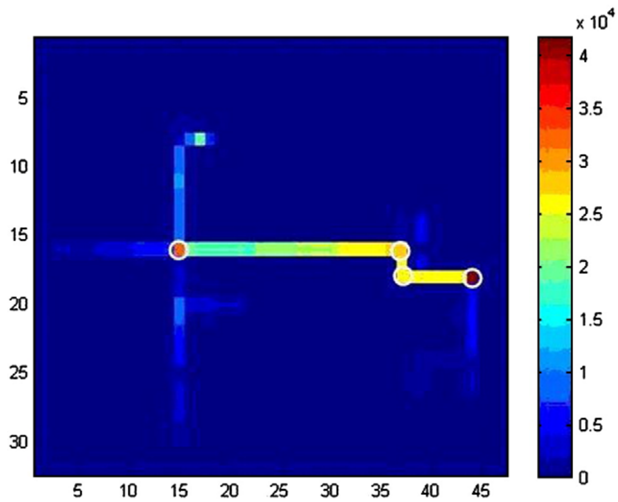

Fig. 12. Colored zones of floor plan indicating the criticality of each demand square.

feasible because the construction of the criticality index in Eq. (1) provides a comprehensive representation, making the underlying methodology adaptable to other RFID-related tracking systems.

Although the case study results are promising and validate the viability of the proposed decision support system, the study is not without limitations. It has a strong assumption that the number of RFID readers is fixed due to some managerial reasons (e.g. budget constraints). The authors are in preparation of an extended methodology which would relax this assumption. The new methodology would address the scenarios where the number of readers can be increased to achieve full (100%) sensor field coverage with the minimum possible number of readers. This extended methodology is intended to utilize the local set covering problem (LSCP) where the main objective is to minimize the cost of achieving a specified level of coverage for a given service floor layout with an arbitrary list of critical assets. Such a solution would provide the decision makers with the information of how many RFID readers (a mix of readers with varying read ranges) are needed at minimum to guarantee a certain level of coverage (up to 100%). Additionally, future directions of this research effort include adding other critical resources such as doctors and nurses to the mix of "assets" that need to be tracked/located in a timely manner at the time of emergency in a healthcare system. These extensions to the proposed methodology aim to find the optimal number of RFID readers and their optimal placement subject to the desired level of system coverage, minimum reader collision, a given set of critical assets and a given specification of the service floor layout. Another interesting point of future research is to conduct a stability analysis for the model parameters. For instance, the recalculation of the severity value (as evaluated by the experts) may be of interest if the demand is dynamic throughout a working day. This analysis would be helpful especially if the RFID readers are portable and can be moved easily from one location to another within the same day. Additionally, the level of the business of a unit might be further analyzed in depth to see whether or not it affects the RFID reader locations as a critical factor. This would particularly have a great importance for the retails shop floors where various departments have the same assets being tracked but the number of customers they serve are far different than each other.

We can state that this study would ease the efforts of the managers to handle the strong constraints of their firms/companies. If the cost is the topmost severe constraint for an RFID-related setting, the managers would be willing to use our methodology to optimize the coverage of the fixed number of RFID readers. In terms of the research implications, the study is the foremost one which incorporates GA-based maximal covering location problem into RFID implementations for a more efficient asset tracking system.

Table 4
Definition of criticality index against coverage performance.

Sensor field coverage / Definition of criticality index	Current placement	Proposed method	Improvement
$c_i = \sum_{k=1}^{L} f_{ki}$	12.9%	23.3%	81%
$c_i = \sum_{k=1}^{L} (d_t)_{ki}$	5.4%	7.5%	38%
$c_i = \sum_{k=1}^{L} (d_t)_{ki} * s_k$	10%	14.9%	49%
$c_i = \sum_{k=1}^{L} f_{ki} * s_k$	9.8%	14.6%	49%
$c_i = \sum_{k=1}^{L} f_{ki} * (d_t)_{ki}$	12.6%	23.5%	87%

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