RFID-Network Planning by Particle Swarm Optimization

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***Abstract*— The design of an ad-hoc network of readers for a complex RFID system in large areas requires the deployment of a large number of readers due to the limited range of reader-tag communication. For passive tags the factors affecting the performance of the reader-tag communication depends on many physical and geometrical parameters. Line of sight is a constraint of the reader-tag link while scattering objects producing electromagnetic interferences affect the shape and the extension of the read-zone i.e. the region where a reader can activate a tag. This region depends not only on the emitted power and reader/tag antennas radiation patterns but also on the propagation environment. When a number of readers are planned in a network, mutual coverage of read-zones and mutual interference among readers are undesired while safety regulation constraints have to be fulfilled in the whole area. Simple and effective models of electromagnetic elements involved in the planning are developed and included in the frame of a Particle Swarm Optimization algorithm. Numerical results show the effectiveness of the method.**

I. Introduction

Radio Frequency Identification (RFID) technology is going to be used in a number of applications involving automatic detection, location, tracking and/or identification of objects and/or people. Passive Ultra-High Frequency (UHF: 880-960MHz) RFID technology is frequently preferred to other RFID variants due to its longer read range and low cost. A basic UHF passive RFID consists of a reader (i.e. a radio-scanner unit) and a number of remote transponders called tags which extract their operating power from the reader signal. Due to the limited interrogation region of readers, large-scale RFID deployments often need multiple transmitters properly placed to cover the entire region of interest [1-3]. The planning of RFID networks, however, has to comply with the possible overlapping among interrogation regions of different antennas. This effect could be a useful redundancy in some applications (localizations) or has to be instead avoided in others (inventory) since it worsen the efficiency of the coverage and produces undesired multiple readings of a same tag.

Focusing on the latter case, the planning of RFID networks is aimed to maximize the overall read region so that tags can be read anywhere within a given environment, while the overlapping regions are minimized. The goal of the planning is fulfilled using the minimum number of antennas in order to reduce the cost and the complexity of the network. The locations of readers' antennas is a degree of freedom of the planning process, but also the emitted power and the orientation angle of reader antennas can be exploited (Fig.1).

The read region of the single reader depends on the power emitted, which is upper-bounded by the regional regulations, on the tag sensitivity over the considered objects and on the orientation of the antennas [4], but it is also affected by the electromagnetic scattering from the nearby scenario.

The planning of RFID network moves away from the planning paradigm of other wireless networks. The down-link (reader-to-tag) is in fact subjected to the severe power threshold of the tag's microchip while the up-link (tag-to-reader), being based on backscattering, involves small power levels. Line of sight between reader antenna and tag antenna is preferred since non-line of sight communications are frequently not possible owing to the poor link-budget or because not useful for the particular application (as in the case of localization). The deployment of network antennas can be made almost everywhere in the environment: for instance, in indoor environments reader antennas can be placed on ceiling, floor and walls but also some furniture structures as shelves and tables can be used to host them. Thus the structure of the network is strictly related to the topography of the environment.

Planning procedures have to include fast electromagnetic tools able to handle the propagation phenomenology with a reasonable accuracy. Although a very reliable prediction of the read region is now affordable by using the state of the art electromagnetic ray tracers, their extensive application to this planning problem however reveals time consuming. Closed-form propagation estimation, retaining the complexity of the free-space formula, are instead preferred.

A. The planning method

The planning method, here proposed, involves a model that simplify the electromagnetic calculations taking into account all (or most of) the system parameters of the reader-tag-environment system including the power/exposure constraints in the UHF range. Fig. 1 shows a region Ω to be uniformly covered using N reader antennas. The ith antenna R_i has interrogation region Ω_i with tilt angle γ_i. Ω_O is overlapping region between two reading region. Dot and star symbols represent the allowed position of the readers $\{\underline{r}_R\}$ and the read test point $\{\underline{r}_T\}$ (i.e. points to check if a tag is readable or not), respectively. This is a constrained optimization problem where constraints concern the maximum value of EIRP, the maximum number of possible antennas N which represent an upper limit to the cost of the network, the permitted position of the antennas, the orientation of antennas, and finally the maximum field strength admitted in man-populated regions of the environment, as required by the exposure limitations. The model encodes all the electromagnetic parameters into geometrical parameters, such as distance and shape, transforming the electromagnetic problem into a geometrical problem. The so formulated RFID network planning is similar to a packing problem in Management, Computer Science, Operations Research [5], and is here handled by the Particle Swarm Optimization (PSO) algorithm [6-7]. The effectiveness of the ellipsoidal model has been checked with different simulated and measured test cases.

II. Planning problem

The allowed position for the readers $\{\underline{r}_R\}$ depends on the specific environment and on other engineering constraints. The read test points $\{\underline{r}_T\}$ quantify the read region's size corresponding to a particular network topology and emitted power, they are dislocated with a rule depending on the particular finalization of the network and with the convention that each $\underline{r}_T$ belongs to the read region provided that the field strength at that point is enough to activate the tag's microchip. Additional *safety test points* $\{\underline{r}_S\}$ are introduced to check if the radiated electric field, at places populated by persons, exceeds the threshold of the regional safety regulations.

The extension of the interrogation region of an antenna depends on the amount of radiated power. In free-space the interrogation region is a scaled volume of the radiation pattern of the antenna but in presence of an obstacle it is shaped by the scattering phenomena. In particular, in indoor environment where many scattered fields contribute to the power received by the microchip, this region is not completely uniform i.e. not a path-connected space, showing jagged zones due to the interference fringes of different contributions. But jagged zones are not useful to quantify the extension of the read region because a variation of a few centimetres in the tag's position could cause an intermittent and not reliable response. Hence network evaluation has to consider a reduced path-connected subset of the interrogation region. A suitable fast electromagnetic model will be introduced to give a simple representation of such region by handy geometrical shapes.

The solution of the planning problem is cast as a constrained optimization aimed to maximize the following *fitness function*:

$$\begin{aligned} F = {} & w_{COV} f_{COV} + w_{OV} f_{OV} + \\ & + w_{EIRP} f_{EIRP} + w_{COST} f_{COST} \end{aligned} \quad (1)$$

where $w_{(.)}$ are suitable weighs ($\sum w_{(\cdot)} = 1$).

The individual contributes of F are defined as follows:

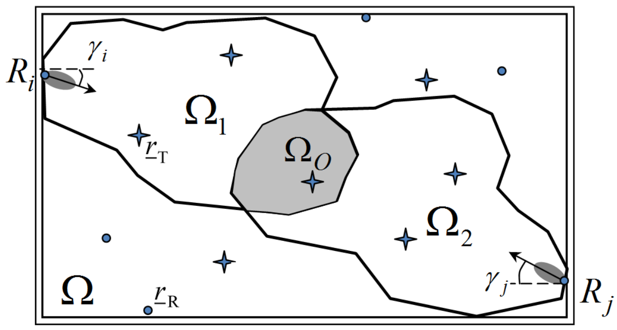

Fig. 1 Scheme of the optimization problem

$$f_{COV} = \frac{meas(\Omega_I)}{meas(\Omega)} \quad (2)$$

$$f_{OV} = \frac{1}{1 + meas(\Omega_O)} \quad (3)$$

$$f_{EIRP} = \frac{1}{1 + \overline{EIRP}} \quad (4)$$

$$f_{COST} = \frac{N_{\max} - N}{N_{\max}} \quad (5)$$

where $\Omega_I = \bigcup_{j=1}^{N} \Omega_j$ is the whole interrogation region;

f_{COV} is the coverage efficiency with $meas(\cdot)$ a suitable measure of the read region which can be calculated as the number of included read test points $\{\underline{r}_T\}$;

f_{OV} refers to the overall overlapping $\Omega_O = \bigcup_{i=1}^{N} (\Omega_i \cap \Omega_i)_{i \neq j}$ among all the interrogation regions;

f_{EIRP} is a measure of the total power radiated by the readers' network; $\overline{EIRP} = \frac{1}{N} \sum_{i=1}^{N} EIRP_i$;

f_{COST} is related to the cost of the network, e.g. it gives a measure of the readers' saving with respect to a given maximum number N_{max}.

The result of the optimization is the position (3 parameters) orientation (2 parameters) number (1 parameter) and emitted power of each allocated reader's antenna. The dimension of the problem may be huge and hence non deterministic (evolutionary) optimization algorithms are preferred to deterministic tools. The PSO algorithm is here applied to maximize the fitness function in (1).

III. Electromagnetic model

The application of the PSO requires the fitness function in (1) to be evaluated thousands of times for each particles of the swarm and for each iteration of the search. A fast but sufficiently accurate electromagnetic model is here introduced to this purpose.

The reader can be characterized by the input power P_{in} and by the radiation vector $\underline{f}_R(\theta,\phi)$ of its antenna. The field at any point of a real environment Ω, including walls or generally scattering objects, can be obtained by application of a field projector P_Ω to the reader's pattern:

$$\underline{E}(\underline{r}) = \sqrt{\frac{Z_0 P_{in} G_R(\theta,\phi)}{2\pi}}\, \mathrm{P}_\Omega \circ [\hat{\underline{f}}_R](\theta,\phi) \qquad (6)$$

where $\hat{\underline{f}}_R(\theta,\phi) = \underline{f}_R(\theta,\phi)/|\underline{f}_R(\theta,\phi)|$ is the normalized radiation vector and G_R is the antenna gain.
In case of free-space the field projector is

$$\mathrm{P}_\Omega \circ [\hat{\underline{f}}_R](\theta,\phi) = \frac{e^{-jk_0 r}}{r} \hat{\underline{f}}_R(\theta,\phi) \qquad (7)$$

with $k_0 = 2\pi/\lambda$ being λ the wavelength.

The power collected by the tag's microchip is

$$P_{R\to T} = \chi \frac{\lambda^2}{(4\pi)^2} |P_\Omega \circ \underline{f}_R|^2 P_{in} G_R(\theta,\varphi) G_T(\theta,\phi)\tau \qquad (9)$$

where $G_T(\theta,\phi)$ is the tag gain and χ is the polarization mismatch between the tag antenna and the incoming field. Typically, the reader emits a circular-polarized field while the tag is a linear polarized antenna and hence χ=0.5 in the free space. In a complex environment the field undergoes a depolarization, but for the sake of simplicity, the average χ=0.5 value is still assumed. The application of the field projector P_Ω to the reader's pattern gets the field at tag location taking account of specific propagation phenomena that could involve reflections and diffractions from walls and generally scattering objects. The *power transmission coefficient* τ accounts for the impedance mismatch between tag antenna and microchip.
The power required to the tag microchip to wake up, p_c is its sensitivity, then the tag is activated when $P_{R\to T} > p_C$.

To apply equations (9) it is necessary to specify the electromagnetic model of readers and tags as well as the field projector. Moreover the region where $|\mathrm{P}_\Omega \circ \hat{\underline{f}}_R|^2$ is path-connected needs to be quickly estimated for any combination of the optimization parameters.

A. Tag antenna modes

Since the tag's gain is not isotropic and the power collected depends on the orientation of the tag which is in general unknown, angle-averaged gain is here considered (simply G_T in the following). The tag is characterized by is microchip's sensitivity p_C and by the power transmission coefficient τ. A macroscopic performance indicator of the tag is the *effective sensitivity* $\tilde{p}_C = p_C/(G_T\tau)$ giving the minimum radiofrequency power that such a tag has to collect to exhibit the same averaged free-space read distance of an isolated perfectly-matched isotropic tag ($G_T\tau$=1). This variable accounts for the performance degradation of the tag due to losses of the object and to the impedance mismatch produced by that. In other words, a real tag attached over a body will performs as a reference ideal tag having a higher power threshold.

B. Reader antenna model

The angular dependence of the reader's antenna gain has to be instead preserved then starting from the consideration that the most used reader's antenna is the circularly polarized patch, the main beam of the radiation pattern can be approximated by an ellipsoid whose larger axis is half the maximum gain, while the smaller axis are related to the antenna beamwidths over the principal planes. In this hypothesis it is assumed that also the interrogation region be approximated by an ellipsoid [8]

$$\frac{(x-a_x)^2}{a_x^2} + \frac{y^2}{a_y^2} + \frac{z^2}{a_z^2} = 1 \qquad (8)$$

where the antenna, placed at $x = 0$, radiates toward x>0. The ellipsoid axes are related to the RFID system parameters, such as the emitted EIRP, the tag sensitivity and the reader's antenna half-power beamwidths on the principal planes (BW_{xy} and BW_{xz}). In particular, the larger axis is

$$a_x = \frac{r_R(\theta_0,\phi_0)}{2} \qquad (9)$$

being $r_R(\theta,\varphi) = \frac{\lambda}{4\pi}\sqrt{\chi P_{in} G_R(\theta,\phi)/\tilde{p}_C}$ the maximum read range in the free-space, i.e. the distance from reader's antenna where $P_{R\to T} = p_C$.
(θ_0, ϕ_0) is the maximum gain direction of the reader's antenna occurring at the broadside direction (i.e. $\phi_0 = 0°$, $\theta_0 = 90°$ in the case of the considered antenna families).
Minor axes are related to the half-power beam-width [8]:

$$a_{y(z)} = a_x \sqrt{\tan\frac{BW_{xy(z)}}{2} \frac{\sin\frac{BW_{xy(z)}}{2}}{\sqrt{2} - \cos\frac{BW_{xy(z)}}{2}}}\,. \qquad (10)$$

Moreover, for typical reader's antennas with circular polarization, the radiation pattern exhibits a rotational symmetry and hence $a_y = a_z$.

In a real environment the path-connected interrogation region (Ω_U) may be smaller than that in free-space owing to the interference of the radiated field with that scattered by walls and objects inside the environment. As the interrogation range is quite short (i.e. the order of few meters) the most important interactions happen with objects placed in the neighbourhood of the antenna. In particular, objects placed in front of the antenna give a greater contribution to the interference than those placed laterally (floor or ceiling) owing to the directivity of the antenna. For this reason it is assumed that among all the possible contributions, only that coming from the main object in front of the antenna is dominant. To further simplify the model, a flat obstacle is considered (as in the case of a wall) placed at distance *D* in front of the reader's antenna (Fig.2). Then a simple two-rays model is able to estimate how much the useful region Ω_U is reduced. In particular, along the shortest line joining the antenna location to the object (i.e. the line perpendicular to the object surface), the *two-rays* field projector can be written as:

$$\mathcal{P}_\Omega \circ \left[\underline{\hat{f}}_{R,\Diamond}\right] = \left(\frac{1}{r} + \frac{g}{2D-r} e^{-jk2(D-r)}\right) e^{-jkr} \qquad (11)$$

where r is an abscissa along that line and g is the Fresnel's reflection coefficient of the object. When the tag moves along this line, the power collected by the tag's microchip is oscillating due to the interference of the direct and reflected ray. The distance r_{2rays} , at which the minimum power collected by the tag equals the effective microchip sensitivity, can be estimated using (9) with the field projector in

(11), by solving the following equation

$$\widetilde{p}_C = \chi \frac{EIRP}{(4\pi)^2} \lambda^2 \left| \frac{1}{r_{2rays}} - \frac{\Gamma}{2D - r_{2rays}} \right|^2 \qquad (12)$$

where $\Gamma = |g|$ and the direction of the reader's maximum gain (θ_0, ϕ_0) is assumed perpendicular to the object surface (Fig.3.a). Then, r_{2rays} gives the maximum distance for tag interrogation.

The function inside "|..|" in above equation is always positive or zero for $0 < r_{2rays} < \frac{2D}{1+\Gamma}$, and hence that equation can be reduced, in this condition, to a second order polynomial

$$r_{2rays}^2 - [2D + (1+\Gamma) r_{FS}] r_{2rays} + 2D\, r_{FS} = 0 \qquad (13)$$

which has two solutions. One of the two solutions is not included in $(0, \frac{2D}{1+\Gamma})$ and hence it is dropped. For the particular case of perfect conductor wall (Γ=1) the maximum read distance predicted by the two-rays model simply reduces to

$$r_{2rays} = D + r_{FS} - \sqrt{D^2 + r_{FS}^2} \qquad (14)$$

Once r_{2rays} has been determined, a new ellipsoid approximating the interrogation region in real environment is obtained by setting $a_x = r_{2rays}/2$ in equations (9).

When the reader's antenna is tilted by an angle γ (Fig.2.b) the two-rays model can be again applied replacing *D* with $R = D/\cos\gamma$ because for small $\delta\gamma$ the path $r_1 + r_2 \approx 2R - r$.

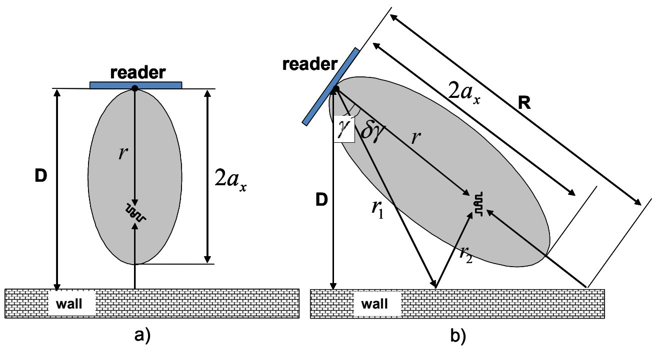

Fig. 2 Ellipsoid model of read-region (dark area) of a reader antenna in front of a wall. a) orthogonal incidence; b) oblique incidence

In short, the ellipsoid model merges together the antenna model and the propagation model and results from a trade-off between the simplicity of the free-space approach and the accuracy of a fully (time-consuming) ray-tracer. In case of obstacles the ellipsoid extension is smaller than that of free-space model.

IV. Experimental and Numerical Results

The ellipsoidal model of the read region has been experimental evaluated for a (CAEN-A948) reader whose antenna is pointing toward the ground at distance *D*=2.25m from it. The reader's antenna has 67° beamwidth (in both the planes) and maximum gain G_{max}=8dB. The reader region is referred to $\widetilde{p}_C = 56\mu W$ commercial meander-line tags (EPC 1 GEN2 LAB-ID UH100) replicated along a *2m*-long wooden leg, with $10cm$ space steps. The leg is then translated in the environment along a line with the purpose to produce a rectangular grid of measurement points. Measurement consists in recording reading and non reading tags. The reader emits 1.2 W EIRP.

A comparison between free-space model, two-rays model, full ray-tracing and measurements is shown in Fig.3. The ray-tracing prediction is shown by the grey region where the fringes zone owing to the interference with the ground reflected field is observable. Continuous line ellipse concerns the two-rays model while the dotted line ellipse refers to the free-space model. Measurements are shown by means of circle and cross markers. Circles indicate interrogating locations, crosses non- interrogating locations. It is noticeable the improvement of the two-ray model with respect to the free-space model.

To highlight the ability of the optimization algorithm to reduce the cost and to enhance the coverage of the network, a complicated topology has been considered. The scenario consists of an L shaped environment (Fig. 4.a), wherein reader's antennas are constrained to be placed only on two side walls (x=0m and y=5m). Three different optimizations are here presented, having gradually released the constraints on the reader's geometrical and electrical parameters. To value the benefit of the optimizations in the considered cases, the fitness function is used as an overall indicator.

At first, number and position of antennas are fixed while orientation and EIRP≤3.2W are optimized. Starting from four antennas, the optimization process tries to reduce the overlapping regions lowering the radiated power and orienting the antennas (Fig.4.b)). Some overlapping regions are however still visible. Removing the constraint on the number of antennas, only three antennas are needed to cover the 95% of the test points (Fig.4.c)): the overall indicator is increased with respect to the previous case (Table I) as the efficiency is enhanced and the cost and overlapping are reduced. Finally all the parameters are free to be optimized and the planning result is shown in Fig. 4.d). The whole coverage is obtained and the overall indicator is greater than the previous cases.

TABLE I
RESULT OF OPTIMIZATION PLANNING OF THE ENVIRONMENTS IN FIG.4

	f_{COV}	f_{OV}	f_{EIRP}	f_{COST}	F
b)	0.98	0.43	0.32	0	0.67
c)	0.95	1	0.30	0.25	0.78
d)	1	0.92	0.30	0.25	0.80

V. CONCLUSIONS

The planning of the deployment of readers in large and complex environments is a trade-off between the maximum read zone required for the particular application and the electromagnetic and topography constraints. Simple and fast electromagnetic models have been applied in the frame of PSO algorithm for planning in real environment. Experimental and numerical results show the effectiveness of the proposed models and optimization tool.

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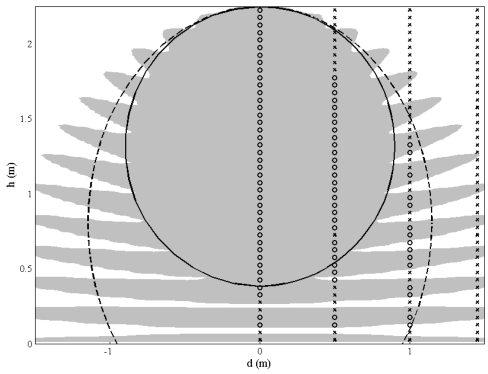

Fig. 3 Interrogation region prediction in case of the reader's antenna pointing toward the ground. Comparison between free-space model (dotted line ellipse), two-rays model (continuous line ellipse), full ray-tracing (gray region) and measurements shown by means of circle and cross markers. Circles concern reading locations, crosses non-reading locations. Reader power: 1.2 W EIRP

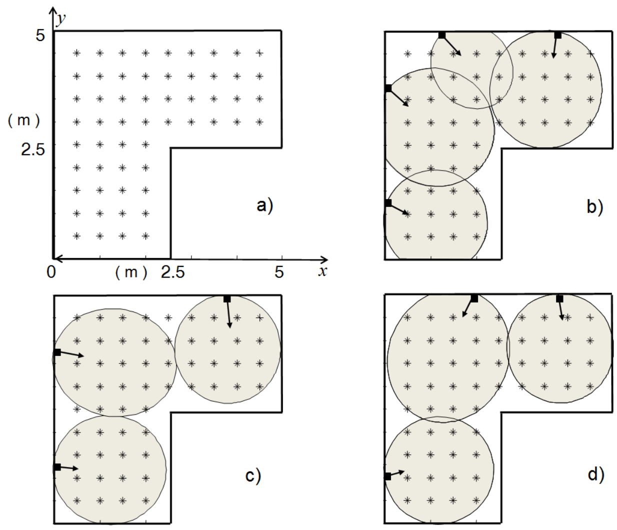

Fig. 4 L-shaped environment wherein network coverage is planned with different constraints. a) set-up with {rT} shown by crosses; b) EIRP and antennas orientation (indicated by arrows) optimized; c) number of readers, EIRP and orientation optimized; d) complete optimization, where also the position of readers is optimized. Arrows show antennas' orientation, ellipses interrogation region. The size of an ellipse is related to the radiated power and to the beam-width of the antenna.