Comparison of a Fast Probabilistic Propagation Model against an Analytical Computational-EM Model and Measurements for the Evaluation of Passive RFID Systems

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***Abstract*—This paper presents the comparison of a fast probabilistic propagation model against an analytical computational electromagnetic (EM) model and measurements performed for the evaluation of passive RFID systems. The results of the probabilistic model compared to the ones of the analytical model, as well as to the measurements, are in fairly good agreement.**

***Index terms*—probabilistic model, analytical model, RFID**.

I. INTRODUCTION

In this paper a comparison between a fast probabilistic model and an analytical Full-Wave model is presented. Both models aim to evaluate the identification performance of passive RFID systems operating at the UHF frequency band (860MHz-930MHz). The probabilstic model, [1], calculates the probabilities of succesfull identification of passive RFID tags at the specified locations. It has been designed so that it can be integrated in automated planning softwares [2], where numerous estimations are needed in small time. Therefore, a rough description of the surrounding environment is only considered, without considering furniture or other objects. Only major indoor propagations mechanisms are considered [4]; that is the direct field and multiple reflections. However, all important characteristics of passive RFID systems are included in the estimations, like antennas' radiation patterns, polarization of the tags and the reader's antennas etc [3].

The analytical Full-Wave model (FDTD), [5], considers a detailed representation of the actual environment. 285 solids representing actual objects inside the simulation room were included in the estimations. The model results in an actual "screenshot" of the field inside the simulated area, where maxima and minima are shown. The simulation time is prohibitive for planning applications. However, it can be used as a benchmark for the evaluation of the performance of the "abstract" probabilistic model. The models are compared against each other and against measurements conducted in a real environment. Comparison of the estimations demonstrated good agreement. Furthermore, both models were compared with measurements conducted in the simulated room. Again, both models demonstrated good agreement. The simulation time was less than 4s in an average laptop for the probabilistic model, while for the same problem, the Full-wave model needed 135h in an advanced workstation.

II. PROBABILISTIC MODEL

The probabilistic model was analytically presented in [1]. The probability of successful identification of passive RFID tags is calculated. Line of Sight Conditions (LOS) are expected, justified by the power constraints of battery-less RFID systems [6]. A passive RFID tag is typically considered successfully identified, if the power that reaches the tag is greater than its wake-up threshold, assuming that the sensitivity of the reader is small enough to receive the backscattered signal from an "awaken" tag. The probability of successful identification equals the probability that the instantaneous power at the tag IC is greater than its wake-up threshold γ. In the presence of a strong LOS path, fading is well described by a Rician probability density function. Hence, the probability of successful identifications is

$$P(X \geq \gamma) = 1 - F_X(\gamma|\nu,\sigma), \tag{1}$$

$$F_X(x|\nu,\sigma) = 1 - Q_1\left(\frac{\nu}{\sigma}, \frac{x}{\sigma}\right), \tag{2}$$

and ν^2 is the power of the LOS path, $2\sigma^2$ is the average power of the other contributions x is the signal's amplitude and $Q_1(a,b)$ is the Marcum Q-function. Therefore, by defining ν and σ at each reception point, we can calculate the desired probability for a single reader-antenna configuration.

For the calculation of the average power of the multiply reflected rays ($2\sigma^2$ in (2)), we consider ray-clusters that include all rays that initially bounce on the same wall, e.g. for a typical room/building, six ray clusters are considered for the six surrounding walls. Within each cluster, we consider the phases of the rays as random variables (key assumption of the model), identically and independently distributed, uniformly over $[0, 2\pi]$. Furthermore, we approximate the magnitude of

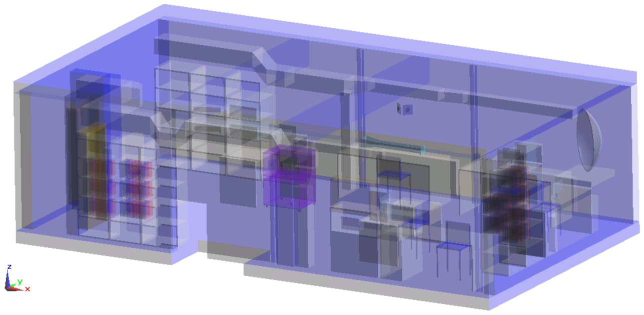

Fig. 1. Perspective view of the realistic model of the laboratory room.

the reflection coefficients of higher order terms with the magnitude of the reflection coefficient of the singly reflected ray of the specific cluster. Based on these approximations, the resulting average power from a given ray-cluster is given as:

$$P_{\hat{\eta}_0} = A\cos^2(\psi)\sum_n \frac{(|\mathit{\Gamma}_1^{\perp}|^2)^n}{r_n^2},$$
$$P_{\hat{\epsilon}_0} = A\sin^2(\psi)\sum_n \frac{(|\mathit{\Gamma}_1^{\parallel}|^2)^n}{r_n^2},\ A = \frac{\lambda^2 W_t G_t(\phi_1,\theta_1)}{(4\pi)^2}, \quad (3)$$

where $\hat{\eta}_0$, $\hat{\epsilon}_0$ are unit vectors perpendicular and parallel to the plane of incidence for the singly reflected ray of the cluster, respectively, ψ is the angle of the incident field vector with $\hat{\eta}_0$, $\mathit{\Gamma}_1^{\perp}$, $\mathit{\Gamma}_1^{\parallel}$ are the perpendicular and parallel reflection-coefficients for the singly reflected ray of the cluster, r_n is the length of the path of each ray in the cluster and $G_t(\phi_1, \theta_1)$ is the transmitting antenna gain at the direction of the singly reflected ray of the cluster. Details on the derivation of the probabilistic model can be found in [1].

III. ANALYTICAL MODEL

A full wave method (Finite Difference Time Domain FDTD) of four readers antennas inside a realistic model of a laboratory room at the Department of Physics, Aristotle University of Thessaloniki, is performed. The method is applied with the use of SEMCAD X [7]. The dimensions of the room are 9.99 x 5.44 x 3.8 m^3. Inside the realistic model, a great number of objects solids (285), with different dielectric properties (including walls, desks, chairs, PCs, metallic pipes of the ventilation system and so forth) are modeled, in order to achieve a better approach of the realistic conditions in terms of field distribution and coverage. The frequency of the simulation is set to 867MHz and the simulation time is 200 periods. The grid resolution is 0.25 cm, resulting in approximately 530 million voxels of the model. The total simulation time is 135 h. in an advanced workstation Fig. 1 shows a perspective view of the realistic model designed in SEMCAD-X.

A patch antenna with cropped edges (circular polarization) is designed to model the readers antennas. The substrate of the antenna is the Nelco FR4 material with a relative permittivity of 4.4 and a electrical conductivity of 4.25 x 10^{-3} S/m. Each of the four antenna models has dimensions 85 x 85 mm^3 and 7.8 dBiC gain. These antennas are placed at 4 different locations inside the realistic model, 1.7 m above the ground. Four different simulations are performed (each one held 135 h), equating the succesive operation of the readers antennas. The total coverage is estimated by the E-field combination of the four aforemetioned simulations.

IV. RESULTS - COMPARISON

Before presenting the comparative results, we will highlight some major differences in the scope of each model. The probabilistic model succeeds in quantifying what ”might” happen at each location. It answers, scientifically, the question ”How probable is it to suffer a failure in the identification in this area?”. However, it cannot pinpoint the exact locations where an actual failure might take place. This can be criticised as a drawback of the model. Yet, it is well known that unless an area is completely shielded electromagnetically and nothing moves inside this area, the received field at any given location suffers from variations with respect to time. Furthermore, an error in the electromagnetic modelling of an actual scatterer will introduce a phase-error in the estimation of the corresponding field which will result in an erroneous evaluation of the final field. Due to these reasons, it is claimed that the proper question for planning applications is the aforementioned one related to probability. Knowing the probability from each antenna results in an additional advantage related to planning applications: the planner can calculate what happens at overlapping ”coverage” areas from different antennas and thus carry out the planning proccess by calculating perfomance metrics for the entire antenna network, greatly reducing the necessary infrastructure, as illustrated in [2].

Analytical models, including FDTD or ray-tracing [8]- [9], are suitable to give a physical insight on what actually happens on a given area. They represent the necessary basis to develop stochastic models as they can highlight dominant propagation mechanisms, the effects of different tecnhiques on the actual field etc. Furthermore, analytical models can illustrate and map the effects of dominant scatterers in the propagation area, which might be the case for certain problems, e.g. ”How can one minimize the field above the bed of a patient inside a hospital room?”. Clearly, one cannot compare the results from the two models in a point-to-point manner, because for each point one model derives probability, while the other model derives field-values. In order to carry out a fair comparison, we calculate statistics, either simulated or measured, over larger areas.

A. Comparison between the two models

Comparison with the probabilistic model for the same room is conducted. In the probabilistic model, only the 6 walls were considered. Assuming a minimum tag's threshold γ, we will calculate the percentage of the area where successful identification was accomplished. For the analytical model

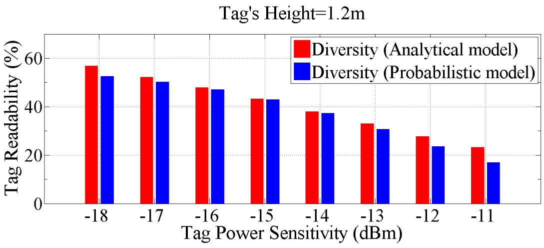

Fig. 2. Comparison between analytical and probabilistic model along a given horizontal slice for different tag's identification thresholds.

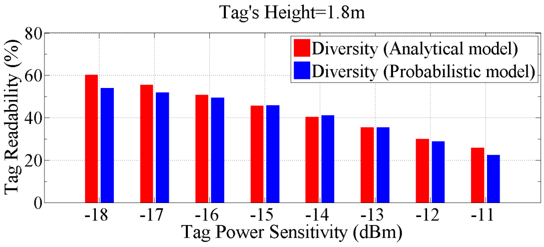

Fig. 3. Comparison between analytical and probabilistic model along a given horizontal slice for different tag's identification thresholds.

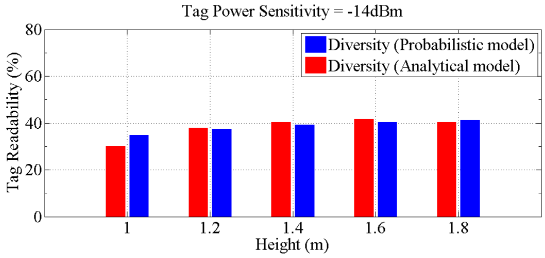

Fig. 4. Comparison between analytical and probabilistic model for the same sensitivity vs. different heights inside the area.

this metric is easily calculated by dividing the number of points with received power above the given threshold to the total number of points. For the probabilistic model, let $U(\gamma)$ represent the percentage of the volume of interest V, where succesful identification of passive tags is accomplished [10] (ch. 4):

$$U(\gamma) = \frac{1}{V}\int_V P_{dV}(X \geq \gamma)dV = \frac{1}{V}\sum_{l=1}^{M} P_l(X \geq \gamma)dV_l \quad (4)$$

For a cubic calculations' grid, with equal spacing among grid points, (4) reduces to $U(\gamma) = \sum_{l=1}^{M} P_l(X \geq \gamma)/M$. We compare the two models on evenly spaced gridpoints for 5 different heights (1.0m, 1.2m, ..., 1.8m) and by increasing the tag's sensitivity from -18dBm to -11dBm (which are typical values for passive RFID tags). Such results for the heights of 1.2m and 1.8m are presented in Figs 2 - 3, respectively. The results agry reasonably well in all heights and for different thresholds. By calculating the results for a given tag's sensitivity, we can compare the two models, as presented in Fig. 4.

Fig. 5. Photo during the measurements.

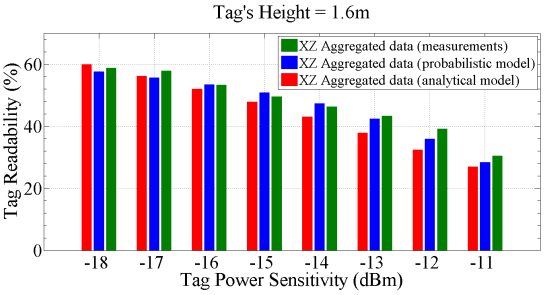

Fig. 6. Comparison between the two models and measurements inside the room as a function of tag power sensitivity (in dBm) for z=1.6m.

B. Comparison with measurements

Measurements were conducted in the simulated environment. A grid of orthogonally polarized tags was constructed inside the lab, as demonstrated in Fig. 5. The tags were hanged by threads, following a similar setup as the one presented in [8]. We reduced the transmitted power from the reader antenna in 1-dB steps and counted the percentage of identified tags for each polarization. These results are presented in Fig 6. It is evident that the two models, as well as the measured results are in fairly good agreement. Both demonstrate a very small root mean square error, namely the rmse is 3.6% for the analytical model and only 1.7% for the probabilistic model. Notice that the analytical model is not more accurate than the probabilistic model, as one might have expected. The reason is the fact that there are numerous uncertainties when modeling such a complex structure that result in significant inaccuracies on the estimated field in the area. Furthermore, some possible advantages of analytical models, e.g. the capability to identify areas of destructive interference, cannot be shown in these measueremnts, where averages of the performance in the entire room are quantified.

V. CONCLUSION

In this paper we have compared the performance of two models that can be used for the evaluation of the performance of passive RFID systems. One model derives probabilities of successful identification of passive RFID tags in very short running time, taking into account the dominant propagation paths and an abstract description of the environment (significant obstacles). The other model applies FDTD to evaluate the field in detailed representation of the environment and requires long running-time. By comparing with measurements, it was found that the two models shared the same accuracy with respect to the evaluated identification performance of RFID systems. The probabilistic model is suitable for planning applications and has already been integrated in automated planning algorithms [2], suitable for large problems (hundreds of antenna configurations). The analytical model or other compuational techniques (e.g. ray tracing [8]) is suitable for the general evaluation of techniques that can be used to improve the performance of RFID systems.

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