High Resolution Multistatic Radar for Indoor Application-Computational Simulation and Strategies to Minimize Errors

Rubem G. Farias, Victor Dmitriev

Federal Unoversity of Pará – DEEC – CEP 66075-900 – Belém – PA –Brasil

Abstract – **A numeric simulation of a multistatic radar using the finite-difference time-domain (FDTD) method is implemented in order to identify the presence of an intruder inside a residence. The radar operates with ultra-wideband (UWB) pulses with the purpose of obtaining high resolution. The transmitted signal has a spectral peak in 1 GHz and the bandwidth of approximately 1 GHz. A transmitter and at least three receivers positioned outside the residence are used to estimate the location of the target without ambiguity. A special emphasis is given to study of the effects of scatterers placed in semi-aleatory way in all rooms of the residence. A strategy is proposed to minimize these effects in order to obtain complete coverage of the residence with small error of the intruder localization.**

Key words – **FDTD Method; UWB microwave sensor; radio scattering; multistatic radar.**

I. INTRODUCTION

The finite-difference time-domain (FDTD) method is adequate to simulate propagation of ultra-wideband (UWB) pulses. These signals are indicated for radar systems and GPS of high resolution [1-7]. Moreover, UWB pulses are more immune to frequency-selective fading inherent to environments rich in scattering such as residences, offices, Labs, storages and others. In order to avoid interference with other radiosystems like cellular phones, GPS, Bluetooth, etc, it is necessary to use spectral scattering for transmission. The combination of ultra-wideband pulses with spectral scattering results in a transmission signal with spectral density of power below the environmental noise. There exist commercial systems for this kind of application. In our simulations, we use omnidirectional antennas which are appropriate for *indoor* environment.

A bidimensional *full wave* treatment using the finite-difference time-domain (2D-FDTD) allows mapping the electromagnetic fields in the entire computational domain represented here by the residence. Also, a set of objects with dimensions that vary in a semi-aleatory way is incorporated in order to represent the furniture and other objects.

This paper is organized as follows: in section II, we describe the environment for simulation, that is, the residence layout and the objects with their electric characteristics. Also, information of the FDTD method is given there. Section III contains a description of the procedures used in the simulations and the data of the intensity of electric field in the receivers. The results of the simulations are described in section IV, and we finish with the conclusions in section V.

Rubem G. Farias, rgfarias@ufpa.br, Victor Dmitriev, victor@ufpa.br

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II. ENVIRONMENT FOR SIMULATION

This environment for simulation is shown in Fig. 1. The internal and external walls have different thickness and electric characteristics. The dielectric constants of the internal and external walls are ε_r = 4.2 and 5, respectively. All the walls have the same conductivity σ = 0.02 S/m. The scatters have the same electric characteristics as the external walls. The remaining environment has characteristics of free space, except the absorbing boundary conditions (ABC) in the boundaries of the numeric domain.

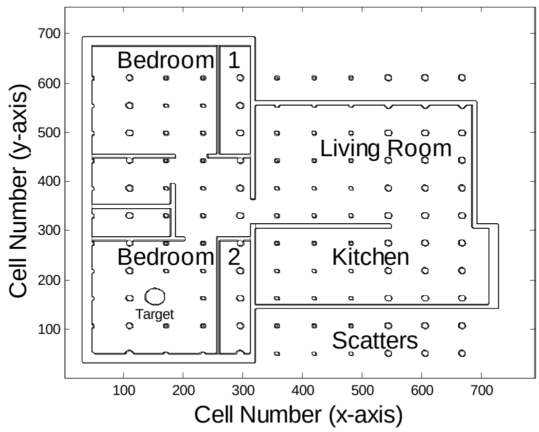

Fig. 1 – Residence layout with target and scatterers.

The simulations are performed using the 2D-FDTD method based on Yee' formulation. Only perpendicular polarization relative to the plan of the Fig 1 is considered in the transmitter antenna. The spacial discretization is made with the dimensions of the square cells equal to 1.5 cm ($\Delta_x = \Delta_y = \Delta_s$). This value corresponds to one-tenth of the free-space wavelength of the excitation pulse in the reference frequency of 2 GHz. To guarantee numeric stability, we have adopted 70% of Courant limit for the temporal increment. This takes to the following expression

$$\Delta_t = 0{,}7\Delta_s / c\sqrt{2} \qquad (1)$$

Here c = 2,997 924 58 x 10.8 m/s is the light speed in the free-space. The ABC used in this paper was the UPML, which presents insignificant reflections. This ABC does not influence the electromagnetic behavior of the environment under study. The parameters of the layers of the UPML are: thickness d = 15 cm (10 cells), maximum conductivity σ_{max} = 15 S/m and polinomy order associated to the spacial variation of the conductivity is m = 4.

The waveform used for the transmission is the Gaussian monocycle given by the function

$$p(t) = -A_p \sqrt{\frac{2e}{\tau^2}}\left(t - t_o\right)\exp\left[-\frac{\left(t-t_o\right)^2}{\tau^2}\right] \qquad (2)$$

where A_p is the maximum amplitude of the pulse, e is the base of the Neperian logarithm, τ establishes the duration of the pulse It depends on the frequency of the spectrum peak, f_o obtained by

$$f_o = \frac{1}{\pi\sqrt{2}}\frac{1}{\tau} \qquad (3)$$

The parameter t_o is the instant in which $p(t)$ has null (center of the pulse). The spectrum of the pulse is obtained by the Fourier transformation with the result

$$P(f) = A_p \tau^2 \sqrt{\frac{\pi e}{2}}\exp\left[1-\left(2\pi f\right)^2\right]\exp\left(-j2\pi t_o f\right) \qquad (4)$$

Fig. 2(a) shows the pulse $p(t)$ with the following parameters: A_p = 1 V/m, $\tau \approx$ 0,255 ns (f_o = 1 GHz) and t_o = 1,8 ns. Fig. 2(b) shows the magnitude of the corresponding spectrum, in dB. Notice that the spectrum is rather wide.

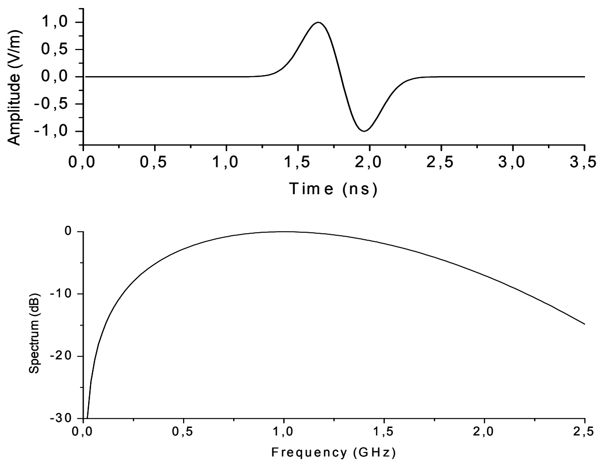

Fig. 2 – (a) Monocycle pulse, (b) its spectrum.

III. LOCALIZATION OF THE TARGET

The method that we present here allows determining the position of the target in relation to the origin of the coordinate system. Two formalisms are involved in calculation process: FDTD and geometrical optic in order to obtain the parameters of the localization ellipse. The transmitter and the receivers are placed in different positions in order to form a multistatic radar. A pulse is transmitted in the absence of the target, and the data of the electric field E_z are obtained in the receivers. Such data are used as reference. Then, a pulse is transmitted with the presence of the target inside the residence. This stage requires a considerable computational effort for the application of the FDTD method. The following stage consists on obtaining the difference among these data (with and without target) followed by the introduction of the additive white Gaussian noise (AWGN) to simulate the environment noise. Finally, the parameters of the ellipses are obtained and the system of non-linear equations are resolved in order to estimate the position of the intruder and the error of the estimation is calculated. Estimation is made for each set of three receivers and the transmitter. In case of a more number of receivers, an estimation of localization is made for each combination of two remote receivers. Among these estimations, we have chosen the one that produces the least error. This result is the final solution for the estimation of the target position. Fig. 3 illustrates the case of three receivers. One of them, Rx1, is local and produces together with the transmitter Tx a circle in which the target is situated. Each remote receiver, Rx2 or Rx3, has an ellipse as a locus.

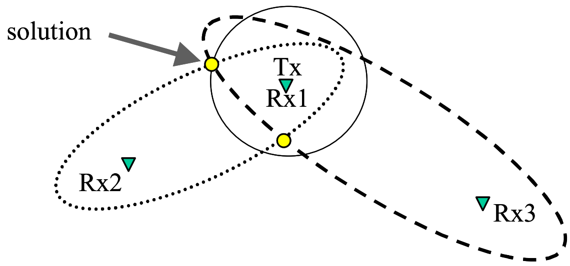

Fig. 3 – Simplified scheme of the multistatic radar.

The parameters of the ellipse of localization are identified in Fig. 4: a is the major semi-axis, b is the minor, $C(x_c, y_c)$ is the center of the ellipse, α is the angle which the major axis forms with the x-axis. T indicates the position of the transmitter, P indicates the target position, and R represents the receiver. The equation of the ellipse is given by

$$F(x,y) = b^2\left[\left(x-x_c\right)\cos\alpha + \left(y-y_c\right)\sin\alpha\right]^2 + a^2\left[\left(y-y_c\right)\cos\alpha + \left(x-x_c\right)\sin\alpha\right]^2 - a^2b^2 = 0$$
(5)

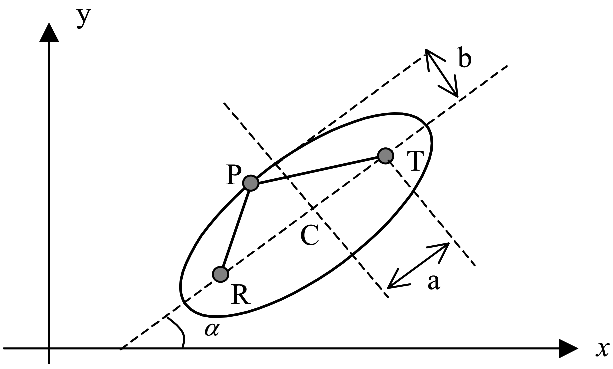

Fig. 4 – Elliptical locus and parameters.

The parameters of the ellipse are obtained from the localization of the transmitter, T, from the receiver, R, and from the distance which the pulse runs in the route transmitter-target-receiver, that is, from Fig. 4, d_{TPR} = TP + PR. This distance is calculated with the use of data of electric field, in each receiver, with and without target, obtained via FDTD. An example of such data is shown in Fig. 5.

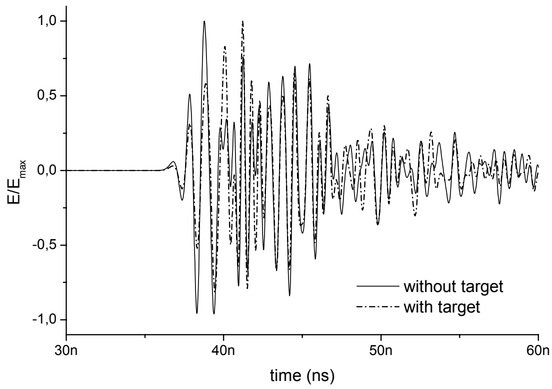

Fig. 5 – Data of electric field in the receiver.

Notice that the difference among the data with and without target is not quite evident. However, when one makes the subtraction among them, the difference is more pronounced as it is seen in Fig. 6.

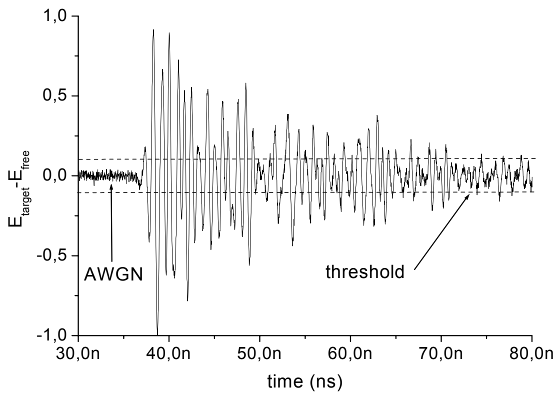

Fig. 6 – Difference among the data of Fig. 5. Here the white Gaussian noise is included with SNR=14dB.

The standard deviation adopted for the AWGN is σ_N = 0,02 S/m. This implies a difference between the power of peak of the signal difference and the rms power of the noise power equal to 34 dB. Because of the walls and the scatterers, among other effects, the attenuation of the signal is very strong, up to 80 dB. A practical solution to reduce this attenuation is to place the transmitter and the receiver inside the residence. The dashed lines in Fig. 6 represent the *threshold* field of 10% to isolate the noise.

The distance d_{TPR} = is calculated using the propagation time, obtained from Fig. 6. This is identified when $|\Delta Ez(t)|$ exceeds the threshold for the first time. The effective propagation speed of the pulse is calculated in one layout which involves the two types of walls, and the speed is pondered by the energy of peak of the signal received by the different receivers. Four receivers are positioned in such a way that the propagation is at angles of 0, 15, 30 and 45 degrees in relation to the *x*-axis. The estimated value was v/c = 0,98255. With all the parameters of the calculated ellipses and circle, the estimation of localization can be obtained through the intersection of the ellipses associated to the remote receivers Rx2 and Rx3. The equation (5) is applied to each receiver. It degenerates to a circle when the transmitter and receiver are on the same point. There are four possible solutions. The chosen one is that which better approximates the locus associated to the local receive, Rx1, of a circle, as indicated in Fig. 3. The process is concluded with the calculation of the estimation error given by

$$v = \frac{\sum_{i=1}^{4} v_i \left|E_i\right|^2}{\sum_{i=1}^{4} \left|E_i\right|^2} \qquad (6)$$

where d_{sol} is the distance between the estimated position of the target and its center, and *r* is the ray of the target. This definition of error is necessary, because the target has significant dimensions compared to the dimensions of the environment. This leads to the following interpretation for this parameter: if $e_R < 0$, then the estimated position by the radar is found in the interior of the target. If $e_R = 0$, the estimated position coincides with a point of the target surface. If $e_R > 0$, the estimated position is out of the target.

IV. RESULTS

Firstly, we consider the simple case of a radar compounded by the transmitter and three receivers, with the empty residence (without any scatterer). The transmitter and the receivers are found in the middle of the living room, while the intruder is found in the bedroom 2 (see Fig. 1). The result of the simulation is presented in Fig. 7. This figure presents the distribution of the electric field in the entire numeric domain for the instant equal to 19,8 ns after the emission of the pulse by the transmitter. The "X" marks the estimated localization of the target. The center of the target is positioned in (2,31m, 2,49m) and the estimated position is (2,16m, 2,74m) with an error of 7,88%. Apparently, the main causes of this error are the diffraction through the doors and the effect of the external walls. In order to obtain error close to zero, the pulse should travel on the routes TP e PR in straight line.

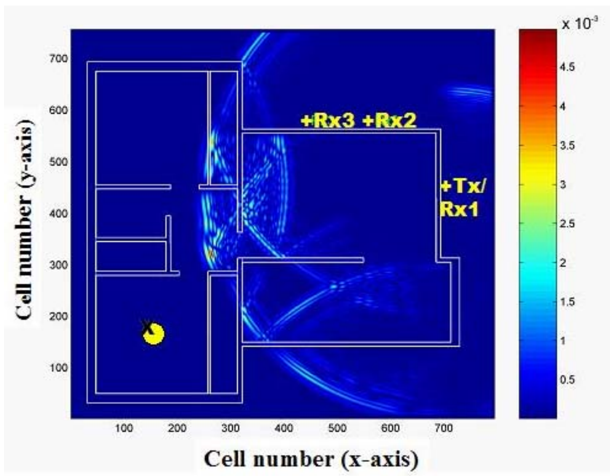

Fig. 7 – Graphic with estimation of localization of the target in empty residence. Position of the elements (in number of cells): Tx/Rx1 (700,452), Rx2 (560,580), Rx3 (440,580), center of the target (154,166) and estimated position is (144,183).

In the following simulation, we put a concentrate group of scatteres in the environment. The objects have the diameters which vary between 18cm and 9cm. Along the y-axis, this variation follows the inverted code of Barker. This is the PN code of length 11 used in communication by the IEEE802 standard. This was made in order to simulate a certain degree of aleatority in the dimensions of the elements of the residential environment. The effect caused by the scatterers is significant as it is shown in Fig. 8.

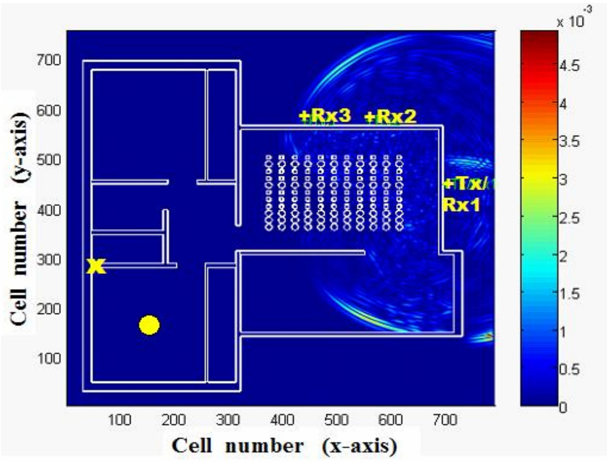

Fig. 8 – Simulation of an environment with scatterers concentrated in one of the environments of the residence.

A strategy to improve the estimation consists in increasing the number of receivers and establishing a new positioning of the equipments. To do so, we have adopted the configurations of Fig. 9. Here, Rx2 and Rx3 have different positions and the receivers Rx4 and Rx5 were included additionally. In this case, it was possible to get an improvement in the estimation. In this simulation, the error is considerable, but it is still possible to detect the intruder in the correct room. In this scheme, the receivers Rx2 and Rx4 are those that causes better estimation. In this example, the scatterers are concentrated. It is worth to verify the case of sparse scatterers distributed in the entire environment.

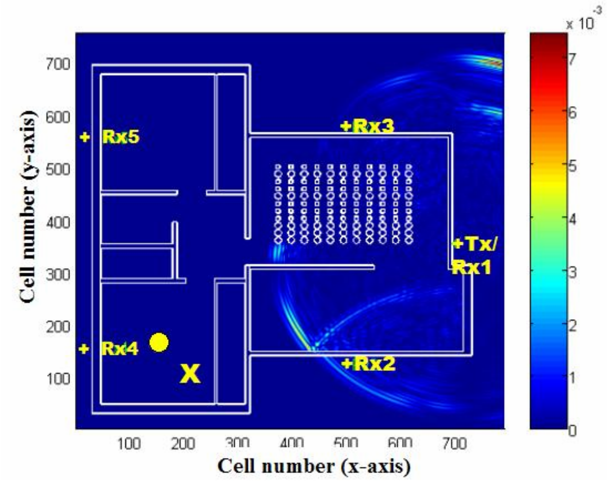

Fig. 9 – Radar with five receivers to decrease error of estimation due to a concentrate group of scatterers.

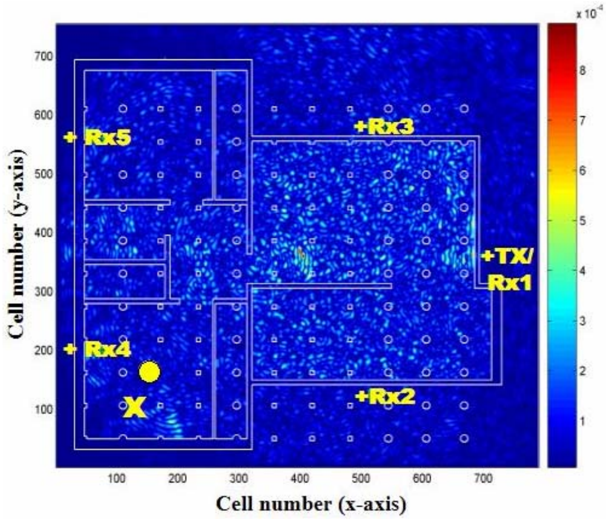

Fig. 10 – Effect of a sparse group of scatterers. The mapping of intensity of field is made in the instant 39,6 ns.

In the simulation of Figs. 9 and 10, it is difficult to find the target with precision, because the pulse runs a very complex route because the transmitter is far from the target. Next, we considered the same system above, except that the transmitter is displaced for room 2. The result is shown in Fig. 11a. The mapping of the field is made at the instant in which the pulse reaches the target in 9,9 ns. In this case, the error of localization is approximately –1,4%. The best estimation was established with the use of the receivers Rx4 and Rx6.

Another alternative to verify the effect of the positioning of the equipments consists on keeping the transmitter on the original position and displacing the target to the environment close to the receiver. The result of the simulation is presented in Fig. 11b.

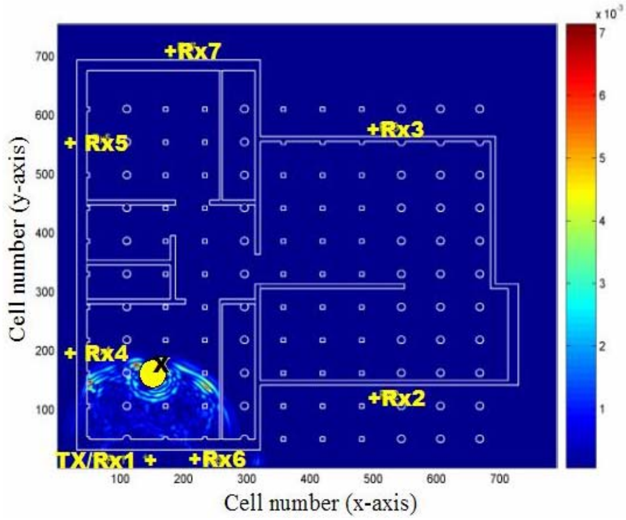

Fig. 11a – Transmitter is displaced closer to the target. Error is only of –1,4% (target reached).

The error of estimation in this case is – 1,4%. The center of the target was positioned in (500,430) and the estimated positioned was of (502,429), that is, the estimation virtually reaches the center of the target.

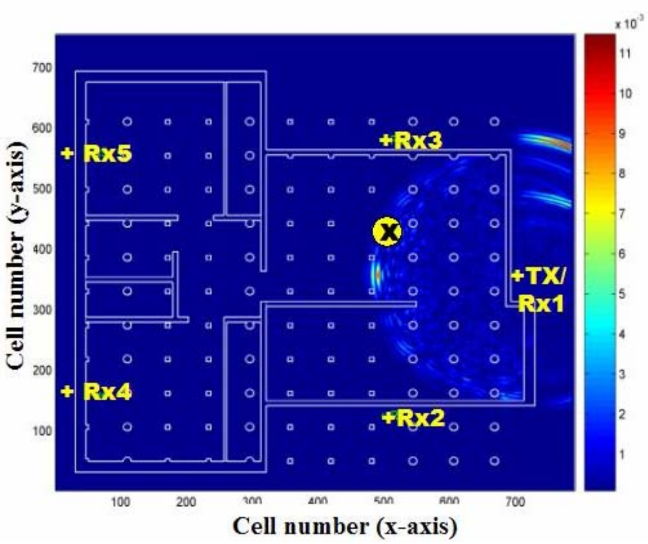

Fig. 11b – Estimation of the position of the target when it is found close to the environment of the transmitter.

In all the simulations, the target is represented by a cylinder of diameter equal to 50 cm, and with electric characteristics (medium) equal to those relative to human being, with $\varepsilon\ r$ = 50 and σ = 0.02S/m.

V. CONCLUSIONS

In this paper we have presented simulations of a multistatic radar operating with UWB pulses. Our method is based on the FDTD technique combined with geometric optic (ellipses of localization). The mathematic procedure was described. Several results of simulation were presented with the aim of minimizing the error due to the electromagnetic scattering caused by objects with different dimensions and positioned in a semi-aleatory way in the environment.

The FDTD method is adequate to solve this kind of problem. It seems that the most feasible solution to obtain precision of the radar in a very complex environment consists on using several receivers. The target and the transmitter cannot be very far from each other. A set of transmitters (sensors) can be used to improve the estimation each one associated to at least three receivers. One can be put cllose to the living room and kitchen (Fig. 11b), another one in bedroom 2 (Fig. 11a), and a third one in bedroom 1. In order to avoid interference among the transmitters, it is necessary to use multiplexation in the time domain (TDM). For synchronism and processing the signals, the equipments could be connected by conventional physical lines or optical fibers. Notice that the transmission rate is typically low, lower than 1 Mbaud.

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