Abstract—This paper presents the statistical analysis of measured propagation data in a femtocell indoor radio environment. Measurements were performed at 1.95 GHz with a 160 MHz channel bandwidth. Time domain sounding technique using PN-sequence with a matched filter was employed. Empirical and theoretical prediction using the Saleh-Valenzuela model and the Finite-Difference Time-Domain (FDTD) method, accelerated via GPU technology, were respectively carried out. So, a comparison between theoretical and experimental simulation is presented.

Keywords - Channel modeling, Channel sounding, FDTD, femtocells.

I. INTRODUCTION

Special indoor environments such as auditoriums have a limited penetration of radio frequency signals from outdoor radio base stations, so they need special attention so that they can be properly covered by wireless high-speed services. It is important to know where to install the femtocell devices in order to guarantee the best quality of service avoiding Intersymbol Interference (ISI) and this requires a good channel characterization that can be achieved through the Power Delay Profiles (PDP) measured in the environment.

The characterization of propagation radio channels with spatial and temporal selectivity can be achieved using a general model of a linear time-varying channel. The channel response can be described in terms of a set of functions that define the physical mechanisms that dominate the behavior of the channel. Zadeh [1], followed by Kailath [2] and Bello [3] have great contributions in this area. In his classical work, Bello developed a symmetrical relationship between the functions describing the system response in the time and frequency domain. Based on this theory, Turin [4] proposed a statistical model for urban multipath propagation. Saleh and Valenzuela [5] extended Turin’s formulation for indoor propagation based on the assumption that the multiple signals reaching the receiver arrive in clusters and each cluster consists on many rays.

Five sections compose this work: Section II describes briefly the Saleh-Valenzuela model. The measurement setup and the sounder are outlined in Section III. In Section IV, the FDTD technique implementation is presented. The results are showed in V, including the results of the simulations and comparisons between both techniques of simulation: Saleh-Valenzuela and FDTD. In Section VI are the conclusions and future works.

II. SALEH-VALENZUELA MODEL

The channel impulse response is given by:

$$h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} e^{j \varphi_{kl}} \delta(t - T_l - \tau_{kl})$$ (1)

where $\beta_{kl}$ is the amplitude $\varphi_{kl}$ the phase of the $k$-th ray inside of $l$-th cluster. The term $e^{j \varphi_{kl}}$ represents a statistically independent random phase associated with each arrival. It is assumed that $\varphi_{kl}$ is uniformly distributed in the interval $[0, 2\pi]$. $T_l$ represents the time of arrival of the $l$-th cluster and $\tau_{kl}$ the time to get the $k$-th ray within the $l$-th cluster. A graphical representation of the model is shown in Fig. 1.

The PDPs obtained from measurements make possible the calculation of the parameters in order to simulate the sounded channel. In this model we need to know the model parameters statistics $\beta_{kl}$, $\tau_{kl}$, $\varphi_{kl}$ which are obtained on the basis of extensive measurements.
The number of clusters and rays per cluster is different for each simulated profile in which time and disposition are defined by a generator of random variables. The amplitudes are defined as $\beta_{kl}$ statistically independent random variables which mean square value $\overline{\beta^2_{kl}}$ is monotonically decreasing in terms of $T_l$ and $\tau_{kl}$. In our model:

$$\overline{\beta^2_{kl}} = \overline{\beta^2_{kl}(T_l, \tau_{kl})}$$

$$\overline{\beta^2_{kl}} = \overline{\beta^2(0,0)} e^{-T_l/\Gamma} e^{-\tau_{kl}/\gamma}$$

The Equation (5) represents the double decay of Fig. 1, with $\Gamma$ and $\gamma$ defining the constant decay of cluster and rays, respectively, and $\overline{\beta^2(0,0)}$ representing the amplitude of the first ray of the first cluster, calculated by:

$$\overline{\beta^2(0,0)} = \frac{P_L(1m)}{\gamma \alpha} e^{-\alpha}$$

Where $P_L (1m)$ represents the propagation loss that occurs for 1 meter distance, $r$ is the distance between transmitter and receiver and $\alpha$ the of propagation loss exponent which was adjusted to 2.7 in our simulations. The value of the amplitude should be obtained picking the statistical value from Rayleigh distribution, taking its mean value

$$p(\beta_{kl}^2) = \frac{1}{\sigma_{kl}^2} e^{-\beta_{kl}^2/\sigma_{kl}^2}$$

Parameters for the Saleh - Valenzuela model were derived from the measured data and the simulation of delay spread was carried out. Then, it was compared to that obtained directly from the measurements and that filtered by CFAR technique. Afterwards, the FDTD method, accelerated via GPU technology, was also tested for simulating the measured PDPs.

### III. MEASUREMENTS SETUP

The environment for the indoor measurements campaign is a (12.32 x 15 x 8) m auditorium at the Catholic University of Rio de Janeiro (PUC-Rio), illustrated in Fig. 2. Eight reception points (RX1 to RX8) were selected near different types of materials like wood, glass and metal, on LOS (line of sight) condition at different distances from the transmitter.

The sounding technique uses time domain measurements of PN sequences with matched filtering implemented by software at the receiver end [6]. A sounding bandwidth of 160 MHz allows a spatial resolution of 3.75 m, with maximum delay of 3.1875 $\mu$s and a theoretical dynamic range of 48 dB. The channel sounder configuration is shown in Fig. 3.

Both transmitter (TX) and receiver antennas are omnidirectional discones with an approximately constant return loss about 15 dB over the frequency range of interest, operating in vertical polarization.

The generated driving signal in Eq. 8 has a central frequency ($f_c$) of 1.95 GHz over a band ($f_b$) of 80 MHz and $t_0 = 12.5$ ns denotes the initial delay; signal (normalized) amplitude and its frequency contents are illustrated in Fig. 4.

$$E_x(t) = E_0 \sin[2\pi f_c(t - t_0)] \exp\{-[2f_b(t - t_0)]^2\}$$ (8)
IV. FDTD IMPLEMENTATION

For the FDTD implementation [7, 8], the discretization of the computational domain followed an uniform grid with spatial steps $\Delta x$, $\Delta y$, $\Delta z = \lambda / 10$, which, for a working frequency of 1.95 GHz, corresponds to $\Delta x$, $\Delta y$, $\Delta z = 0.0154$ m. Numerical dispersion was thereby avoided and, by proper choice of the temporal step ($\Delta t = 0.0266$ ns), calculated according to Courant criteria [9] and used in central difference approximation of Maxwell equations, numerical stability was assured. Also, for the truncation of the domain, 5 UPML layers were implemented accordingly [10].

For the $(12.32 \times 15 \times 8)$ m scenario at hand and a spatial step of 0.0154 m, a total of 55757318 FDTD cells are represented, each cell associated to six (electric field values as well as to four flags indicative of the type of material present at each spot. Also, field values are 4 bytes real numbers while flag lengths are 1 byte each, implying a memory need of 30 bytes per cell and a total memory requirement of about 16.72 GB to address the present problem, which was perfectly handled by the supercomputer of CESUP/UFRGS of 324 GB (RAM) processors where the application was running [7].

The CUDA FDTD version of the code was changed to work on GPU Tesla S1070 with 240 kernels, 4 Teraflops, clock rate 1.44 GHz and 16 GB of global memory. The $(x,y,z)$ $E$ and $H$ field components were stored on the device memory as 32 bit floating point variables. A texture memory was used to store, as a pointer stream, the material types in the model space. In both of these cases, the 3D volume was flattened into 2D and was accessed via an algorithm based on 3D to 2D address translation. This allows the entire 3D space to be updated in one render pass and also avoids potential "read after write" data corruption. The material type pointer stream was used for material property lookups stored in textures. $E$ and $H$ scattered field update calculations were converted to fragment programs, taking the E and H fields values stored in textures as inputs [7].

The constitutive parameters of different materials of the environment are input parameters that are taken into account in the simulation algorithm. The values in Table 1 are associated to different colours in Fig. 6. Also, TX and RXs in Figs. 6 denote the position of transmitter and receiver antennas.

![Constitutive parameters of different materials.](image)

**Table I**

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative permittivity</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>3.0</td>
<td>0.001</td>
</tr>
<tr>
<td>Concrete</td>
<td>6.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Glass</td>
<td>2.7</td>
<td>0.008</td>
</tr>
<tr>
<td>Metal</td>
<td>1.0</td>
<td>1.0x10^9</td>
</tr>
</tbody>
</table>

The application of the Saleh - Valenzuela model generated a set parameters adjusted to the power delay profiles acquired in each measurement point. This set is comprised of: decay rates of cluster ($\lambda$) and rays ($\lambda$), the interarrival time of cluster, ($T_c$) and rays ($\tau_{ad}$), the number of paths ($k$) and clusters ($l$).

The mean values calculated for all measurement locations are shown in Table II.

![Points of measurement (different materials).](image)

**Table II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mean values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>23 ns</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>11 ns</td>
</tr>
<tr>
<td>$K$</td>
<td>8</td>
</tr>
<tr>
<td>$l$</td>
<td>2</td>
</tr>
<tr>
<td>$T_c$</td>
<td>90 ns</td>
</tr>
<tr>
<td>$\tau_{ad}$</td>
<td>23 ns</td>
</tr>
</tbody>
</table>
V. RESULTS

A. Measured data

In Fig. 7 are the PDPs measured at each receiver point. From the analysis of the measured PDPs, the Saleh-Valenzuela model parameters were derived.

The application of the Saleh-Valenzuela model generated a set parameters adjusted to the power delay profiles acquired in each measurement point. This set is comprised of: decay rates of cluster (\(\Lambda\)) and rays (\(\lambda\)), the number of paths (\(k\)), the number of clusters (\(l\)), the interarrival time of cluster (\(T_l\)) and rays (\(r_{kr}\)). The mean values calculated for all measurement locations are shown in Table II.

Figure 7. Measured power delay profiles.

B. Simulation with the Saleh-Valenzuela model

In order to analyze the suitability of the Saleh-Valenzuela model to describe the channel, 1000 power delay profiles were generated and the convergence of this simulation was tested. So, the Fig. 8 presents the convergence of this simulation process showing the delay spread versus the number of simulations. From the results it is possible to conclude that 500 PDPs were sufficient to generate the channel response.

The mean value of the RMS delay spread is 14 ns, 15 ns from the measured PDP filtered with the CFAR technique [10] and 22 ns from the measured PDP without application of filtering technique. From this result it is possible to observe a good agreement between the results obtained with the filtered measured data and the Saleh-Valenzuela simulation since the relative error is smaller than 5%.

C. FDTD results

The power delay profiles simulated with FDTD technique are shown in Fig. 9 for each receiver point. A first comparison between the measured (Fig. 6) and FDTD calculated (Fig. 8) PDPs indicates good agreement for short delays below 60 ns (18 meters). Some severe discrepancies are observed between 60 and 300 ns. So, more analysis and comparisons between FDTD calculations and measured data are underway.

Fig. 8. Convergence evaluation of Saleh-Valenzuela model.

The CDFs of the RMS delay spread obtained from unfiltered and CFAR filtered data, and from simulations with FDTD and the Saleh-Valenzuela model, are shown in Fig. 10.

The simulated RMS delay spread with both techniques, are compared to that obtained from the unfiltered measurements in each position of the receiver and this shown in Fig. 11.

Fig. 9. FDTD Simulation power delay profile

Fig. 10. Simulated and Measured CDFs of RMS delay.
An efficient sounding technique was implemented to test the behavior and help to characterize the radio propagation of a single indoor channel. Further, the parameters of the Saleh-Valenzuela model for the channel were obtained. The model validity was tested by simulating 500 and 1000 profiles with the extracted parameters and comparing the CDFs of RMS delay spread for measured and simulated profiles. A good agreement was observed. The average RMS delay spread obtained with the Saleh-Valenzuela model was 14 ns and the corresponding value obtained from the measurement was 15 ns.

An FDTD software tool was also implemented and used to simulate power delay profiles at the receiver points. Initial comparison between FDTD generated and measured PDPs indicate an average RMS error of the order of 8 dB [12]. The RMS delay spreads obtained from the Saleh-Valenzuela simulated PDPs showed underestimation while that obtained with FDTD technique were overestimated, when compared with that calculated from the measurements.

As future works we will perform new measurement campaigns in different scenarios in order to improve the validity of the simulation results of models cited in this work.

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