A GAUSSIAN BEAM TRACKING METHOD
FOR INDOOR PROPAGATION CHANNEL MODELING

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ABSTRACT

The use of a Gabor frame based decomposition of source fields allows the representation of radiated fields as a superposition of shifted and rotated Gaussian beams. Gaussian beam tracking through multiple reflections and transmissions is straightforward owing to Gaussian beams asymptotic properties. Fields can then be evaluated by summation of analytic terms representing transformed Gaussian beams. It must be noted that the parameters of a given transformed Gaussian beam have to be calculated only once for all observation points. Channel impulse responses simulated by this method in an indoor environment at 60GHz are presented and compared to measurement results.

INTRODUCTION

Future wireless communication systems may have to operate in the millimeter wave band in order to meet requirements for higher data rates. For these systems, operating mainly in office buildings in a multipath propagation context, accurate channel modeling, with configurational (space-time) and spectral (wave number-frequency) properties treated simultaneously, is needed.

Methods based on discrete phase space representations seem well suited to such problems. These representations lead to the decomposition of a source distribution into a set of elementary functions [1]. Among these techniques, the windowed Fourier transform is particularly used in most cases when wave tracking has to be performed. The reason is that the elementary window of such a transform can be taken to be a Gaussian function, and Gaussian functions possess highly desirable features. Firstly, they provide the best possible simultaneous localization in spatial and spectral domains. Secondly, their radiated fields can be put in the form of shifted and rotated Gaussian beams, which can be tracked easily in a complicated environment. Their propagation and transformation through interfaces are known in closed form through asymptotic evaluation, taking advantage of their spectral localization [2], [3].

The channel impulse response simulation method proposed in this paper aims at a fast, but accurate enough, computation of fields in a multireflecting environment. The proposed method is using a fully rigorous procedure, known as ”Gabor frame decomposition” [4], based on a windowed Fourier transform.

In the present paper we first outline the formulation of the method: the basics of Gabor frame based representation of source fields and of Gaussian beam propagation are presented, and the procedure employed for Gaussian beam tracking is described. Coupling to a receiving antenna and amplitude delay profiles evaluation are then addressed. Finally, simulated results are presented and compared to measured results before concluding.

FORMULATION OF THE METHOD

Source Field Decomposition and Gaussian Beam Propagation

In the Gabor frame expansion the elementary functions of the source field decomposition are Gaussian windows which are translated in the spatial and spectral domains [4] as shown in Fig.1.

Taking xOy as the source plane and an x-polarized source, we decompose the source field $E_x(x,y,0)$ into a set of elementary functions w_{mnpq} which are obtained from a single Gaussian window w by spatial and spectral translations:

$$E_x(x,y,0) = \sum_{m,n,p,q} A_{mnpq} w_{mnpq}(x,y) = \sum_{m,n,p,q} A_{mnpq} w(x-ml_x, y-pl_y) e^{i(n\kappa_x x + q\kappa_y y)} \qquad (1)$$

where l_x, l_y and κ_x, κ_y are respectively the spatial and spectral shifts and $m,n,p,q \in \mathbb{Z}$.

Such an expansion (1) has been shown to be stable only if the set of windows constitutes a frame, which requires that the

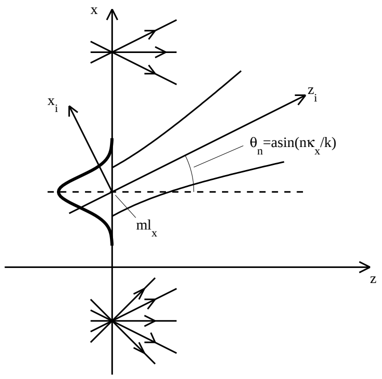


Figure 1: Decomposition of the source field into a set of elementary Gaussian beams.

spatial and spectral domains be oversampled. This oversampling can be chosen so as to optimize computation time, or to cope with wideband signals [5] or with the specific geometry of the problem. The oversampling factor, as well as the width of the windows are thus important flexible parameters.

The coefficients A_{mnpq} can be computed efficiently by a windowed Fourier transform from the source field and the dual function of the Gaussian window.

The field radiated by each Gaussian window can be represented by spectral integrals and evaluated asymptotically by the stationary point method within the limits of the paraxial approximation [3]. This evaluation leads to a closed form expression which represents a generalized Gaussian beam. It can be put in the form of a complex ray using the same formalism as for geometrical optics rays, but with a complex curvature matrix. Incident fields radiated at any observation point are thus expressed rigorously as a discrete superposition of a moderate number of shifted and tilted elementary Gaussian beams.

When one of these Gaussian beams is incident on a plane interface, the reflected and transmitted fields are easily expressed by spectral integrals. Closed form expressions can then be obtained via asymptotic evaluation of these integrals within the paraxial approximation. The interaction of one elementary beam with an interface thus gives rise to two new Gaussian beams, a reflected one and a transmitted one.

For a given source field, once the transformation of each elementary beam by the different interfaces is known in closed form, the total reflected or transmitted field can easily be evaluated by superposition. Multiple reflections will be handled by an iterative procedure, as will be shown in the next section.

Beam Tracking

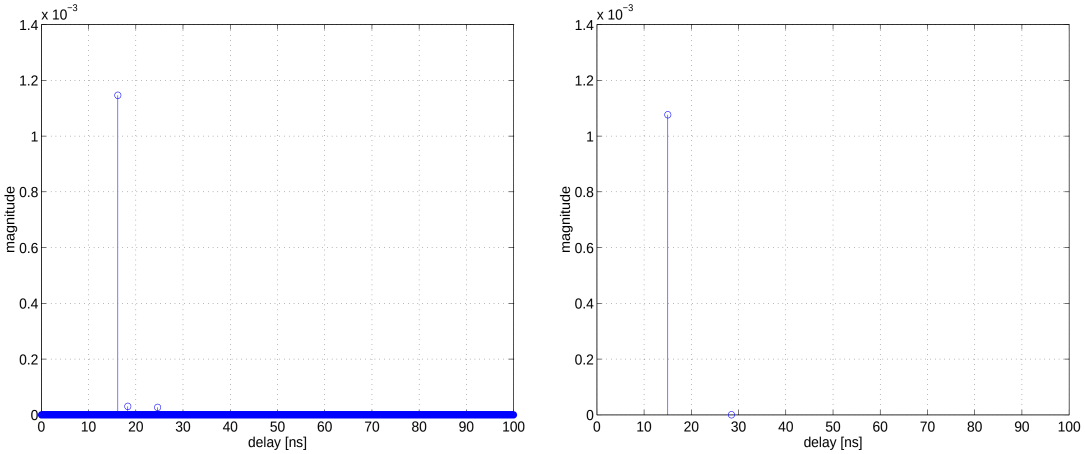
A model of plane surfaces is used to describe the indoor environment geometry. The simulation analysis considers all combinations of reflections (between walls, floors and ceilings) and transmissions until a threshold level is reached.

The procedure is as follows. After interaction of a given beam with a surface, the reflected and transmitted beams, which are fully characterized by a few data (axis direction and origin, amplitude, complex curvature matrix), are taken as incident beams for the next interaction with a plane, where they will create again two beams, a reflected one and a transmitted one. This recursive procedure, performed for every beam obtained from the source field decomposition, leads to all the beam axis paths in the total environment. Geometrical characteristics for every beam (position of its axis direction and origin...) are stored in a file. In order to calculate the field received by an antenna located in a room, we extract from the file only the beams propagating through that room, and evaluate the total field by superposition of the fields created by those beams. Such a geometrical approach is computationally efficient.

Coupling Factor

In order to take into account realistic antenna patterns we calculate the coupling factor between incident field and the antenna. To this end, we only have to consider the contribution of the beams passing through the room where the antenna is located and arriving from the half-space situated in front of the directive antenna. The signals received from each of these beams are summed up to obtain the total received signal transmitted to the receiver by the antenna.

The coupling factor between a Gaussian beam and an aperture antenna is computed using a normalized inner product between the electric field at the antenna aperture and a three-dimensional field representation of the Gaussian beam.



(a) Magnitude of the measured channel impulse response.

(b) Magnitude of the simulated channel impulse response.

Figure 2: Channel impulse response.

Using asymptotic evaluations of the coupling integrals arising in this inner product leads to an analytical form of the coupling factor. In the case of a receiving horn feeding a metallic waveguide, this coupling factor expresses the complex amplitude of the modes generated in the guide by the received beam. This analytical expression will be computed to know the contribution of each beam to the received signal.

Channel Impulse Response Simulation

We start by performing a Gaussian beam decomposition of the source field. These beams are tracked through the environment, following the procedure described above, and finally we obtain the received signal corresponding to each beam received by an antenna (taking into account the coupling factor). To simulate the channel impulse response, we compute the received signal and the propagation delay corresponding to each beam passing through the room where the receiving antenna is located.
Knowing that Gaussian beams equiphase surfaces are spherical, to determine the propagation delay at point $M(x, y, z)$ we consider the delay at point M' situated on the beam axis on the same equiphase surface as the M point. The propagation delay until the M' point is easy to determine from the expression of an elementary Gaussian beam in the paraxial approximation, and so we obtain the amplitude-delay profile for a given environment, which gives us access to the narrow band channel impulse response.

NUMERICAL RESULTS

Experimental Configuration

The measurements performed at ENIC (Ecole Nouvelle d'Ingénieurs en Communications, France) consist of amplitude/phase measurements using a network analyzer at 1601 equidistant frequency points. Measurements were performed in the 57 - 59 GHz frequency band. The measurement site was a small laboratory (7.1 x 5.1 x 2.8 m) and transmit and receive antennas were both waveguides. The time domain response is obtained by the network analyzer from the measured samples in the frequency domain response using the Inverse Fast Fourier Transform (IFFT). The magnitude of the computed time domain response is given in Fig. 2a. A dominant LOS component and some multipath components with various propagation delays can be clearly seen. The threshold level in the delay profile was chosen equal to 20 dB below the peak.

Channel Impulse Response Simulation

Following the procedure previously described, we performed simulations of the channel impulse response in the same configuration as the one used for measurements.

In our simulations, the inner structure is modeled by a combination of rectangular reflecting surfaces. Each surface of the walls, assumed to be planar and smooth, is characterized by scalar reflexion and transmission coefficients. We consider only reflections and transmissions and ignore diffraction and diffuse scattering. In fact, only the Gaussian beams incident on a "corner" are diffracted, as Gaussian beams are of limited transverse extent, by contrast with plane waves. Working in the millimeter wave part of the frequency spectrum still reduces the influence of diffraction.

The source distribution is decomposed on a frame made of 6λ wide Gaussian windows. To represent accurately enough the field radiated by the transmit waveguide, 360 beams were taken into account.

For every beam propagating through the room where the receiving antenna is located, we calculate the coupling factor to the receiver and the corresponding delay. Representing the amplitude-delay profile we obtain the channel impulse response shown in Fig. 2b. The computation time of the Matlab procedure on a Pentium III based PC with 300MHz clock rate is less than 3 minutes.

Comparison of these simulation results with measured results shows acceptable agreement. Several sources of discrepancies can be identified: the relative orientation of antennas in measurement configuration is not known, and in simulation the antennas have thus been put face to face; the electrical properties of the building materials, which affect the field strength of each beam, are not precisely known either. Finally, the influence of furniture was not taken into account in these results, although the method allows to.

CONCLUSION

In this paper, a method of propagation modeling well suited for wireless indoor applications at millimeter-wave frequencies was described and comparisons with measurement results in such an environment were performed. The formulation of the method has been presented, including: the representation of source fields as a superposition of Gaussian beams, a Gaussian beam tracking procedure through multiple interactions, the coupling factor to a given receiving antenna pattern, and amplitude-delay profiles evaluation.

The comparisons performed with measurements in a real environment showed a promising correlation between simulations and measurement results.

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