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Nourddine Azzaoui, Laurent Clavier

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Nourddine Azzaoui
Institut de Mathématique de Bourgogne(IMB)
Université de Bourgogne
9 avenue Alain Savary, 21000, Dijon France.
Email: nourddine.azzaoui@u-bourgogne.fr

Laurent Clavier
IEMN UMR CNRS 8520
and TELECOM Lille 1, from
(GET/INT - TELECOM Lille 1) France.
Email: Laurent.Clavier@iemn.univ-lille1.fr

Abstract—In order to make realistic simulations of the radio propagation mechanism in ultra-wide band channels, an appropriate model is usually needed. In this paper we give a new technique of modeling the impulse response of the 60 Ghz channel. This new approach is based on the spectral analysis of α-stable processes. Our new model present many advantages : firstly, the channel is characterized only by a one deterministic function(spectral density) in the place of four parameters. Secondly, the estimations procedures deals directly with the measured transfer functions this avoid loosing informations in data pretreatments. Finally, an estimation of the spectral measure permit to directly generate the impulse response.

INTRODUCTION

One fundamental and primary issue in developing wireless communication systems is to model the mechanism of radio propagation channel. This problem becomes more difficult with the multipath behaviors in the transmission medium. A large number of channel models have been developed and are successfully used in the actual communication systems. However, other communication solutions are under development on ultra-wideband (UWB) [1], [2] and at extremely high frequencies [3], [4], [5]. Those new approaches importantly modify the way we consider the propagation channel. Classical statistical models have been based on the study from Bello [6] and on the Wide Sense Stationary (WSS) and Uncorrelated Scatterers (US) properties. However the WSS areas are very limited when the wavelength is only a few millimeters [7] and the US property does not hold when the time resolution is too high [2].

As a consequence new approaches are needed to model the channel. The IEEE 802.15.3a standards task group proposes a model for UWB channels [2] based on the Saleh and Valenzuela approach [8]. This model introduces two Poisson processes to model the path time of arrival; the path amplitude laws are Rayleigh distributed in the initial model and for a rather narrow band they are log-normal with an additional shadowing factor. This model is then difficult to use for theoretical performance analysis and development of adapted digital communication and signal processing solutions [1].

In this paper we propose a new solution to address the statistical channel modeling problem using α-stable processes. It is based on the fact that the random transfer function $H(f, \cdots)$ can be considered as α-stable process. In this case it can be uniquely identified by a spectral measure μ. From this spectral measure a set of random variables can be generated and used directly in the calculation of the channel impulse response. Several factors made us think about this approach: firstly, the high variability of the random variables realizations is not compatible with Gaussian distributions but is highly suitable to α-stable distributions. Secondly we did not want to loose information in preprocessing the data, like with the unavoidable windowing of the inverse Fourier Transform. Finally, the statistical properties of α-stable distributions make them appropriate models for phenomena with great variability. Besides, the Gaussian distributions, which is widely used in classical channel models, are a special case of α-stable.

The rest of the paper is organized as follows: in the first section, we introduce the conditions in witch our measurements were made and a brief overview of classical channel modeling in the 60 GHz band. We show what are the limits of previously developed models. In section II, we give a justification of our approach, some basic results on α-stable distributions and the theoretical description of our model. In the third section, we develop the tools necessary to estimate the spectral measure representing the channel and how to generate the impulse responses. Finally, to evaluate our model we consider an ultra wide band channel in the 60 GHz band [9]. We apply the model to observed data collected in IEMN[1] [10].

I. THE 60 GHZ CHANNEL

A. Channel Sounding

1) The channel sounder: The 60 GHz channel sounder developed in IEMN [10] is a wide band frequency sounder based on a vector analysis of the transfer function. Two heterodyne emission and reception heads have been developed

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[1]Institut d'Eléctroniques de Micro-electroniques et de Nano-technologies

by monolithic integration with frequencies ranging from 57 to 59 GHz and with intermediate frequencies of 1 to 3 GHz. A dedicated network analyzer allows, after calibration, the vectored measure of the frequency transfer function. The 2 GHz channel bandwidth is measured by spanning by steps of 1.25 MHz the continuous wave generated by the sounder. After the Inverse Fast Fourier Transform operation on the measured data, one can extract the wide band impulse response of the channel. The frequency span yields a delay resolution of 0.5 ns. The frequency step yields a maximum measurable delay of 800 ns.

In our measurements, the environment was kept static. Only the receiver was moved between two measurements by using an automated positioning system that consists in a linear table of 50 cm with a step-motor driven millimeter screw along it.

The measurement system has been dimensioned in such a way that the signal-to-noise ratio at the network analyzer was not less than 10 dB. The apparatus dynamic was of 124 dB. A transmitted power of 10 dBm was sufficient to guarantee this measurement quality on a transmitter - receiver distance that can reach 45 m.

2) Antennas and room: The room where measurements were made in is presented on Fig. 1. It is a computer laboratory. The transmitter was fixed in a corner, close to the roof, pointed toward the opposite corner. The receiver was placed in several positions in order to represent as many configurations as possible. Measurements were performed at 26 different places (sites) in the room. At each site, the portable receiver moved over 250 positions on a graduate ruler by steps of 2 mm. Horizontal linear polarization patch antennas were employed [11]. The gains were of 12 dB. The 3 dB beam width was of $100°$ at the transmitter and $30°$ at the receiver.
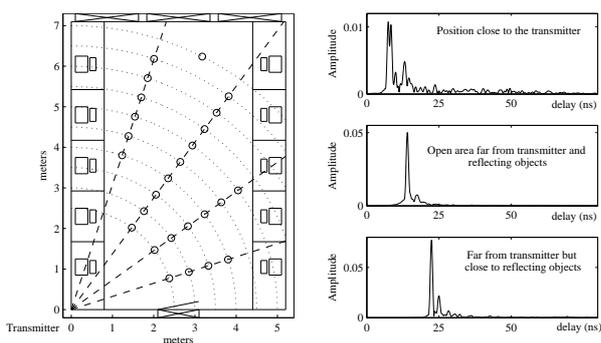

Fig. 1.   Room where measurements were done.

B. Short description of selected previous works.

A few papers have proposed models for the 60 GHz channels. Some are based on deterministic modeling and generally ray tracing [12], [13], [14], [15] that gives satisfying results. However our goal is to run digital communication simulations and the ray tracing approach implies a too high complexity; that's why we chose a statistical approach.

The channel can be represented by a linear filter characterized by its impulse response given by,

$$h(t) = \sum_{k=1}^{N} a_k \delta_{t-\tau_k} e^{i\theta_k}, \tag{1}$$

where, a_k, τ_k, θ_k and N are respectively the amplitude, the delay, the phase of path k and the paths' number. Extensive works about modeling the impulse response was made in the literature [16]. But, the main difficulties are the path delays and their amplitudes. Phases are usually considered as uniformly distributed over $[0, 2\pi]$ because the path length is much larger than the wavelength [7].

The path time of arrival distribution is not a completely solved problem [12], [17], [18]. Saleh and Valuenzela proposed a statistical model [8], supposing rays arrive in clusters. It is the most widely used statistical model for the 60 GHz indoor channel [19], [20], [21] and it is also a choice for the Ultra Wide Band channel model [2]. However the different distributions that are introduced to model delays and amplitudes make it difficult to use for theoretical developments.

C. Modeling difficulties and new approach

a) Delays: If it is tempting to describe the arrival times in terms of a Poisson distribution, it was shown in [22] that, in the case of 60 GHz channel in small rooms, this modeling is not accurate. At other frequencies, the same results were also obtained. Turin [23] introduced, for frequencies 488, 1280 and 2980 MHz, a modified Poisson process where the Poisson parameter changes when a path arrives. Suzuki [24] further developed the model and proposed the $\Delta - K$ model. His idea is that if, in a bin a path arrives, the probability to have a path in the next bin increases. Saleh and Valenzuela [8] studied indoor propagation and showed that the 7.5 GHz channel can be modeled by a mixture of two Poisson's distributions. One determines the arrival time of clusters and the second the arrival time of paths in each cluster. Other models were also proposed using a Weibull distribution [25]. In [26], the clustering effect is not observed and the probability of receiving a multipath component, within discrete excess delay intervals of 7.8 ns wide, is approximated with piecewise functions. In [17] a measurement campaign at 39 and 60 GHz in an outdoor environment is presented. A model based on a non-stationary Poisson process is proposed. In [18], α-stable distributions are proposed for delay modeling and some theoretical and experimental justifications of the model are given.

b) Amplitudes: For amplitude distributions, it is usually considered that each detected path is the superposition of several paths. Many studies have been made to model such components. If the number of paths is sufficiently large then due to the central limit theorem, both in-phase and quadrature components, the received signal have gaussian distributions. A careful derivation of the resulting amplitude distributions, depending on the number of paths merging as one, is done

in [7]. When the number of merging paths is large enough Rayleigh, Rice or Nakagami distributions are obtained. Other studies have lead to different types of distribution, especially lognormal [26], [25]. The discussion on delays and amplitudes

shows the difficulty to find the right model for a given application. This difficulty is even greater when the channel band becomes wider and when the carrier frequency gets higher. The recent IEEE 802.15 proposal for the Ultra Wide Band channel is based on a modified version of the Saleh and Valuenzela model [2] and underlines the difficulties of the modeling.

D. Classical assumptions

So far and in previous works [12], [27], [28], judicious hypothetical Wide Sense Stationary and Uncorrelated Scatterers (WSSUS) assumptions have been adopted in modeling the 60 GHz radio channel, without however any criticism about these statistical properties. It appears however that those assumptions are not valid for our situation:

- In the context of millimeter waves, one single office room will show various behaviors and characteristics. Measurement results in [27] show strong dependence of useful statistical parameters on the propagation environment. Different regions in the same environment exhibit different statistical behaviors and need different model derivations. Besides, the local area where the WSS assumption is verified are reduced to a few cm^2 due to the small wavelength.
- Due to the increase in the bandwidth, more paths should be resolved. But, as a consequence, possible correlation between multipaths components could be induced by finite resolution of radio communication systems and/or space limitations inherent to the confined indoor channel. As a consequence the uncorrelated scatterers property does not hold.

E. Data Processing

Our measurement setup is based on a network analyzer. In fact, in addition to errors committed by the measurement instruments, we have lost informations in three levels :

- *The frequency span of the measurements* induces errors in the calculation of the inverse Fourier transform (IFT). We thus loose temporal accuracy since close impulses can not be detected.
- *The frequency step* hides event that could happen between successive samples.
- *The statistical distribution parameters' estimation* introduces errors depending on the size of the observations' sets. This becomes critical when the stationary areas become small, which is the case in the millimeter wave band considered.

Inevitable errors occur due to measurements, estimation or due to the model itself. One goal is to minimize these errors in order to get closer to reality and to extract the maximum of information from the data. We propose to make the statistical

analysis in the frequency domain, with the minimum data preprocessing in order to take benefit from all information contained in the transfer function measured by the channel sounder. Besides we propose a new statistical model which do not rely on second order statistics.

F. New approach

The key of the statistical study that one can carry out is in the nature of the transfer function H which is theoretically the Fourier transform of the received signal if a Dirac pulse was sent:

$$H(\omega) = \int e^{jt\omega} h(t) dt \qquad (2)$$

$h(t)$ is the unknown impulse response of the channel at a given time t. Because of the the random configuration of the transmission environment $h(t)$ is also random. In other words h is a stochastic process $(h(t,.), t \in \mathbb{R})$ and consequently the transfer function is also a stochastic process that may be represented as represented by a stochastic integral :

$$H(w,.) = \int_{\mathbb{R}} e^{jwt} d\xi(t), \qquad (3)$$

where $d\xi(t) = h(t,.)dt$ is a random measure. In order to
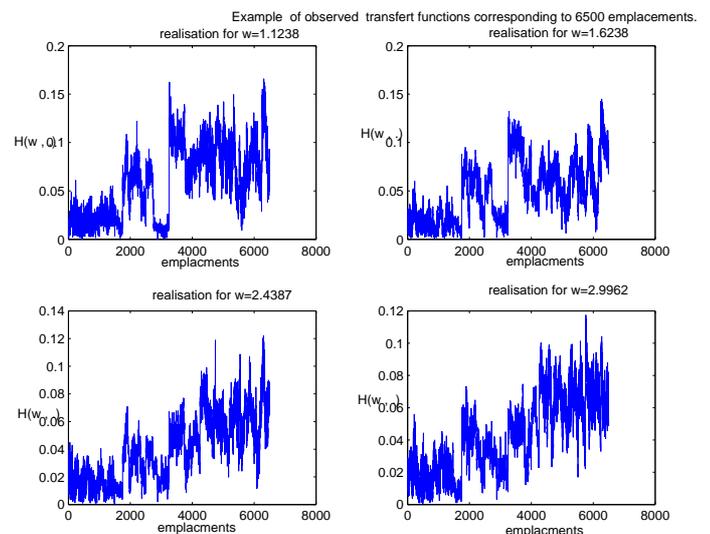

Fig. 2. Realization of the channel attenuation at different frequencies for all the emplacements.

have an idea about the individual distributions of the random variable $H(w,.)$, we present in Fig. 2 its realizations measured in all the positions of the room. We remark that, for given frequency w, the random variable $H(w,.)$ exhibits a large variation. This fact is confirmed by the test of infinite variance [29]. Fig. 3 shows that the variance of real and imaginary part of observed transfer function may be considered as tending toward infinity.

It is known that α-stables variables and processes are good models for phenomena with infinite variance [30]. In our situation, one of the important aspect of these processes
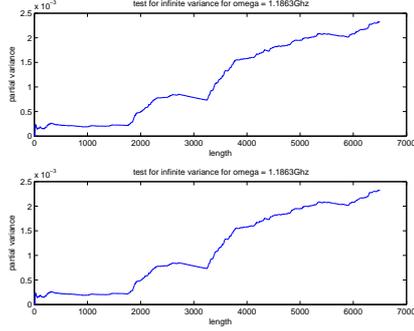
Fig. 3. Test of infinite variance for some observed attenuation at given frequencies

lies on the fact that they can take into account the great variability caused by the relative great size of the rooms and extreme values due to scatterers. The main idea of our work relies on the characterization of the stochastic process $H(w,.)$ given in (3), where $d\xi$ is assumed to be α-stable random measure. It is shown in [31], that under suitable conditions the random transfer function $H(w,.)$ may be characterized by a spectral measure μ defined on $\mathbb{R}$. In contrast with the classical models we are brought back to estimate only one deterministic function in the place of many parameters or many processes.

II. NEW IMPULSE RESPONSE MODEL - THEORETICAL CONSIDERATIONS

In this section we present some theoretical bases on α-stable processes. More details can be found in [31], [30], [29].

c) Symmetric α-stable random vectors and processes: A real centered random vector $X^d = (X_1, X_2, ..., X_d)$ is said to be symmetric α-stable (SαS) if and only if its characteristic function is expressed as:

$$\phi(t_1, ..., t_d) = \exp\{-\int_{S_d} \left|\sum_{i=1}^{d} t_i s_i\right|^\alpha d\Gamma(s_1, ..., s_d)\}, \quad (4)$$

where Γ is a unique symmetric measure defined on the unit sphere S_d of $\mathbb{R}^d$, see [30]. The definition of a complexe SαS vector is generalized naturally by using the real and imaginary parts. Hence a complex random vector, $X^d = (X_1, .., X_d)$ with $X_j = X_{j,1} + \jmath X_{j,2}$, is S$\alpha$S if the real vector $(X_{1,1}, X_{1,2}, ..., X_{d,1}, X_{d,2})$ is also SαS. Cambanis [31] has defined the covariation of two components of the SαS vector X^d by :

$$[X_i, X_k]_\alpha \triangleq \int_{S_d} (s_{1,i} + \jmath s_{2,i})(s_{1,k} + \jmath s_{2,k})^{<\alpha-1>} d\Gamma, \quad (5)$$

where $z^{<\alpha>} = |z|^{\alpha-1}\overline{z}$, and $\overline{z}$ is the conjugate of z. In general, unlike the covariance, the covariation is not symmetric nor bilinear. However it plays a similar role as the covariance in many practical situations [32].

A real or complex stochastic process $\xi = (\xi_t, -\infty < t < \infty)$ is SαS if and only if all finite subset $(\xi_{t_1}, ..., \xi_{t_n})$ of ξ is a symmetric α-stable vector. This is equivalent to the fact that all linear combinations of ξ is also an SαS random

variable. We are interested in harmonizable processes that can be represented with a stochastic integral as in (3). Cambanis [31] have shown that if the process ξ is with independent increments[2] then the covariation function of H is given, for all w and w', by :

$$C(w, w') \triangleq [H(w, .), H(w', .)]_\alpha = \int_{\mathbb{R}} e^{\jmath(w-w')\lambda} \mu(d\lambda) \quad (6)$$

The proof of this result is detailed in [31]. It is also shown that the spectral measure μ is unique and it characterizes the stochastic process $H(\omega, .)$. Equation (6) shows that the covariation function may be expressed as the Fourier transform of the spectral measure μ. This also implies, by the inverse Fourier transform, that μ can be uniquely determined by the covariation function. In other words, the channel characterized by its transfer function may also be identified through the spectral measure μ.

d) Generating the impulse response.: We now present the new model of the impulse response considering that the transfer function is given by (3) where ξ is symmetric α-stable process with independents increments. Let μ be the spectral measure characterizing the random transfer function of the channel and let v be the random variable having the probability distribution $\hat{\mu} = \frac{\mu}{\mu(\mathbb{R})}$. It is shown in [30] that the transfer function $H(w, .)$ may be decomposed in Lepage [33] series as :

$$H(\omega, .) \stackrel{d}{=} (\mu(\mathbb{R}).C_\alpha)^{\frac{1}{\alpha}} \sum_{i=1}^{\infty} \gamma_i \Gamma_i^{-\frac{1}{\alpha}} e^{\jmath\omega v^i}(S_i^1 + \jmath S_i^2) \quad (7)$$

where : Equality "$\stackrel{d}{=}$" means equality in distribution. (γ_i) are independent copies of Rademasher random variable γ, i.e. $P(\gamma = -1/v) = P(\gamma = 1/v) = 1/2$. The random variables (Γ_i) are the arrival times of a Poisson process, they are gamma distributed of rate i, $(v_i)_i$ are independents copies of the random variable v and finally, (S_i^1, S_i^2) are independents copies of a continuous random variable uniformly distributed on the unit circle. By using the properties of convergence in distribution, the equality (3) and the fact that $\int_{-\infty}^{\infty} e^{-\jmath\omega(t-v^i)}d\omega = 2\pi\delta_{(t-v^i)}$, one can calculate the inverse Fourier transform with respect to ω in the equality (7), this leads to :

$$h(t, .) \stackrel{d}{=} (\mu(\mathbb{R}).C_\alpha)^{\frac{1}{\alpha}} \sum_{i=1}^{\infty} \gamma_i \Gamma_i^{-\frac{1}{\alpha}}.(S_i^1 + \jmath S_i^2)\delta_{(t-v^i)} \quad (8)$$

The random impulse response, given in (8), may be assimilated to the structure of the theoretical impulse response of a linear channel given in (1). Since the arrival times of Poisson process (Γ_i) are gamma distributed with parameter i so as i tend toward infinity $(\Gamma_i^{-1/\alpha})$ goes to 0. The vanishing property of the term $(\Gamma_i^{-1/\alpha})$ makes the amplitude of the impulse response

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[2] A stochastic process (ξ_t) is with independents increments if for all $t_1 < t_2 < \cdots < t_n$, the random variables $\xi_{t_2} - \xi_{t_1}, ..., \xi_{t_n} - \xi_{t_{n-1}}$ are independents.

too small as the order of arrivals increases. This property allows a truncation of the sum (8) as

$$h(t,.) \overset{d}{=} (\mu(\mathbb{R}).C_\alpha)^{\frac{1}{\alpha}} \sum_{i=1}^{N} \gamma_i \Gamma_i^{-\frac{1}{\alpha}}.(S_i^1 + \jmath S_i^2)\delta_{(t-v^i)}) + R_N(\alpha)$$

(9)

The stopping threshold N can be determined to have a given accurateness, this technique is discussed in [34].

e) Physical constraints: Due to the limited time resolution of the experimental instruments, we can observe our signals only in discrete instants (with step= 0.5ns). In order to overcome this problem we usually make the hypothesis that an observed value is the result of the superposition of all the rays arriving between tow successive sampling instants. The estimated impulse responses are also calculated by using the same technique.

III. APPLICATION TO THE 60 GHZ CHANNEL

The aim of this section is to use our new model to generate impulse responses characterizing the 60 Ghz channel from the observed data. To reach this purpose we follow the steps :

1) From the observed transfer functions we estimate efficiently the density f of the spectral measure μ. To reach this purpose there exist many works treating this issue. For example in the case of continuous time processes we cite [32]. But since we deal with discrete observations of the transfer function we use the estimation techniques introduced by [35], [36].
2) From the estimated density f we generate independents copies of the random variable v by using techniques presented in [37].
3) Finally, we determine the threshold integer N which permits to truncate the sum (9) in order to have a given precision see [34].

The resolution of these three steps allows to directly generate the impulse response of the channel without estimating
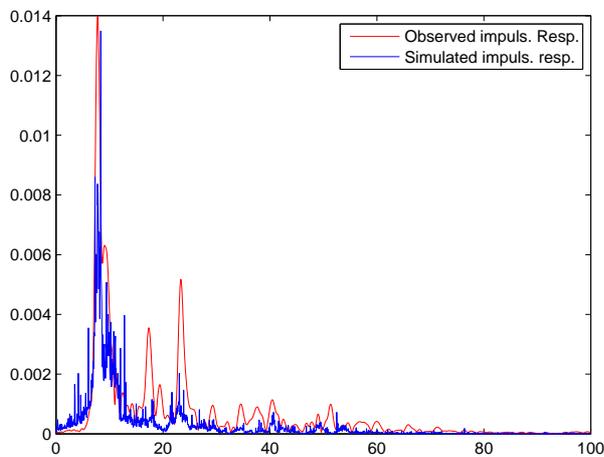

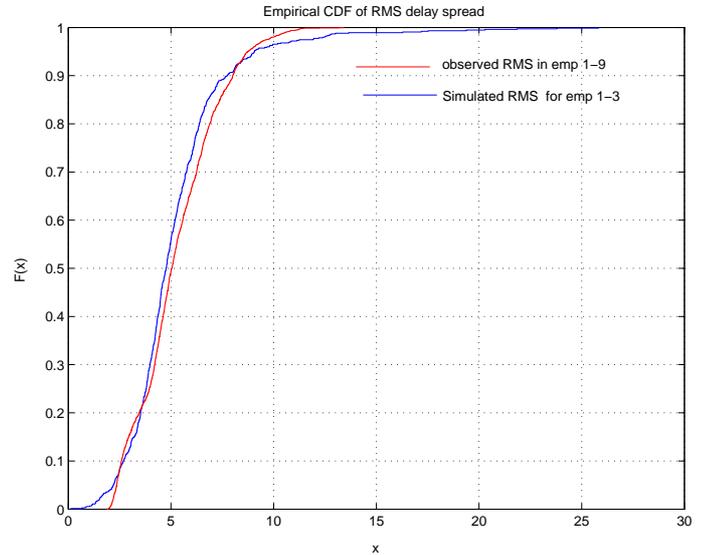Fig. 4. Example of observed and simulated impulse responses.

[b]

Fig. 5. example of RMS delays calculated from observed and simulated impulse responses.

separately its four parameters and without imposing any conditions on the parametric nature of their distributions.

In order to show that our model is an appropriate one in the case of the 60 Ghz channel, we have tested it against the observed impulse responses collected in the room presented in Fig.1, after a synchronization to positions close to the transmitter.

For instance in Fig. 4 we present in the same graphic an example of an observed impulse response and the mean of 1000 simulated using our model. In addition to the visible closeness of simulated and reals data, we notice that the model is able to detect the arrival times with a great precision.

There exist many classical techniques permitting to verify the appropriateness of channel models. The most used are the coherence bandwidth and the (RMS) delay spread. We have choose to use this last one witch given by :

$$RMS = \sqrt{\frac{\sum t^2 |h(t)|^2 - (\sum |t.h|)^2}{\sum |h(t)|^2}}$$

(10)

The idea is to compare, in the same graphic, the cumulative distribution function of RMS delay calculated form observed impulse responses and those generated by the model and eventually make a goodness of fit test. In our case, Fig.5 illustrate the closeness of the simulated and observed cumulative distributions of the RMS delay. Note that this fact is not confirmed by a kolmogorov-Smirnov test but from the graphic Fig.5 we can conclude that the model take in account the most situations observed in the room. The extreme cases illustrated by the long tails of the simulated distribution may describe some other situations that we have not measured.

IV. CONCLUSION

Our theoretical channel model present many advantages that make it simple and portable : In contrast to the classical models it acts directly on the measured transfer function. This property makes it more accurate because we don't loose in using intermediary pretreatment of the information like for instance the passage to the time domain. Besides this, in the classical models, we are brought back to estimate many parameters(delays, amplitudes, phases, number of arrivals) whereas, in our model we estimate only a one deterministic function characterizing the channel. Finally, although the estimation is based on the transfer function, we directly generate the impulse response.

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