Analysis and modelling of the randomness in terminals antennas

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Invited paper

Abstract

This paper addresses the modelling of the radioelectric properties of wireless terminals, taking into account the numerous sources of variabilities which can be encountered in a real use context. After an introduction about the major issues, it first concentrates on antenna statistical modelling and secondly on the combination of terminal and radio channel variabilities. Antenna statistical modelling is tackled through a small signal approach which is valid when the randomness is "small" and also more generally by using modal expansion methods for the electromagnetic fields, which allows carrying out the statistical analysis on the parameters of the modes. Combined terminal and channel modelling is approached by analysing the statistics of the "effective gain" of the terminal in its local propagation context and by modelling it with simple and suitably approximate distributions such as the lognormal.

Keywords: Antennas, mobile communications, wireless terminals, statistical modelling, radio channel.

1. Introduction

Traditionally, antennas are designed, simulated and measured in isolation, i.e. in a rather ideal case which is not realized when the antenna is used in practice. More or less strong disturbances appear on the antenna characteristics when the true ground plane and the casing are taken into account or when electromagnetic objects are present in the vicinity of the antenna. While some of these disturbances can properly be computed using deterministic techniques, others are highly variable by nature and do not lend themselves easily to deterministic modelling. Most generally these effects are just ignored or described very roughly by assuming an ad hoc gain margin. However the growing complexity of nowadays wireless communication systems, the greater variability of application contexts and the greater needs for enhanced performance plead for better taking into account the terminal in the performance evaluation of physical layer schemes and of radio access networks in general. Thus advanced approaches intended to achieve a trade-off between complexity and accuracy are needed. Statistical methods provide a suitable framework for this purpose, since they intend to condense this complexity into a small number of statistical quantities, such as moments of distributions functions. In this section we address such issues, by first concentrating on the statistical modelling of antennas themselves, then by including the radio channel variability in order to combine both antenna and channel variabilities into a single statistical description of an antenna in its local propagation environment.

The statistical approach for antennas is part of a general trend and progress nowadays as regards the incorporation of uncertainty in electromagnetism

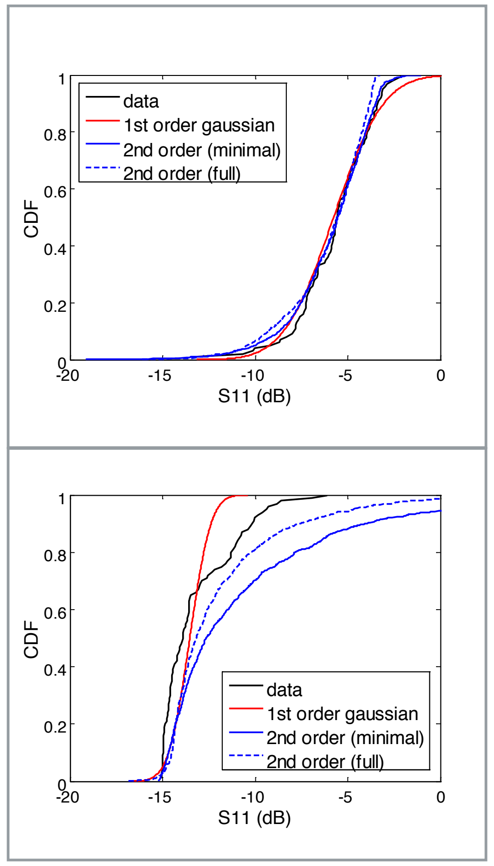
■ **Figure 1.** *A view of wireless terminals in contact with their immediate environment.*

■ **Figure 2.** *Input-output relation between random terminals parameters and the antenna quantities of interest.*

Generally speaking, a statistical model can be seen as an input-output relation: the input includes the set of stochastic variables which constitutes the input stochastic space and the multivariate law of probability for these variables. This law may factorize if the various variables are independent, but most often this will not be the case. For instance if the size of a casing is allowed to vary widely, the length and width will not be entirely independent. In this case, a suitable choice or transformation of the input variables may be useful, such as keeping the length but using the aspect ratio rather than the width. The output is the set of antenna characteristics of interest, together with their probability density function (PDF). In the general case again, these characteristics will not be independent. The input-output relation embodies the complex electromagnetic phenomena involved in the change of output characteristics with a modification of the input variables.

2. Statistical antenna modelling

In this part we address the elaboration of statistical methods accounting for the variabilities of antenna characteristics. Early works in another context have been carried out a long time ago already, although not very much popularized [1]. However, providing representative and simple

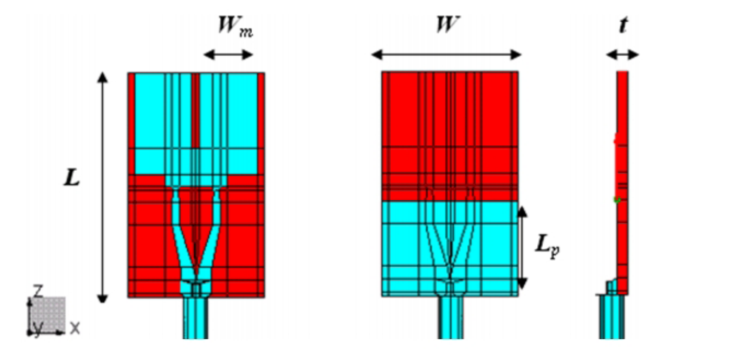


■ **Figure 3.** *Satistics of a dipole reflection coefficient at 0.9 GHz (top) and 1.04 GHz (bottom).*

statistical models of antennas in their use context is all but a simple problem. Several general issues have been discussed in [2], such as the relevance of categorizing antennas through major antenna characteristics. Another question is the choice of the maximum distance within which disturbing objects may be considered to be part of the antenna, as close disturbances both increase the complexity and much affect the antenna behaviour. Last but not least the quality criteria for statistical antenna modelling were also addressed. The statistical approach for antennas is part of a general trend and progress nowadays as regards the incorporation of uncertainty in electromagnetism [3].

p	*1*	*2*	*3*	*4*	*5*	*6*
<f> *(GHz)*	*1.628*	*3.176*	*5.591*	*7.915*	*10.897*	*14.996*

■ **Table 1.** *Natural frequencies empirical mean (DFMM "class")*



	DFMM	
	Original Design	r.v.
W	20 mm	[20; 28] mm
L	33 mm	[33; 43] mm
t	1,524 mm	[1,5; 1,6] mm
W_m	9,1 mm	[9,1; 12,1] mm
L_p	14 mm	[14; 18] mm
ϵ_r	2,33	[2,1; 2,6]

■ **Figure 4.** *DFMM design (left) and DFMM design parameters (right).*

2.1 Small signal analysis

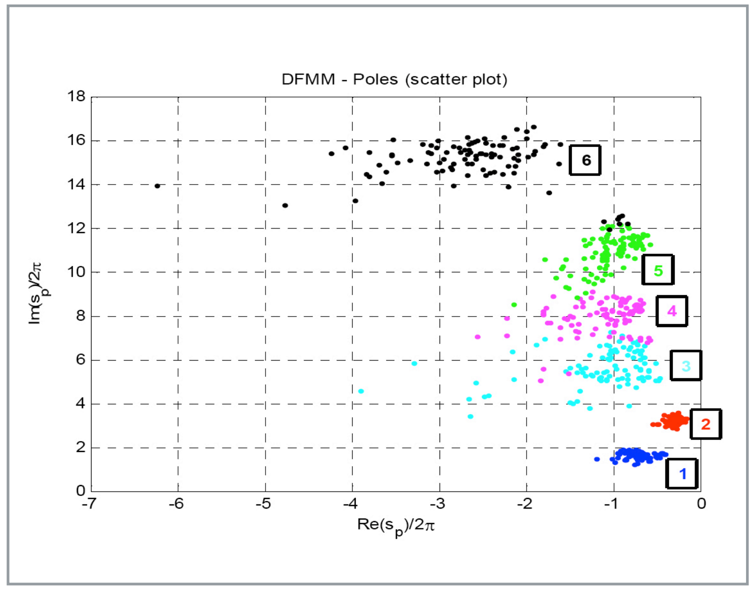
The input-output relation embodies the complex electromagnetic phenomena involved in the change of output characteristics with a modification of the input variables. This relation may be (highly) non linear if the input parameters vary widely. In the work [4], a small signal analysis of the input-output relation is carried out, whereby the author expresses the output variables as a Taylor expansion of the vector of input variables:

$$g(\mathrm{a}+\Delta\mathrm{a}) = g(\mathrm{a}) + \Delta\mathrm{a}^t \cdot \nabla g + \frac{1}{2}\Delta\mathrm{a}^t \cdot \Delta g \cdot \Delta\mathrm{a} + o\left(\|\Delta\mathrm{a}\|^2\right) \quad [1]$$

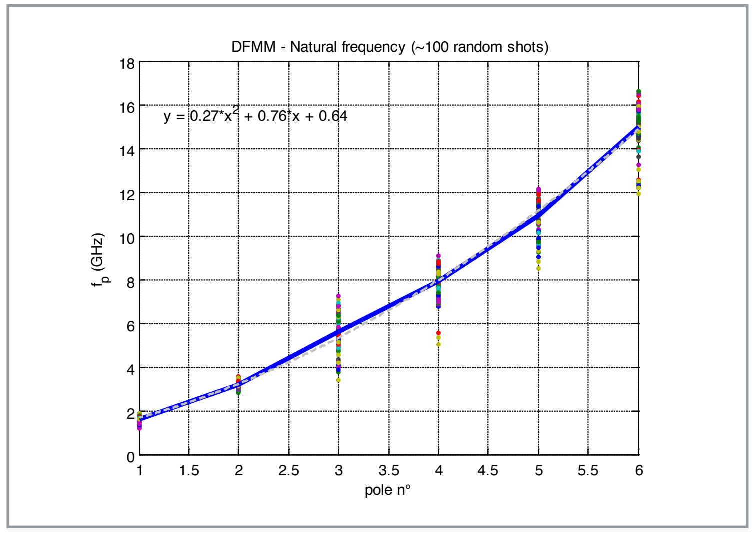
where $\boldsymbol{a}$ is the fixed vector of "nominal" parameters, Δa is the random vector of perturbations, Δa^t stands for its transpose, and Δg is the hessian. To the first order, any output variable is Gaussian distributed if the input variables are Gaussian distributed and independent. The deviation to Gaussianity is observed for large input parameters variations or when the output variable is e.g. close to an extremum, which requires at least 2nd order expansion and leads to asymmetric distributions. An example is shown in Figure 3 for the return loss of a dipole at the frequency of 0.9 GHz where the dipole is imperfectly matched and at 1.04 GHz corresponding to excellent matching (minimum return loss). The computation of the expansion coefficients may require a large database of antennas for sufficient accuracy. Through a suitable choice of the input variables vectors, it is possible to minimize the size of this database (minimal set) or alternatively to increase the accuracy (full set), see e.g. Figure 3.

2.2 Statistical analysis and modelling using parametric models

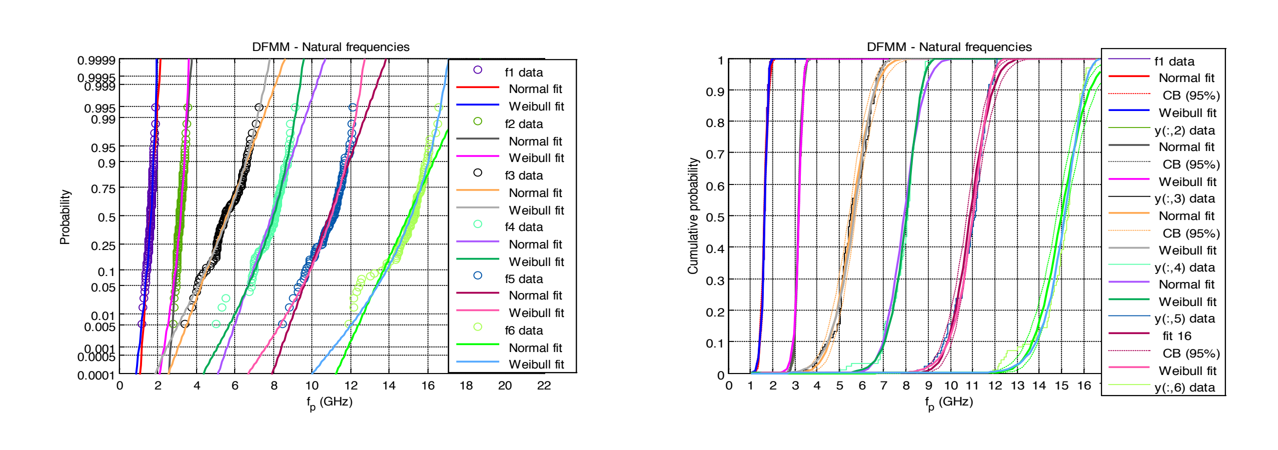
Multidimensional models of the Far Field (FF) radiation characteristics of multiband, wideband or UWB antennas – i.e. frequency (or time) and angular dependent – or Multiple Antenna System (MAS), can be particularly useful in the context of end-user applications, mainly communications – i.e. involving small size antennas and/or terminals – provided they are both



■ **Figure 5.** *DFMM statistics: 1st poles scatter plot (SEM for P = 12).*



■ **Figure 6.** *DFMM statistics: empirical means and dispersion of f_p (SEM for P = 12) and quadratic fit.*

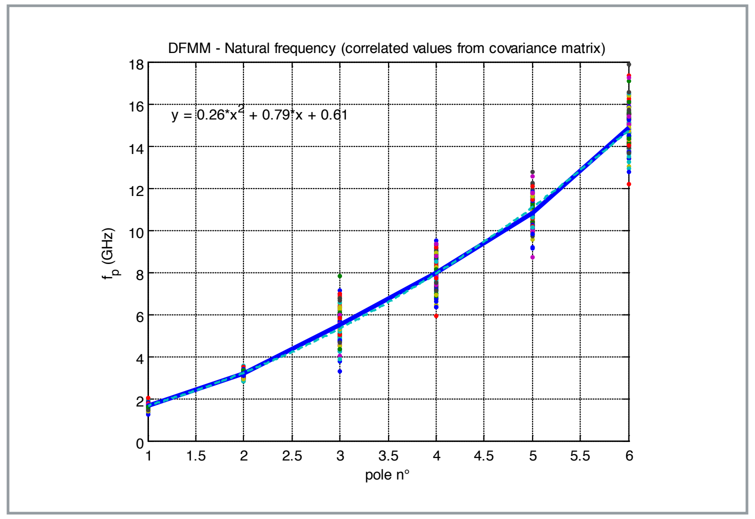


■ **Figure 7.** *DFMM statistics (SEM for $P = 12$): probability plots (left) and CDFs (right) of natural frequencies f_p.*

Pole n°	Estimated parameters					
	Normal			Weibull		
	μ	σ	LL	a	b	LL
1	1.628	0.139	54.06	1.688	14.525	59.20
2	3.176	0.157	42.34	3.251	21.228	36.77
3	5.591	0.810	-116.6	5.934	8.052	-115.7
4	7.915	0.745	-108.6	8.217	14.623	-97.0
5	10.897	0.795	-114.8	11.240	17.874	-107.2
6	14.996	1.008	-137.9	15.406	21.427	-123.1

■ **Table 2.** *Natural frequencies: Estimated parameters (DFMM "class")*

simple and realistic. Such models can advantageously replace in various kind of simulations (e.g. at the radio link level or in ray tracing solvers, etc.) excessively simplistic, but inaccurate, models – such as a simple scalar figure, often a "mean gain" – or complete models (or measurements) both excessively heavy and unnecessarily precise. As previously pointed out, the topic is manifold: the modelling of all FF radioelectric properties of single UWB (or multiband) antennas (belonging to various antenna "classes") with an extremely "light" database and at a low computational cost [6], [7], [8], is addressed hereafter. An indirect approach is used here to reduce the complexity of the statistical analysis, which is applied to the parameters extracted from a parametric modelling based on a drastic order reduction technique: the Singularity Expansion Method (SEM) [9], [10] and the Spherical Mode Expansion Method (SMEM) [11]. This is an alternative to the direct approach in which the statistical analysis is directly applied on "primary" relevant radioelectric quantities such as the antenna efficiency, directional gain or transfer function (more general for UWB antennas), etc.



■ **Figure 8.** *DFMM statistics: randomly generated samples for f_p (from correlated model).*

To build up the stochastic population of antennas, several *generic designs* are considered. A "generic design" is the union of a geometry represented by a set of design parameters and of the space these parameters are allowed to span. For each generic design, a Monte Carlo analysis is performed: N_A "antenna realizations" are generated from random shots of the design parameters (assuming an a priori probabilistic model, often uniform or Gaussian for the independent parameters). These antennas are then electromagnetically simulated, and some of their properties – with relaxed constraints w.r.t. the initial (optimized) design – are verified: for example, samples which are not sufficiently matched (antenna reflection coefficient S_{11} above an a priori threshold, -6 dB e.g.) or present an insufficient realized gain (G_r below a threshold, 0 dBi e.g.) are considered outliers and discarded (and replaced by a new random shot if required). The FF radiation characteristics of any passive antenna can be fully represented by its Antenna Transfer Function (ATF), defined here as [12]:

$$\mathcal{H}(s,\hat{\mathbf{r}}) = \frac{r e^{\gamma r}}{a_1(s)}\sqrt{\frac{4\pi}{\eta_0}}\cdot\mathbf{E}^{\infty}(s,\mathbf{r}) \qquad [2]$$

where $\gamma = s/c$ ($= jk$ in the harmonic case), $\boldsymbol{r}$ is the radial vector, $\hat{\boldsymbol{r}}$ the unit radial vector ("$\hat{\boldsymbol{r}} = (\theta,\varphi)$" in the functions argument), and η_0 the free space impedance.

Applying the SEM and the SMEM to the FF, it has been shown in [13] that, by linearity, the ATF – and the Antenna Impulse Response (AIR), given by inverse Fourier Transform – can be expanded as:

$$\mathcal{H}(s,\hat{\mathbf{r}}) \approx \widetilde{\mathcal{H}}_{N,P}(s,\hat{\mathbf{r}}) = \sum_{p=1}^{P}\left[\sum_{n=1}^{N}\sum_{m=-n}^{n}\sum_{u=1}^{2} R_{nmp}^{(u)}\hat{\Psi}_{nm}^{(u)}(\hat{\mathbf{r}})\right]\cdot(s-s_p)^{-1} \qquad [3]$$

$$h(t,\hat{\mathbf{r}}) \approx \widetilde{h}_{N,P}(t,\hat{\mathbf{r}}) = \sum_{p=1}^{P}\left[\sum_{n=1}^{N}\sum_{m=-n}^{n}\sum_{u=1}^{2} R_{nmp}^{(u)}\hat{\Psi}_{nm}^{(u)}(\hat{\mathbf{r}})\right]\cdot e^{s_p t} \qquad [4]$$

where $\{s_p\}$ is the set of poles, $\{\hat{\Psi}_{nm}^{(u)}\}$ *are the vector spherical wave functions with* $u = \{1, 2\} = \{TE, TM\}$ [13], and $\{R_{nmp}^{(u)}\}$ is the set of modal residues (for the pole p and the TM or TE (n,m) mode). It is assumed here that all the poles‡ $s_p=\sigma_p \pm j\omega_p$ are complex, hence appearing in conjugate pairs (as the AIR h is real). The modal residues verify the general relationship $R_{nmp^*}^{(u)} = (-1)^m[R_{n,-m,p}^{(u)}]^*$ [6] where p^* is the index of the conjugate pole of index p; so that the total number of complex parameters N_T of the truncated representation is $N_T=P/2 + PN(N+2) \sim PN(N+2)$.

Note that N_T is considerably smaller than the initial dataset $\{\mathcal{H}(f_n,q_q,j_m)\}|_{n=1,\ldots Nf,\ q=1,\ldots N\theta,\ m=1,\ldots N\varphi}$. The modelling procedure is as follows: 1. The ATF $\mathcal{H}(f,\hat{\boldsymbol{r}})$ is computed in the Frequency Domain (FD) from Electromagnetic (EM) simulations of the FF, 2. The AIR $h(t,\hat{\boldsymbol{r}})$ is computed from $\mathcal{H}$ by inverse Fourier Transform, after, if required, appropriate processing (windowing, etc.), 3. The SEM is applied to h to extract the first P dominant poles $\{s_p\}$ and their residues $\boldsymbol{R}_p(\hat{\boldsymbol{r}})$, with the Generalized Matrix-Pencil (GMP) algorithm [14]-[16].

The modal residues are computed with the SMEM of the preceding residues, with a truncation to order N, and 5.The modelled ATF is reconstructed following "backward" the previous procedure, and the Total Mean Squared Error (TMSE) is assessed. The "free" parameters P and N are chosen according to a predefined TMSE threshold during the preliminary step of the parametric modelling of the *initial design* –generally optimized under usual design constraints such as matching threshold, bandwidth, radiation characteristics, etc.

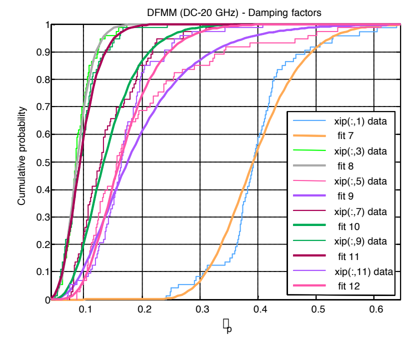
‡Related to natural frequencies $f_p = \Im m(s_p)/2\pi)$ and damping factors $\xi_p = -\mathbf{Re}(s_p) / |s_p| = -\sigma_p / |s_p|$.

§*Dual-Fed Monopole in Microstrip* technology.

C =

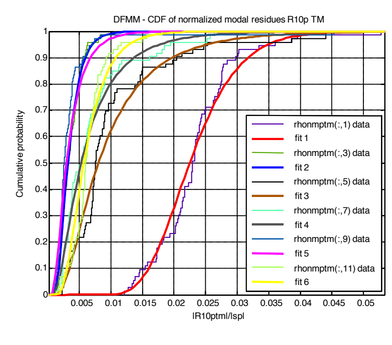
0.0194	-0.0006	0.0759	0.0457	0.0489	0.0491
-0.0006	0.0247	-0.0439	0.0132	0.0462	-0.0667
0.0759	-0.0439	0.6554	0.1543	0.2645	0.4426
0.0457	0.0132	0.1543	0.5556	0.4323	0.4168
0.0489	0.0462	0.2645	0.4323	0.6314	0.4231
0.0491	-0.0667	0.4426	0.4168	0.4231	1.0164

For a considered generic design (e.g. the DFMM§, Figure 4, [17], [18], [19], [20]) a representative statistical set is generated from EM simulations (WIPL-D® here), and each realization is submitted to the abovementioned process and represented by its parametric model dataset $\{s_p, R_{nmp}^{(u)}\}$. For example, a model with $P = 12$ poles and a truncation to order $N = 5$ of the SMEM – corresponding to a convenient tradeoff between order reduction and accuracy (TMSE) – gives a data compression rate of 99.67 % (compression ratio of ~300), considering the initial simulated dataset of 129 600 complex parameters (ATF of 200 frequencies x 18 elevations x 36 azimuth) and the model dataset of $N_T = P/2 + PN(N+2) = 426$ complex parameters.



p	Moments	
	μ	σ²
1	0.398	0.005
3	0.091	0.0005
5	0.196	0.009
7	0.144	0.003
9	0.097	0.0009
11	0.17	0.003

■ **Figure 9.** *DFMM statisics: damping factors ξ_p. Inverse Gaussian fit model.*



p	Moments	
	μ	σ²
1	0.023	$4.0\ 10^{-5}$
3	0.003	$3.3\ 10^{-6}$
5	0.010	$5.9\ 10^{-5}$
7	0.007	$3.1\ 10^{-5}$
9	0.004	$6.2\ 10^{-6}$
11	0.006	$1.1\ 10^{-5}$

■ **Figure 10.** *DFMM statistics: normalized modal residues $\left|\hat{R}_{10p}^{(TM)}\right| = \left|R_{10p}^{(TM)} / s_p\right|$. Inverse Gaussian fit model.*

models are evaluated with the Maximum Likehood Estimation (MLE) method and the Akaike information criterion (AIC) is used

First, the poles are analysed: Figure 5 is a scatter plot of the P/2 (= 6) first ones (with positive *natural frequencies* $f_p = \Im m(s_p)/2\pi$). The empirical distribution of the natural frequencies are then analysed and fitted with several models: their empirical means are given Table I.

Figure 6 shows the f_p empirical means and dispersión. To further reduce the number of model parameters, a quadratic fit as a function of the pole index is also proposed:

$$< f_p > = a\,(p-1)^2 + b(p-1) + <f_1> \quad [5]$$

To fit the empirical distribution, several models are tested, in particular Normal, Weibull and Nakagami. The probability plots and CDFs are presented in Figure 7: CB (95%) gives the confidence bounds for the normal fit. The parameters of the models are evaluated with the Maximum Likehood Estimation (MLE) method and the Akaike information criterion (AIC) is used (rather than a hypothesis test) for selecting the best model among the chosen set. For the f_p, Weibull is generally the winner although the normal fit performs also well most of the time (Figure 7).

In adfdition, it is clear that the frequencies f_p are significantly correlated so that 2nd order statistics are required; the covariance matrix C is computed from the following data:

In practice, implementing this model involves generating $P/2$ correlated normal variables (for each pole pair) Y_p. This can be done from a normalized (unit mean and variance), uncorrelated, Gaussian vector $\boldsymbol{X}$, introducing the Cholesky decomposition of the covariance matrix $\boldsymbol{C}$, and the vector $\boldsymbol{M}_{fp}$ of mean values, as follows:

$$\mathbf{Y} = \mathbf{X} \times \mathrm{chol}(\mathbf{C}) + \mathbf{M}_{\mathrm{fp}} \quad [6]$$

$\boldsymbol{M}_{fp}$ being given in Table I (or from Eq. 5) and $\boldsymbol{C}$ provided above. Figure 8 gives an example of random shots generated from this model (which should be compared to Figure 6). The statistics of the damping factor and first modal residues are given in Figure 9-Figure 11.

Note that, to achieve a complete model, the statistical laws (PDFs and correlations) of all the parameters, which are complex, should be known: first, whether the statistics should be considered regarding a modulus/phase or real/imaginary parts representation – or any other of representation, normalized or not – is still under investigation; secondly, it is obvious that – like the natural frequencies – the damping factors on one hand and the modal residues on the other hand are strongly correlated (at least as regards the phase) requiring the computation of several covariance matrices. This has been partly done in [8] for the simpler case of a class of omnidirectional antennas, which require many fewer parameters.

3. Combining antenna and channel randomness

While in the previous paragraph the analysis bore on the antennas as such, a series of works carried out within COST 2100 intend to describe the effective antenna system behaviour in its local environment. From a utility perspective indeed, a terminal antenna is always operating in a local propagation environment and both fully determine the characteristics and performance of the radio link. For that reason, these works intend to provide an effective antenna terminal performance from the radioelectric point of view, which implies to account for the propagation characteristics in addition to those of the antenna.

In the work [5] and more completely in [21] the author addresses this problem in the context of cognitive radio simulators, which need to take into account a wide spectrum domain. The effective gain (EG) combines the angular and polarization characteristics of the local propagation and of the antennas through the following definition:

$$EG = \sum_n |A_{nH}|^2 G_{rH,n} + \sum_n |A_{nV}|^2 G_{rV,n}$$

$$\text{subject to the normalization} \quad \sum_n |A_{nH}|^2 + \sum_n |A_{nV}|^2 = 1 \quad [1]$$

where A_{nH}, A_{nV} are normalized amplitudes of path n in H and V polarizations incident on the terminal, with antenna gains $G_{rH,n}$ and $G_{rV,n}$ in the incoming directions. This equation expresses EG as a simple sum of received powers and it implies that interference terms between multipaths are neglected in order to express long term averaging of the inter-path interferences. From the definition of EG, it is clear that a hypothetical isotropic antenna with unit gain on both polarizations verifies $EG=1$ whatever the channel. Both the path powers and the antenna gains are considered as random variables, thus EG is stochastic in nature and need be statistically described. It is indeed possible to statistically analyse and model the global antenna-channel behaviour of the radio terminal in its environment, by incorporating both the stochastic character of the terminal and of the channel. In [21] this has been done for a few examples of terminals and channels. Personal computers (PC) with an ultra wide band (UWB) antenna have been investigated through electromagnetic simulations on one hand and commercial dual frequency handsets have been measured on the other. In the former case both the position and the orientation of the antenna have been randomly varied, together with random variations of the size of the PC casing and screen. For the latter, the orientation, tilt and distance to head of the handset have been scanned over a small discrete set. Radio channels have been described using a subset of the WINNER channel model [22][23], providing the angular power spectrum and the cross-polarization discrimination and allowing to generate suitable stochastic realizations of the channel. Such characteristics are related to the type of local environment (such as indoor, urban LOS or NLOS etc.), according to the WINNER channel model or other standardized models.

As a result of the stochastic character of both the terminal and the local propagation, EG is a random variable whose statistical distribution is obtained after combining the terminal randomness and the propagation randomness. Since both are affected by strong variations especially when there are obstructions, the lognormal distribution may be anticipated as a good candidate for the EG statistics. This is shown in Figure 12, where the CDF of the EG over ~1.5 to 6 GHz every 500 MHz is shown for a simulated PC. The comparison with a perfect lognormal distribution is indeed quite acceptable. In the case of the handset, the mean EG and its spread are shown in Figure 13. The camel like structure highlights the dual band performance, with peak values of the mean EG on the order of -10 dBi. This small figure has three main origins: i) the imperfect matching between the antenna radiation lobes/polarization and the channel wave angles/polarization ; ii) the masking effect by the head which may hide the antenna from powerful paths ; iii) the head and hand absorption and antenna detuning which reduces the total antenna efficiency. However the spread of ~5 dB shows that large deviations on EG around its mean can occur, due to the various sources of randomness. The root mean square error (RMSE) between the true distribution and the lognormal model is also shown, being smaller than 1 dB in most cases.

This approach was also applied to an electromagnetically simulated laptop PC [24], without or with the presence of a human body. The various masking effects produced by parts of the laptop itself or by the body result in more or less thick tails in the CDF of the EG, which may prevent a proper fitting by a single lognormal distribution. In such a case a mixture of distributions is more appropriate, e.g. a mixture of Gaussian distributions applied to the EG expressed in dB, which is a generalization of the simple lognormal. Through this slight complication enhancement, the RMSE between the true distribution can again fall well below 1 dB, which can be considered very sufficient for many needs. This can be seen on Figure 14, computed for three types of channels (indoor NLOS, urban LOS and highway LOS).

The effective gain (EG) combines the angular and polarization characteristics of the local propagation and of the antennas

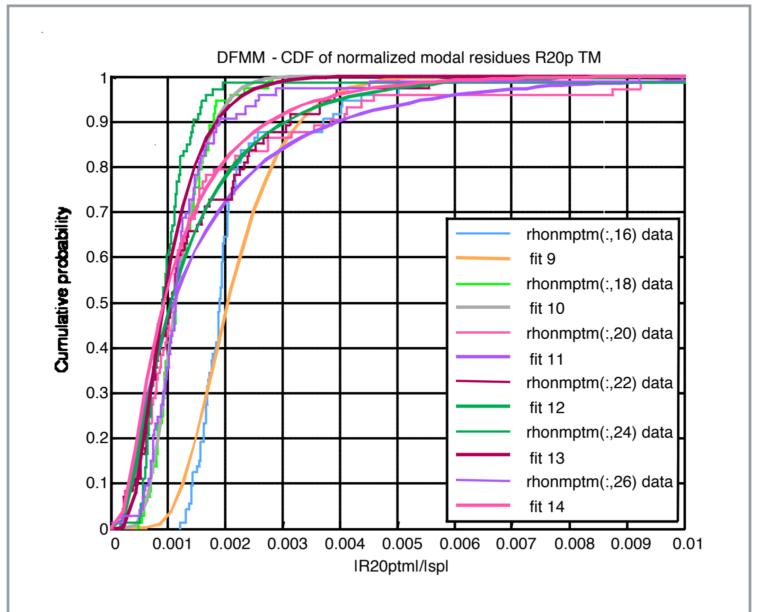


Figure 11. *DFMM statistics: normalized modal residues* $\left|\hat{R}_{20p}^{(TM)}\right|$. *Inverse Gaussian fit model.*

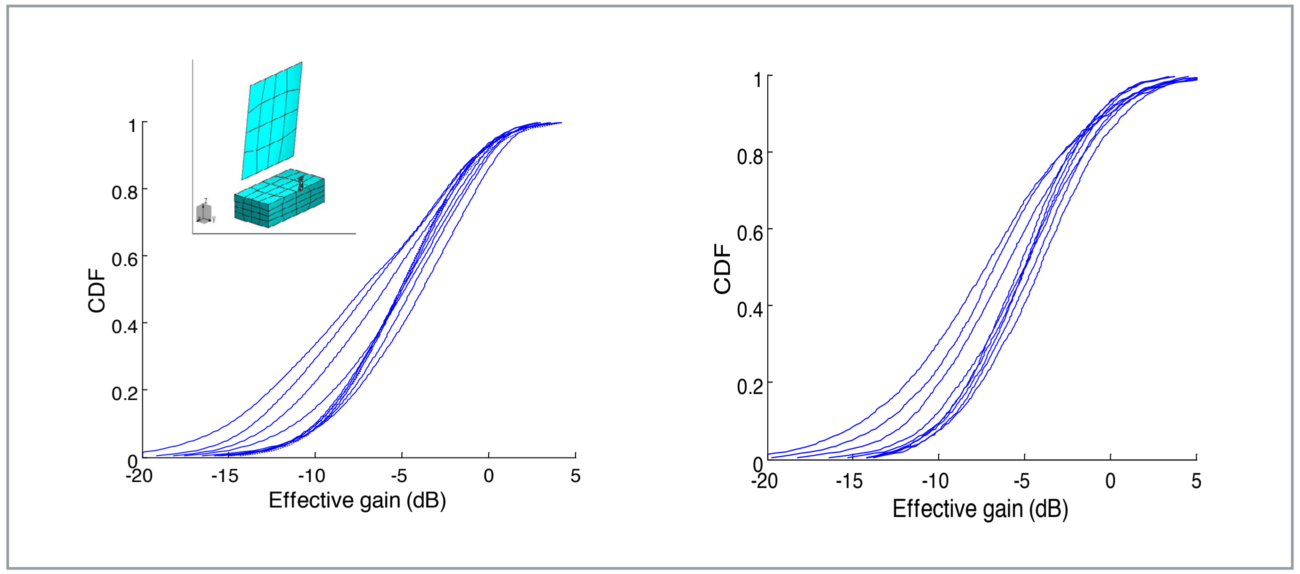
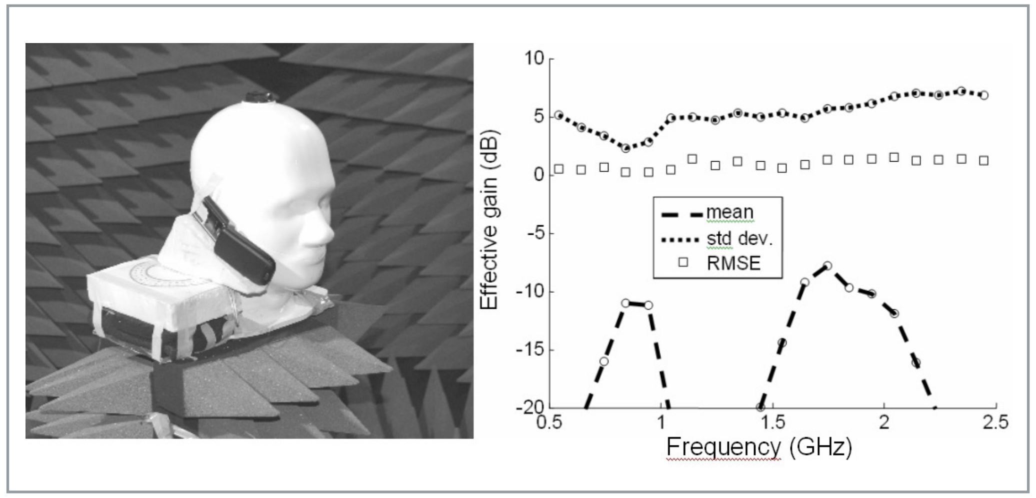
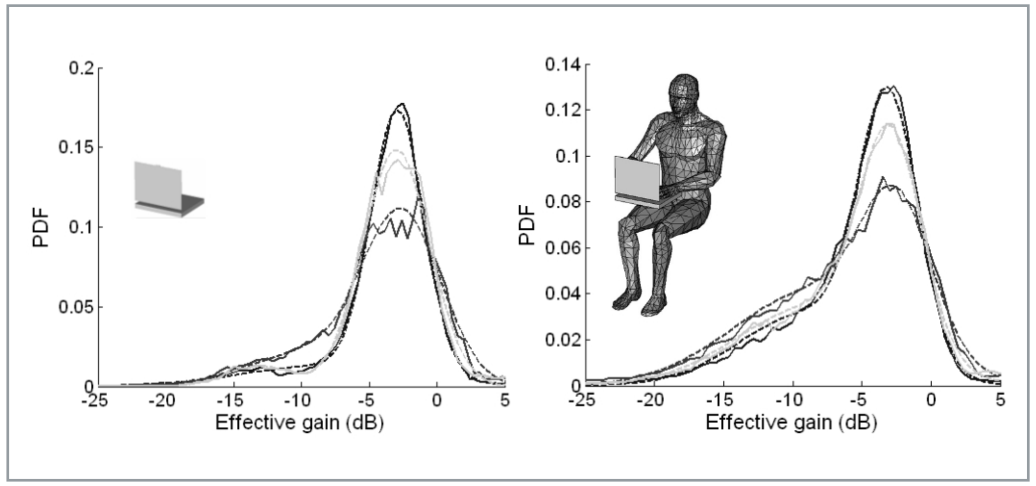


Figure 12. *Statistics of the effective gain every 500 MHz for a desktop PC ; left : original data ; right : best fit lognormal distribution*

the spread of ~5 dB shows that large deviations on EG around its mean can occur, due to the various sources of randomness to be put at the appropriate places



■ **Figure 13.** *Handset on a phantom head (left) and corresponding EG vs. frequency computed for an urban LOS channel.*



■ **Figure 14.** *PDF of the EG for a laptop without (left) or with (right) the presence of a human body, for three different channels. The full line is the true PDF and the dashed is the mixture model.*

6. Summary and conclusions

In this work we addressed the modelling of complex antenna behaviour in the context of wireless terminals operation, taking into account or not the electromagnetic close disturbances and the local propagation context. A statistical approach is a natural way to describe this complexity in the manner it is commonly done for radio channels.This implies to model the statistics of the considered input parameters and of the input-output relation in order to properly describe that of the output parameters. For this purpose it is necessary to have the availability of a database of the relevant antenna characteristics, obtained from electromagnetic simulations or from measurements. Since the size of this database need be carefully chosen, as it affects the accuracy of the extracted statistical distributions, a special attention will have to be given to efficient methods for this extraction in order to maximize the accuracy to size ratio. In this paper, a few examples of the statistical analysis of antenna behaviour have been presented. As regards the intrinsic antenna behaviour, it has been shown that parametric modelling of the antenna electromagnetic behaviour was a useful intermediate step, as it provides a strong compression of the amount of data, especially when the antenna possesses a high symmetry. As regards the effective radioelectric performance of wireless handsets in voice call mode use case, it has been shown that using a simple model of the local radio propagation combined with the full radiation behaviour of these terminals resulted in an approximately lognormal distribution of the effective gain, which could be well approximated together with its frequency dependence. In another example (personal computer), the statistics are not lognormal but exhibit significant low gain tails, which clearly stem from the masking influence of the user person.

From these results, we conclude that a statistical approach of antennas behaviour in complex use cases is both feasible and provides useable models for the advanced description of antenna systems in wireless networks. Future work will need to address more use cases, a variety of types of antennas and radio terminals, the exploitation of these models towards performance evaluation of physical layer techniques and wireless systems and the finding of methods to maximize the distribution accuracy/database size ratio.

Acknowledgment

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