New Results on Top-down and Bottom-up Statistical PLC Channel Modeling

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Abstract

In this paper we consider two different approaches for statistical power line channel modeling. The first method follows a top-down approach where the channel transfer function is obtained from an analytical expression whose parameters are drawn from certain statistics. The second method is less conventional and follows a bottom-up approach where the transfer function is computed using transmission line theory applied to a randomly generated network topology. We compare the two methodologies and show that they are both capable of statistically represent real channels.

Index Terms

Multipath model, transmission line theory, statistical modeling.

I. INTRODUCTION

IN the literature most of the efforts are spent toward the attainment of a power line communications (PLC) channel simulator able to manage complex networks with accuracy and efficiency. Even if a good simulator represents a fundamental prerequisite, it is not sufficient for the design of reliable communication systems. In fact, a simulator typically reproduces only a specific channel response given all the information about the network topology or given certain parameters from experimental measurements. In the two cases the approach is referred to as bottom-up or top-down respectively. Therefore, the major drawback of a simulator is that it can generate only a specific channel response, while for the design of communication systems the generation of statistically representative channel responses is required.

We tackle the problem of the channel response statistical generation following both a top-down [1], and a less conventional bottom-up approach [2], in Section II and III respectively. Some comparison among the two methodologies is reported which shows that they are in good agreement despite the simplicity of the former method (Section IV).

II. STATISTICAL TOP-DOWN CHANNEL MODELING APPROACH

The considered top-down approach follows the multipath propagation model [3] that uses the following analytic expression for the Channel Transfer Function (CTF)

$$H(f) = A \sum_{p=1}^{N_p} g_p e^{-j(2\pi d_p/v)f} e^{-(\alpha_0 + \alpha_1 f^K)d_p} , \qquad 0 \le B_1 \le f \le B_2 \tag{1}$$

where g_p synthesizes the reflection and transmission contributions for the path p, d_p is the length of the path, v is the speed of light in the TL structure and A is a given attenuation coefficient. The factor

$$e^{-(\alpha_0 + \alpha_1 f^K)d_p} \tag{2}$$

is a frequently used approximation for the attenuation factor of the line. The parameters α_0, α_1 and K can be optimized to obtain results in good compliance with experimental ones. The channel is statistically modeled as a finite line of length L_{max} with an attenuation factor determined by Eq. 2 where reflectors, that generate paths, are placed according to a Poisson arrival process with intensity $\Lambda [m^{-1}]$. This means that on average there is a reflector every $1/\Lambda$ meters and $L_{max}\Lambda$ paths.

The path gains g_p can be statistically modeled in two different ways. The former one assumes g_p to be complex random variables with a lognormal distribution for the amplitude and a uniform distribution in the interval $[0, 2\pi]$ for the phase. Lognormality is a good assumption for a variable that gathers, by means of a product, the contribution of independent and random factors. The latter option exploits approximations allowed by experimental results and assumes a uniform distribution in the interval $[-1, 1]$ for the path gains. It can also be shown that α_0, α_1, K and Λ are the only parameters that affect the average path-loss $PL = E[|H(f)|^2]$ [4], [5]. Since the path-loss is directly connected to the channel capacity, by the appropriate setting of the parameters α_0, α_1, K and Λ it is possible to generate channel frequency responses that have a specified capacity on average. This is described in detail in [4] and [6].

For the numerical results we use, for simplicity and space limitations, a unique set of parameters as reported in Tab. I. Consequently, the path loss realizations are gathered around a given average path-loss profile.

III. STATISTICAL BOTTOM-UP CHANNEL MODELING APPROACH

Bottom-up channel modeling exploits TL theory to derive the channel transfer function from the knowledge of the network topology, the cable parameters and the appliance impedances that are connected to the network. To realize a bottom-up statistical simulator we have proposed to use a statistical model for the network topology and parameters in [2]. Two main issues arise with this approach. First, the need of deriving a statistically representative topology model. Second, the need of an efficient method to compute the CTF from a given topology realization since in general this task can be computationally intense. The latter issue has been addressed in [2] where we have proposed to partition the topology into sections and then, to compute each section CTF via a voltage ratio approach instead of the more common method that relies in the calculation of the ABCD matrices. The former issue, i.e., the random topology generation, is addressed in this contribution.

In our approach the channel simulator is realized using a topology that is randomly generated from a model derived by the observation of regulations and common practices in real scenarios. We have carried out an analysis of the Italian indoor scenario that satisfies all the European rules and recommendations on that matter. We surprisingly found a quite regular structure where outlets of adjacent rooms are connected to the same node, referred to as "derivation box", and all the derivation boxes are connected together at a second level according to nearness and reachability rules. We have also observed that on average all the outlets fed by the same derivation box are nearby placed around the referenced derivation box in a limited area that has quite regular dimensions for all derivation boxes. So we have concluded that the location plan could be divided in elements that contain a derivation box and associated outlets. By the experimental observation about the existence of regular dimensions, we therefore propose to simplify the representation using elements of the same area that are referred to as "clusters". The particularity of clusters is that even if there is no bond in their shape, in practice they can always be well represented by a rectangle with a fixed area, but variable dimension ratio. A simpler representation uses a square shaped cluster.

Each cluster contains all the outlets connected to a derivation box and the derivation box itself. Different clusters are usually interconnected only through the derivation boxes. In particular, a cluster can contain more rooms, but also a room may belong to more than one cluster. Therefore, in general there is no direct correspondence between rooms and clusters, but between derivation boxes with associated outlets, and clusters. However, the observation suggests a significant correspondence between the clusters and the room shapes. This allows an easier understanding of the network topology and of the cluster displacement starting from the location plan.

According to the experimental observations, and with the proposed partition of the topology into clusters, we have derived a statistical topology generation algorithm, where a location plan is build up as a random displacement of neighboring clusters. Outlets are distributed along the cluster's perimeter according to a statistical model obtained from observations and similarly the position of the derivation box in each cluster is determined. In particular, the outlets are placed only along the sides of the clusters and are connected to the associated derivation box according to the three most common practices that we have found, i.e., a ring structure that satisfies the minimum distance criterion, a ring topology with conductors placed along the sides only, and a bus topology. At the second layer, connections between derivation boxes fulfill the reachability and the nearness criteria with cables of section according to norms such that voltage drops are reduced. The special role played by the service panel, that is a derivation box itself, is taken also into account.

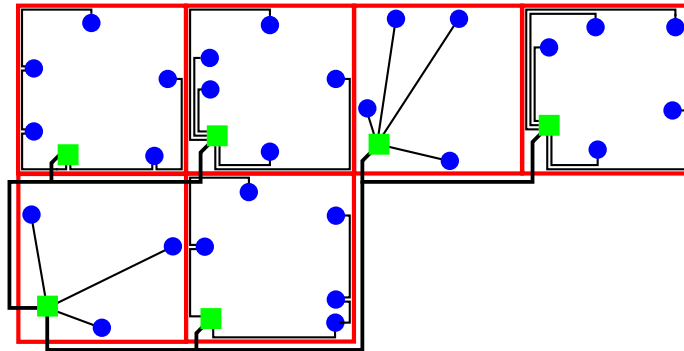As an example, we report in in Fig. 1 a topology arrangement generated by the algorithm.

Fig. 1: An example of topology arrangement generated by the algorithm. Derivation boxes and outlets are represented by the squared and dotted markers respectively.

IV. ANALYSIS AND COMPARISONS

As explained in Section II, the top-down simulator is able to generate channel frequency responses that exhibit an average path-loss related to the particular set of values chosen for the parameters α_0 α_1, K, Λ and L_{max}. Herein, we consider channel responses belonging to a unique class of parameters. Thus, they yield a given average path-loss profile (besides the

normalization factor A). In Tab. I we summarize the values. More details are given in [4] and [5]. A broader set of classes with different average path-loss profiles can also be defined by the appropriate fitting of the parameters as it is done in [6]. Each path-loss class defines also a certain class of channel capacity.

The initialization of the bottom-up simulator is less complex because it requires the definition of parameters that have a more direct topological meaning. In particular, we here report results for the bottom-up simulator that assumes topologies of area $150 m^2$ and clusters of area $20 m^2$.

The CTF is in the band 1-30 MHz, and the number of realizations obtained with both simulators is 1000. The impulse response is obtained via the inverse fast Fourier transform with $2N$ points and sampling frequency step-size $F_s = 60/2N MHz$. The corresponding impulse response samples are therefore given by $h_i = h(iT_s)$ with $T_s = 1/(2NF_s)$.

We first evaluate the statistics of the root-mean-square (RMS) delay spread of the channels. It is an important metric for system design [7] and it is defined as

$$\sigma_\tau = \sqrt{\frac{\sum_{i=0}^{2N-1} (iT_s)^2 |h_i|^2}{\sum_{i=0}^{2N-1} |h_i|^2} - \left(\frac{\sum_{i=0}^{2N-1} iT_s |h_i|^2}{\sum_{i=0}^{2N-1} |h_i|^2} \right)^2}. \tag{3}$$

The RMS delay spread cumulative distribution function is shown in Fig. 2 for both channel simulators. Both simulators yield a lognormal distribution for the delay spread which matches experimental results from measurements [7]. The variance of the delay spread with the two simulators is different but this can be easily justified by the fact that the top-down simulator draws channels from a unique set of parameters, i.e., they belong to a unique path-loss/capacity class, while the second one gathers the contribution of channels that are found in a certain topology layout (area) and that belong to a broader variety of path-loss/capacity classes. In other words, the bottom-up simulators generates channels associated to a broad range of capacity and delay spread as it is observed, for instance, in an in-home scenario. A larger variance of delay spread can be obtained with the top-down approach if we use different set of initialization parameters as it is done in [6].

The fact that there is a relation between delay spread and channel capacity is proved in Fig. 3 where we have partitioned the channel realization of the bottom-up simulator into 5 classes of capacity according to Tab. II, assuming a transmitted Power Spectral Density (PSD) of -50 dBm/Hz and additive white Gaussian noise with PSD = -140 dBm/Hz. In particular, we have divided the capacity range 0 − 900 Mbps into 5 intervals of 180 Mbps each. This representation is similar in spirit to the one proposed in [4], [5], where however 9 capacity intervals were proposed for channels in the 1-100 MHz frequency band. For each capacity class we have evaluated the mean value and the standard deviation of the RMS delay spread. In Fig. 3, the marker and the line segment represent the mean and the standard deviation respectively. Lower capacity channels are associated to a higher mean and variance delay spread. Furthermore, since the top-down simulator (with the given parameters) yields a delay spread mean of $0.32 \mu s$ and standard deviation of $66 ns$ respectively, we conclude that channels generated with the top-down simulator belong to class 5 of Fig. 3.

In Tab. II we also report the percentage of channel realizations belonging to each class with the bottom-up simulator. For the considered topology model, the most frequent are class 3 and 4, which is in accordance with the measurements in [4]. Note that the broad range of capacity values is due to the fact that we consider all possible combinations of outlets, with a low noise PSD value.

We now consider the average channel gain (ACG) that is defined as [7]

$$G = 10^{\frac{G_{dB}}{10}} = \frac{1}{N} \sum_{i=0}^{N-1} |H_i|^2. \tag{4}$$

In Fig. 4 we report a quantile-quantile plot of the ACG expressed in dB (G_{dB}) versus a normal distribution. The figure shows that the ACG in dB is normally distributed with both simulators. We also note that the bottom-up G_{dB} spans an higher range of values which is in good agreement with the previous considerations about the RMS delay spread and capacity.

TABLE I: PARAMETERS OF THE TOP-DOWN SIMULATOR

Parameter	Value
$\alpha_0 \ [m^{-1}]$	0.003
$\alpha_1 \ [s/m]$	10^{-9}
K	1
$\Lambda \ [m^{-1}]$	0.2
$L_{max} \ [m]$	300
A	0.01

TABLE II: CHANNEL CLASSES, BANDWIDTH 29 MHz

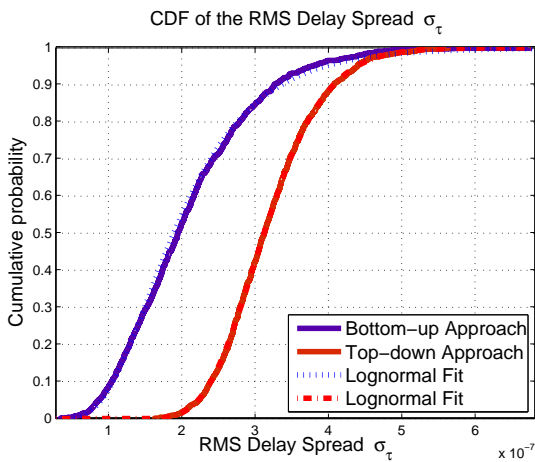| Class	Capacity interval [Mbps]	Percentage of channels
1	720 − 900	0.9 %
2	540 − 720	18.8 %
3	360 − 540	37.6 %
4	180 − 360	27.5 %
5	0 − 180	15.2 %

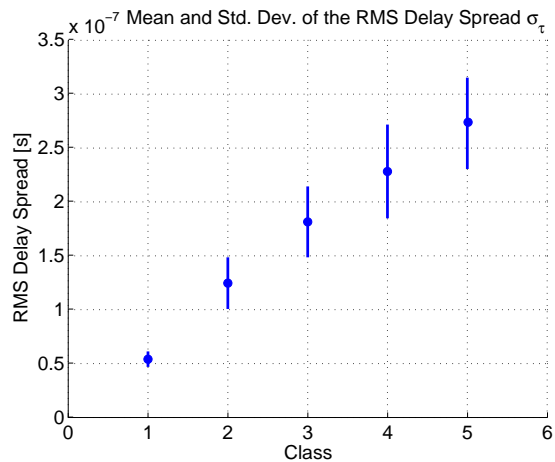Fig. 2: Cumulative Distribution Functions (CDF) of the RMS delay spread. Bandwidth 29 MHz.

Fig. 3: Standard deviations and mean values of RMS delay spread in each class of capacity. Bandwidth 29 MHz.
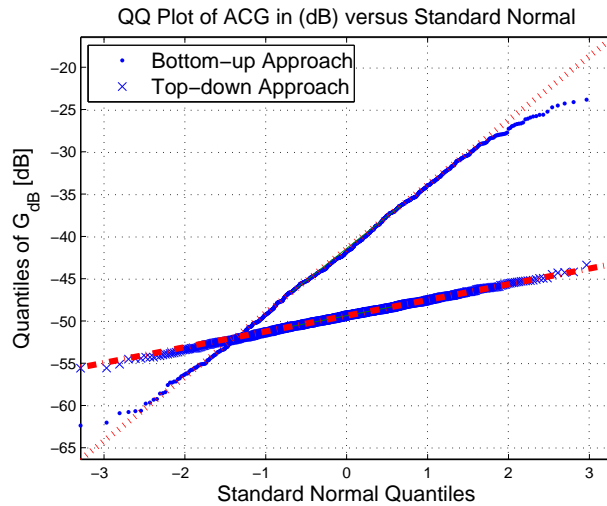

Fig. 4: QQ plot of the average channel gain in (dB) versus the standard normal.

V. CONCLUSION

We have proposed and compared two different approaches for statistical channel modeling and simulation, a top-down and a bottom-up approach. Despite the significant different metodology, they both generate channels that are significantly related to the ones obtained from measurement campaigns [4], [7]. The top-down simulator is simpler and allows to generate channels belonging to a certain class of capacity [6]. The bottom-up approach ensures a deeper connection with the physical reality and allows an understanding of the transmission effects over real electrical grids.

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