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Ray based Multipath Simulation Tool for Studying Convergence and Estimating Ergodic Capacity and Diversity Gain for Antennas with Given Far-Field Functions

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Abstract

We propose that the rich isotropic multipath environment should be a reference environment for OTA (over-the-air) characterization of wireless stations for use in multipath, in the same way as the anechoic environment is a reference environment for antennas mounted on masts and rooftops. The rich isotropic multipath environment is emulated by a well designed reverberation chamber, but also by a spherical array of probes in an anechoic chamber. The present paper describes a ray-based simulation tool, ViRM-Lab, which enables users to study the performance of arbitrary user-defined multiport antenna located in user-specified multipath environment. The antennas are defined by their far-field functions of the embedded element (with the other ports matched-load terminated). The environment can be determined by its Angle-of-Arrival (AoA) distribution, richness, and polarization balance. The code is made in such a way that the convergence of the cumulative distribution function (CDF) received on all ports can be studied, as well as the convergence of the statistical expectations when estimating the ergodic Shannon capacity and diversity gain.

1. INTRODUCTION

The anechoic chamber is well established as a reference environment for characterizing antennas and wireless stations with directive beams that are used under dominant line-of-sight (LOS), such as when they are mounted on masts and rooftops. In the same way there is needed a reference environment for characterization of antennas and wireless stations that are used with small antennas in multipath environments with fading.

In the present paper we propose that the reference environment should be a so-called rich isotropic environment, i.e., an environment in which the angles-of-arrival (AoA) of many simultaneous incoming waves are uniformly distributed over the surrounding sphere. This environment has also been referred to as a 3D environment, and a uniform spherical environment. It is known that such isotropic environments can be emulated inside a well-designed reverberation chamber, if it is large enough in terms of wavelengths [1]. However, it is also clear that it can be emulated by an anechoic chamber with many simultaneously operating probes distributed over the whole sphere around the device under test (DUT). There are still questions whether or not a 2D arrangement of such probes in one plane can emulate the same. Definitely, from the studies reported in [2] it is clear that 2D tests will not give a unique value for the quality of the DUT unless there is introduced an averaging over a statistical change of the orientation of the DUT relative to the vertical axis.

In order to study the effects mentioned, we have developed a simulation software called ViRM-Lab (Visual Random Multi-path environment Laboratory), which studies the uncertainties and uniqueness of the efficiencies, correlation, diversity gain and ergodic capacity of user-defined antennas, when this is located in a user-defined statistical field environment of any kind.

The aim of the present paper is to describe ViRM-Lab and show some calculated results. The results support our belief that a rich isotropic environment is a good reference environment. We compare an isotropic 3D environment with a 2D environment for many realizations (i.e., many sets of random incoming waves). Also we show that a user moving around in a 2D environment will experience the same ergodic parameters as a user in our proposed 3D environment. Our studies are limited to the spatial 3D characteristics of the multipath channel (and not delay spread and Doppler).

ViRM-Lab is implemented in MathWorks MATLAB and available for free (contact the corresponding author for a copy). The source code is open and enables the user to specify the input in a MATLAB script. This gives the user great flexibility. The results can be presented as animated plots.

The terminology used in the present paper has been explained in [3] with references. The definitions of mean effective directivity (MED) and apparent diversity gain used in the present papers are explained in [2] with appropriate references.

2. DESCRIPTION OF VIRM-LAB, STUDIED CASES, AND RESULTS

2.1. Description of ViRM-Lab and studied cases

The user specifies a scenario by first defining the statistical multipath environment in terms of the distribution of AoA, the number of simultaneous waves for each realization, and the number of realizations. We use the term "realization" for a given set of waves realized by a random distribution function. ViRM-Lab allows any environment specified by the user, e.g., a Laplacian random distribution, but in the present paper we limit ourselves to the 3D environment and the 2D environment. The 3D environment has an isotropic uniform distribution and the 2D environment has only incoming waves from the azimuth plane. One realization for each distribution is shown in Fig. 1. The wave directions (rays) defined by the AoAs are normals (not shown) to the red squares that illustrate wavefronts. The polarization of each wave is indicated by the black ellipses on the red squares, and the phase can be associated with the radial location of the red square from the origin in the center. The interference pattern formed by all incoming waves are illustrated by the color plot in the center, presenting the absolute value of the voltage received at a port of a vertical incremental dipole over a horizontal surface (xy-plane) that has a diameter of 5 wavelengths.

After setting up the environment, the positions and orientations of the DUT are defined. In the present paper the DUT is either fixed in the origin of the coordinate system for many realizations, or moving around in random positions and orientations.

Finally, the antenna far-field functions are defined. One DUT may have several antennas and use diversity. The far-field can be imported from any numerical simulation tool's output data files or selected among some predefined canonical antennas such as dipoles, monopoles, pencil beams, and Huygen's sources. In the present paper we use two incremental electric dipoles with different orientations or two pencil beams with different polarizations. The pencil beams are linearly polarized and have the shape "$\cos^n(\theta/2)$" with n chosen so that the -3 dB half beam width is 45 degrees.

ViRM-Lab can thereafter be used to study the effects on the estimated MED, capacity and diversity gain by making statistical expectations (averages) over the samples of the above cases.

The ray-based multipath code can be extended to more advanced studies if needed, such as more types of environments, time spread and Doppler spread, but initially the main intention is to determine under which conditions the rich isotropic multipath environment can be used as a reference environment for OTA measurements. Therefore, the focus has been on the spatial direction characteristics of the environment and not the time-domain and frequency-domain characteristics. It is believed that the spatial characteristics can be studied separately from the two others.

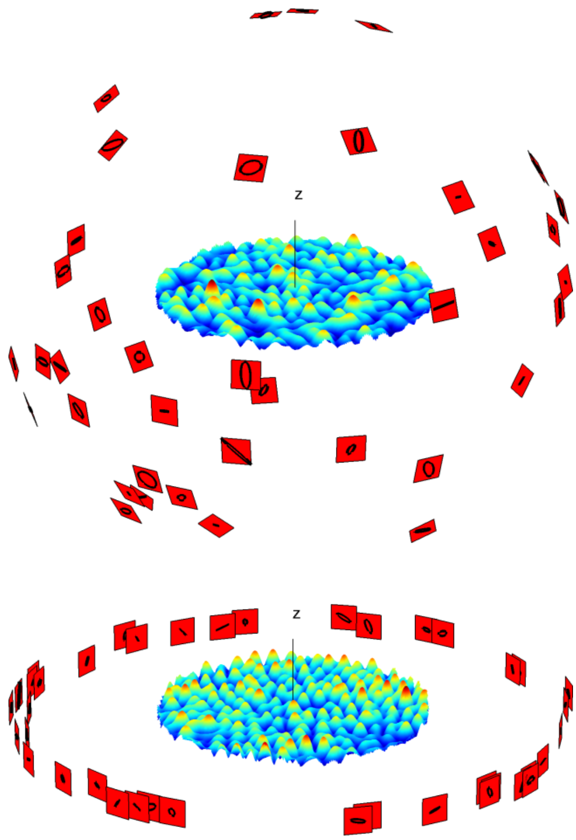

Fig. 1. Visualization of statistically generated incoming waves for 3D isotropic environment (top) and 2D environment (bottom).

The methods behind ViRM-Lab are based on published approaches that are well established and have been validated by measurements, such as the equivalent circuit of receive antennas in [4] that in [5] was used to model capacity of a multiple input multiple output (MIMO) antenna and validated by measurements in reverberation chamber. Validation over large bandwidths, including also results from measurements in anechoic chambers was presented in [6].

2.2. Simulation results

In Fig. 2 results are calculated when the antennas are in a fixed position and orientation and we gather samples by generating new set of incoming plane waves from the distribution functions of the respective environment. In Fig. 3 results are calculated for only one given set of incoming plane waves and instead the antennas are moved around in random positions and with random orientation.

We have defined two kinds of antennas, incremental electric dipoles and pencil beams, as described in the previous section. Both of them have efficiency one, i.e., there are no losses. Because of this, the theoretical MED should be -3 dB, due to the fact that an antenna only can receive one polarization in any direction.

In Fig. 2 (top) we see that in the 3D environment the MED of all antennas indeed converge to the correct value of -3 dB. However, in the 2D environment (same plot), the MED converge to wrong values, and different values dependent on the orientation of the antennas. We see that the vertical dipole, which radiates most in the azimuth plane, will have a higher (incorrectly) estimated MED. The pencil beams, which in this case are z-directed and not radiating much in the azimuth plane, get a very low (incorrect) estimate of the MED.

The next parameter we consider is diversity gain. For this, the two orthogonal dipoles are considered to be two receiving branches of the same DUT, and the two pencil beams are also considered to be two receiving branches of the same DUT. We use selection combining and, since the antenna radiation patterns are completely orthogonal in the two cases, we should expect a diversity gain of 10.48 = 10.2 dB. We refer to the diversity gain as

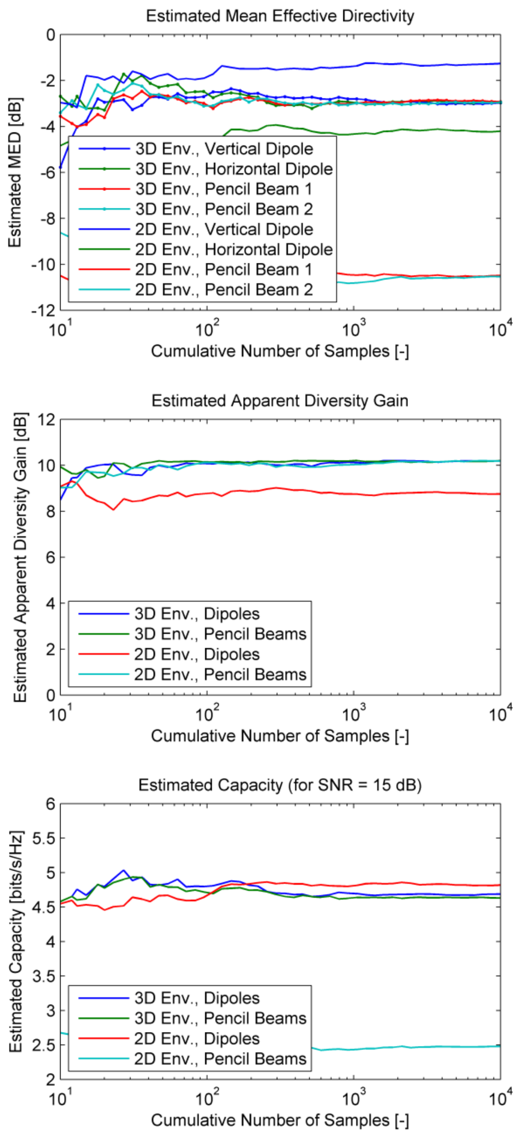

Fig. 2. In theses plots the antennas are in fixed positions and orientations. We see that only in the 3D environment, the parameters converge to the same value.

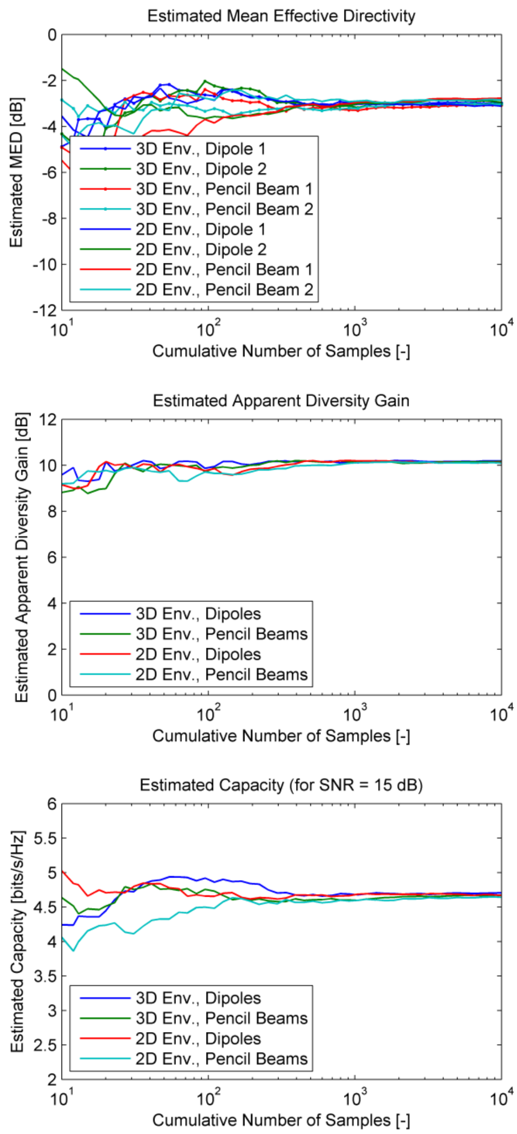

Fig. 3. In these plots the antennas are moving around in random positions and orientations. Then, all parameters converge to the correct value, regardless of environment.

the apparent diversity gain (ADG) as defined in [5]. It is calculated with the following formula

$$G_{\mathrm{ADG}} = \sqrt{1 + (10.48^2 - 1)\frac{e_{\min}}{e_{\max}}(1 - |\rho|^2)}, \quad (1)$$

where e correspond to the efficiency and ρ the correlation, see [7].

We see in Fig. 2 (middle) that in the 3D environment, we get the correct value of the ADG. For the 2D environment, we actually get a correct value for the pencil beams, but only because they happen to radiate equally in the azimuth plane. The dipoles does not radiate equal in the azimuth plane and therefore we get and incorrect value of the ADG.

Finally we have considered the Shannon capacity for a signal-to-noise ratio (SNR) of 15 dB.

Again, we see in Fig. 2 (bottom) that in the 3D environment, the two DUTs converges to the same correct value, which is around 4.65 bits/s/Hz. The dipoles in the 2D environment give an incorrect value, but quite close to the correct value. The pencil beams in the 2D environment gives a far too low estimate of the capacity, due to the fact that they radiate very little in the azimuth plane.

If instead we consider the case when we move around the antennas into random positions and orientations, as shown in Fig. 3, the results are quite different. Here, all the estimated parameters of the antennas or DUTs converge to the correct value, regardless of environment. The case with the 2D environment is similar to a real user with, e.g., a mobile phone in, e.g., an urban environment. The arrival of the signal is mainly from the azimuth plane, but since the user moves around and can hold his mobile phone in many different orientations, the relevant parameters, in average, correspond to that of the 3D isotropic reference environment.

3. CONCLUSION

The isotropic 3D environment gives the same ergodic MED, diversity gain and capacity, independent of the (fixed) orientation of the DUT. In the 2D environment, these parameters depend on the orientation of the DUT.

If the DUT is moved around in random positions and orientations, the MED, diversity gain and capacity converges to the same value independent of environment.

This means that the isotropic 3D environment is a good reference environment, even if the user in reality is present in other types of environments, provided he is not in a fixed position and orientation.

4. ACKNOWLEDGMENT

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