IEEE P2718 Working Group Activity: Open Source Code Development for the Characterization of Unintentional Stochastic Radiators

IEEE P2718 Working Group Activity: Open Source Code Development for the Near Field Characterization of Unintentional Stochastic Radiators

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***Abstract*—The analysis of stochastic electromagnetic fields is gaining more and more relevance due to the exponential growth of complex high-performance electronic systems. Stochastic electromagnetic fields are characterized by auto and cross-correlation functions which can be obtained from experimental data. Different methods have been proposed for the numerical propagation of correlation information within the near-field region of a stochastic radiator. As a guidline for general geometries, near-field Green's functions combined with the method of moments can be used for the numerical estimation of field correlations in the near-field surrounding a device under test. In the ray-tracing limit, a more insightful propagation method based on the Wigner transformation has been devised, through which it is also possible to estimate the propagation of stochastic fields in the near-field. This paper reports on a proposed guide to the measurement and prediction of the propagation of stochastic fields with supporting software recently available in the IEEE Standards repository. The software is available in the open source Python programming language to encourage wide use and development of new versions.**

***Index Terms*—Stochastic Field Emission, Near-Field Scan, Autocorrelation Function, Wigner Transform.**

I. INTRODUCTION

THE growth of internet-enabled intelligent infrastructures requires complex, high-performance and highly integrated electronic systems. The amount of unwanted electromagnetic interference (EMI) grows with the expected increase in clock speed, operating frequency, and circuit density. Radiated EMI is caused by fast transistors due to switching and information transfer processes within electronic devices. EMI can be described by stochastic electromagnetic (EM) fields that typically originate from a sufficiently large number of statistically independent processes that cannot be easily predicted [1]. The characteristics of stochastic EM sources are a wide spatial extension, fast and almost random transitions in the time domain and a low average power of the local radiated fields [2]. Acurate modeling of stochastic EM fields is essential to improve the design of electronic devices, taking into account their susceptibility to EMI [3]. Traditionally, potential sources of EMI are evaluated in the frequency domain by assuming static emissions. A widely used technique for characterizing emissions is near-field scanning (NFS) due to its high measurement accuracy and reliability [4], [5]. This approach involves the measurement of radiated emissions to estimate the currents flowing within the circuit and extract the dipole moments necessary for the reconstruction of the respective sources [6]–[9]. Despite its effectiveness, this technique is not valid for multifunctional devices with different operating modes and digital broadband receivers. Therefore, a new approach is needed for a standardization procedure which takes full account of time-dependence and uncertainty. Characterization of noisy EM fields is based on the assessment of the statistics of the EM field source distribution using auto and cross-correlation functions or spectra [10]. A full characterization of stochastic EM fields also requires steps to reduce the complexity of handling the amount of data to be collected and processed [11], [12].

II. HISTORY AND SCOPE

Starting from these premises, the European Cooperation in Science and Technology (COST) action IC1407 'Advanced characterisation and classification of radiated emissions in densely integrated technologies' (ACCREDIT) has taken steps to fully address the challenges posed by the stochastic nature of broadband radiated EMI in current and future complex multifunctional systems, through an international research program. This program is specifically aimed at creating efficient behavioral models of propagation and interaction of stochastic fields starting from experimental methods. These methods involve measurements for EMI in the time or frequency domain using broadband near-field probes [13]. To this end, COST action IC1407 has played a key role in intensifying a broad collaboration between various researchers of universities and industries that involves the study of stochastic EM fields. Techniques proposed in existing standards do not facilitate an accurate prediction of the evolution of the spectral power density in the vicinity of a device under test (DUT) if the radiated emission are due to sources with arbitrary degrees of correlation. The collaboration within COST action IC1407 triggered an effort towards standardization of characterization techniques for radiated stochastic EM fields, taking measurement and subsequent modeling techniques into account. This effort led to the formation of a working group within the IEEE standards association: P2718 - Guide for Near Field Characterization of Unintentional Stochastic Radiators. The goal of the P2718 working group was to propose a novel approach, which is able to estimate the propagation of stochastic fields emitted by statistical EM sources and which takes full account of field correlations. The aim was to write a useful guide to assist near and far-field predictions, source reconstruction, and emission source microscopy. This new approach is based on the propagation of correlation information of the near field data, measured by NFS techniques, using a propagator based on Green's functions or the so-called Wigner transformation, both also investigated in [14]. The latter method provides a spatial representation of the waves in phase space of position and direction of propagation [15], allowing one to obtain an accurate and precise estimate of the propagation of stochastic fields. The Green's-function-based approach also allows for near and far-field considerations of the evolved energy density and can be implemented using numerical Green's functions, extracted for more complex geometries. The aim of these works was not limited to put forward an approach that goes beyond the limitations of previous models but to provide an open source automatic algorithm capable of assessing the propagation of stochastic EM fields in the near and far-field with improved accuracy, starting from experimental data obtained in the near-field. While the information content of EM near-field correlation matrices can be very rich, the correlation matrix evolves into toeplitz structure in the far-field [16]. Data reduction on acquired and computed near-field correlation data can be performed for example by applying principal component analysis [12], [17].

III. Guide under development content

The measurement of stochastic fields in a transverse plane requires the measurement of the field correlation over a geometrical plane close to the DUT's surface, 30 cm $\times$ 30 cm in the present case, as illustrated in Figure 1. In order to sample the field correlations, two identical moving near-field probes that independently scan across this plane are required. The scanning resolution required depends on the probe's spatial resolution and sensitivity and the receiver dynamic range. In our case, the 5 mm spatial resolution has been used. Data are acquired in frequency domain by using a vector network analyzer (VNA) properly calibrated. The location of the probes needs to be also recorded by the data acquisition system. The probe position can be found from the actuator encoders or a laser tracking system could be incorporated. Near-field scanning is sensitive to the position accuracy because the spatial distribution can rapidly vary. Errors caused by imprecise sampling and their correction have been studied by several authors for deterministic fields [14], [18]. The scanner position accuracy should be at least $1/10$-th of the smallest probe dimensions. Keeping the probes stationary during the VNA sweep is also essential to maximize the accuracy. The velocity profile of the probe movement should be such that this is ensured (i.e. there should be no mechanical vibrations induced by the scanning process). Also mechanical rigidity of the scanner structure and position repeatability should be taken care of. The engine and control system adopted for the scanner movements should be also be checked in terms of radiated emissions in the adopted frequency band prior to scanning, to avoid any interference with the DUT.

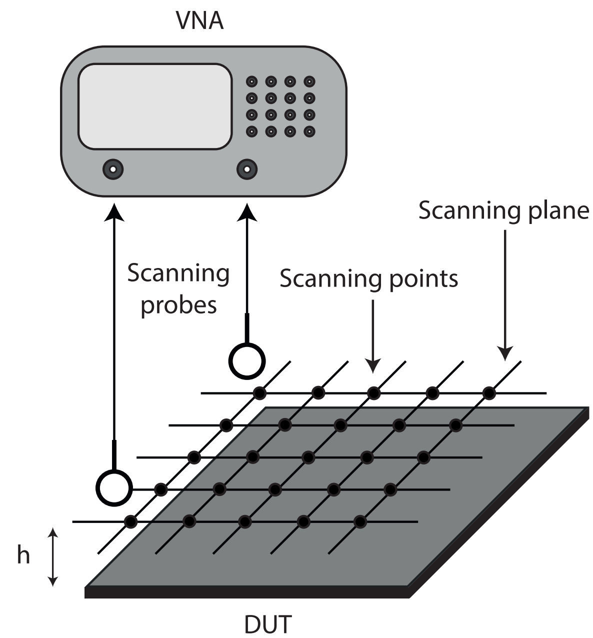

Fig. 1. Near field scanning using two different probes. The experiment set up includes the reference and the scanning probes connected by amplifiers to the VNA. The DUT 's size is 30 cm $\times$ 30 cm with the probe spatial resolution of 5 mm.

In the next chapter, we will go deeper into the implemented algorithm.

IV. Open Source Code

Following the theoretical formulation [19] of the model and experimental comparison, we moved towards the development of the open source algorithm capable of evaluating the propagation of stochastic EM fields in the far field starting from experimental data through the Wigner Transform approach [20], [19]. The code was written entirely in the open source programming language Python (version 3.9.7) in the Jupyter Notebook interactive development environment. The notebook, in addition to reporting the lines of code with the relative comments, shows the theoretical formulation from which the algorithm was obtained. This allows the understanding of both the meaning of the execution cells as well as the proposed analytical procedure. The notebook in question reports an example of evaluation of the propagation of stochastic fields generated by an extended planar source. In particular, starting from the measurements of the fields at a distance of 1 cm from the source, we estimated the propagation of the stochastic fields at a distance of 10 cm from the source itself. Following the loading of all the necessary libraries, the measurements of the magnetic fields H at 3 GHz at 1 cm from the source are loaded into the calculation environment. The dataset consists of an array of complex floats, from which the autocorrelation matrix (ACM) is calculated at a distance of 1 cm. To calculate the ACM from the measurement data, a machine with at least 16 GB of RAM is required. To make simulation possible for any machine and also speed up execution times, the ACM is already supplied at a distance of 1 cm from the source. Therefore it is enough to simply import it, without having to

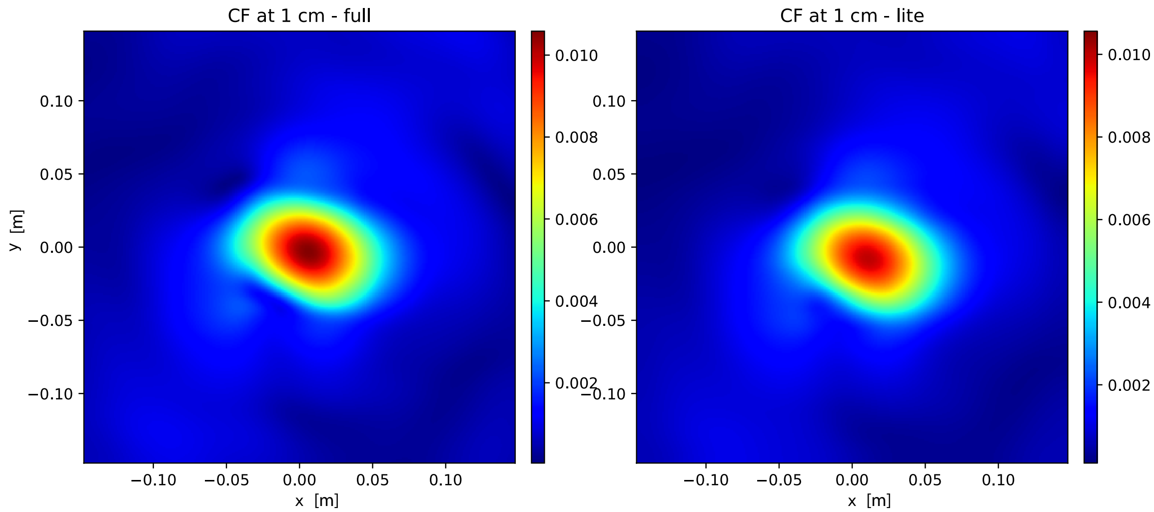

Fig. 2. Correlation functions at 1 cm from the planar surface. On the left, the full size correlation function, on the right, the lite version after data reduction, are reported.

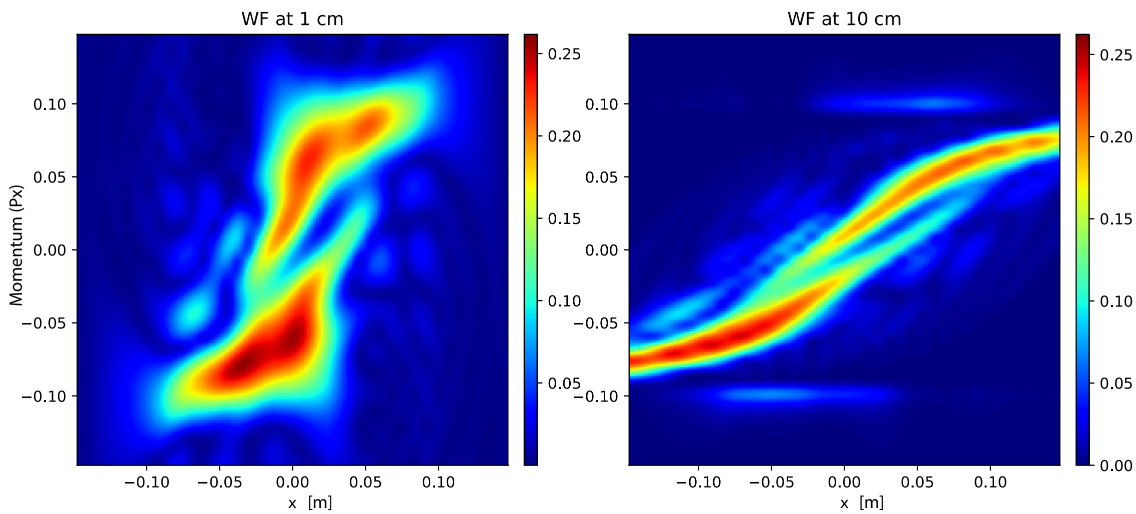

Fig. 3. Wigner function at heights of 1 cm (on the left) and 10 cm (on the right) obtained from the correlation functions.

calculate it. If you are still interested in calculating it, just execute the relative execution cell. Furthermore, since the ACM at 1 cm is (60,60,60,60) size, to reduce the computational cost of the entire simulation, the data reduction of the dataset has been performed. The reduction foresees the decrease of the resolution of the ACM without loss of the information content, passing from a 4 dimensional matrix of the dimension of (60,60,60,60) to the dimension of (20,20,20,20). The 4 dimensional dataset is given by x and y coordinates of the two probes. For the visualization of the data, instead, quadratic interpolation was carried out to increase the resolution again at the moment of visualization. This allows to greatly minimize the calculation times and still obtain high resolution results. Although it is possible to calculate a reduced version of the ACM, the notebook offers the freedom to start the simulation using the maximum size ACM. In this case, however, the machine must have at least 16 GB of RAM. Otherwise, it is possible to run the code even on machines with RAM of less than 8 GB. In Figure 1, the full size (left) and reduced (right) ACM graphs are shown. The mathematical expression by which the ACM was obtained is defined as follows [1]:

$$\mathcal{C}_z\left(\mathbf{x}_a, \mathbf{x}_b; \tau\right) = \begin{bmatrix} C_z^{xx} & C_z^{xy} & C_z^{xz} \\ C_z^{yx} & C_z^{yy} & C_z^{yz} \\ C_z^{zx} & C_z^{zy} & C_z^{zz} \end{bmatrix} = \left\langle \mathbf{H}\left(\mathbf{x}_a, z; t+\tau\right) \mathbf{H}\left(\mathbf{x}_b, z; t\right) \right\rangle \tag{1}$$

where $\langle\rangle$ is an appropriate ensemble average, H the magnetic field, x_a and x_b two different spatial locations and t the time from 0 to T. For more details, refer to [19]. Following the evaluation of the ACM at 1 cm from the source, an appropriate change of variables with respect to the variables x and y of the ACM was performed. Subsequently, the Wigner transform (WT) of the ACM at 1 cm was calculated. The WT is obtained as follows:

$$\mathcal{W}_z(\mathbf{x}, \mathbf{p}) = \int \mathrm{e}^{-\mathrm{i}k\mathbf{p}\cdot\mathbf{s}} \Gamma_z\left(\mathbf{x} + \frac{\mathbf{s}}{2}, \mathbf{x} - \frac{\mathbf{s}}{2}\right) \mathrm{d}\mathbf{s} \tag{2}$$

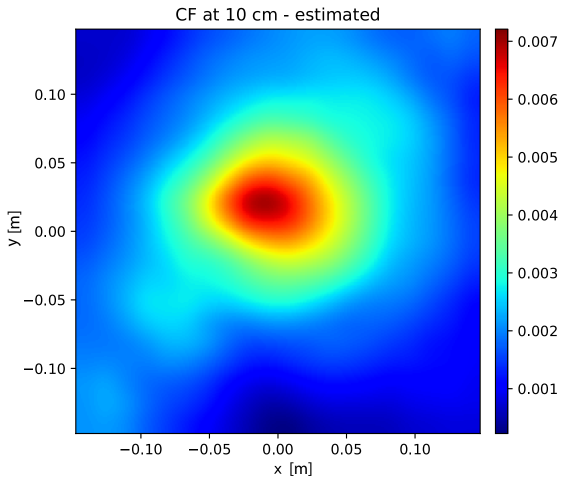

Fig. 4. Correlation function at height of 1 cm from the source obtained from the measurement data (on the left), and the estimated one at height of 10 cm (on the right).

where Γ_z is the representation of the CF at frequency domain (by the Fourier transform):

$$\Gamma_z(\mathbf{x}_a, \mathbf{x}_b; \omega) = \int_{-\infty}^{\infty} \mathrm{e}^{-i\omega\tau} C_z(\mathbf{x}_a, \mathbf{x}_b; \tau)\, d\tau \tag{3}$$

where k is the constant wavenumber coordinates $(\mathbf{x}, \mathbf{s})$ related to $(\mathbf{x_a}, \mathbf{x_b})$ by the transformation:

$$\begin{cases} \mathbf{x} = (\mathbf{x}_a + \mathbf{x}_b)/2 \\ \mathbf{s} = \mathbf{x}_a - \mathbf{x}_b \end{cases} \tag{4}$$

so that $\mathbf{x}$ is the average position and s is the difference in positions of a pair of measured fields. More explicitly, $\mathbf{s} = (s_x, s_y)$ represents, in the NFS of planar sources, the in-plane displacement (for fixed z) between measurement positions. The conjugate momentum vector $p = (p_x, p_y)$ takes the geometrical meaning of the components of the wavevector parallel to the source plane. The WT of the ACM at 1 cm is shown in Figure 2. For the calculation of the propagation of the stochastic fields at a distance of 10 cm from the source, on the other hand, the Frobenius-Perron approximation relative to the WT of the ACM at 1 cm was performed. More specifically, individual tangent vector components of the in-plane magnetic field have been measured and used to guide and verify the approximate transport equations. Starting from the momentum space, the propagation of ACM along the normal direction to the source is defined as follows:

$$\tilde{\Gamma}_z(\mathbf{p}_{a'}, \mathbf{p}_b) = \mathrm{e}^{ikz[T(\mathbf{p}_a) - T^*(\mathbf{p}_b)]} \tilde{\Gamma}_0(\mathbf{p}_{a'}, \mathbf{p}_b) \tag{5}$$

where

$$T(\mathbf{p}) = \begin{cases} \sqrt{1-p^2} & \text{for } p^2 \leq 1 \\ i\sqrt{p^2-1} & \text{for } p^2 > 1 \end{cases} \tag{6}$$

The Frobenius Perron transport equation for the WT can then found by inserting (5) into (2)

$$\mathcal{W}_z(\mathbf{x}, \mathbf{p}) = \iint \mathcal{G}_z(\mathbf{x}, \mathbf{p}, \mathbf{x}', \mathbf{p}') \cdot \mathcal{W}_0(\mathbf{x}', \mathbf{p}')\, \mathrm{d}\mathbf{x}'\mathrm{d}\mathbf{p}' \tag{7}$$

where

$$\mathcal{G}_z(\mathbf{x}, \mathbf{p}, \mathbf{x}', \mathbf{p}') = \left(\frac{k}{2\pi}\right)^2 \delta(\mathbf{p} - \mathbf{p}')\, \mathbf{1} \cdot \\ \cdot \int \mathrm{e}^{\mathrm{i}k(\mathbf{x}-\mathbf{x}')\cdot\mathbf{q} + ikz(T(\mathbf{p}+\mathbf{q}/2) - T^*(\mathbf{p}-\mathbf{q}/2))} \mathrm{d}\mathbf{q} \tag{8}$$

and 1 is the unit dyad. This procedure made it possible to obtain the WT of the ACM at a distance of 10 cm. In Figure 3, the WT at 1 cm (left) and the WT at 10 cm (right) are shown. After an appropriate change of variables with respect to the variables x and y, as previously done for the ACM at 1 cm, the inverse Wigner Transform of the propagated ACM has been obtained. In this way, the propagation of the stochastic EM fields is obtained at a distance of 10 cm starting from the measurement data of the fields at 1 cm from the planar source. Figure 4 shows the ACM at 1 cm (left) obtained from the experimental data and the ACM at 10 cm (right) estimated following the procedure just described. Using a Green's function based propagator for correlation functions or spectra, we can accurately compute the evolution of the stochastic EM field in near and far-field. The propagator can be formulated based on analytical or numerical Green's function, both in frequency or time domain [21], [22]. These circumstances make this method very versatile in different application scenarios. EM field correlations between the observation points x_a and x_b are obtained for field correlations evaluated on a surface containing the EM source distribution at coordinates $x_a\prime$ and $x_b\prime$. The field dyadic correlation spectrum $\Gamma_\mathbf{F}$ can be obtained using the source-field dyadic Green's function $G_\mathbf{FJ}$ as [10], [21]

$$\Gamma_\mathbf{F}(x_a, x_b) = \int\int G_\mathbf{FJ}(x_a - x'_a) \times \\ \times \Gamma_\mathbf{J}(x'_a, x'_b)\, G^\dagger_\mathbf{FJ}(x_b - x'_b)\ \mathrm{x}'_b\, \mathrm{x}'_b \tag{9}$$

Here, $\Gamma_\mathbf{J}$ denotes the source current correlation dyadic,

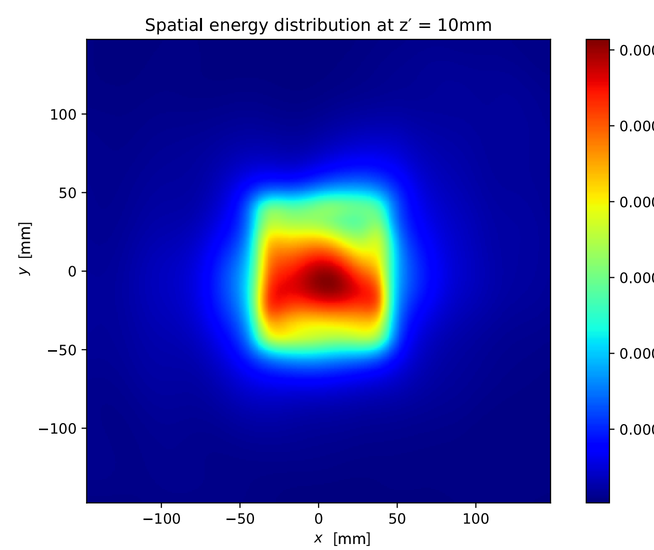

Fig. 5. Spatial energy distribution at z'=10 mm.

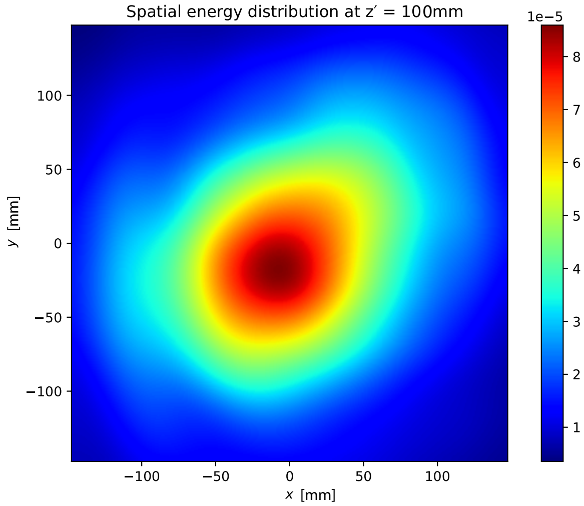

Fig. 6. Spatial energy distribution at z'=100 mm.

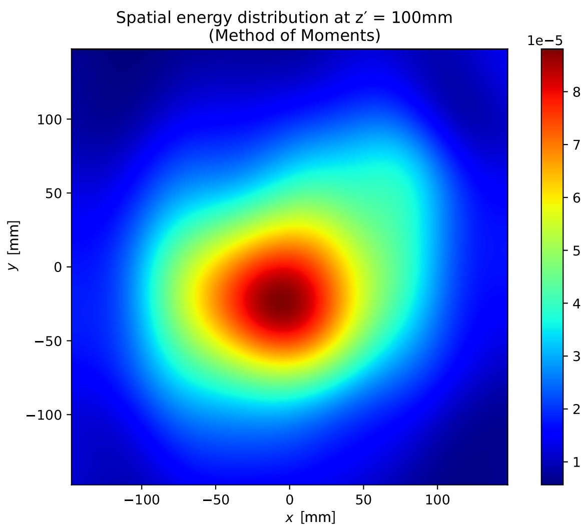

Fig. 7. Spatial energy distribution at z'=100 mm by the method of moments.

obtained from

$$\Gamma_{\mathbf{J}}\left(x_a, x_b\right) = \left\langle \mathbf{J}_{e,m}\left(x_a, \omega\right) \mathbf{J}_{e,m}^{\dagger}\left(x_b, \omega\right)\right\rangle \tag{10}$$

accounting for either electric or magnetic source current terms, given by the indices $_{e,m}$. The formula for propagating the EM field correlation (9) can be treated numerically by concept of the Method of Moments (MoM) and thus, to transfer (9) into a set of linear algebraic equations. This is being accomplished by introducing a set of vectorial basis functions which are first used for the expansion of the field and source current functions into these basis functions. Furthermore, these expansion functions are being used, along with a set of testing functions, latter are possibly also identical with the former set, to establish the moment matrix from above Green's function based integral formula. The resulting set of algebraic equations is given by

$$C^V\left(\omega\right) = \mathbf{Z}\left(\omega\right)\, C^I\left(\omega\right)\, \mathbf{Z}^{\dagger}\left(\omega\right), \tag{11}$$

where C^V is the correlation matrix of the expansion coefficients, termed generalized voltages, of the electric field expansion, while C^I is the correlation matrix of the expansion coefficients of the source current distribution. $\mathbf{Z}$ is the moment matrix [21], [23]. The Green's function, if not available analytically, can be obtained numerically from conventional EM full wave solvers for deterministic scenarios. Time-domain formulations, analytical and numerical, are discussed in [22], [24], [25]. Figures 5, 6, and 7 show the measured spatial energy density in the source plane as well as measured and numerically propagated, latter based on the measured source plane data, spatial energy density in the observation plane. In this example, the field correlation data has been propagated using the method of moments approach.

V. More Information

Although the notebook reports an example starting from our measurement data, the algorithm is applicable to any incoming dataset and to any dimension. This implies the algorithm does not remain bound only to sample datasets of such dimensions, but allows the user to run the code on their datasets by appropriately modifying the lines of code of interest and entering the size of their data. In fact, the notebook initializes various parameters that can be changed based on the information on measurement data obtained, and will be able to calculate the stochastic fields at any distance. This allows the user to modify and update the code having all the tools necessary to bring the guide to better and future versions. In addition to the notebook version, the code has been reported in a python script that can be executed directly from the terminal without the need to open and run the Notebook. In addition to the files previously described, a function for converting the dataset from .mat to .pt has been included, giving the user the possibility to process data from .mat files as well. All the material including the datasets, scripts and the Notebook are stored in the IEEE Standard Association repository, where the user can access, download the contents, execute the code and possibly propose changes. In order to open and run the Notebook it is not strictly necessary to install Jupyer Notebook or Jupyter Lab, but it is possible to access platforms such as Google Colab that allow the user to load the notebook and run it without the need to download any library in Python. An example of the open source code written on Jupyter Notebook can be found on the repository available at the following link: https://standards.ieee.org/ieee/2718/6983/

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