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Multiport Network Modeling for Reconfigurable Intelligent Surfaces: Numerical Validation with a Full-Wave PEEC Simulator

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Abstract

Reconfigurable Intelligent Surface (RIS) modeling and optimization are a crucial steps in developing the next generation of wireless communications. To this aim, the availability of accurate electromagnetic (EM) models is of paramount important for the design of RIS-assisted communication links. In this work, we validate a widely-used analytical multiport network for RISs by means of a well-established full-wave numerical method based on the Partial Elements Equivalent Circuit (PEEC) approach. Numerical results show good agreement between the two methods, thus demonstrating i) the considered multiport network model being effective and ii) the PEEC method being appropriate for EM modeling of RIS-assisted wireless links.

1 Introduction

Reconfigurable intelligent surface (RIS) has been recognized as an innovative paradigm for electromagnetic (EM) wave manipulation, signal modulation, and smart radio environment reconfiguration [1, 2]. RISs are artificial metasurfaces composed of periodic or aperiodic subwavelength electric or magnetic resonators, which can be controlled in order to induce dynamic reflection/transmission amplitude and phase responses, thereby shaping reflected and transmitted wavefronts. This allows for the reconfiguration of the scattering patterns according to the direction of the incident waves and the locations of the users.

In order to analyze and optimize RIS-assisted wireless systems, communication models that consider the physics and EM characteristics of the RIS's scattering elements must be sufficiently realistic, accurate, and tractable. This calls for EM models that allow for an appropriate description of propagation phenomena and the mutual coupling among the radiating elements in the RIS. A circuit-based communication model for RIS-assisted wireless systems that is based on evaluating the mutual impedances between all the radiating elements (transmit/receive antennas, passive scatterers) is presented in [3]. A time domain macromodel of the RIS, including transmitters and receivers, has been introduced in [4].

The scope of this work is twofold: i) to validate the analytical model of the RIS introduced in [3], and ii) to prove the versatility of the Partial Elements Equivalent Circuit (PEEC) method for the EM modeling of communication channels. Specifically, we analyze the performance of RIS-aided channels by optimizing the tunable terminations of the RIS, and quantifying the obtained performance gains.

2 System Model

This section describes the two approaches employed to model RIS-aided channels: the numerical approach based on the PEEC method and the analytical framework based on multiport network theory. As stated in [3, 4], the communication channel can be conceptualized as a multiport system. Accordingly, certain ports model the transmitters, while others model the receivers or scatterers.

The overall system can be characterized by the impedance matrix $\mathbf{Z}_{sys}$, which takes into account the interactions between transmitters, receivers, the RIS, as well as the presence of scattering objects in the environment. This impedance matrix can be defined as

$$\mathbf{Z}_{sys} = \begin{bmatrix} \mathbf{Z}_{TT} & \mathbf{Z}_{TS} & \mathbf{Z}_{TO} & \mathbf{Z}_{TR} \\ \mathbf{Z}_{ST} & \mathbf{Z}_{SS} & \mathbf{Z}_{SO} & \mathbf{Z}_{SR} \\ \mathbf{Z}_{OT} & \mathbf{Z}_{OS} & \mathbf{Z}_{OO} & \mathbf{Z}_{OR} \\ \mathbf{Z}_{RT} & \mathbf{Z}_{RS} & \mathbf{Z}_{RO} & \mathbf{Z}_{RR} \end{bmatrix}, \tag{1}$$

where $\{T, R, S, O\}$ denote the transmitter, receiver, RIS, and the scattering objects in the environment, respectively. Moving from the knowledge of $\mathbf{Z}_{sys}$, the communication channel matrix $\mathbf{H}_{E2E}$ can be determined as described in [5]

$$\mathbf{H}_{E2E} = \mathbf{Z}_{RL}\left[\mathbf{Z}_{ROT} - \mathbf{Z}_{ROS}\mathbf{Z}_{sca}\mathbf{Z}_{SOT}\right]\mathbf{Z}_{TG}, \tag{2}$$

where $\mathbf{Z}_{RL} = \left(\mathbb{I}_L + \mathbf{Z}_{RR}\mathbf{Z}_L^{-1}\right)^{-1}$, $\mathbf{Z}_{TG} = \left(\mathbb{I}_L + \mathbf{Z}_{TT}\mathbf{Z}_G\right)^{-1}$, and $\mathbf{Z}_{sca} = \left(\mathbf{Z}_{SS} + \mathbf{Z}_{SOS} + \mathbf{Z}_{RIS}\right)^{-1}$. In particular, $\mathbb{I}_L$ is the identity matrix, $\mathbf{Z}_G$ and $\mathbf{Z}_L$ are the diagonal matrices containing the impedances of the voltage sources of the transmitters and the load impedances at the receiver; $\mathbf{Z}_{TT}$ and $\mathbf{Z}_{RR}$ are the matrices containing the self and mutual impedances at the transmitter and receiver; $\mathbf{Z}_{ROT}$, $\mathbf{Z}_{ROS}$, $\mathbf{Z}_{SOS}$ and $\mathbf{Z}_{SOT}$ are the matrices containing the mutual impedances between different array elements, including the scattering objects in the environment.

2.1 The PEEC Method

The PEEC method relies on a circuit-based model [6] to represent EM phenomena related to transmitters, receivers, and scattering elements. Specifically, the PEEC formulation is based on the Electric Field Integral Equation (EFIE) and the continuity law for the electric current. One of the key advantages of the PEEC method is its capability to describe the behavior of complex structures by means of standard circuit variables, namely node potentials and side electric currents.

To obtain the PEEC representation, the considered system, e.g., an antenna element, is first divided into smaller units (mesh), consisting of elementary volumes and surfaces. The electric currents are assumed to flow through the elementary volumes, while the electric charges are assumed to exist on the elementary surfaces of the mesh. Then, the coupling between the currents flowing in the volumes and the charges on the surfaces are considered. The magnetic interaction among the currents is described by partial inductances denoted as $\mathbf{L}_p$, while the electric interactions among the charges are represented by potential coefficients denoted as $\mathbf{P}$. Finally, the application of Kirchhoff laws to the PEEC equivalent circuit leads to the following Modified Nodal Analysis (MNA) representation in the frequency domain:

$$\begin{bmatrix} \mathcal{Z}(s) + s\mathbf{L}_p & -\mathbf{A}^{\mathbf{T}} \\ \mathbf{A} & s\mathbf{P}^{-1} + \mathbf{Y}_{\ell e}(s) \end{bmatrix} \begin{bmatrix} \mathbf{I}(s) \\ \Phi(s) \end{bmatrix} = \begin{bmatrix} \mathbf{V_s}(s) \\ \mathbf{I_s}(s) \end{bmatrix} \tag{3}$$

where $\mathcal{Z}(s)$ is the impedance matrix accounting for the impedance of conductors or dielectrics elementary volumes, $\mathbf{Y}_{\ell e}$ is the lumped admittance matrix that contains all the lumped admittances connected to the nodes of the equivalent circuit and $\mathbf{A}$ is the incidence matrix [6, Eq. (13.6)]. The knowledge of the voltage and current sources, denoted as $\mathbf{V}_s(s)$ and $\mathbf{I}_s(s)$ respectively, allows one to determine the unknown vectors $\Phi(s)$ and $\mathbf{I}(s)$, which represent the node potentials and branch electric currents, respectively. Once $\Phi(s)$ and $\mathbf{I}(s)$ are obtained, $\mathbf{Z}_{sys}$ is determined.

We remark that the described approach yields a comprehensive EM characterization of the considered system, thus providing deep insights on several system features. For instance, the obtained PEEC description can be exploited to accurately characterize the end-to-end channel gain, to design impedance matching strategies and for signal integrity studies. Therefore, the PEEC method represents a versatile and powerful tool for the analysis and the optimization of RIS-aided wireless links.

2.2 Analytical Model

According to the methodological approach proposed in [3], the transmitting and receiving antennas, as well as the scattering elements of the RIS, are assumed to be cylindrical thin wire dipoles composed of perfectly conducting material. These dipoles possess a finite but negligible radius, denoted as a, which is much smaller than the dipole length, ℓ. The thin wire dipoles are connected to complex-valued tunable impedances.

The determination of the communication channel gain depends on the knowledge of the mutual impedances between the thin wire dipoles. Based on [3], the self and mutual impedances describing the system are given by

$$Z_{qp} = \int_{z_q-\ell_q/2}^{z_q+\ell_q/2} \int_{z_p-\ell_p/2}^{z_p+\ell_p/2} g_{qp}(z',z'')\tilde{I}_{z,p}(z')\tilde{I}_{z,q}(z'')dz'dz'' \tag{4}$$

where $\tilde{I}_{z,\chi}(z') = \sin\left[k_0\left(\ell_\chi/2 - |z'-z_\chi|\right)\right]/\sin\left(k_0\ell_\chi/2\right)$ is the distribution current that is assumed to be sinusoidal, and $g_{qp}(z',z'') = j\eta_0(4\pi k_0)^{-1}\mathcal{F}_p(\mathbf{r}_{S_q},z')\mathcal{G}_p(\mathbf{r}_{S_q},z')$. The characteristic impedance in vacuum is $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$, and the wavenumber is $k_0 = 2\pi/\lambda$, where μ_0 and ε_0 are the permittivity and permeability in vacuum, and λ is the wavelength. The terms $\mathcal{F}_p$ and $\mathcal{G}_p$ are defined in [3].

3 RIS Optimization

The configuration of the RIS is obtained by utilizing the algorithm recently proposed in [5]. The approach is based on the block coordinate descent method, which optimizes the tunable impedances of the RIS iteratively. At each iteration, specifically, the algorithm optimizes a single tunable impedance while keeping the others fixed. The proposed approach is based on the application of Sherman-Morrison's inversion formula, Sylvester's determinant theorem, and Gram-Schmidt's orthogonalization method. Thanks to this approach, a closed-form solution for the optimal impedance is obtained at each iteration, which ensures that the algorithm requires fewer iterations and less time to converge compared with state-of-the-art benchmarks, while guaranteeing better performance.

4 Numerical Results

We consider a scenario consisting of a transmitter that is constituted by 4 thin wire dipoles, deployed along the x-axis, with the first dipole being centered in $\mathbf{r}_{Tx} = [0\ 0]$ on the xy-plane, and the 4 dipoles being spaced by $\lambda/2$; a single receiving dipole of length $\lambda/2$ centered in $\mathbf{r}_{Rx} = [9.6\lambda\ 14.4\lambda]$ on the xy-plane; and an RIS, which consists of an array of dipoles deployed along the x-axis, with the first dipole being centered in $\mathbf{r}_{RIS} = [0\ 24\lambda]$. The interdistance of the RIS elements is $d = \lambda/8$ on the xy-plane, and three sizes for the RIS are considered with a number of elements N_{RIS} equal to 4, 16 and 64. Figure 1 shows the system con-

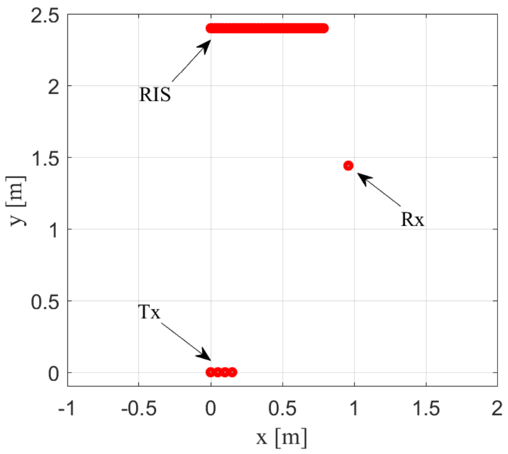

Figure 1. System setup for a 64 elements RIS.

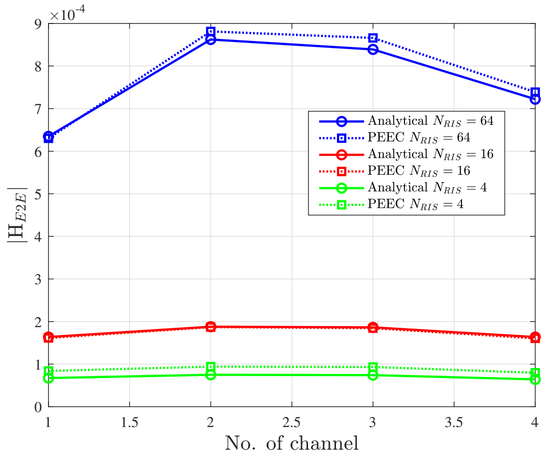

Figure 3. Channel gain with optimized RIS terminations.

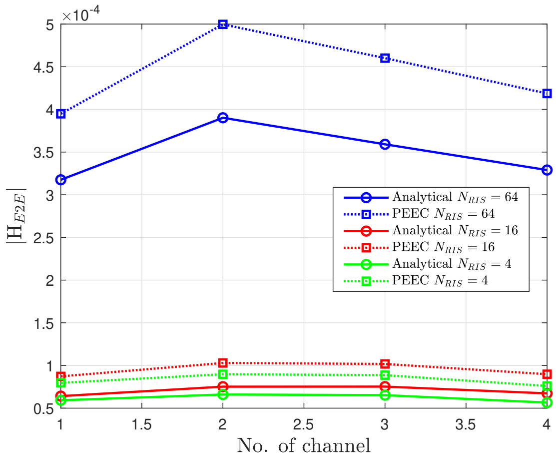

Figure 2. Channel gain with unoptimized RIS terminations.

figuration of an RIS with 64 elements. The resonance frequency is set to 3 GHz, which correspond to a wavelength of $\lambda = 10$ cm. The considered analytical and numerical methods for system characterization are those described in Section 2, and the end-to-end the channel gain is obtained using (2). In our evaluation, the direct path between the transmitting and receiving antennas array is assumed to be blocked by obstacles.

Figure 2 illustrates the channel gain when the RIS terminations are not optimized. For this evaluation, resistive type RIS terminations are considered, where all the terminations are set to 0.2 Ω. It is possible to observe that the analytical characterization and the PEEC electromagnetic simulator exhibit consistent performance trends and provide similar performance.

Figure 3 compares the channel gain when the RIS terminations are obtained by applying the optimization algorithm described in Section 3, where the algorithm is initialized by setting all the terminations to 0.2 Ω. It can be observed that optimizing an RIS is a crucial step, since a substantial improvement of the channel gain is obtained. Again, the analytical model and the PEEC simulator are in good agreement.

5 Conclusion

In this paper, we validated a recently proposed multiport network model for RIS-assisted wireless communication channels by means of a numerical simulator based on the PEEC method.

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