# Design and Optimization of Reconfigurable Intelligent Surfaces Using the PEEC Method

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Abstract—The design and optimization of Reconfigurable Intelligent Surfaces (RISs) are key challenges for future wireless communication systems. RISs are devices that can manipulate electromagnetic (EM) waves in a programmable way, thus enhancing the performance and efficiency of wireless links. To achieve this goal, it is essential to have reliable EM models that can capture the behavior of RISs in different scenarios. This work demonstrates that the Partial Elements Equivalent Circuit (PEEC) method is a powerful tool for EM analysis of RIS-aided wireless links. It might also be integrated with optimization algorithms in order to optimize wireless communication networks.

### I. INTRODUCTION

Reconfigurable intelligent surfaces (RISs) are a novel technology that can enhance wireless communication systems by smartly manipulating the electromagnetic waves in the environment. An RIS is composed of a large number of nearly-passive scattering elements, that can be programmed to adjust their reflection, absorption, or refraction properties. By doing so, an RIS can create favorable propagation conditions for wireless signals, such as beamforming, interference cancellation, or secure communications [1]. One of the main advantages of RISs relies in the capability of focusing the scattered field, meaning that it can concentrate the wireless energy in a desired direction or location. This is an enabler for enhancing the performance of wireless networks in terms of coverage, capacity, energy efficiency, and security. However, to achieve this goal, accurate communication models that take into account the physics and electromagnetic (EM) features of the RIS elements are of paramount importance for optimizing RIS-aided systems. Importantly, this calls for EM-consistent models that accurately describe the wave propagation and RIS elements, at a tractable complexity [2], [3], [4].

Moreover, a crucial aspect is to optimally configure the RIS according to the channel state information (CSI). The optimization problem consists of finding the optimal configuration of the RIS elements that maximizes a certain objective function, such as the received signal power, the signal-tonoise ratio, or the secrecy rate. The optimization of RISs is a challenging task for several reasons. First, the RIS elements have discrete and finite states, which makes the optimization problem non-convex and combinatorial. Second, the CSI of RIS-empowered wireless links is difficult to obtain since an RIS do not have any active components for channel probing. Third, the optimization problem may involve multiple RISs, multiple users, and multiple objectives, which increases the complexity and the dimensionality of the problem. An EMconsistent optimization algorithm was introduced in [5].

In this work, we propose the Partial Elements Equivalent Circuit (PEEC) method [6] as an effective and powerful tool for the EM characterization of RIS-aided communication channels. Moreover, we stress the importance of optimizing the RIS configuration by considering the RIS radiation pattern [7]. Finally, to demonstrate the effectiveness of the PEEC method, we compare the obtained results with those obtained with the commercial software Feko.

## II. THE PEEC METHOD

The PEEC method is a powerful computational technique for analyzing EM phenomena in various systems and structures [6]. It solves the Electric Field Integral Equation (EFIE) and the Continuity Equation (CE), but, differently from the Method of Moments (MoM) [8], the two equations are kept separate and, thus, the currents and charges (or potentials) are kept separate as well. The geometry is meshed using volumes and surfaces, which can be hexahedra/quadrilaterals or tetrahedra/triangles. 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. This allows for identifying an equivalent circuit to which the Kirchhoff voltage and current laws are enforced. The interactions of the electric field are described by the coefficients of the potential P, and the interactions of the magnetic field are described by the partial inductances  $L_P$ . The conductor losses are captured by resistances and the polarization currents in dielectrics by capacitances [6]. The main advantage of a circuit representation for an electromagnetic problem is the possibility of adding linear and nonlinear components, and the possibility of solving the resulting circuit in both the frequency and time domains. The resulting PEEC equivalent circuit can then be analyzed using various techniques such as the Modified Nodal Analysis (MNA) [6] in the frequency domain, as follows:

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

where  $\mathcal{Z}(s)$ , represents the impedance of the elementary volumes of conductors or dielectrics. The lumped admittance matrix,  $\mathbf{Y}_{\ell e}$ , encompasses all the lumped admittances linked to the nodes of the equivalent circuit, and  $\mathbf{A}$  is the incidence matrix [6, Eq. (13.6)]. The unknown vectors of node potentials



Fig. 1. System configuration.

and branch electric currents, denoted by  $\Phi(s)$  and I(s) respectively, can be determined from the voltage and current sources,  $V_s(s)$  and  $I_s(s)$  respectively. From the model, it is possible to calculate the impedance matrix of the entire system,  $Z_{sys}$ , which accounts for the interactions between the transmitters, receivers, scatterers, and RIS. The resulting analysis provides insights on the system behavior, including the channel gain, impedance matching, and signal integrity.

## III. RIS OPTIMIZATION

The goal of RIS optimization is to maximize the achievable rate, which represents the highest rate at which data can be reliably transmitted over a wireless link. The RIS terminations affect the achievable rate, which can be written as a function of them. We adopt the algorithm introduced in [5], which computes the optimal load impedances one by one in an iterative manner. The algorithm uses three key mathematical techniques, such as Sherman-Morrison's formula, Sylvester's theorem, and Gram-Schmidt's method, to simplify the optimization problem and find a closed-form solution for the optimal impedances at each iteration of the algorithm. This makes the algorithm faster and more efficient than existing methods, as it needs fewer iterations and less time to converge.

#### **IV. NUMERICAL RESULTS**

We consider the scenario illustrated in Fig. 1, consisting of thin-wire dipoles. The transmitter is centered in  $\mathbf{r}_{Tx} = [4 \ 0 \ 3]$ m; the receiver is centered in  $\mathbf{r}_{Rx} = [2 \ 3.46 \ 1]$  m, and the RIS, consisting of an array of dipoles, is centered in  $\mathbf{r}_{RIS} = [0 \ 0 \ 2]$ m. The array is made up of two rows of 32 dipoles arranged on the yz-plane, and the elements are spaced by  $d_y = \lambda/8$ and  $d_z = 3\lambda/4$ , with  $\lambda$  being the wavelength. The dipoles are parallel to the z-axis, and their length is  $\lambda/2$ . The resonance frequency is 28 GHz, corresponding to  $\lambda \cong 1$  cm. The red dots in Fig. 1 indicate the ports for feeding and terminating the dipoles. Figure 2 shows how the scattered field of the RIS is optimized in both the azimuth ( $\phi$ ) and the elevation ( $\theta$ ) planes. With respect to the RIS center, the receiver is oriented towards  $60^{\circ}$  in the  $\phi$ -plane, and approximately towards  $104^{\circ}$ in the  $\theta$ -plane. The results show a good agreement between the PEEC model and Feko.



Fig. 2. Normalized radiation pattern:  $\phi$ -plane (left);  $\theta$ -plane (right).

#### V. CONCLUSION

In this study, we proposed the PEEC method as an effective tool for EM modeling in RIS-aided wireless systems. We showed that the PEEC formulation can be efficiently integrated in existing optimization algorithms and validated the results by using a commercial EM simulator.

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