

Performance Evaluation of Linear Antennas Loaded with Optimized Time-Modulated Circuit Elements

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Time-modulated circuit configurations are frequently utilized to achieve unprecedented control over the transmission, reflection and scattering response of electromagnetic waves from metamaterial and metasurface structures. Despite their advantages, they have rarely been applied in the context of traditional antenna analysis and synthesis problems. While a few studies have demonstrated the circumvention of fundamental limits for Electrically Small Antennas (ESAs) (A. Mekawy, H. Li, Y. Radi, A. Alù, "Parametric Enhancement of Radiation from Electrically Small Antennas," *Phys. Rev. Appl.*, **15**(5), 2021) using parametric amplification, such approaches still require the modulation frequency of the circuit to be significantly higher than the carrier source frequency. Recently, we introduced the concept of harmonic engineering and synthesis for conventional antenna problems using a traditional microstrip patch antenna radiator loaded with time-modulated permittivity material, thereby theoretically demonstrating amplification and suppression of radiated harmonic frequencies (D. Yang, A. Das, S. D. Campbell, D. H. Werner, "Harmonic Engineering of Antennas with Time-Periodic Substrate Permittivity," *Physical Review Applied* - Accepted for Publication, 2025). Building on this from an antenna engineering standpoint, we present the concept of discrete loading of linear wire antennas with time-varying circuits at multiple locations, highlighting the antenna performance improvements compared to its non-time-varying counterparts (Fig. 1). This is in sharp contrast with scenarios where time-varying circuit loads are employed as efficient matching networks. Furthermore, several optimization techniques are utilized to achieve desired cost functions with objectives to enhance antenna performance parameters such as bandwidth, impedance response, gain, directivity, radiation efficiency, *etc.*

The solution of such a problem is obtained by following a three-stage process. First, behavioral macromodel parameters of the antenna are extracted by replacing circuit loads with lumped-ports. Second, the antenna and time-varying loads are analyzed together using matrix equations. Finally, the results from the previous stages are combined to compute the electromagnetic fields radiated by the antenna. This framework is further integrated with multiple optimization algorithms for performance enhancement studies. Various single- and multi-objective optimization techniques, including Genetic Algorithms (GAs) and the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) are considered in this work. The proposed formulation and several numerical examples will be presented and discussed.

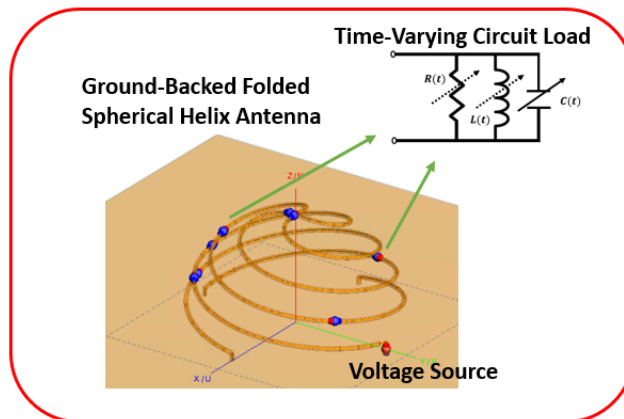


Figure 1. Time-varying circuit loaded Folded Spherical Helix antenna.