Mathematical and Statistical Models for the Electromagnetic Coupling in Complex Systems

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Abstract—This work aims to develop fundamental mathematical and statistical algorithms for the spatio-spectral analysis of electromagnetic coupling in large, complex electronic systems. The objective is attained by cutting across traditional disciplinary boundaries between electromagnetic theory, wave chaos physics, random statistical analysis and computational science. The work achieves a physics-based model and simulation capability that predicts both spatial and spectral characteristics of high power radio-frequency induced current and voltages in complex electronic systems.

Keywords-electromagnetic coupling; statistical analysis

I. RESEARCH OVERVIEW

The directed energy (DE) high power radio-frequency (HPRF) weapons have become an increasing threat to various mission-critical and safety-critical defense systems and facilities. The intentional electromagnetic (EM) interference from the HPRF sources may introduce noise or signals into circuits and electronics of the target system, thus degrade, disable, or damage the system. To rapidly assess the vulnerability and susceptibility of electronics due to the HPRF attack, it is essential to develop a deep-domain understanding of the physics of HPRF-to-target-to-electronics coupling.

As recognized by many scientists and engineers in the DE and Counter-DE research community, the physics of HPRF-to-target-to-electronics interaction is extremely complex. Most of electronics are hosted inside protective metallic enclosures, metal castings, and computer boxes. The HPRF energy first needs to couple into the target enclosure/casing through open apertures or seams, and then interact with the sensitive electronics. In the high-frequency regime, the complex boundary of the enclosure can lead to high modal density and high modal overlap [1]. Wave solutions inside these enclosures show strong fluctuations that are extremely sensitive to the exact geometry of the enclosure, the location of internal sensors and electronics, and the operating frequency [2]. Research regarding HPRF effects on missiles has shown large variations not only between designs, but also between different serial numbers due to assembly methods, cable routing, and component variations [3].

This paper aims to answer this growing and pressing science and engineering need. One significant outcome is the stochastic Green's function (SGF) method. The SGF is an innovative theoretical solution to Maxwell's Equations in the complex wave-chaotic media [4]. The derivation of time-harmonic SGF leverages the physics of wave-chaotic dynamics and the mathematics of random matrix theory (RMT). Comparing to existing statistical EM approaches, the SGF rigorously integrates the coherent and incoherent propagations within a comprehensive form, which does not appear to be available in the literature. Based on the SGF, a novel stochastic integral equation (SIE) method is proposed. The SIE-SGF method statistically replicates the multipath, ray-chaotic interactions between transmitters and receivers. The work accomplishes a first-principles mathematical model resolving the transmitting correlation, propagation correlation, and receiving correlation in the multipath, wave-chaotic environment.

Furthermore, we recognize that most real-world EM systems often exhibit mixed chaotic and regular wave dynamics. Therefore, it is of great practical importance to rigorously study and incorporate these non-universal effects. We have developed a hybrid deterministic and stochastic formulation incorporating component-specific characteristics, investigated an in-situ SGF addressing the site-specific short-orbits, and designed a Lorentzian-weighted frequency averaging to predict the system-specific ensemble behavior. The developed predictive models have been validated and verified in various experimental settings, including complex 3D metallic cavities, quasi-2D interconnected cavities, and 3D cascaded cavities.

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The work is supported by AFOSR/AFRL Center of Excellence: The Science of Electronics in Extreme Electromagnetic Environments.