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The UNM COE team includes: Ganesh Balakrishnan, David Dietz, Gregory Heileman, Sameer Hemmady, Zhen Peng, Edl Schamiloglu, Yang Shao, and Payman Zarkesh-Ha. In addition, several graduate students participate in the research: Sadhvikas Addamane, Shen Li, Nishchay Sule, Luis Valbuena, and undergraduate Desmond Awungayi.

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. Effects of extreme electromagnetic interference (EEMI) on VLSI design – Research and develop predictive physics-based models for electronic components stressed beyond their normal operating parameters due to direct injected electromagnetic interference.

   The purpose of this portion of the project is to design and fabricate basic CMOS test structures using standard technology nodes to be used for EEMI testing and analysis. Over the past year, we designed and fabricated wafers containing elemental semiconductor devices – NMOS, PMOS, inverters, inverters with electrostatic discharge (ESD) protection, ring counters and buffers using 1x and 10x device scales. Also, the same circuit topologies were replicated in the 350 nm, 180 nm, 130 nm, 90 nm, and 65 nm TSMC processes. All test circuits were tested and found to be operational. In addition, we performed direct injection testing for input and power supply injection using cw excitation with frequencies spanning 100 MHz to 4 GHz, and power levels from -30 dBm to +30 dBm. The variation in the transfer characteristics of these individual devices was captured. We also developed predictive models for describing the scaling laws for NMOS devices and inverter sections.

2. Effects of EEMI on software execution – Research and develop predictive models to characterize the functional (software) upset of digital electronics due to physical interaction of EEMI with underlying circuitry (collaboration between Professor Hemmady and Professor Antonsen, UMD).

   The purpose of this project is to develop a predictive model describing functional software upset of a complicated digital electronic system due to EEMI influence. We focus on the use of microcontrollers, which serve as ideal surrogates for large, more complicated digital systems. In addition, we developed a FPGA-based experimental framework to reproducibly inject glitches into the clock stream and power supply of the microcontroller, while it is executing specific software instructions. We studied the statistical behavior of software glitches and are developing a stochastic, Markov based modeling framework to predict software behavior as a function of injected glitch parameters. This work is performed in collaboration with UMD.

Another portion of this work seeks to find a way to write resilient code for EEMI environments. We want to have a predictive model of how the different states of a computation changes under EEMI. In addition to the Markov chain approach we are looking at this through a Turing machine approach (can EEMI be used to change a computer from performing one set of instructions to a completely different set of instructions?) and as a hybrid automata. Two manuscripts are being prepared for submission: one on a 4-bit processor testbed for software predictive models and one on the consequences of targeted extreme EEMI on software execution.

3. Investigate and develop innovative algorithms to fuse deterministic computational electromagnetic algorithms with stochastic electromagnetic models for coupling into complicated cavities (collaboration between Zhen Peng's CEM group, Professor Schamiloglu's group, and Professor Antonsen, UMD).

The main achievements of year 2 by the UNM Computational Electromagnetics (CEM) group are three-fold:

(1) First-principles analysis and verification tools for complex electronic systems ranging from circuit, package, board and system levels. The emphasis is placed on advancing parallel algorithms that are provably scalable, and facilitating a design-through-analysis paradigm for emerging and future electronic systems. The advancements answer the following fundamental questions: (i) how do we exploit the natural hierarchy in electrical systems during the modeling and simulation? (ii) can both the simulation capability and modeling fidelity of electromagnetic field-based simulators scale with the exponential growth in computing power? (iii) how to reduce the computational complexity for the multi-scale simulation of complex electronic systems?

The work has advantages over the existing approaches in three aspects: (i) the use of an adaptive and scalable geometry-aware domain decomposition (DD) method to conquer the geometric complexity of physical domains. This work not only leads to scalable convergence in DD iterations, but also simplifies the preparation of electromagnetic analysis-suitable models from electrical computer-aided design layouts. (ii) a hierarchical coarse-grained method to reduce the computational complexity for multi-scale modeling of electronics. The multi-level skeletonization is employed to construct effective basis functions, the so-called skeletons, with individual sub-systems of different scales. (iii) this work also serves as a basis for parallel and scalable computational algorithms to reduce the time complexity via advanced high performance computing (HPC) architectures. A hybrid Message Passing Interface (MPI)/OpenMP parallel implementation of the proposed framework is developed and tested on shared and distributed memory supercomputers.

(2) Quantitative statistical electromagnetic analysis of antennas and electronics in complicated enclosures. Characterizing the EMI and microwave effects on antennas and electronics within large complicated enclosures (e.g. computer box, reverberation chamber, aircraft fuselage) is an important and challenge problem. In the high-frequency regime, wave solutions inside these enclosures show strong fluctuations that are extremely sensitive to the exact geometry of the enclosure, the location of internal electronics, and the operating

frequency. The response of one configuration of the enclosure may not be useful in predicting that of a nearly identical enclosure. Furthermore, real-world EMI with electronic systems also involves a very high degree of uncertainty. The electromagnetic source, propagation/interference path, and targets of interest are often unknown. Therefore, it necessitates a statistical characterization of the EMI and system behavior.

This work presents a different methodology comparing to existing methods in the literature. A hybrid deterministic and stochastic formulation is proposed, in which small components (electronics, antennas, etc.) in the computational domain are modeled using first-principles and large portions (cavity enclosures, scattering environments, etc.) are modeled statistically. The key ingredients are a non-overlapping domain decomposition (DD) formulation, and a stochastic Green's function method that quantitatively describes the universal statistical property of chaotic systems through random matrix theory (RMT).

The work seamlessly integrates the universal statistical properties of the chaotic environments and the site-specific features within a comprehensive statistical analysis framework. Furthermore, it establishes a surrogate modeling capability, which generates the statistical electromagnetic interference in nearly real-time while retaining the underlying first-principles analysis.

(3) Validation and verification of the proposed computational framework. To evaluate the feasibility of the proposed work, we have carried out a number of experimental verification and validation (in collaboration with Ghadeh Hadi, Sameer Hemmady, and Edl Schamiloglu) studies. In a representation exploration we considered a complicated 3D aluminum box. The paddle-wheel mode stirrer is used to generate an ensemble of measurements. Two X-band waveguide (WG) antennas mounted on the opposite walls are used as the transmitter and receiver. The electromagnetic fields inside the box exhibit strong fluctuations due to a mix of regular cavity eigenmodes and chaotic eigenmodes. This work successfully predicts the probabilistic in-situ performance and co-site interference between two antennas. We observe very good agreement comparing computational results and measurements.

4. Investigate EEMI effects on optoelectronics through multi-physics analysis

Due to the high transmitting volume and speed of network traffic on the internet: video streaming, clouding computing, and the Internet of Things (IOT), fiber-optic laser transmitters will continue to be one of the major research focus areas in the next decade. The objective of this work is to investigate and develop computational models to predict laser transmitter behavior in the presence of EEMI. The advancements will lead to a comprehensive multi-physics analysis toolset for a variety of optoelectronics.

This year we focused on the following developments:

(i) Investigation of a time domain multi-physics solver hybridizing first-principles electromagnetic models and laser diode behavior models.

The laser diode is extremely sensitive to electrostatic discharge, high current levels and current spikes. These currents may be induced intentionally or unintentionally by electromagnetic interference. The developed time domain solver seamlessly integrates the rigorous solution of Maxwell subsystem and non-linear behavior modeling of optical subsystem through the circuit-field relations. It can accurately characterize the induced RF currents on the laser diode pins.

(ii) Measurement of laser diode I-V curve with various injected RF currents.

We purchased 5 types of optoelectronic components. All of them are TO-can packages, and we plan to extend the testing to the butterfly package in the next year. The components are ready for two sets of tests. One set is 980 nm lasers and silicon detectors, and another set is 1550 nm telecom lasers and InGaAs. We finished the I-V curve measurements on one laser transmitter with injected RF currents with frequency varying from 10 MHz – 100 MHz and power from -20 dBm to 18 dBm. We will extend our present experimental capability to test more laser diode parameters and conduct more testing on other laser diodes.

(iii) Development of a predictive model for laser diode behavior with RF currents.

From the measurement data we observe that the injected RF currents indeed affect the I-V curve cut-off voltage. Measurement data show that RF current at lower frequency and higher power level affect the cut-off voltage the most. Simulations show that the RF current at this level will increase the bit error rate of transmitted data.

5. Photonic interconnects and future devices: Effects of EEMI on single photon emitters (collaboration between Professor Balakrishnan's group and Professor Waks' group at UMD).
   In a collaborative effort between Prof. Waks' group at UMD and Prof. Balakrishnan's group at UNM quantum dot-based samples were grown with ultra-low dot density that are ideal for the fabrication of single photon devices. The molecular beam epitaxy of the devices was conducted at UNM followed by patterning using an e-beam writer and subsequent optical characterization done at UMD. There were significant results this year, with the first demonstration at UNM of single dot emission from telecom-wavelength 1.55 µm InAs quantum dots grown on InP. This has, in the past, been a challenge due to the difficulty in realizing and isolating single dots for InAs on InP substrates. With the successful realization of single dot emitters at 1.25 µm and 1.55 µm we envision device fabrication in the coming year followed by studies to understand the effects of EEMI on such devices.

6. Research frameworks for uncertainty quantification and investigate the origin of "randomness" in EEMI interaction with electronic devices and software processes.

   We have developed an analytic model for a single inverter to compute the stochastic signal time delay, t_D, resulting from a stochastic power supply V_{dd} driving the inverter as well as to compute the probability of failure of any digital circuit employing only a single inverter. We have also extended this model to a pair of inverters; the formalism used for the pair is extendable to any number of inverters and we will so extend it fully in Year 3. As an early result in this direction, we have also derived an expression for the probability of failure of a circuit containing a very large ("infinite") number of inverters in a special case of our formalism; we will as well in Year 3 explore the extension of this result to other cases. We will also begin to investigate stochastic behavior to other logic gates as a consequence of stochastic V_{dd}.

University of Maryland

Principal Investigator – Thomas Antonsen, Jr.

The UMD COE team includes: Steven Anlage, Thomas Antonsen, Jr., Neil Goldsman, Ed Ott, and Edo Waks. In addition, several graduate students participate in the research: Tystan Koch, Ke Ma, S. Aghaeimeibodi, Z. Luo, Bisrat Addisie, Farasatul Adnan, Min Zhu, Zhiyuan Fu.

Researchers and students at UMD are engaged in a number of basic studies relevant to the operation of electronic equipment in extreme electromagnetic environments as part of the collaborative COE sponsored by AFOSR and AFRL. Broad areas include: basic mathematical characterization of field distributions in systems, measurement of EM coupling in different topologies, and effect of extreme electromagnetic environments on future semiconductor and optoelectronics devices. Within these broad areas the following specific studies are highlighted:

a) Distribution of electromagnetic wave energy on networks
An experimental setup consisting of a microwave network is used to simulate quantum graphs. The random coupling model (RCM) is applied to describe the universal statistical properties of the system with and without time-reversal invariance. The networks which are large compared to the wavelength, are constructed from coaxial cables connected by T junctions, and by making nodes with circulators time-reversal invariance for microwave propagation in the networks can be broken. The results of experimental study of microwave networks with and without time-reversal invariance are presented both in frequency domain and time domain. With the measured S-parameter data of two-port networks, the impedance statistics and the nearest-neighbor spacing statistics are examined. Moreover, the experiments of time reversal mirrors for networks demonstrate that the reconstruction quality can be used to quantify the degree of the time-reversal invariance for wave propagation.

b) Statistics of fields in systems with both regular and chaotic ray trajectories
Mixed systems are systems for which ray trajectories in the enclosure may be chaotic or regular depending on the initial conditions for the ray. The RCM assumes all ray trajectories are chaotic. Past work of ours on a particularly shaped two-dimensional cavity showed that the statistics of impedance matrices were modified when both chaotic and integrable trajectories were present. However, that shape was not typical in that the regions in phase space of integrable and regular trajectories were distinct. The more generic situation is that the regions are intertwined. We are now considering a model that has this property. The Method of Moments has been implemented

to solve the Helmholtz equation in a 2D cavity. This is an essential step in order to obtain the numerical eigenfrequencies and eigenmodes of the mixed system 2D cavities we are interested in. We need the eigenfrequencies and eigenmodes to check if the Random Coupling Model gives the correct prediction of the cavity impedance probability distribution or not.

As a starting point, we choose to solve the potential field in a unit circle, with the boundary condition being zero potential value on the boundary. Given this setup, we should be expecting to get the eigenfrequencies and eigenmodes the same as the well-known solution for TM modes in a circular waveguide. We have since generalized to the case of a cavity whose perimeter is defined by two pairs of circular arcs with different radii. The lengths of the arcs and their radii of curvature is selected such that the tangent vector to the perimeter is a continuous function as one travels around the perimeter. The next step is to add ports and measure impedance statistics.

c) Using computational electromagnetics codes to determine Random Coupling Model parameters

Calculating the coupling of electromagnetic energy through an aperture into a large enclosure is complicated due to interference between waves entering the aperture and waves reverberating in the enclosure. A first principles calculation of this phenomena requires resolving all details of the aperture and the enclosure. Use of the Random Coupling Model will obviate resolving the details of the enclosure. However, there is as yet a prescription for combing a CEM calculation of an unbacked aperture with the RCM. We are working with Zhen Peng of UNM to develop such a prescription. A mathematical formulation of the technique has been developed and plans are underway to implement this approach in one of the UNM CEM codes. As a first step in the process of merging the RCM with a computational electromagnetics code (CEM) we have considered the model 2D problem of an aperture backed by a section of waveguide. This problem can be solved numerically using HFSS. The section of waveguide may be extended to infinity, the radiation case, terminated with a boundary condition representing an enclosure with regular trajectories, or terminated with a boundary condition as stipulated by the RCM. This will allow comparison of these three possibilities in a computational setting.

d) Experimental Tests of the RCM to determine its regime of validity,

The random coupling model (RCM) has been successfully demonstrated as a method to characterize the electromagnetic coupling between ports in large complex enclosures. The model characterizes the system in terms a statistical impedance matrix. In its formulation, it has the advantage of requiring only the loss parameter of the enclosure and the radiation impedance at each of the ports for a full statistical description of the coupling between the ports. However, a challenge remains in finding a practical method to measure the radiation impedance, especially at a port with significant localized power loss. We have developed practical techniques to measure the radiation impedance of the port and the loss parameter. In the case of a lossy port in the complex enclosure, a generalized antenna model is adopted, and the radiation efficiency of the antenna is used to modify RCM's impedance matrix description. The method has been verified with calculations and validated by measurements. We are currently determining the lower frequency limit of the RCM. Measurements have been made down to the frequency range of the lowest 50 modes of the cavity. At this frequency finite sample size becomes the dominant limitation.

e) Experiments on field distributions in scaled geometries, (ONR funded)
We are now extending the RCM to include consideration multiple connected enclosures, each of which is ray chaotic. However, to test the RCM under increasingly realistic scenarios requires experimental facilities currently beyond our means at UMD. To address this problem the UMD group has received an ONR-DURIP grant to develop a scaled-down electromagnetic test setup operated a reduced temperature to maintain the correct scaling for resistive losses. Tests have been performed on this setup at a frequency such that the volume is 450 wavelengths on each dimension. Issues being addressed include modifications of the RCM to account for quasi-optical coupling losses in this small wavelength regime.

f) Application of density functional theory to determine the effect of radiation and defects on characteristics of a new class of FETs,
Unwanted electromagnetic signals can couple to micro-devices and nano-devices via printed circuit board traces. MOS Gate Oxides are especially vulnerable to induced terminal voltages in the presence of these signals. Modern oxide layers are very thin and can have defects (Oxygen Vacancies), which enhance the vulnerability of circuits to. Calculation of the behavior of these vacancies requires a quantum mechanical treatment. There are two basic mechanisms for device damage and various subsets of these damaging processes: Gate oxide damage and Device damage due to joule heating induced by excessive voltage and currents in the MOSFET conducting channel between the source and the drain. We have used Density Functional Theory (DFT), plus related modeling tools, to calculate these mechanisms and assess their relative importance.

g) Effects in high-performance photonic interconnects based on novel materials.
We have developed silicon compatible SiN photonic waveguides coupled to 2D materials. We have fabricated the passive devices, demonstrated waveguiding, and shown that these waveguides are highly insensitive to HPM excitation. We have coupled monolayer WSe2 to SiN waveguides and demonstrated injection of light emission into the waveguide with high efficiency. We have also developed 2D heterostructures with electrical contacts in order to electrically inject carriers to generate light emission. Recently, Halide perovskite semiconductors have emerged as prominent photovoltaic materials since their high conversion efficiency and promising light emitting materials in optoelectronics. In particular, easy-to-fabricated colloidal perovskite nanocrystals based on CsPbX3 quantum dots have been intensively investigated. Their luminescent wavelength can be tuned precisely by their chemical composition and size. This opens new applications, including light-emitting diodes and optical amplifiers, due to their promising performance as emitters. We have demonstrated the Purcell enhancement effect of CsPbBr3 perovskite nanocrystals by coupling them to an optimized photonic crystal nanobeam cavity. This is a first crucial step towards realization of integrated on-chip coherent light sources with low energy consumption for robust optical interconnects.