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High-Density Signal Interface Electromagnetic Radiation Prediction for Electromagnetic Compatibility Evaluation

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High-Density Signal Interface Electromagnetic Radiation Prediction for Electromagnetic Compatibility Evaluation

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Abstract

Radiated power calculation approaches for practical scenarios of incomplete high-density interface characterization information and incomplete incident power information are presented. The suggested approaches build upon a method that characterizes power losses through the definition of power loss constant matrices. Potential radiated power estimates include using total power loss information, partial radiated power loss information, worst case analysis, and statistical bounding analysis. A method is also proposed to calculate radiated power when incident power information is not fully known for non-periodic signals at the interface. Incident data signals are modeled from a two-state Markov chain where bit state probabilities are derived. The total spectrum for windowed signals is postulated as the superposition of spectra from individual pulses in a data sequence. Statistical bounding methods are proposed as a basis for the radiated power calculation due to the statistical calculation complexity to find a radiated power probability density function.

ACKNOWLEDGMENTS

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FIGURES

NOMENCLATURE

cdf	cumulative distribution function
dB	decibel
DOE	Department of Energy
DUT	device under test
EMC	electromagnetic compatibility
FY	fiscal year
LDRD	laboratory directed research and development
pdf	probability density function
pmf	probability mass function
SNL	Sandia National Laboratories

1. INTRODUCTION

This report is a final summary for work performed for a laboratory directed research and development (LDRD) project performed in fiscal year (FY) 2016 and FY2017. The LDRD project described in this report is entitled: High-Density Signal Interface Electromagnetic Radiation Prediction for Electromagnetic Compatibility Evaluation. This report provides an overview of the project and information discovered over the execution of the technical work.

The premise of this project is to advance the state of the art in radiated power prediction for high-density interfaces. A method was recently developed by the author to characterize interface radiated power through designed single-port and two-port excitations during radiated power measurements. Radiated power characterization measurements are used in this approach to calculate quantities in a matrix that quantify radiated power properties of a high-density interface. A complete radiated power characterization fills the entire characterization matrix, enabling exact radiated power calculations for single-port or multi-port excitations of interest. Challenges exist in obtaining complete radiated power characterization information for large-scale, high-density interfaces due to the number of measurements required. In practice, only partial characterization information is likely to be available and approaches to calculate radiated power with incomplete characterization information has not been well studied. Radiated power calculations with incomplete incident power information has also not been well studied, and this incomplete information is a common occurrence in digital signaling applications (non-periodic signal conditions).

The goal of this project is to derive radiated power calculation approaches given the practical scenarios of incomplete characterization information and incomplete incident power information. The scope of this research is limited to methods for characterizing radiated power, and the investigation of high-density interface layout feature contributions to the radiated power is left for a future study. It is assumed some portion of the high-density interface scattering parameter matrix or the radiated power characterization matrix is known in the presented information scenarios. Research progress presented in this report consists of some initial investigated ideas and potential next steps that need further research and validation. This project was reduced in scope to facilitate a greater focus on electromagnetic qualification projects to meet Sandia priorities. Background information on this LDRD project is presented in Section 2. Research progress and results are presented in Section 3. Conclusions are given in Section 4.

2. PROJECT BACKGROUND

2.1. Project Purpose

Quantifying the electromagnetic radiation properties of high-density interfaces is a significant challenge in the electromagnetic compatibility (EMC) design community. EMC engineers struggle to assist designers in the development of these interfaces since robust, quantitative methods for comparing the radiated emissions of multiple designs are not widely available. The scalability of high-density interfaces has compounded issues in developing characterization approaches since most analytical solutions are unique to specific geometries. An analytical approach was recently proposed by the principal investigator of this project that can quantify the radiated power of high-density interfaces with few geometrical assumptions. Although the proposed approach is shown to work well for small-scale interfaces with fewer than ten signal lines at an interface, challenges remain in the developed approach in regards to its applicability to large interfaces with 10's or 100's of signal lines. A large amount of data is required to estimate the radiated power from large interfaces with the present theory, which, may be impractical to acquire. The first objective of this project is to formulate radiated power estimates from reduced data sets. Bounding approaches with the limited available data and applicable geometry symmetry at an interface may be used as the basis for the solution. The second objective of this project is to develop an approach to quantify radiated power with practical, non-periodic signal conditions which the present theory does not address. The solution for this objective will likely use statistical bounding methods to produce statistical radiated power estimates.

2.2. Proposed Technical Approach

The need to predict radiated emissions from high-density connectors has become important in recent years to reduce risk in failing electromagnetic radiation requirements. Despite the growing importance, industry is lacking a practical method to quantify radiation from high-density connectors (connectors containing 10's or even 100's of signal lines) where input signal can be easily modified. Many methods at present have limited flexibility for evaluating electromagnetic radiation changes with different signaling and termination conditions. Changes to signal pin assignments, signal pin terminations, or input signal characteristics often require many additional simulations or measurements with significant completion times for present approaches.

A method to quantify the radiated power from high-density connectors was presented in [1]-[3] in an effort to meet industry needs. In [1], a matrix approach was presented to characterize power losses at a printed circuit board/connector interface, where matrices quantifying the power losses were defined as "power loss constant matrices". This approach is based on network parameters and the conservation of power and can be used to characterize any of the power losses (radiation, material, or total power loss). Unique excitations in simulations or measurements are used to find entries in the power loss constant matrix for each power loss mechanism. Radiated power can be calculated for customizable signaling conditions that do not require additional measurements or simulations once the power loss constant matrix is fully known for radiated power. Expanding upon [1], a method to statistically estimate maximum radiated power bounds was presented in

[2]. The statistical estimates were based on practical considerations where the phase of the input signals may not be known and an incomplete radiated power loss constant matrix is available. Statistical bounding methods employing the Markov and Chebyshev inequalities were used to estimate the maximum radiated power assuming the power spectra of the input signals to the connector were known and the phase of the input signals were independent, uniformly distributed random variables.

Although the research in [1]-[3] illustrate a fundamental approach to quantifying high-density connector radiation, there are many practical shortfalls that remain to be addressed to improve the applicability of the theory to more real-world problems. This LDRD project is formulated to address some practical shortfalls of the radiated power estimation research. The first objective of this project is to formulate radiated power estimates with less data on the signal propagation and power loss properties of a high-density interface. A large amount of data is required to estimate the radiated power form large interfaces with the present theory, which, may be impractical to acquire. Formulating a radiated power estimate from less data will reduce experiment times at the cost of additional margin in the provided estimates. A study is also needed to quantify information impact on radiated power estimates, so data of the largest impact may be acquired when only limited measurements or simulations are feasible. Possible research avenues for data reduction opportunities include:

1. investigating scattering parameter matrix construction methods to build the scattering parameters of a full connector when only a partial matrix is known,
2. developing a worst case analysis approach where the off-diagonal elements in the total power loss constant matrix are modified and assigned as the off-diagonal elements in the radiated power loss constant matrix,
3. using geometry symmetry to "copy and paste" known radiated power loss constant values for untested ports, and,
4. formulating radiated power bounding measurements for minimum and maximum radiation.

The expected result from the first objective is an analysis approach to formulate radiated power estimates with varying amounts of data. Data availability scenarios will be based on anticipated practical conditions.

The second project objective is to develop radiated power estimates for high-density interfaces when practical, non-periodic signals are present at the interface. The present theory relies on periodic signals for the radiated power estimates, and a challenge area for the theory is to modify it to account for non-periodic signals. This research avenue is of interest because system designers often desire to know the radiated power of an interface when interrogated by real-world "random" bit sequences used in a product design rather than pseudo-random bit sequences. The analysis for the second objective will be uncoupled from the first objective as all desired information about the high-density interface will be assumed to be known. The analysis approach will consist of treating the non-periodic signals as periodic signals with a moving time window. Data rates, logic voltage levels, and the probability of bit flip will be assumed to be known. The resulting analysis should show the magnitude spectrum and the phase spectrum of the input signals as random variables. A solution for a statistical radiated power limit will be attempted from statistical bounding methods due to the multi-dimensional nature of the probability density function integral and cumulative distribution function integral. Significant technical challenges may exist in the statistical bound quantity evaluation since the integral for the mean and standard deviation of the radiated power loss may not be feasible to evaluate analytically.

2.3. Relationship to Prior and Other On-Going Work

Radiation from connectors is extensively studied in the literature, though a majority of the literature focuses on cases where the connectors are electrically small [4]-[7]. Only recently have connectors been studied when they are electrically large and shown to be the dominant radiators [1]-[3], [8]-[11]. Many of the radiation studies performed are based on the current and voltage driven models in [5]. Additional efforts to quantify radiation from connectors have included finite-difference time-domain simulations [12]-[15], common mode current measurements [12]-[13], [15], electromagnetic field measurements [15]-[16], transfer impedance measurements [17]-[18], and connector inductance measurements and calculations [19]-[20]. Although these previous studies provide some clarity on the radiation properties of connectors, these studies lack the ability to predict radiation from high-density connectors where signaling conditions may be varied. Recent research performed by the principle investigator in [1]-[3] addresses some practical questions associated with high-density connector radiation. The proposed research in this LDRD project seeks to address some of the practical shortfalls of the radiated power prediction presented in [1]-[3] as previously discussed.

2.4. Technical Background

2.4.1 Metrics for Radiated Emissions

Electric and magnetic fields are often the primary metrics used to quantify radiated emissions from a device under test (DUT). Radiated emissions measurements typically involve field measurements taken at fixed distances from a DUT in open air or anechoic environments. Multiple measurements with varying DUT orientations are used to attempt capturing worst case radiated emissions, where the objective is to orient the main lobe of the radiation pattern towards the field measuring antenna. A challenge with this measurement approach is the radiation pattern for most practical DUTs are unknown, and it is unlikely the main lobe of a radiation pattern will be pointed towards a measuring antenna over the entire measurement frequency range.

Radiated power is an alternative metric that can be used to quantify radiated emissions that avoids problems with an unknown DUT radiation pattern. Radiated power measurements facilitate robust comparisons between product designs and does not require attempts to capture radiated emissions from worst-case incidence angles for each design. DUT radiated power is related to radiated electric field as shown in the derivation below.

2.4.2 Antenna Radiated Power and Electric Field Relation Derivation

The average power density for a transmitter (or a DUT) with an observation point in the far-field can be written as [21],

$$W_t = e_t \frac{P_t D_t}{4\pi R^2}$$
(1)

where, W_t is the average power density, e_t is the radiation efficiency of the transmitting antenna, P_t is the transmit power or incident power applied to the antenna terminals, D_t is the transmit antenna directivity, and R is the distance from the observation point to the antenna.

Radiated power can be defined as [21],

$$P_{rad} = e_t P_t$$
(2)

and the average power density for a uniform plane wave can be written as [21],

$$W_t = \frac{|E|^2}{2\eta}$$
(3)

where, E is the peak electric field and η is the wave impedance. Using (2) and (3) in (1), (1) can be re-written to solve for the far-field electric field as [21],

$$|E| = \sqrt{\frac{\eta P_{rad} D_t}{2\pi R^2}}$$
(4)

As seen in (4), the calculation of the far-field electric field is a function of the DUT radiated power, directivity, and distance to the observation point. The electric field and DUT directivity have an implied theta and phi dependence in spherical coordinates. In most cases the directivity of practical DUTs is unknown over space and frequency. In cases where maximum quantities are of interest, bounding estimates for the DUT may be used to calculate worst case far-field electric field values. Estimating maximum bounds for DUT directivity is an area in need of further research.

2.4.3 Simplified Radiated Power Representation for a Multi-Port Network

Radiated power can be used to compare radiated emissions design performance for high-density interfaces. While the radiated power calculation does not consider directivity properties of these interfaces, it may be reasonable to assume that many of these interfaces have worst case directivities on the same order of magnitude. With this assumption, direct comparisons of the radiated power for various designs may be used to quantify designs with the best radiated emissions performance, where smaller radiated powers correspond to better performance.

Challenges in the radiated power calculations for high-density interfaces are revealed from further analysis of (2). Radiated power is a function of the transmitter radiation efficiency and incident transmit power. In circumstances where the incident power is known, the significant challenge in defining radiated power is defining the radiation efficiency for a strongly coupled, multi-port antenna structure. If each port is considered as a single antenna, where M is the number of ports defined in the high-density interface, the overall radiated power cannot be written as a summation of the individual radiated powers due to the coupled nature of the unintentional antennas. Alternatively stated,

$$P_{rad,total} \neq \sum_{i=1}^{M} e_{t,i} P_{t,i} \tag{5}$$

in general. A general form for the radiated power can be written as,

$$P_{rad,total} = \sum_{i=1}^{M} e_{t,i} P_{t,i} + Mutual\ Coupling\ Terms \tag{6}$$

where, the mutual coupling terms can be written as a complex function of two-port incident power combinations and coupling factors. The presence of mutual coupling terms is validated by considering separable antennas first characterized independently and then considering antennas operated in the presence of one another. When the antennas are operated in the presence of one another, a fraction of the radiated power will be captured by other present antennas and dissipated in attached loads which makes (5) and (6) apply. Similar corollaries can be made for the coupled antenna structures of a high-density interface, but with inseparable antenna structures. It should be noted in this case the mutual coupling terms of (6) can be either additive or subtractive. Equation (6) also illustrates an additional challenge in the radiated power calculation when the transmit power is not clearly known as can be the case for digital signaling applications.

2.4.4 Scalable Radiated Power Calculation for a Multi-Port Network

Clarity on the form of (6) is derived in [1]. A method to characterize power losses at a high-density interface was presented in [1] using power loss constant matrices. This method is based on network parameters and the conservation of power and can be used to characterize any of the power losses (radiation, material, or total power loss). A brief overview is presented here.

The total power loss at a high-density interface can be written as a summation of radiated power loss and material power loss as

$$P_{loss,total} = P_{rad,total} + P_{mat,total} \tag{7}$$

where, $P_{loss,total}$ is the total power loss, $P_{rad,total}$ is the total radiated power, and $P_{mat,total}$ is the total material loss. $P_{mat,total}$, in general, represents losses in both conductors and dielectrics. Any of the power losses in (7) can be written in a general form as [1]

$$P_{loss,gen} = (1/2)[a]^H[a] - (1/2)[a]^H[\tilde{P}_{const}][a]$$
(8)

where $[a]$ represents the inputs to the high-density interface as an incident power wave vector with units of $\sqrt{Watt}$ and is based on generalized scattering parameters [22], H denotes the complex conjugate transpose, and $[\tilde{P}_{const}]$ is a frequency dependent power loss constant matrix for an M-port network defined by

$$[\tilde{P}_{const}] = \begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,M} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ P_{M,1} & P_{M,2} & \cdots & P_{M,M} \end{bmatrix} = \begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,M} \\ P_{1,2}^{*} & P_{2,2} & \cdots & P_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ P_{1,M}^{*} & P_{2,M}^{*} & \cdots & P_{M,M} \end{bmatrix}.$$
(9)

From (8)-(9), $P_{loss,total}$, $P_{rad,total}$, and $P_{mat,total}$ can be written as [1]

$$P_{loss,total} = (1/2)[a]^H[a] - (1/2)[a]^H[\tilde{P}_{loss,const}][a]$$
(10)

$$P_{rad,total} = (1/2)[a]^H[a] - (1/2)[a]^H[\tilde{P}_{rad,const}][a]$$
(11)

$$P_{mat,total} = (1/2)[a]^H[a] - (1/2)[a]^H[\tilde{P}_{mat,const}][a].$$
(12)

The general forms for the total power loss constant matrix, $[\tilde{P}_{loss,const}]$, the radiated power loss constant matrix, $[\tilde{P}_{rad,const}]$, and the material loss constant matrix, $[\tilde{P}_{mat,const}]$, are given in (13)-(15).

$$[\tilde{P}_{loss,const}] = \begin{bmatrix} P_{l1,1} & P_{l1,2} & \cdots & P_{l1,M} \\ P_{l1,2}^{*} & P_{l2,2} & \cdots & P_{l2,M} \\ \vdots & \vdots & \ddots & \vdots \\ P_{l1,M}^{*} & P_{l2,M}^{*} & \cdots & P_{lM,M} \end{bmatrix}$$
(13)

$$[\tilde{P}_{rad,const}] = \begin{bmatrix} P_{r1,1} & P_{r1,2} & \cdots & P_{r1,M} \\ P_{r1,2}^{*} & P_{r2,2} & \cdots & P_{r2,M} \\ \vdots & \vdots & \ddots & \vdots \\ P_{r1,M}^{*} & P_{r2,M}^{*} & \cdots & P_{rM,M} \end{bmatrix}$$
(14)

$$[\tilde{P}_{mat,const}] = \begin{bmatrix} P_{m1,1} & P_{m1,2} & \cdots & P_{m1,M} \\ P_{m1,2}^{*} & P_{m2,2} & \cdots & P_{m2,M} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1,M}^{*} & P_{m2,M}^{*} & \cdots & P_{mM,M} \end{bmatrix}$$
(15)

The total power loss constant matrix can be found from single-ended network parameters, $[\tilde{S}]$, using

$$[\tilde{P}_{loss,const}] = [\tilde{S}]^H[\tilde{S}] \tag{16}$$

whereas, $[\tilde{P}_{rad,const}]$, and $[\tilde{P}_{mat,const}]$, must be found from single- and two-port excitations. The diagonal elements in $[\tilde{P}_{rad,const}]$ and $[\tilde{P}_{mat,const}]$ are found from the single-port excitations and the off-diagonal elements are found from the two-port common-mode and phase-shifted excitations. $[\tilde{P}_{rad,const}]$ and $[\tilde{P}_{mat,const}]$ can be found through simulations or measurements as shown in [1]. Using (7) and (10)-(15), it is shown in [1] the power loss constant matrices are related by

$$[\tilde{P}_{loss,const}] = [\tilde{P}_{rad,const}] + [\tilde{P}_{mat,const}] - [\tilde{I}] \tag{17}$$

where $[\tilde{I}]$ is the identity matrix.

The radiated power formulations of (6) and (11) share the same challenges for the radiated power calculation, though written in different forms. Correlating the two formulations, the transmitter radiation efficiency is directly related to the definition of $[\tilde{P}_{rad,const}]$ and the transmitter power is given by $(1/2)[\bar{a}]^H[\bar{a}]$. Equation (11) provides a deterministic method to quantify the radiated power from a high-density interface when all characterization information is known. A challenge arises for large-scale interfaces in formulating a complete $[\tilde{P}_{rad,const}]$ matrix, as the number of measurements or simulations required to fill this matrix may not be feasible. For example, the total number of excitations required to fill the entire power loss constant matrix, assuming only two excitations are needed to solve for each unique complex power loss constant, is M^2, where M is the number of ports defined at the high-density interface. This full characterization challenge forms the basis for the research in objective 1 and objective 2 of this LDRD project.

3. RESEARCH PROGRESS AND RESULTS

3.1 Progress with Objective 1

The first project objective was to develop an analysis approach to estimate radiated power from a high-density interface when limited information on the signal propagation and power loss properties are available. This objective was based on the following interrelated questions associated with radiated power calculations from a high-density interface:

1. How can radiated power be calculated or estimated if limited information is known about a high-density interface?
2. How do various radiated power estimates compare in terms of margin and what are the dominant variables in these calculations?
3. If limited experiments or simulations are available to characterize high-density interface properties, what information should be acquired to provide the highest fidelity radiated power estimates possible?

Most of the progress towards objective 1 was made in answering the first technical question above.

Insight into radiated power calculations can be achieved with an in-depth analysis of (11) and the matrix entries in $[\tilde{P}_{rad,const}]$. When $[\tilde{P}_{rad,const}]$ and $[\tilde{a}]$ are fully known, radiated power is readily calculated from (11). Diagonal elements in $[\tilde{P}_{rad,const}]$ quantify the radiated power loss when each port in a multi-port network are fed individually. Off-diagonal elements in $[\tilde{P}_{rad,const}]$ quantify the radiated power loss when ports are fed simultaneously and are a strong function of mutual coupling effects in the multi-port network. In many cases the diagonal elements in $[\tilde{P}_{rad,const}]$ likely dominate the overall radiated power calculation, since self-terms regularly dominate over mutual coupling effects. The diagonal elements can range from 0 to 1 and do not depend on signal phase. Although the magnitude of the off-diagonal elements can potentially be on the same order as the diagonal elements, in practice the off-diagonal element magnitudes are often much smaller. Some of the off-diagonal terms can be close to 0 and negligible for port combinations with small coupling. Identification of these port combinations require additional information that cannot be easily identified beforehand to the understanding of the studied high-density interface operating physics. Contributions of the off-diagonal terms to radiated power calculations are both port excitation dependent (magnitude and phase) as well as term value dependent. The off-diagonal terms in $[\tilde{P}_{rad,const}]$ can be thought of as a modulating factor to the baseline calculation formulated by the diagonal elements. As seen in (19) in [1], diagonal elements in $[\tilde{P}_{rad,const}]$ inform the calculation of off-diagonal elements. When the off-diagonal elements are not calculated from two-port excitations, the diagonal elements can serve to formulate bounds on the off-diagonal elements.

Radiated power characterization of a high-density interface can be performed by direct or indirect characterization methods. The direct characterization method involves radiated power measurements for prescribed port excitations that enable $[\tilde{P}_{rad,const}]$ element calculations as indicated in [1]. Direct characterization is often simpler than indirect characterization since the desired physics for study are interrogated directly. An indirect characterization method of radiated power involves total power loss characterization and material power loss characterization, where radiated power characteristics are inferred with the conservation of power as defined in (7) and (17). A challenge with indirect radiated power characterization is due to a potential lack of correlation between material power losses and radiated power losses. This potential lack of correlation allows the signs of off-diagonal power loss constants for material losses and radiated power losses to be different, thereby increasing the bounds on unknown, off-diagonal parameter values. The values of the power loss constant parameters for both material losses and radiated power losses are still constrained by the conservation of power.

The basis for the first technical question in objective one is motivated by the need to calculate radiated power estimates when only partial characterization information is available for a high-density interface. This is a practical issue since for many scalable interfaces which at best only partial characterization of $[\tilde{P}_{rad,const}]$ and partial total loss information may be available. Plausible information scenarios and accompanying radiated power calculation strategies are presented below. It is assumed some portion of the high-density interface scattering parameter matrix or $[\tilde{P}_{rad,const}]$ is known in most of the information scenarios. The indicated scenarios are not designed to be all encompassing, but rather a set of information scenarios that may be reasonably encountered with a measurement based power loss characterization approach.

Scenario 1 – Complete S-parameters known, incident powers known

The total power loss can be calculated from S-parameter information via (10) and (16) in this scenario. Although the total power loss consists of radiated power loss and material power loss as given in (7), the percentage of the total power loss responsible for radiation is not known without further information. The fraction of the power loss due to radiation can widely vary based on design, the number of ports implemented in a design in place of resistive loads, input signaling, and other parameters. An approach for radiated power calculation is to assign a conservative percentage of the total power loss as due to radiation. The challenge with this approach is in the development of the conservative percentage without additional information. All the calculated total power loss can be equated to the radiated power loss, but in many cases this assumption can lead to a significant overestimate of the actual radiated power from an interface.

Scenario 2 – Complete S-parameters known, limited radiated power information known for a few single-port excitations, incident powers known

Information from Scenario 1 is included in Scenario 2, but with the addition of some limited radiated power information for a few single-port excitations. The same total power loss percentage approach as suggested in Scenario 1 can be used to calculate radiated power in Scenario 2. Radiated power information for the few single port excitations can be used to inform the selection of the conservative total power loss percentage for radiated power estimates. The percentage of the total power loss due to radiation can be calculated for the few known single-port excitations, and the total power loss percentage applied for other port excitation situations.

Scenario 3 – Diagonal entries known in $[\tilde{P}_{rad,const}]$, incident powers known

Scenario 3 represents a minimum radiated power characterization of all ports in a high-density interface. The diagonal entries in $[\tilde{P}_{rad,const}]$ are found from single-port excitations using (11), where practically these entries must be found prior to any off-diagonal elements due to parameter dependencies. Exact radiated power calculations for multi-port excitations are not possible without knowledge of the off-diagonal entries in $[\tilde{P}_{rad,const}]$. It can be shown that the diagonal entries in $[\tilde{P}_{rad,const}]$ can be used to inform the bounds of the off-diagonal elements. Potential approaches for radiated power calculations under this information scenario includes worst case analyses or maximum statistical estimates. Further research is needed to illustrate the form of the radiated power calculation solutions for this information scenario.

Scenario 4 – Varying degrees of information about the high-density interface regarding signal propagation and power losses as indicated by Scenario 1-Scenario 3, incident powers unknown

Previous information scenarios focused on cases where partial characterization information is known, and the incident powers are fully known. An equally important parameter for the radiated power calculation which may not be fully known are the inputs to the radiated power calculation: incident powers. In some cases such as digital signaling applications, the incident powers may not be precisely known. Limited interface characterization information coupled with limited incident power information create a unique challenge in calculating radiated power estimates. Equation (11) alone does not provide clear insight for radiated power calculations under this information scenario. In many cases, even when incident powers are not precisely known, bounds for the incident powers or statistical properties are either known or can be estimated. Potential solutions for the radiated power estimates include the analysis methods presented in Scenario 1 – Scenario 3 with modifications. Statistical approaches for radiated power estimates may include the well-known Markov or Chebyshev inequalities. Additional research is needed for this information scenario due to its significant complexity and is the premise for some of the research in objective 2.

3.2 Progress with Objective 2

The second objective was to develop a radiated power estimate for high-density interfaces when incident power information is not fully known for non-periodic signals at the interface. Random digital signaling at a high-density interface presents a challenge for deterministic radiated power calculations determined by (11) since the exact data signals may not be known. An approach to handle the uncertainty in the deterministic signals is to formulate a statistical problem where statistical properties of the inputs signals are typically known or measurable.

The technical problem under study in this project is limited to the following constraints and assumptions to facilitate a first order solution:

- The data structure for input signals is known such as logic levels, dc offset, coding scheme, bit rise time, bit fall time, and data rate.
- The bit sequence formulations can be constructed from a two-state Markov chain.

- Bit transition probabilities are either known or can be acquired via measurement for each data channel.
- The data signal spectrum is computed over a time-window (a short-term fast Fourier transform approach) containing multiple bits where the windowing function is known.
- Time windows used for spectrum calculations are far from the beginning of a bit sequence.
- Some or all the S-parameters and power loss information for the high-density interface is known.

3.2.1 Bit State Probability Derivation from a Two-state Markov Chain

Calculating the signal spectrum over a time window still requires knowledge if each bit in the windowed sequence is positive or negative. The bit state in a windowed sequence can be determined statistically when modeling the bit sequence formulation as a discrete-time, two-state Markov chain. The last bit state in a Markov chain is assumed to only be dependent on the immediately preceding state rather than all previous states in a bit sequence. Thus, the probability of a bit sequence occurring is the product of the transition probabilities (one-step state transitions) times the probability of the first bit state. A two-dimensional transition probability matrix can be formulated if the one-step state transition probabilities are fixed and do not change with time. General bit state probabilities can be derived from initial state probabilities and the transition probability matrix for a two-state Markov chain as follows.

The state transition diagram for a two-state Markov chain is illustrated in Figure 1 [23]. State 0 is logic low and state 1 is logic high. α is the probability the next state is logic high given the present state is logic low. $1-\alpha$ is the probability the next state is logic low given the present state is logic low. β is the probability the next state is logic low given the present state is logic high. $1-\beta$ is the probability the next state is logic high given the present state is logic high.

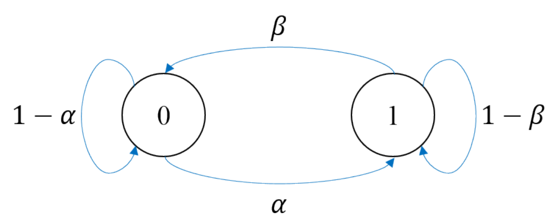

Figure 1. State Transition Diagram for a Two-state Markov Chain

The transition probability matrix derived from Figure 1 is summarized as,

$$P = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix}. \tag{18}$$

The state probabilities at a discrete-time index n is represented as

$$[p(n)] = \{p_j(n)\} \tag{19}$$

which, is a row vector of state probabilities at time n. It can be shown the state probability mass function (pmf) at time n is given by [23]

$$[p(n)] = [p(0)]P^n \tag{20}$$

where, $[p(0)]$ is the row vector of initial state pmfs and P^n is the transition probability matrix raised to the power of n. P^n can be found numerically for finite n or analytically using matrix diagonalization methods. P^n for the transition probability matrix in (18) can be found as [23]

$$P^n = \frac{1}{\alpha+\beta}\left\{\begin{bmatrix}\beta & \alpha\\ \beta & \alpha\end{bmatrix} + (1-\alpha-\beta)^n\begin{bmatrix}\alpha & -\alpha\\ -\beta & \beta\end{bmatrix}\right\}. \tag{21}$$

If the initial state probabilities are assigned as $[p(0)] = [p_0(0) \quad 1-p_0(0)]$, then it can be shown the state pmf for bit n is then

$$[p(n)] = \begin{bmatrix}\frac{\beta}{\alpha+\beta} & \frac{\alpha}{\alpha+\beta}\end{bmatrix} + (1-\alpha-\beta)^n\begin{bmatrix}p_0(0) - \frac{\beta}{\alpha+\beta} & -p_0(0) + \frac{\beta}{\alpha+\beta}\end{bmatrix}. \tag{22}$$

In general, when n is large or $n \to \infty$, (22) reduces to

$$[p(n)] \approx \begin{bmatrix}\frac{\beta}{\alpha+\beta} & \frac{\alpha}{\alpha+\beta}\end{bmatrix}. \tag{23}$$

Bit state probability at time n becomes independent of the initial state probabilities and is a function of the transition probabilities in (23). Another implication of (23) is the probability of each bit state at time n is effectively independent of previous bit states for large n. A simplifying assumption for the analysis of the radiated power from a high-density interface with random digital signals is then for n to be large. This assumption is satisfied with the condition that time windows used for spectrum calculations are far from the start of a bit sequence.

3.2.2 Radiated Power Calculation Strategy for Random Digital Signals

Data traffic within a modeled time window can be represented as a summation time-delayed positive and negative square or trapezoidal pulses as a first order approximation. The complete spectrum for the bit sequence in the time window is calculated from the summation of spectra for each individual pulse, accounting for the time delay of each individual pulse. This first order approximation assumes the rise time and fall time of each pulse are approximately the same so each bit can be represented as a consistent bit waveform structure. Equation (23) can be used to calculate the probability of a positive or negative pulse and this information incorporated into the calculated spectrum for a windowed bit sequence. The statistics associated with having a positive or negative pulse in the time-domain translates, in general, to statistical magnitude and phase spectra for the windowed bit sequence. Radiated power calculations using (11) and statistical incident power spectra results in the radiated power becoming a random variable. The radiated power becomes a complex function of random variables associated with bit assignments in windowed sequences for each port.

Probabilities for achieving a radiated power level can be found by solving for the probability density function (pdf) or cumulative distribution function (cdf), however, this is likely not feasible; calculating the pdf and cdf integrals may not be tractable analytically for the radiated power random variable due to the multi-dimensional nature of the pdf and cdf integrals with the large number of bit assignment random variables. A potential, alternative approach to inform radiated power magnitude probabilities is to calculate probability bounds based on moments of the radiated power random variable. The well-known Markov and Chebyshev inequalities are possible solutions for radiated power bounds. Another method for constructing the radiated power pdf and cdf could be based on Monte Carlo simulations. Further research is needed to validate the proposed solutions.

4. CONCLUSIONS

Radiated power calculation approaches were proposed for practical scenarios of incomplete high-density interface characterization information and incomplete incident power information. These approaches are based on in-depth understanding of radiated power calculations and are not constrained to a specific interface geometry. Approaches for information scenarios with little information include using total power loss to estimate radiated power loss as a fraction of the total power loss. Other suggested solutions for moderate information scenarios include using diagonal entries in the radiated power loss constant matrix, as well as worst case analyses or maximum statistical estimates to account for unknown off-diagonal entries. Many of the potential radiated power calculation solutions require further research for solution validation and to provide additional solution insight.

A high-level approach was also formulated to calculate radiated power for high-density interfaces with non-periodic signals at the interfaces. It is shown non-periodic data signals can be formulated from a two-state Markov chain. Long data sequences are illustrated as having bit state probabilities determined solely by bit state transition probabilities and independent of initial state probabilities. The incident power spectra to be used in radiated power calculations is postulated to be represented as a superposition of the spectra from individual pulses in a data sequence. Suggested solutions for radiated power calculations include formulating statistical bounds due to the complex statistics associated with the proposed statistical analysis approach. Additional research is needed to determine these statistical radiated power bounds.

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