Study on the Use of Different Transmission Line Termination Strategies to Obtain EMI-Diverse Redundant Systems

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***Abstract* — In this paper, the application of different termination schemes (source-termination, load-termination, source-and-load-termination) is studied to achieve EMI-diverse behavior in a redundant system comprising three parallel traces. This redundant system is disturbed by strong incident fields under reverberation room conditions. Reverberation room conditions refer to the situation where multiple plane waves are incident onto the system-under-study, each with a random angle-of-incidence, polarization and phase. Two different geometries are compared: a non-redundant system comprising a single trace on a PCB and a redundant system comprising three parallel traces. The different termination schemes are applied on both geometries. A reciprocity-based technique is used to efficiently calculate the induced voltages and the resulting bit error probability in the different geometries. It is shown that, on its own, use of different termination schemes is not able to provide EMI-diverse behavior.**

Keywords— EMI Risk Management, electromagnetic diversity, redundancy, functional safety

I. Introduction

Sophisticated electronic technologies are increasingly used in mission-critical and safety-related applications where ElectroMagnetic Interference (EMI) can result in significant risks for society and the environment. Modern-day vehicles, medical devices, critical infrastructures, smart machines and smart production environments are prominent examples as they are complex systems in which electrical/electronic systems take an ever more active role, often with the objective of developing into fully autonomous systems in a few years' time. Therefore combined expertise in ElectroMagnetic Compatibility (EMC), Functional Safety and Risk Management will gain huge importance in many industrial sectors in the very near future like automotive, medical, mechatronics, manufacturing, communications, to name a few.

Unfortunately, EMC engineering shares very few concepts and terminology with Functional Safety engineering, as EMC engineering is driven by showing compliance to legislative rules like the EMC directive (2014/30/EU)[1]. As a result, EMC engineering currently follows a rule- and test-based approach. Namely, during design a number of guidelines are prescribed which result in the default application of a set of mitigation techniques (filtering, shielding, cable routing etc.). Testing is then used to validate whether the system meets the requirements of EMC standards or not. However, this rule-based approach has several significant shortcomings. Recent literature [2]-[5] has shown that classical EMI shielding, grounding, filtering and testing on their own can never lead to a feasible and economically affordable approach to guarantee safety due to the many possible variations of EMI that can occur during the lifetime of an electronic system. As is described in the most recent IET Guide on EMC for Functional Safety [6] as well as in the IEEE Standard Draft P1848 [7] on *Techniques and Measures to Manage Functional Safety and Other Risks with Regard to Electromagnetic Disturbances*, a totally new methodology imposes itself where the classical EMI mitigation techniques are complemented with appropriate hardening Techniques and Measures (T&Ms) which are typical for Functional Safety. Unfortunately, none of these T&Ms were originally developed to deal with EMI. So, they need to be improved, adapted and their effectiveness for EMI needs to be demonstrated.

One such hardening technique is the use of redundancy. This means that one implements two or more identical sets of hardware and software receiving the same inputs and performing the same operations. When a malfunction occurs in one of these 'parallel channels', a comparator/voter detects that their outputs no longer agree and triggers appropriate actions to maintain safety. Unfortunately, EMI is a complex phenomenon which has to be seen as a systematic, common cause failure. Indeed, "systematic" because a given system design will always behave in the same way when a given EMI is applied. "Common cause" because EMI influences many different components at the same time. As EMI is a systematic common-cause failure, the malfunctions that EMI creates in identical channels can easily be so similar that the comparator/voter cannot tell that there was a problem at all. An important challenge is how to apply, in a cost-effective way, EMI-diverse parallel channels within a redundant system. With EMI-diverse, we mean here a system where the output response is different for the same incident EMI.

In [8]-[10], the effectiveness of spatial diversity was studied where the electromagnetic disturbance comprises strong incident fields under a single plane wave or reverberation room conditions. Here, reverberation room conditions refers to the situation where multiple plane waves are incident onto the system-under-study, each with a random angle-of-incidence, polarization and phase. In this paper, another possibility to obtain EMI-diverse parallel channels is explained, namely the use of different termination schemes within the parallel channels: source-termination, load-termination and source-and-load-termination [11]. This diversity technique is studied under reverberation room conditions, as this is the most representative for real-world situations.

The remainder of this paper is organized as follows. Section II describes the geometry under study. Section III briefly explains the reciprocity-based technique to efficiently calculate the induced voltages on the parallel channels. Section IV details how to obtain the resulting bit error probability. Section V numerically compares the effectiveness of using different termination schemes to obtain EMI-diverse redundant systems. Section VI draws concluding remarks and gives directions for future work.

II. Geometry under study

Two different geometries will be compared:

1. A single Printed Circuit Board (PCB) with a single microstrip (Fig. 1). This is the reference situation (non-redundant system). The microstrip is driven by a 1V source with a 10 Ohm output impedance (as a typical value for a driver IC's output impedance), while at its other end it is connected to a 10 MOhm load (representing the high input impedance of a receiving IC). Four variants of this non-redundant system will be considered (Fig. 2), namely (i) no termination applied, (ii) source-termination, (iii) load-termination, and (iv) source-and-load-termination.
2. A single PCB with three parallel, identical microstrips (Fig. 3). All microstrips are driven from 1V sources with 10 Ohm output impedance and connect to 10 MOhm loads. Here, five variants are considered, namely (i) no termination applied on any of the microstrips, (ii) source-termination applied on all three microstrips, (iii) load-termination applied on all three microstrips, (iv) source-and-load-termination applied on all three microstrips, and (v) a different termination strategy applied to each microstrip.

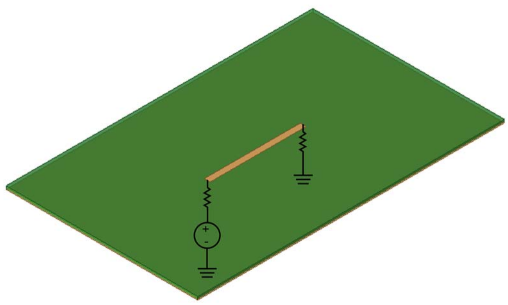

Fig. 1. Single PCB with one microstrip (reference situation)

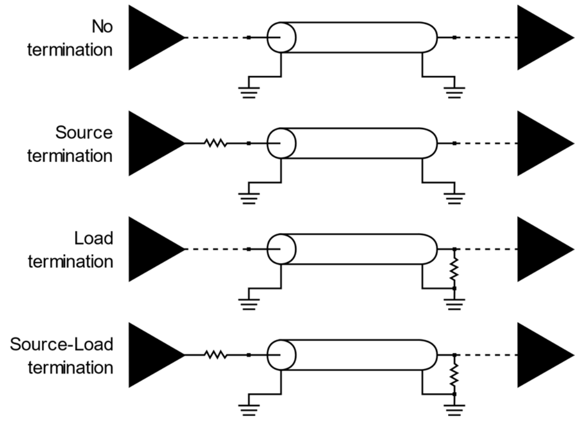

Fig. 2. Different termination strategies

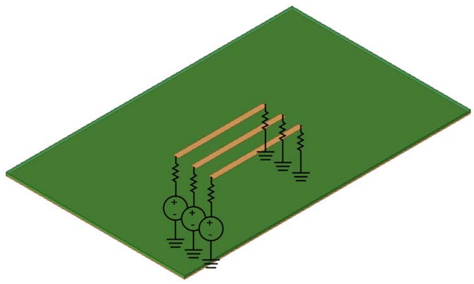

Fig. 3. Single PCB with three parallel microstrips

In all cases, the PCB is a FR4 substrate of 10 cm by 16 cm and 1.6 mm thickness. All microstrips have a width of 3 mm and a length of 5 cm.

III. Efficient calculation of the induced voltages under reverberation room conditions

In order to efficiently calculate the induced voltages at the ends of the microstrips under reverberation room conditions, the antenna-reciprocity based algorithm proposed in [12] for predicting the coupling of plane waves to a system-under-test is used, with the plane-wave representation of a realistic EM environment with many reflections [13][14]. In [13][14], the fields within a reverberation room are represented in a statistical means by using the plane-wave integral representation. This representation states that the fields within a reverberation chamber can be described by superposing a large number of independent plane waves coming from arbitrary directions and with arbitrarily varying polarizations and phases. As a result the induced voltages and currents can be obtained by a Monte Carlo simulation in which one considers M experiments each of which comprising N plane waves.

A brute-force method where a full wave simulation is done for every separate plane-wave, would lead to exponential simulation times. In contrast, the methodology used in this paper is very efficient as it requires only one full-wave simulation per port within the system-under-study, and the result is exactly the same compared to using separate full wave simulations. Briefly described, this methodology comprises three main steps:

1. Run a full-wave simulation of the geometry-under-study as a radiating multi-port antenna system;
2. Calculate the system's impedance matrix and far-field patterns;
3. Use the antenna-reciprocity theorem to calculate the induced voltages or currents for an arbitrary incoming plane wave;

As a result, only a limited number of full-wave simulations (i.e. one per port) is needed. The reader is referred to [12] for full details on this reciprocity-based method.

In the statistical plane-wave representation of a reverberation room like environment, care has to be taken to correctly represent the statistical behavior of the incoming plane waves. No direction of arrival, no polarization or no phase should get any privilege. In this paper, we use the reasoning described in [13] for the statistical distribution of the different parameters (spherical coordinates):

- The azimuth angle φ is uniformly distributed in the range $[0, 2\pi]$.
- The polar angle θ is chosen such that $\cos(\theta)$ is uniformly distributed in the range [-1, 1].
- The polarization angle ψ is uniformly distributed in the range $[0, \pi]$.
- The phase angle α is uniformly distributed in the range $[0, 2\pi]$.

In order to obtain the correct (average) field strength after superposing all random plane waves, the amplitude of each separate plane wave is normalized by $1/\sqrt{N}$ [12].

In what follows, M and N are chosen to be 10.000 and 200, respectively for the Monte Carlo Simulation.

IV. Calculation of the Bit Error Rate

In this paper, the Bit Error Rate (BER) is calculated by disturbing a bit pattern of 100 randomly chosen bits (50/50 probability for a '0' and a '1') - transmitted over the microstrip(s) - with the M different sets of N plane waves mentioned in Section III. The BER is defined as:

$$\text{BER} = \frac{\text{number of bits received incorrectly}}{M \times \text{length bit pattern}} \quad (2)$$

Where the number of bits received incorrectly, is a result of an ideal voter, which does 2 out-of 3 (2oo3) majority voting of the outputs of the three traces.

The system's impedance matrix, calculated in the first step of the reciprocity-based algorithm described in Section III, can be used to calculate the resulting bit patterns. This is done for each given bit pattern (encoded into actual voltage levels) at the input ports of the microstrips and the resulting bit patterns (again expressed in voltage levels) at the output ports.

For the encoding and decoding, the unipolar NRZ-L encoding metric was used. For encoding, the voltage level for a '0' and a '1' at an input port is 0 V and 1 V, respectively. This results in a theoretical output voltage at the load side of (almost) 1 V in the non-terminated, source-terminated and load-terminated situations and 0.5 V in case of source-and-load-termination. For the decoding, the thresholds used to differentiate between a '0' or a '1' are set to $1/3^{th}$ and $2/3^{th}$ of the theoretical output voltage, respectively. If the voltage is below the $1/3^{th}$ threshold, then a '0' is seen. The same goes when the voltage is above the $2/3^{th}$ threshold, at which moment a '1' will be read. For any values in between the thresholds, the bit is seen as faulty, to create a worst-case result.

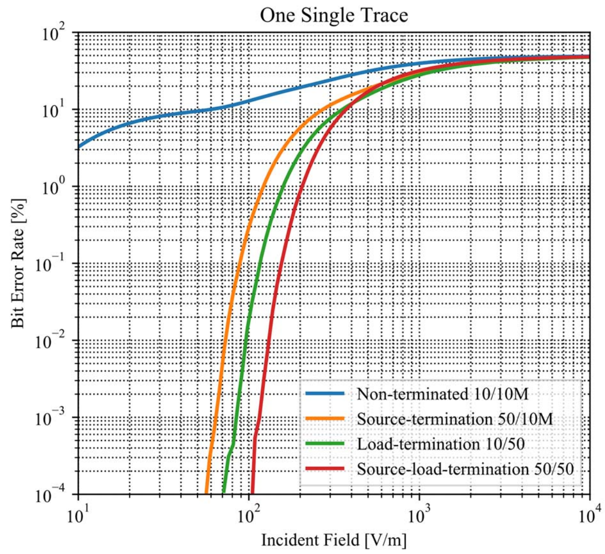

Fig. 4. BER for a 200 MHz random bit pattern propagating over a single microstrip disturbed with an EMI frequency of 500 MHz and this for non-terminated, source-termination, load-termination and source-load-termination.

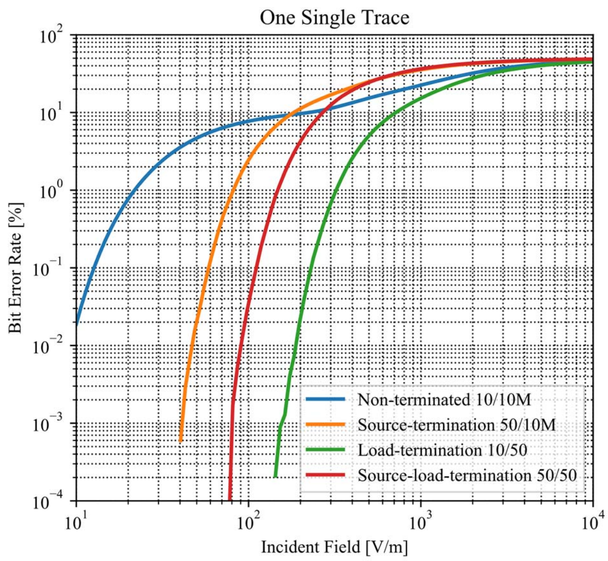

Fig. 5. BER for a 200 MHz random bit pattern propagating over a single microstrip disturbed with an EMI frequency of 1.5 GHz and this for non-terminated, source-termination, load-termination and source-load-termination.

To simplify processing, a decoding technique is used where we don't look at the transient behavior of the received bit patterns, but only at the middle of each received bit. So our analysis does not take in account e.g. any Schmitt-trigger detection technique.

V. Numerical Results

In all examples below, the required full-wave simulation of the geometries-under-study were performed with the FDTD solver of EMPro from Keysight Technologies [15]. The reciprocity-based post-processing and BER calculations are done using an in-house developed simulation framework in which the bit pattern, bit pattern frequency, encoding and decoding technique, EMI frequency, etc. can be freely chosen.

For the results given below, two frequencies for the EMI disturbance are considered, namely 500 MHz and 1.5 GHz. The bit pattern frequency has been fixed to 200 MHz.

A. Single microstrip (i.e. non-redundant system)

Figures 4 and 5 show the BER for the non-redundant single microstrip case for an EMI frequency of 500 MHz and 1.5 GHz, respectively. Both figures show that the BER is quite severe when no correct termination of the microstrip is applied. Indeed, this causes the digital signal and induced EMI voltages to reflect and propagate several times over the microstrip. This causes a very distorted output-signal which is already wrong at relatively low EMI field levels. Even without any EMI disturbance applied, the output can already be wrongly interpreted due to these multiple reflections.

Comparing the three different termination schemes, one notices that all termination schemes give – as expected – a significant improvement compared to the non-terminated case. However, care has to be taken in drawing conclusions from Figs. 4 and 5 regarding the most optimal termination scheme. Based on Figures 4 and 5 on might be tempted to conclude that load-termination is the best termination scheme. However, consider Figures 6 and 7 which show the BER versus EMI frequency for a fixed (average) incident field of 100 V/m and 1000 V/m, respectively. One notices that overall the load-termination is better than the source-termination. A possible explanation could be that load-termination does not cause reflections to occur at the load side and only minor ones at the input side. Therefore the reflected voltage that propagates from the input back to the output, will already be quite small. Overall, the best choice is to match or terminate both ends of the microstrip.

B. Three parallell microstrips (i.e. redundant system)

Figures 8 and 9 show the BER for the system with three physically parallel microstrips and this for an EMI frequency of 500 MHz and 1.5 GHz, respectively. The differently matched or terminated traces are terminated with 50/50, 50/10M, 10/50 Ohm (In/Out). Changing the order of these terminations between the traces has no influence on the BER, so only one situation of differently terminated traces is shown. Figures 10 and 11 show the BER versus EMI frequency for a fixed (average) incident field of 100 V/m and 1000 V/m.

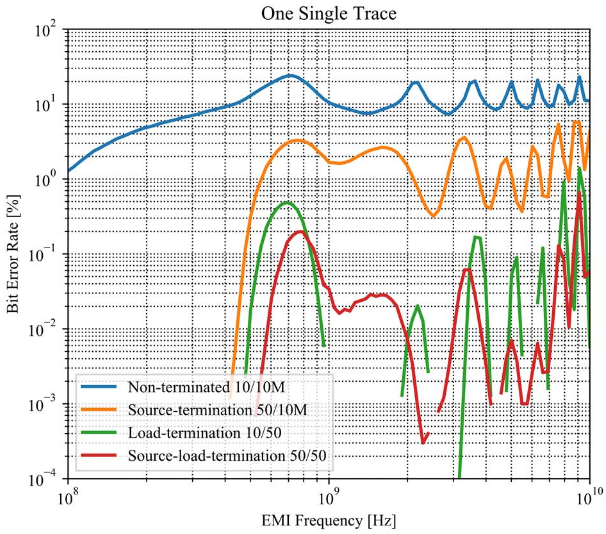

Fig. 6. BER for a 200 MHz random bit pattern propagating over a single microstrip disturbed with an 100V/m EMI disturbance at varying frequencies and this for non-terminated, source-termination, load-termination and source-load-termination.

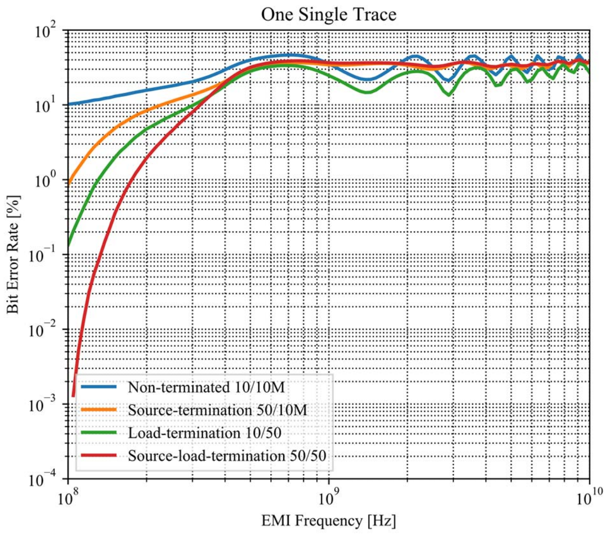

Fig. 7. BER for a 200 MHz random bit pattern propagating over a single microstrip disturbed with an 1000V/m EMI disturbance at varying frequencies and this for non-terminated, source-termination, load-termination and source-load-termination.

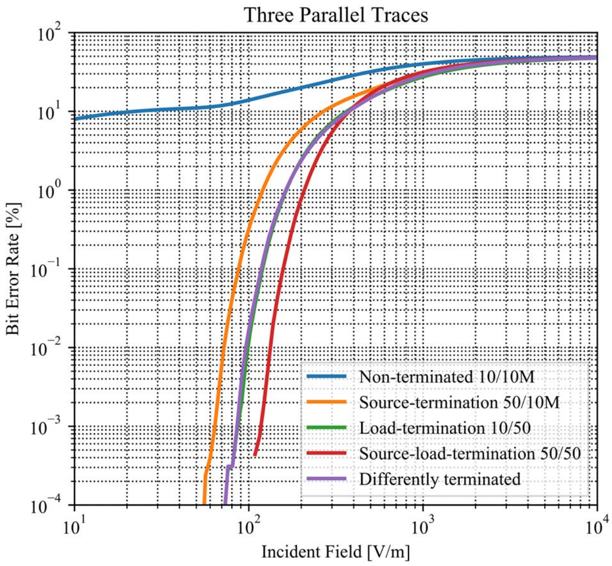

Fig. 8. BER for a 200 MHz random bit pattern propagating over three parallel traces disturbed with an EMI frequency of 500 MHz and this for equally terminated traces with non-terminated, source-termination, load-termination, source-load-termination and the three traces differently terminated.

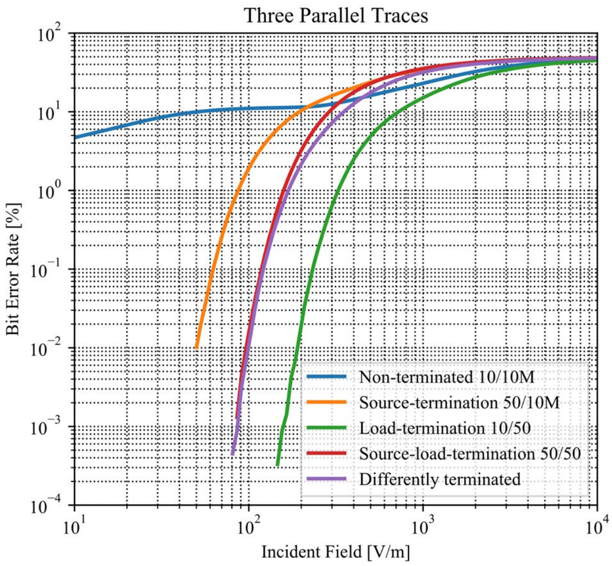

Fig. 9. BER for a 200 MHz random bit pattern propagating over three parallel traces disturbed with an EMI frequency of 1.5 GHz and this for equally terminated traces with non-terminated, source-termination, load-termination and source-load-termination and the three traces differently terminated.

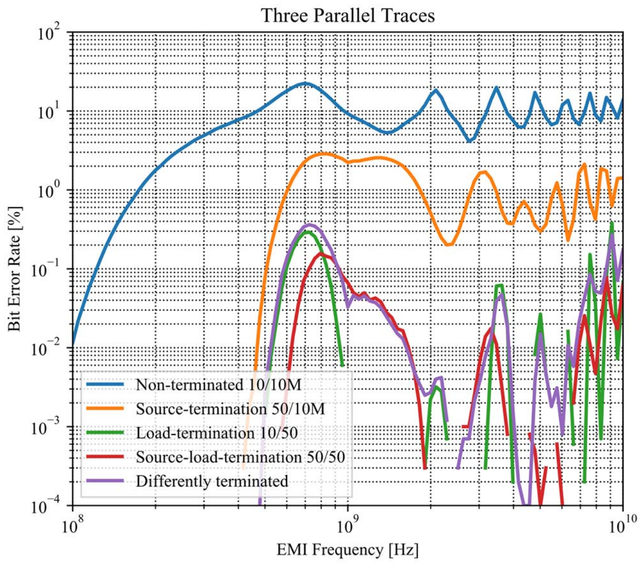

Fig. 10. BER for a 200 MHz random bit pattern propagating over three parallel traces disturbed with an 100V/m EMI disturbance at varying frequencies and this for non-terminated, source-termination, load-termination, source-load-termination and the three traces differently terminated.

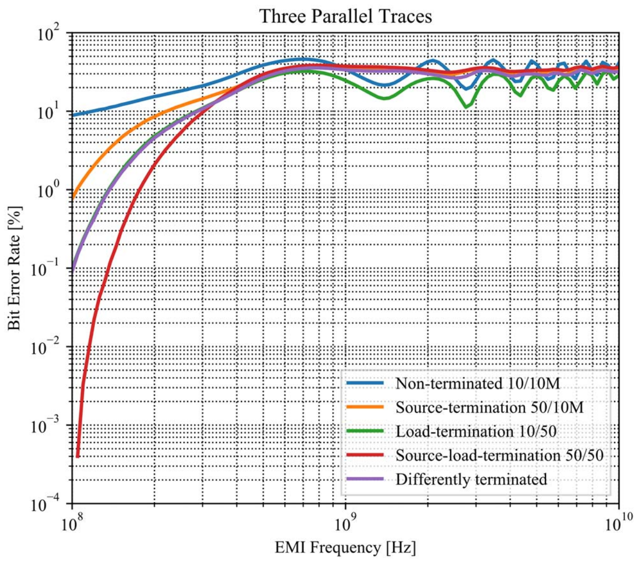

Fig. 11. BER for a 200 MHz random bit pattern propagating over three parallel traces disturbed with an 1000V/m EMI disturbance at varying frequencies and this for non-terminated, source-termination, load-termination, source-load-termination and the three traces differently terminated.

Comparing these results with those for the single microstrip, we noticed that three parallel traces don't give a significant improvement for the BER (as was also concluded in [8]-[10]). In addition, trying to achieve EMI-diverse behavior with different termination schemes results in a worse BER than when one matches all three microstrips at both source and load side.

VI. Conclusion

This paper studied the effectiveness of the application of different termination schemes to provide EMI-diverse behavior. Two different geometries were compared: a non-redundant system comprising a single trace on a PCB and a redundant system comprising three parallel traces on a single PCB. A reciprocity-based technique was used to efficiently calculate the induced voltages and the resulting bit error probability in the different geometries. It is shown that, on its own, use of different termination schemes is not able to provide EMI-diverse behavior. For future work, one can check the effect of different termination combinations when one or more of the ends of traces are closer to the edge of the PCB or when the traces are on multiple PCBs.

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