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# Effectiveness of Time Diversity to Obtain EMI-Diverse Redundant Systems

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***Abstract*—In this paper, the effectiveness of applying an extra time delay to the data transmitted over redundant channels to cope with harsh electromagnetic interference is studied. The redundant system is compared with and without extra time delay and compared with a non-redundant system, which is the reference situation. The geometries under study are disturbed by strong incident fields, which represent reverberation room conditions. These conditions refer to the planewave integral representation, where multiple planewaves with random angles, polarisations and phases are combined and normalised, to create a reverberation room like environment. A reciprocity based technique is used to efficiently calculate the induced voltages and the resulting bit error rate for the different situations. Because of the properties of the geometries that are under test and the introduction of a time-delay in the transmitted data-stream, the moment the induced voltage due to EMI is sampled is different, which causes an EMI-diverse system. The results show that using time-diverse signals optimized for the main disturbance frequency to be expected, is a very effective way of creating EMI-diverse behaviour. In a majority voting (2oo3) system it is possible to eliminate all triple occuring faults. Even for higher field strengths and different EMI frequencies, the time diversity method performs well (better than other EMI-diverse techniques).**

## I. Introduction

With the advent of autonomous vehicles, Smart Cities, Industry 4.0 and all kind of Internet-of-Things related applications, our society and lives will very quickly become highly dependent on high-tech electronics. Unfortunately, all high-tech electronics are sensitive to ElectroMagnetic Interference (EMI), while the increasing electrification of vehicles, machines, etc. also means a much harsher electromagnetic environment. In addition to this, people recognize that Intentional EMI will be a serious risk in the near future.

Not surprisingly, the discipline of EMI Risk Management (previously called EMC for Functional Safety) has gotten quite some attention [1], [2]. A major breakthrough in this area was the development and outrol of the IET Code of Practice on this topic [3], which is now being transformed into an IEEE Standard [4]. The methodology described in these documents states that to cope with severe EMI-related risks, one should aim at developing EMI-resilient systems. An important aspect for this is the ability to introduce fault-tolerant behavior into the system. This means that the system should be able to continue working, if necessary with a reduced functionality, in case a fault or an error occurs. Redundancy, in combination with majority voting, is a classical way to achieve this. However, in order to work against EMI, the redundant system should have EMI-diverse properties, i.e. the behavior of the redundant channels should be different if disturbed by the same EMI. In [3], [4], different ways are mentioned to do so. These include, amongst others, inversion, spatial diversity, frequency diversity, and time diversity. Some of these techniques have already been studied, e.g. in [5], [6] the effectiveness of spatial diversity has been studied, in [7] the effect of inversion has been exploited and in [8] the effect of different matching schemes is compared. In this paper, time diversity is investigated. With time diversity, the data is sent over the different redundant channels with a certain time delay between those different channels. The most optimal delay is deduced in this paper.

The remainder of this paper is organized as follows. In Section II the different geometries that are studied are explained. Section III explains how the EMI environment is generated and how the induced voltages are calculated. Section IV clarifies how the Bit Error Rate is defined. Sections V and VI show what time diversity is and how this performs by numerical experiments, respectively. Finally, Section VII draws concluding remarks.

## II. Geometries under study

Two different geometries will be compared:

1) A single PCB with a single 50 Ohm microstrip (Fig. 1). This is the reference situtation (non-redundant system). The microstrip is driven with a 1V power supply with a 50 Ohm output impedance. The other end of the microstrip is terminated with a 50 Ohm load.
2) A single PCB with three 50 Ohm microstrips parallel next to each other (Fig. 2). This is the redundant system. All three microstrips are driven with a 1V power supply with a 50 Ohm output impedance, and are terminated with 50 Ohm loads.

In all cases, the PCB is an FR4 substrate of 10 cm by 16 cm and has a thickness of 1.6 mm. All traces are 3 mm wide and have length of 5 cm. The space between the three parallel traces is 7 mm. The bottom of the PCB is covered with a ground plane.

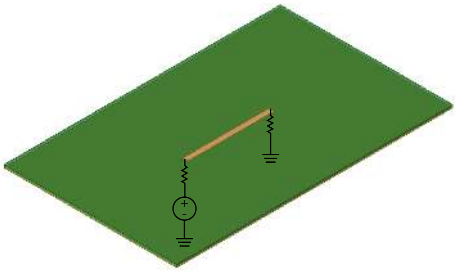

Fig. 1. Single PCB with one 50 Ohm microstrip (reference situation).

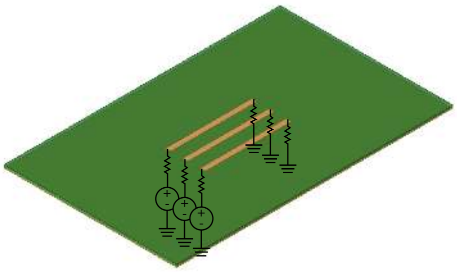

Fig. 2. Single PCB with three 50 Ohm microstrips.

## III. Calculation of induced voltages under reverberation room conditions

Calculating the induced voltages at the end of the microstrips due to incoming disturbances can be done using several methods. One of those methods is using a full-wave simulation for each possible way an EMI disturbance could disturb the Device-Under-Test (DUT). This would require a huge amount of simulations and simulation time. Therefore, an efficient reciprocity based algorithm is used. This method uses only one full-wave simulation that calculates the far-field of the DUT, where each port is excited separately. Using the far-field data and the reciprocity theorem, the induced voltages on those ports can be calculated [9]. In addition, this paper considers the harsh EMI-environment to be a reverberation environment, because of its similarities with the real world, consisting of a lot of reflections. These conditions are created by using the planewave integral representation for reverberation chambers as presented in [10]. This states that a reverberating environment can be represented by a superposition of randomly chosen plane waves (according to the appropriate statistical distributions). The amount of planewaves that are combined together could be represented as the amount of modes that are simultaneously excited in a real chamber [11]. By combining planewaves together, the total power will be higher than the actual power, therefore we need to apply a normalization rule for each separate planewave:

$$E_N = \frac{E_0}{\sqrt{N}} \tag{1}$$

The planewaves that are combined are a set of N planewaves, each with random properties, according to the parameters defined in Table I. To represent the continuously changing nature of a reverberant environment, this simulation is done M times and each time a different set of N planewaves is chosen.

TABLE I
Statistical Distribution of Angles

| Variable | Symbol | Distribution |
|---|---|---|
| Polar angle | $\theta$ | $arccos(U(-1,1))$ |
| Azimuth angle | $\varphi$ | $U(0,2\pi)$ |
| Polarization angle | $\psi$ | $U(0,\pi)$ |
| Phase angle | $\alpha$ | $U(0,2\pi)$ |

## 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, each of them with a 50% chance for a '0' or a '1'. The bit pattern is applied to the input of the microstrips as voltages, by first encoding them using the Non-Return-to-Zero-Level (NRZ-L) encoding scheme. This means that a '0' will be translated to 0V and a '1' will be translated to 1V. The length of one bit will be one period of the bit-frequency ($f_{bit}$). For decoding a Schmitt-Trigger function would require transient analysis and would require a lot of measurement points. As we already have a lot of parameters to sweep, the decoding has been simplified to the theoretical sample-point in the middle of the received bit. To decide if the received voltage is a '0' or a '1', two thresholds are considered: $1/3^{rd}$ and $2/3^{rd}$ of the theoretical maximum output voltage. When the received value is above the highest threshold, the value is decoded as '1', when the received value is below the lowest threshold, the value is decoded as '0'. When the received voltage lays between the two thresholds, the bit is considered as faulty, which is translated in the framework to a '2'. This way, the worst case BER is considered at all times.

The propagation delay of the bits has been calculated using the S-parameters and its derived group-delay. For the reference situation, the BER can easily be calculated because there is only one output. For the redundant system, we apply majority voting. This technique lets us understand that at least N-out-of-M (NooM) - in this case 2oo3 - outputs should be the same, and that will be the final output. The outputs of both systems are compared with the input bitstream, and the amount of bits received incorrectly are saved. After M simulations for one fixed field strength or disturbance frequency, the BER is calculated as follows:

$$BER = \frac{number\ of\ bits\ received\ incorrectly}{M * length\ bit\ pattern} \tag{2}$$

This sequence is repeated for different values of field strength or disturbance frequencies.

## V. Time Diversity

To create an EMI-diverse system, different options are possible. In [5] and [6] the effectiveness of spatial diversity, i.e.

diversifying the place and orientation of the traces was studied. Furthermore, in [8] the use of correctly/differently matching the trace terminals was studied. And in [7] the effectiveness of inversion for a two-channel redundant system was compared to a single trace mechanism, and the occurrence of false positives was investigated.

These are all methods that are diverse and realisable in terms of hardware, but are not based on the encoding mechanism of the data. Therefore, another approach is taken in this paper, where the diversity property is created by changing the way the data is transmitted. The reasoning behind time diversity is that the data is sampled at a constant rate (the bit-frequency), and that point in time never changes. This means that for all three redundant channels, where the voltage induced because of EMI is nearly the same, the sampled value will be nearly the same every time. If we could change that point in time where the three different channels are sampled, a different value from the disturbance will be sampled, and this would create a straightforward EMI-diverse system. This principle is shown in Fig. 3 where the timeshift is represented by a percentage of the period of the EMI frequency. This methodology uses the opposite of the EMI properties from the spatially diverse system. Here we want to use the property that the induced EMI is nearly the same, where in [5] the goal was to change the system in such a way, that the voltage induced by EMI is as diverse as possible, because of the way the striplines ware oriented in space. In the next section, the most optimal combination of time-delays for the data-stream of the redundant channels is investigated.

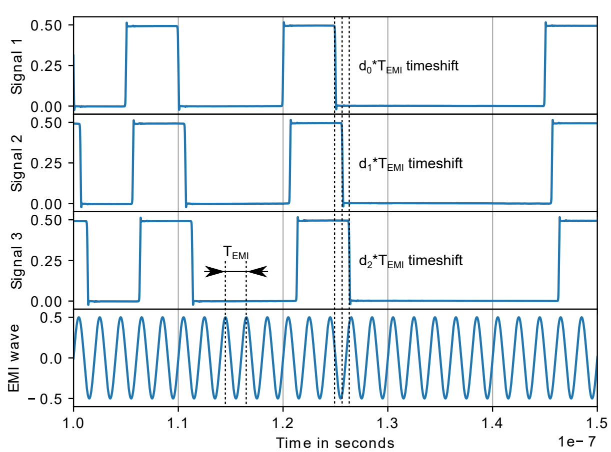


Fig. 3. The three input signals in comparison with a disturbance signal. Each $d_x$ equals a percentage that is multiplied with the period of the disturbance, which represents the timeshift of the bits, to create a time-diverse system.

## VI. Numerical results

In all results that follow, the required full-wave simulations of the DUTs were performed with the FDTD solver EMPro from Keysight Technologies [12]. The creation of the reverberation environment, reciprocity-based post-processing and BER calculation are done using an in-house developed simulation framework in which the bit pattern, bit-frequency, encoding scheme, decoding scheme, EMI frequency, EMI strength, etc. can be freely chosen.

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

As a reference, the simulation is first done for one single trace on a PCB. This shows the baseline or reference Bit-Error-Rate (BER). This BER can be seen in Fig. 4, in function of the incident field strength.

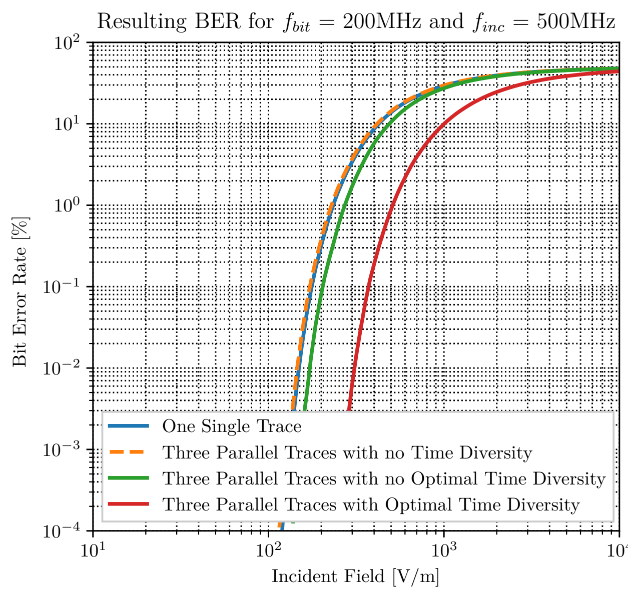


Fig. 4. Comparison between the BERs of only one trace that is disturbed and three parallel traces that are disturbed. The latter is simulated with no shifts in time, no optimal and with optimal timeshifts to get the best BER.

### *B. Three parallel microstrips (i.e. redundant system) without Time Diversity*

When we look at the BER of three parallel microstrips without Time Diverse properties in Fig. 4, and compare it with the one of only one trace, there is almost no difference. This is due to the similarities between the traces as stated in the previous section. The induced voltages will have nearly the same amplitude and phase and therefore this system is less EMI-diverse, thus causing no improvement in the BER.

### *C. Three parallel microstrips (i.e. redundant system) with Time Diversity*

As can already be seen in Fig. 4, there are different combinations of timeshifts that will give different results. Using the knowledge that the response to the incoming disturbance is nearly the same on all three traces, the following idea was tested to find the most optimal combination of timeshifts.

When shifting the bit pattern in the right way, there must be a combination of delays, where the sampled points are the most diverse, which causes two or three faulty bits to occur

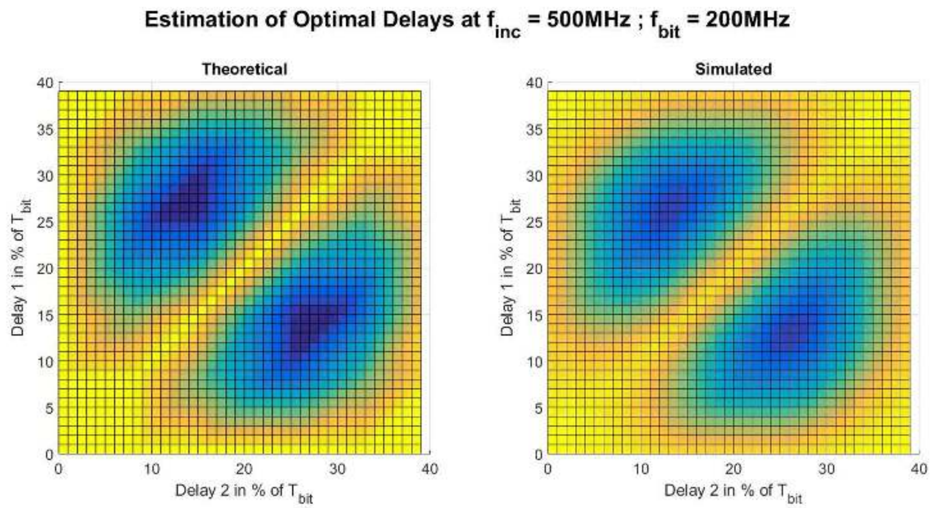


Fig. 5. Comparison between the resulting BER for a theoretical sweep of time delays for the input signals, and the actual simulations from the simulation framework. The color indicates the BER, where darkblue indicates a low BER, and yellow a high BER.

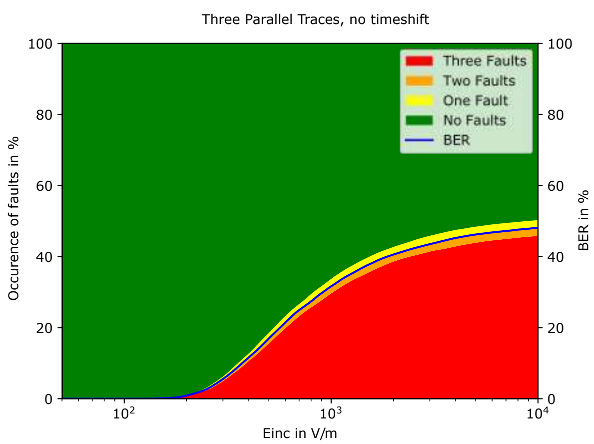


Fig. 6. Occurrence of the different faults, compared to the BER in function of the field strength, for a three microstrip system, without time diversity.

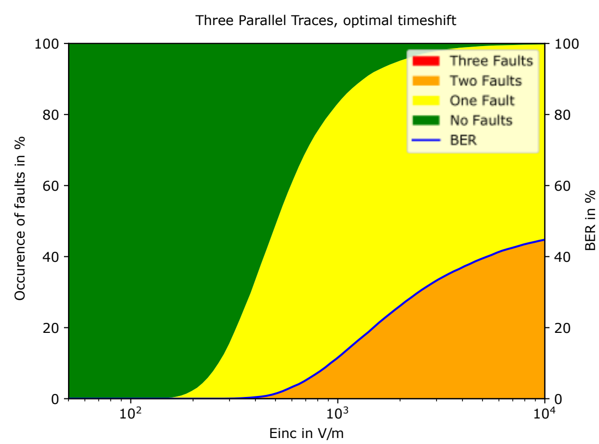


Fig. 7. Occurrence of the different faults, compared to the BER in function of the field strength, for a three microstrip system, with the optimal time diversity for three traces, equalling a 0%, 33% and 66% time shift.

less. A quite brute-force method was used here to find out what combination of timeshift is the most optimal. This was done by creating a list of 100 random bits, and encoding them to voltages, the same way as would be done in the simulation framework. A sine-wave with the desired EMI frequency is used to simulate the incoming disturbance. The time delay between the bit patterns is sweeped for two of the three trace inputs, one input is fixed at 0% or no time delay. The profile of the sweep is from 0%-40% of the period of the bit-frequency, which is equal to 0%-100% of the period of the EMI frequency. In the case that the EMI frequency is 500MHz and the digital signal frequency is 200MHz. These settings are chosen through all of the experiments that follow. The phase of the disturbance is uniformly distributed in order to average out the relative time delay between the bit patterns and the EMI disturbance.

The results in Fig. 5 show that, when using three traces, a timeshift of 0, 1/3 and 2/3 times the period of the incoming EMI wave has the best result. When we look at a sinewave and take three samplepoints that are shifted 120° at all times, one notices that those points are the most different when comparing to other combinations of timeshifts. The theoretical method is compared with actual simulations from the simulation framework. A visual comparison is enough to conclude that the previously assumptions are correct.

Fig. 6 and 7 shows the occurrence of the amount of faults in function of the field strength. Fig. 6 shows that with no time diversity, three simultaneous faults occur the most, and almost no double or single faults occur. This is because of the equal EMI properties of the three traces. Fig. 7 on the other hand shows that, with the most optimal time diverse configuration,

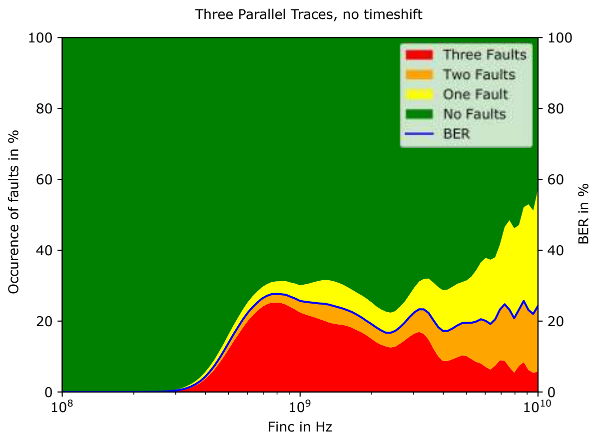


Fig. 8. Occurrence of the different faults, compared to the BER in function of the disturbance frequency, for a three microstrip system, without time diversity.

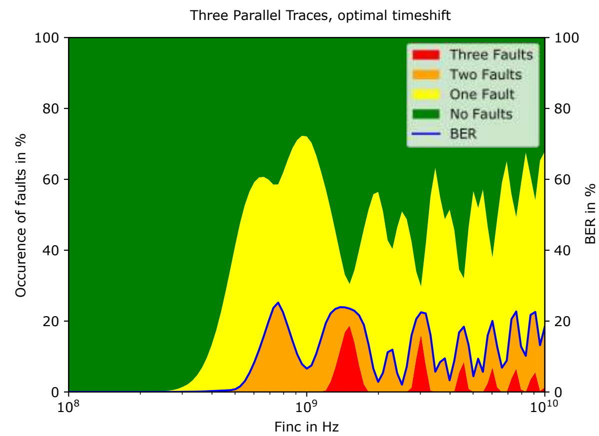


Fig. 9. Occurrence of the different faults, compared to the BER in function of the disturbance frequency, for a three microstrip system, with the optimal time diversity for three traces, equalling a 0%, 33% and 66% time shift.

all of the triple faults have been eliminated, and on top of that, the BER is lower. This at a cost of an increase in single and double faults, of which the single faults are still recoverable because of the majority voting system. Because the overall BER now only includes the double faults, we can see that errors start occurring at a higher field-strength than without time diversity.

A step further was taken by keeping these time delays for a disturbance frequency of 500MHz fixed, and check the BER response in function of the EMI frequency. Firstly, as a reference, Fig. 8 shows the BER-response from 100MHz to 10GHz EMI frequency, at a field strength of 500V/m. The figure shows that the BER decreases as the frequency increases, which is due to the similarity of the induced voltages as the distance between the traces is no longer negligible in comparison with the wavelength. With other words, the system is again becoming more spatially diverse, which causes our goal to create a time diverse system to be less effective. With traces of a length of 5cm, the resonance frequency of half a wavelength lays around 1.5GHz. Fig. 9 uses those same settings, but now with the optimal timeshifts. We can see that, at the resonance and multiples of the resonance frequencies, the three faults come back, but at the other frequencies, the three faults are eliminated. This is due to the resonance properties, where the voltage that is induced is much higher.

## VII. Conclusion

This paper concludes that time diversity is an effective way of creating an EMI-diverse system, when the user knows what EMI frequency is most likely to occur. The explained technique maintains a good performance when changing the EMI frequency, except for resonance, where the induced voltage is too high to be able to reproduce the transmitted data signal. The necessary time shift for the digital signal is linked to the amount of traces and EMI frequency. All of these results can be extended to other sets of multiple traces, like a 3oo5 system, where 5 traces are used, and where the optimum phase shift is 72° or 1/5th of the period of the EMI frequency.

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