Development of an EMI Detector Based on an Inverted Data Pair with Reduced Number of False Negatives

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***Abstract*—This paper proposes a design of an EMI detector, based on an inverted data pair, for the detection of unwanted electromagnetic disturbances on a wired communication channel with the aim to reduce the overall safety risks related to bit errors on such a communication channel. The EMI detector can detect unwanted electromagnetic (EM) disturbances and generate a warning, which can help the system to follow a precautionary procedure. The performance of the EMI detector is analysed by simulating a random pattern of transmitted bits through a wired channel in the presence of (continuous wave) EMI with varying amplitude, phase, frequency and phase difference between the lines in the inverted data pair. This performance itself is determined by two main metrics: (I) false positives, the number of generated warnings when there is no bit error and, (II) false negatives, the number of bit errors without any warning given by the detector. An ideal EMI detector would have zero false positives and zero false negatives. In this paper, the goal is mainly to reduce the number of false negatives. The EMI detector can be made by using low-cost electronics. It works quite effectively in most of the cases and works better than other detectors presented before in literature.**

***Index Terms*—EMI Sensors, EMI Risk management, EMC, functional safety**

I. Introduction

Over the years, the use of electric, electronic, and programmable electronic (E/E/PE) is continuously increasing in our lives. The swift advancement in electronics solved a number of problems and continually adds more comfort to our daily lives. On the other hand, with a high increase in the use of electronic devices, the problem of unwanted EM disturbances is becoming more significant every day. The demand for sophisticated and safe electronic devices is continuously rising for mission-critical applications. Electromagnetic interference (EMI) can affect performance, corrupt the information, and at the extreme, cause a fatal failure of the system [1]. For the same reason, Electro-Magnetic Compatibility (EMC) Engineering and System Safety Engineering are both gaining importance.

In many electronic devices, safety-related risks due to errors in communication channels are critical, especially as we are moving towards e.g. autonomous systems. For decades, wired channels have played a pivotal role in the communication networks and still represent one of the essential mediums for electronic data transfer. The probability of disturbance in wired channels due to EMI is continuously rising [2]. The increase in the demand for sophisticated and safe transmission channels, leads to the desire for the development of EMI resilient communication networks. A number of techniques have been proposed in the recent past to protect the data from EMI [3]. Conventional methods used for the protection of systems from EMI include shielding, filtering and grounding, followed by a testing campaign according to pre-described standards. However, this way of working can not be practically suitable to guarantee that EMI will not cause safety risks over the full lifetime of the electronic device. The latest IET guide on EM resilience [4] and the IEEE standard P1848 [3] propose implementation of hardening techniques and measures first developed for functional safety, but now adapted to better cope with EMI, along with the classical EMI mitigation techniques.

Most EMI resilience techniques are trying to ensure safe data transmission by using redundant transmission channels with spatial, frequency and time diversity, followed by a voter [5]–[7]. Other methods are focusing on detecting and correcting bit errors by using a software based approach [8],

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No 812.790 (MSCA-ETN PETER). This publication reflects only the authors' view, exempting the European Union from any liability. Project website: http://etn-peter.eu/.

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[9]. Sadly, previous research has shown that these techniques are not able to detect EMI in all cases and that there are certain conditions where they fail to ensure that the received data is identical to the transmitted one. Typical cases include simultaneous data corruption/bit flips in all redundant channels. This creates the dire need for the development of an EMI detector that can warn the receiver end about the possible occurrence of EMI and, hence, about possible data corruption.

Therefore, this paper describes the development of such an EMI detector based on the use of an inverted data pair. Performance of the EMI detector is determined based on two main metrics, namely the number of false positives and false negatives. False negatives occur when EMI corrupts the data but the detector is not able to detect the EMI, while false positives are the cases where EMI is present but did not disturb the data and the EMI detector generates nevertheless a warning. In the case of a communication channel that is used for mission- or safety-critical applications, false negatives have to be avoided at all times as they can directly lead to critical failures of the system, while false positives have to be minimized in order to ensure sufficient availability of the system. Given the absolute necessity to minimize and, preferably, completely avoid the occurrence of false positives, the focus of this paper is on removing false negatives.

The proposed EMI detector is designed for a wired communication channel, which could be simple data transmission lines present in a personal computer or sophisticated communication lines inside or between mission-critical autonomous devices acquiring data from sensors or transmitting signal to actuators. The EMI detector will detect if a signal is experiencing unwanted EM interference, which can help the system to follow a precautionary procedure for ensuring the overall safety and reduce the safety risks related to EMI, thereby making system EMI-hardened by design.

The remainder of this paper is organized as follows: Section II briefly describes the mechanism for EMI detection. Section III analyzes the performance of the EMI detector with varying (continuous wave) EMI signals and suggests some improvements. Section IV deduces the outcome from the results and draws concluding remarks.

II. PROPOSED EMI DETECTOR

In [10], the authors mention broadly applicable Techniques and Measures (T&M) for making a system EMI resilient by design. These T&M include the use of diverse redundant channels, opting for spatial, frequency and time diversity or using an inverted data on identical channels for enhancing the system safety. In [11], the authors implemented inversion diversity by using two data transmission lines for transferring data, where one data transmission line was used to send the original non-inverted data and the other data transmission line to send inverted data. At the receiver end, the inverted data line is again inverted. Comparing the output of both lines by a comparator helps in determining disturbances due to EMI. Such an inverted pair is actually a first version of an EMI detector. Although the technique looks upright at first sight, a number of cases can occur in practice in which EMI generates bit flips in both lines simultaneously. This makes detection of the bit errors with the comparator impossible. This leads to the question if one can develop an improved inverted pair that can detect EMI in all cases.

This paper proposes an addition of hardware to the inverted data pair to detect incoming EMI in the form of a continuous wave (CW) with the main goal of reducing the number of false negatives.

Fig. 1 shows the full block diagram of the inverted data pair and the additional proposed EMI detector.

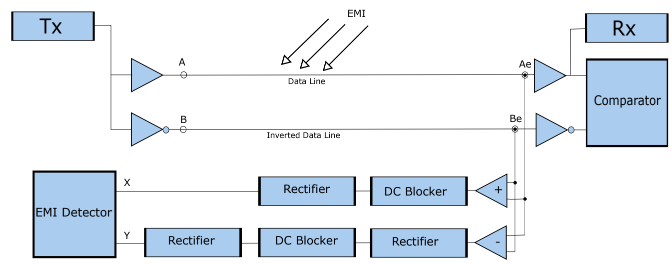

Fig. 1: EMI Detector Block Diagram

The data on both lines can be defined as A and B for the regular and inverted data, respectively. The voltages at the receiver or end point (e) $(A_e$ and $B_e)$ are defined as

$$A_e(t) = \mathrm{A}(t) + \mathrm{EMI}(t) \tag{1}$$

$$B_e(t) = \mathrm{B}(t) + \mathrm{EMI}_i(t) \tag{2}$$

with

$$\mathrm{EMI}(t) = \mathrm{Amp} \cdot \sin\left(2\pi f_{\mathrm{EMI}} t + \theta\right) \tag{3}$$

$$\mathrm{EMI}_i(t) = \mathrm{Amp} \cdot \sin\left(2\pi f_{\mathrm{EMI}} t + \theta + \phi_D\right). \tag{4}$$

The frequency of the EMI is defined as f_{EMI} and will never be referenced in absolute values in this paper. The frequency of the EMI will always be referenced against the bit frequency f_{BIT} by $f_{\mathrm{ratio}} = \frac{f_{\mathrm{EMI}}}{f_{\mathrm{BIT}}}$. The incoming phase of the EMI is defined as θ while the phase difference between both lines is defined as ϕ_D. Ideally, both data transmission lines are close to each other and, hence, have little phase difference ϕ_D between the EMI coupling to each of the lines. Yet, at higher frequencies, with a wavelength smaller or equal to the distance between both line, the phase difference can be quite significant.

At the receiver side (RX) there is a simple detector that samples the bit in the center of each bit. Data is transmitted continuously on the data transmission lines in the form of bits. Each bit uses the predetermined time for the transmission of bits known as the bit duration T_{bit}. The transmitter uses the unipolar Non-Return-to-Zero-Level (NRZ-L) encoding, where 0V represents the binary '0', and 1V represents a binary '1'. The receiver samples the bits in the middle of the bit duration T_{bit} and considers a voltage less than 0.33V as a binary '0' and a voltage greater than 0.66V as '1'. Between the two thresholds a worst case scenario is assumed and, hence, the bit is always flipped in our study. The comparator inverts the received bits on the inverted data line and compares them with those received on the non-inverted data line. If the bits are not equal a warning is sent to the system such that an appropriate action can be taken.

The comparator though, is not performant enough, in the sense that it will not always detect a bit error. Hence, it will produce unwanted false negatives. Therefore, the use of additional hardware is proposed. This hardware creates the following signals:

$$\mathrm{X} = |(A_e + B_e) - mean\,(A_e + B_e)| \tag{5}$$

$$\mathrm{Y} = ||A_e - B_e| - mean\,|A_e - B_e||\,. \tag{6}$$

The implementation of (5) and (6) can be represented by hardware as shown in Fig. 1. The result of (5) will be equal to $|\mathrm{EMI} + \mathrm{EMI}_i|$ as the DC blocker removes the constant $\mathrm{A}_e + \mathrm{B}_e = 1$ V and the rectifier converts the result to an absolute value. In the ideal (theoretical) case where $\phi_D = 0$, (5) would provide $|2 \cdot \mathrm{EMI}|$. However, in practice there will always be a phase difference between two lines as a small distance will always exist between two lines. Hence, there will be a phase difference between the two EMI induced voltages. Therefore another signal (6) is created to retrieve $|\mathrm{EMI} - \mathrm{EMI}_i|$. The same reasoning can also be seen in Table I.

Both (5) and (6) are then sampled in the EMI detector at a sample rate f_{sample} which needs to be higher than the bit sampling frequency f_{BIT}. In this paper f_{sample} is chosen to be 3 times f_{BIT}. The samples are taken in the middle of the bit, the middle of the bit $-\frac{1}{f_{\text{sample}}}$ and the middle of the bit $+\frac{1}{f_{\text{sample}}}$, as shown in Fig. 2. After sampling, a trigger needs to create a warning. The voltage threshold to create a warning is defined as V_{thres}.

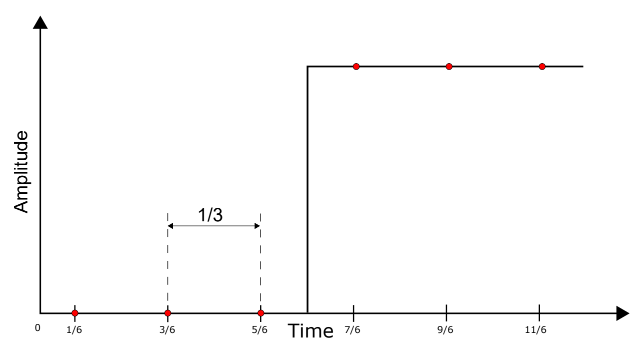

Fig. 2: Sampling of the Bits

III. Evaluating the EMI Detector

In order to analyse the performance of this proposed EMI detector, several simulations have been performed. The EMI detector is implemented as a mathematical model in Python. In these simulations, the data $\mathrm{D}(t)$ consists out of 10000 random bits on which several EMI signals ((3) and (4)) are added as described in (1) and (2). The phase of the EMI θ varies from 0 to 359° with a step of 1° while the phase difference between the lines ϕ_D is kept at a constant of 10°. All metrics shown in this section are always the average percentage over all possible θ. The amplitude of the EMI, Amp, can be calculated from a given Signal to Interference Ratio (SIR) (7). The SIR is defined as the ratio between the root mean square (rms) of the disturbed signal A_{rms} divided by the rms of the interferer EMI_{rms}.

$$\mathrm{SIR} = 20 \cdot log_{10}\left(\frac{A_{rms}}{\mathrm{EMI}_{rms}}\right). \tag{7}$$

The frequency of the EMI can be calculated by $f_{\text{ratio}} = \frac{f_{\text{EMI}}}{f_{\text{BIT}}}$. The threshold voltage V_{thres} is defined as 0.33 V if not mentioned otherwise.

In the figures that follow, several metrics are shown:

- The bit error rate (BER) measured at RX
- The number of false positives of the proposed EMI detector
- The number of false negatives of the proposed EMI detector
- The number of false positives of the comparator
- The number of false negatives of the comparator

In Figs. 3, 4 and 5, f_{ratio} equals 100, 1, and 0.001, respectively. For all the different f_{ratio} the number of false negatives from the comparator are very similar and start to appear at a SIR = -10 dB. The new EMI detector never shows false negatives except in the case where $f_{\text{ratio}} = 0.001$. The reason behind false negatives at lower frequency ratios is a limitation of the rectifier circuits (5),(6) used after the adder and subtractor. The reasoning behind (5) only holds for significantly high EMI induced voltages, while (6) is only valid when $|\mathrm{A}_e - \mathrm{B}_e|$ is less than $mean|\mathrm{A}_e - \mathrm{B}_e|$. At lower frequency ratios, phase difference plays an important role; even a small phase difference between the lines can change the amplitude of EMI induced voltages significantly, leading to a failure of (6). A disadvantage of the new EMI detector is that it produces more false positives than the comparator, which could influence the availability of the system.

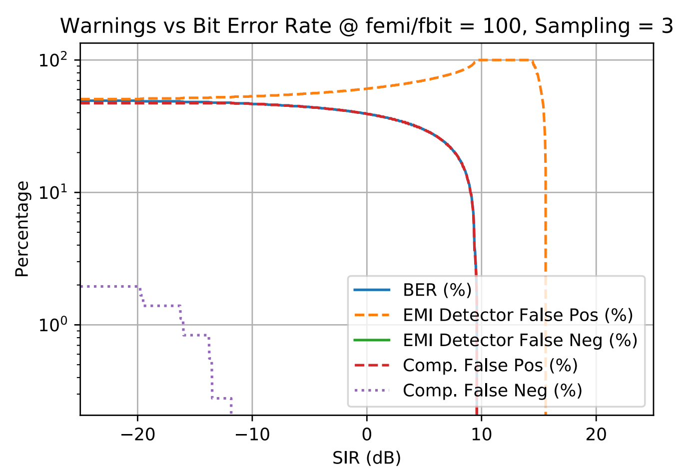

Fig. 3: Response of the EMI Detector for f_{ratio} = 100, ϕ_D = 10° and $V_{\text{thres}} = 0.33$V

TABLE I: Response of Improved EMI Detector

Tx	A	B	Ae	Be	X	Y	RX	EMI detection X	EMI detection Y
‘1’	1V	0V	$1V + \text{EMI}$	$0V + \text{EMI}_i$	$\lvert\text{EMI} + \text{EMI}_i\rvert$	1V	‘1’ or ‘x’	X != 0V ? YES	Y != 0V ? YES
‘0’	0V	1V	$0V + \text{EMI}$	$1V + \text{EMI}_i$	$\lvert\text{EMI} + \text{EMI}_i\rvert$	-1V	‘0’ or ‘x’	X != 0V ? YES	Y != 0V ? YES

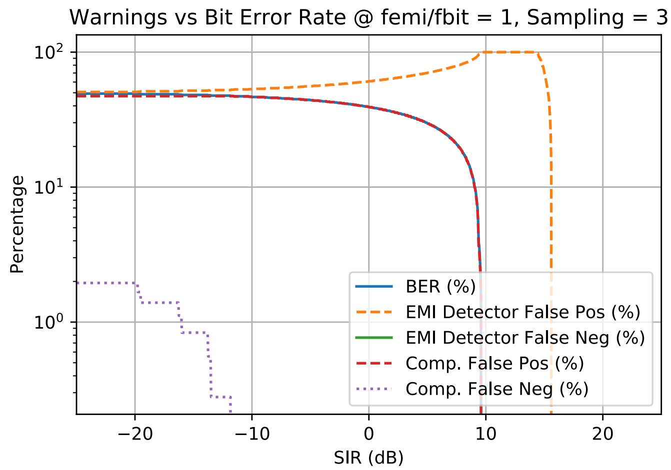

Fig. 4: Response of the EMI Detector for $f_{\text{ratio}} = 1$, $\phi_D = 10°$ and $V_{\text{thres}} = 0.33\text{V}$

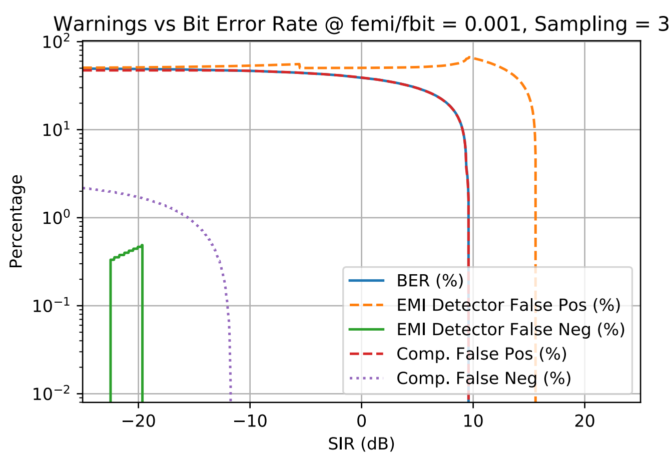

Fig. 5: Response of the EMI Detector for $f_{\text{ratio}} = 0.001$, $\phi_D = 10°$ and $V_{\text{thres}} = 0.33\text{V}$

More thorough research also revealed presence of false negatives at EMI frequencies, f_{EMI}, close to sampling frequency f_{sample} or close to an integer multiple of f_{sample}. The reason of this sensitivity is aliasing of the EMI with a frequency higher or equal to the sampling frequency to a lower perceived frequency ratio f_{perc}. Mathematically, the perceived frequency can be defined as f_{perc} equals $f_{\text{ratio}}\ mod\,(f_{\text{sample}})$.

For example a $f_{\text{ratio}} = 6.001$ would result in $f_{\text{perc}} = 0.001$, given that $f_{\text{BIT}} = 1$ and $f_{\text{sample}} = 3$. This example is also shown in Fig. 6.

Besides the amplitude and the frequency, another value, more specifically the phase difference between the two traces

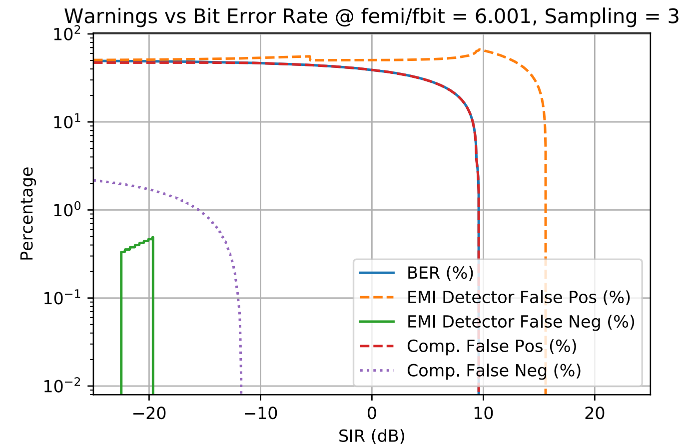

Fig. 6: Response of the EMI Detector at $f_{\text{ratio}} = 6.001$, $\phi_D = 10°$ and $V_{\text{thres}} = 0.33\text{V}$

ϕ_D could possibly have an effect on the number of false negatives. Since false negatives only occur at very low f_{perc}, the f_{ratio} is kept at 6.001 for the all the following figures. Figs. 7, 8 and 9 show the performance of the EMI detector for $\phi_D = 2°, 30°$ and $45°$, respectively. Fig. 6 already showed the performance at $10°$.

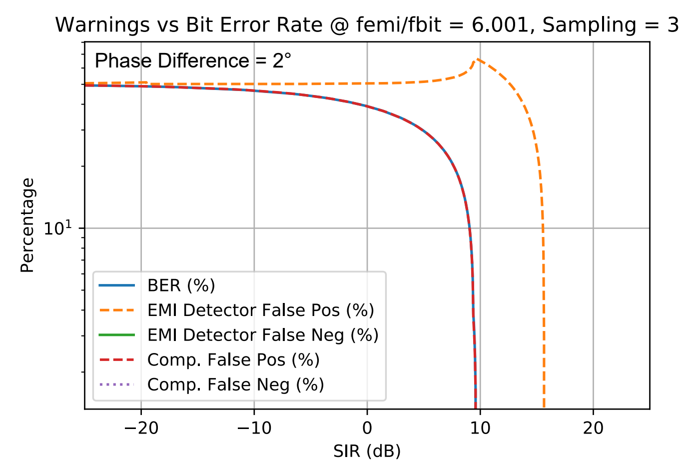

Fig. 7: Response of the EMI Detector for $f_{\text{ratio}} = 6.001$, $\phi_D = 2°$ and $V_{\text{thres}} = 0.33\text{V}$

It is clear that the phase difference ϕ_D has a large influence on the SIR-region for which the false negatives occur. The larger the distance between the two traces the lower the SIR where false negatives occur.

The biggest disadvantage of this EMI detector are the higher number of false positives. The detector creates a warning when

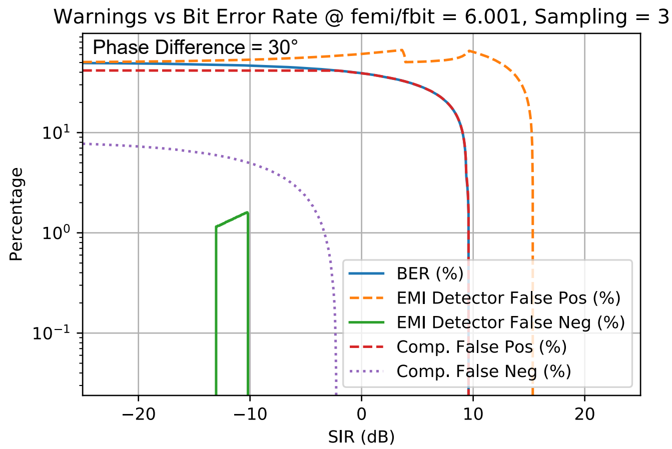

Fig. 8: Response of the EMI Detector for $f_{\text{ratio}} = 6.001$, $\phi_D = 30°$ and $V_{\text{thres}} = 0.33\text{V}$

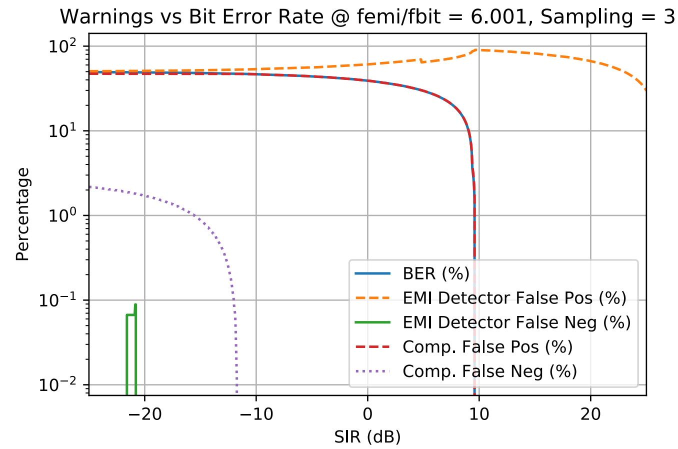

Fig. 10: Response of the EMI Detector $f_{\text{ratio}} = 6.001$, $\phi_D = 10°$ and $V_{\text{thres}} = 0.1\text{V}$

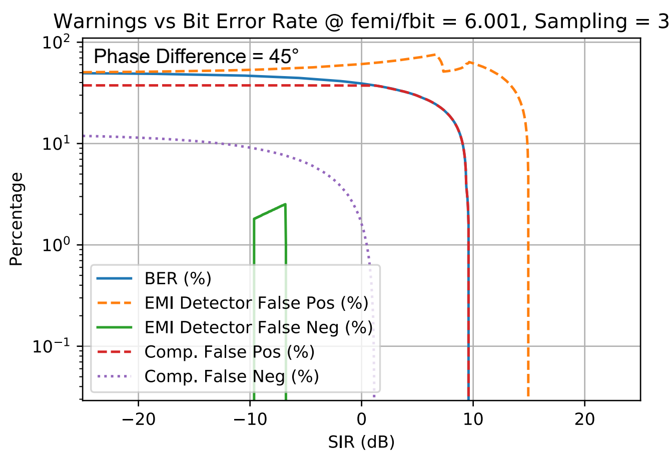

Fig. 9: Response of the EMI Detector $f_{\text{ratio}} = 6.001$, $\phi_D = 45°$ and $V_{\text{thres}} = 0.33\text{V}$

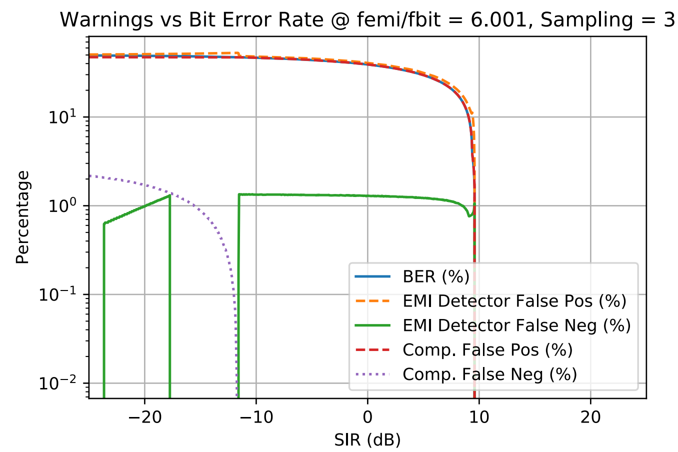

Fig. 11: Response of the EMI Detector $f_{\text{ratio}} = 6.001$, $\phi_D = 10°$ and $V_{\text{thres}} = 0.66\text{V}$

there is no need to create a warning and, hence, would decrease the availability. The number of false positives is depending on V_{thres}. In Fig. 10 the voltage threshold V_{thres} is lowered to 0.1V and shows a lot more false positives as compared with Fig. 6 using a $V_{\text{thres}} = 0.33\text{V}$. On the other hand the number of false negatives are decreased.

In Fig. 11 the voltage threshold has been increased up to 0.66 V. In this case the number of false positives are decreased drastically, but as a consequence, the number of false negatives increased.

The value of V_{thres} in this type of EMI detector should always be chosen according to the application and the number of allowable false negatives and positives.

IV. Conclusion

This paper proposed the design of a specific EMI detector detecting single continuous waves on a inverted data pair. It can be concluded that the proposed detector works quite more effectively for the detection of EMI compared with a simple inverted pair as proposed in [11]. The performance of the proposed EMI detector and the comparator in [11] has been simulated and specified by two main metrics. More specifically the number of false positives and the number of false negatives. The main goal in this paper was to reduce the number of false negatives. Which in its turn can help to drastically improve the safety of modern systems that rely heavily on digital communication. Yet, it is not an ideal detector. Therefore future work will focus on further decreasing the number of false negatives and false positives. Also, the performance of this EMI detector will be tested again multi-frequency EMI or even pulses and wireless communications signals.

References

[1] J. Lannoo, A. Degraeve, D. Vanoost, J. Boydens, and D. Pissoort, "Study on the use of different transmission line termination strategies to obtain EMI-diverse redundant systems," in *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-*

Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC), May 2018, pp. 210–215.

[2] J. Van Waes, J. Lannoo, J. Vankeirsbilck, A. Degraeve, J. Peuteman, D. Vanoost, D. Pissoort, and J. Boydens, "Effectiveness of hamming single error correction codes under harsh electromagnetic disturbances," in *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*, Aug 2018, pp. 271–276.

[3] K. Armstrong and A. Duffy, "P1848 - IEEE Draft Techniques & Measures to Manage Functional Safety and Other Risks With Regard to Electromagnetic Disturbances," 2017. [Online]. Available: https://standards.ieee.org/project/1848.html

[4] K. Armstrong, "The new IET Guide – how to do EMC to help achieve Functional Safety," in *Making Systems Safer*. Springer London, 2010, pp. 187–210.

[5] J. Lannoo, J. Van Waes, A. Degraeve, D. Vanoost, J. Boydens, and D. Pissoort, "Effectiveness of time diversity to obtain EMI-diverse redundant systems," in *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*, Aug 2018, pp. 288–292.

[6] A. Degraeve and D. Pissoort, "Study of the effectiveness of spatially EM-diverse redundant systems under reverberation room conditions," in *IEEE International Symposium on Electromagnetic Compatibility*, vol. 2016-September. Institute of Electrical and Electronics Engineers Inc., sep 2016, pp. 374–378.

[7] J. Lannoo, A. Degraeve, D. Vanoost, J. Boydens, and D. Pissoort, "Effectiveness of inversion diversity to cope with EMI within a two-channel redundant system," in *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility, EMC/APEMC 2018*. Institute of Electrical and Electronics Engineers Inc., jun 2018, pp. 216–220.

[8] J. Van Waes, D. Vanoost, J. Vankeirsbilck, J. Lannoo, D. Pissoort, and J. Boydens, "Resilience of Error Correction Codes Against Harsh Electromagnetic Disturbances: Fault Mechanisms," *IEEE Transactions on Electromagnetic Compatibility*, pp. 1–11, aug 2019.

[9] J. Van Waes, J. Vankeirsbilck, J. Lannoo, D. Vanoost, D. Pissoort, and J. Boydens, "Complementary fault models for assessing the effectiveness of hamming codes," in *2019 28th International Scientific Conference Electronics, ET 2019 - Proceedings*. Institute of Electrical and Electronics Engineers Inc., sep 2019.

[10] D. Pissoort, J. Lannoo, J. V. Waes, A. Degraeve, and J. Boydens, "Techniques and measures to achieve EMI resilience in mission- or safety-critical systems," *IEEE Electromagnetic Compatibility Magazine*, vol. 6, no. 4, pp. 107–114, Fourth 2017.

[11] J. Lannoo, A. Degraeve, D. Vanoost, J. Boydens, and D. Pissoort, "Effectiveness of inversion diversity to cope with EMI within a two-channel redundant system," in *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, May 2018, pp. 216–220.