A System's Perspective on the Use of EMI Detection and Correction Methods in Safety Critical Systems

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***Abstract*—In this paper we discuss the condition assessment definitions previously used to analyse the effectiveness of ElectroMagnetic Interference (EMI) detectors/correctors. It is shown that those definitions do not resemble the correct condition and an expansion is needed. New expanded condition assessment definitions are presented and evaluated in comparison with the old ones for a two out of three majority voter system used in an Electro Magnetic (EM) diverse system. The new definitions provide a better insight into the effectiveness of EMI detectors on its own or in correctors. We also discuss the use of the new definitions in a multi-layer error detection and correction system.**

***Index Terms*—EM resilience, EMC, Risk management, EMI detectors/correctors**

I. INTRODUCTION

The swift advancement of technology has solved many problems in our daily lives, and it is continuously adding comfort to our daily lives. In the recent past usage of Electrical, Electronic, and Programmable Electronic (E/E/PE) devices has increased drastically. At the same time, with the advent of autonomous vehicles, Industry 4.0 and Internet of Things (IoT) the need for correct and safe operation in sophisticated mission- and safety-critical systems is continuously rising.

Electromagnetic Interference (EMI) is known to many people as the cause of buzzing sound when someone brings a mobile phone closer to an old radio speaker. Unfortunately, all electronic devices are vulnerable to electromagnetic disturbances leading to EM interferences (EMI). At the same time, all E/E/PE devices generate electromagnetic disturbances. EMI can corrupt the signal, and in extreme cases, it can cause fatal errors. In order to keep the devices in a safe operation especially in harsh electromagnetic (EM) environments, a focus on managing safety risks due to EM disturbances is gaining more and more importance [1].

Advanced applications of smart devices are significantly dependent on the communication channel between the different devices and/or the outside world. The robustness and resilience of the communication channel depends on many factors, including EMI, playing a crucial role in assuring the system's functional safety. For the same reason, the combination of the disciplines of Electro-Magnetic Compatibility (EMC) Engineering and Functional Safety Engineering is gaining huge importance.

The emergence of EM Risk Management and EM resilience [2]–[5] gave a new perspective to the above. One of the significant breakthroughs in this area was the development of IET code of practice on EM resilience, which is now transformed into standard IEC 1848 Techniques & Measures to Manage Functional Safety and other risks with regard to Electromagnetic Disturbances [6]–[8]. IEEE 1848 focuses on the methodology to cope with severe EMI-related issues using a risk-based approach rather than a commonly used rule- and test-based approach. Overall, IEEE 1848 provides a concept for EM resilience and focuses on minimizing possible errors and failures. It provides an extensive list of techniques and measures to ensure that overall systems stay acceptably safe despite the presence of often unforeseen EM disturbances. IEEE 1848 proposes hardening techniques and measures that focus on minimizing errors due to EMI or detecting them,

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followed by correction of these errors or switching the overall system to a safe state. To ensure the system's safety, the researchers focus on various techniques and measures. The majority of them try to ensure safe data transmission by using redundant transmission channels with frequency, inversion, spatial, and time diversity, followed by a majority voter [9]–[11]. Some of the methods are focused on detecting and correcting bit errors by using a hardware or software-based approach [12]–[14]. Lastly, many researchers are working on different software-based error correction techniques [15], [16]. All correction techniques have the ability to notify its user if it did or did not perform a correction. Hence, a correction technique also acts as an EMI detector.

In all of these error detection or correction techniques and methods, the condition assessment (i.e. the assessment of the detector, either on its own or in a correction technique, on the condition of the measured channel) is classified in four basic definitions: True Positives, True Negatives, False Positives and False Negatives. Note that when a stand-alone EMI detector is considered, the condition is based upon the received values while if a correction system is applied, the condition is based on the corrected output. As will be shown in this paper, these condition assessment definitions are not sufficient to fully analyse the performance and effectiveness of the previously mentioned techniques. Hence, in this paper we present new expanded condition assessment definitions to provide a better analysis of the proposed EM resilience techniques. With this paper, we want to raise awareness about the effectiveness of EM (error) detection systems and share how they can be analysed correctly as an addition to the IEEE 1848 [8] recommending to use these EM detection systems.

This paper is organized as follows: Section II discusses problems with the current definitions on a two out of three (2oo3) voter. Section III briefly explains the new definitions through the application on the 2oo3 voter. Section IV discusses how these definitions can be used to evaluate multiple detection layers after each other. Section V deduces the outcome from the results and draws concluding remarks.

II. THE FLAWS IN THE CURRENT CONDITION ASSESSMENT OF EMI DETECTORS

In order to show the flaws in the current condition assessment of EMI detectors the example of a triple modular redundant architecture with a 2oo3 majority voter, which is a correction technique, is used as an example.

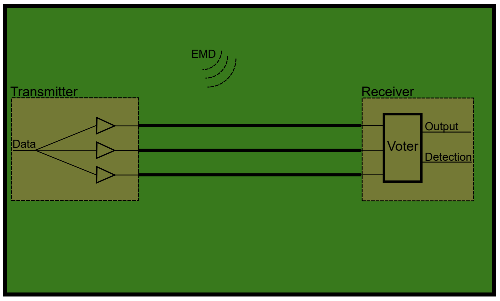

Fig. 1. Triple modular redundant architecture

In Fig. 1 a triple modular redundant architecture has been employed in conjunction with majority voting for the implementation of various EM-resilience techniques such as time diversity [9], [17], frequency diversity [18] etc. Such EM-diverse systems lead to a significant improvement in the Bit Error Rate (BER) performance and a considerable reduction in the total number of false negatives. The condition assessment definitions which has been used so far in the above-mentioned implementations are shown in Table. I. These definitions are useful for understanding the safety and availability aspects of the system. However, the above-mentioned definitions do not illustrate whether data itself decides the final outcome or an external source like EM disturbances. Therefore, a revision of the definitions is required in order to fully understand the underlying phenomenon. The 2oo3 voter used in [9], [17] is used as an example. In order to explain the problem with the previous definitions, six unique cases are shown in Table II for the majority voter example. Note that in the following discussion we indicate the problems with the old definitions and do not yet discuss the new definitions.

A) In Table II transmitted data 'x' is sent over the channel. The EM disturbance, however, forces a '1' or a '0' on all the three traces ('1' in the example). In that case, the voter receives a '1' on all three traces regardless of what the actual sent data 'x' was. If 'x' was a '1' then the assessment condition is a True Positive (TP). On the other hand, if 'x' was a '0', then it results in a False Negative (FN). In both cases the channel gets saturated and the EM disturbance is deciding the final outcome. In the case of the TP, it is just a matter of luck that the received output is the same as the transmitted data since data is actually not used by the voter to make the final decision. Hence, a new definition for this kind of TP is needed, which shows that the channel or the EMI decides the final outcome of the result. The case of the FN is even worse since EMI enforces a wrong output at the receiver. Furthermore, no warnings can be issued by the voter in both TP and FN since the voter sees identical bits on all

TABLE I
ORIGINAL CONDITION ASSESSMENT DEFINITIONS

Detector outcome	Receiver output	System effect	Upper layer effect
True	Positive	No effect	Data is used
True	Negative	Reduces availability	Warning
False	Positive	Reduces availability	Warning
False	Negative	Reduces safety	Data is used, no warning

TABLE II
2OO3 VOTER EXAMPLE

Case	Trace 1	Trace 2	Trace 3	Data Input	Voter input	Received output	Old definitions	New definitions
A	1	1	1	1	111	1	TP	CTP
				0	111	1	FN	CFN
B	1	0	1	1	101	1	FP	CFP
				0	101	1	TN	CTN
C	1	x	1	1	111	1	TP	CTP
				0	101	1	TN	CTN
D	1	x	0	1	110	1	FP	DFP
				0	100	0	FP	DFP
E	1	x	x	1	111	1	TP	DTP
				0	100	0	FP	DFP
F	x	x	x	1	111	1	TP	DTP
				0	000	0	TP	DTP

the three channels.

B) The example of case-B is shown in row 2 of Table II. The EM disturbance, in this case, forces a ‘1’ on two of the three traces and a ‘0’ on the 3rd one. This scenario could arise when the traces are placed sufficiently electrically apart from each other. The voter receives a ‘101’ as input regardless of what the actual sent data ‘x’ was. If ‘x’ was a ‘1’ then it results in a False Positive (FP). On the other hand, if ‘x’ was a ‘0’, then it results in a True Negative (TN). Here as well, the channel is getting saturated and EMI is deciding the final outcome. Just like the TP in the previous case, in the case of FP, it is again serendipity that the received output is the same as the transmitted data since data is not used by the voter to make the final decision. The voter, however, in this case is able to generate a warning since all the three received bits are not identical. From a safety point of view, a FP is a favourable scenario, although it does reduce the availability. In the case of a TN, EMI is enforcing a wrong output at the receiver, but the voter is able to generate a warning. In both cases we are however again lucky that the EM disturbance forced data on the line that is able to be detected.

C) The example of case-C is shown in row 3 of Table II. The EM disturbance, in this case, forces a ‘1’ on two of the three traces and the data (or the sender) forces ‘x’ on the 3rd one. The voter receives ‘111’ as input if ‘x’ is a ‘1’, and ‘101’ if ‘x’ is a ‘0’ . If ‘x’ is a ‘1’ then it results in a True Positive (TP). On the other hand, if ‘x’ is a ‘0’, then it results in a True Negative (TN). Here as well, the channel is getting saturated and EMI is deciding the final outcome even though the sender is enforcing the data ‘x’ on one of the channels. No warning can be issued in the case of the TP, so it is quite dangerous from the safety point of view. The voter, however, in the case of the TN is able to generate a warning. Both are bad scenarios from a safety point of view, but at least in the case of the TN there is a possibility of triggering the system’s safe mode of operation.

D) The example of case-D is shown in row 4 of Table II. The EM disturbance, in this case, forces a ‘1’ on one of the traces and a ‘0’ on the 2nd trace, and the data (or the sender) forces an ‘x’ on the 3rd one. The voter receives a ‘110’ as input if ‘x’ is a ‘1’, and ‘100’ if ‘x’ is a ‘0’ . In both cases, it results in False Positive (FP) and although an EM disturbance is present, it is still the data that decides the output. In comparison to the previous cases, the channel health in this case is sound as data ‘x’ is determining the final outcome. It is also a favourable scenario from the safety aspect. Availability is the main concern in this case since an error is detected while there is none.

E) The example of case-E is shown in row 5 of Table II. The EM disturbance, in this case, effects only one of the traces while the data (or the sender) forces an ‘x’ on the other two. The voter receives ‘111’ as input if ‘x’ is a ‘1’, and ‘100’ if ‘x’ is a ‘0’ . If ‘x’ is 1, then it results in a True Positive (TP) and if ‘x’ is 0, again a FP. Just like case D, the channel health in this case is also sound as data ‘x’ is determining the final outcome despite EMI interference. In the TP case, however, it is favourable from both the safety and availability aspects as the correct output is received and also the voter is not triggering a false alarm.

F) CASE-F is the ideal scenario where the channel does not get corrupted despite being exposed to EMI. Data ‘x’ is correctly received on all three channels and EMI has no effect on the communication.

This example clearly illustrates that the conditions like a True Positive and False Positive do not always resemble a possible safety vulnerability. They could be forced by an EM disturbance. Hence new definitions are needed that show what forces the output of the receiver, is it the Data from the transmitter or the Channel itself?

III. AN EXPANDED CONDITION ASSESSMENT DEFINITION

In Section II it has been shown that the current condition assessment of EMI detectors has possible flaws. A True Positive is seen as a safe state of the transmitter channel model, while EMI or another error could also lead to a True Positive. In order to overcome these flaws, new condition assessment definitions have been developed and are presented

TABLE III
EXPANDED CONDITION ASSESSMENT DEFINITIONS

Receiver output defined by:	Detector outcome	Receiver output	Channel health	System effect	Upper layer effect
Data	True	Positive	Good	No effect	Data is used
Channel	True	Positive	Bad	Reduces safety	Data is used, no warning
Data	True	Negative	Good	Reduces availability	Warning
Channel	True	Negative	Bad	Reduces safety	Warning
Data	False	Positive	Good	Reduces availability	Warning
Channel	False	Positive	Bad	Reduces safety	Warning
Data	False	Negative	Good	Reduces safety	Data is used, no warning
Channel	False	Negative	Bad	Reduces safety	Data is used, no warning

in this section. The previous section clearly indicated that there should be at least multiple types of a 'True Positive'. Hence, for every possible condition assessment definition shown in Table I two new condition assessment definitions are defined providing new insights used in the analysis of the effectiveness of EMI detectors.

In Table III the new expanded condition assessment definitions are shown. An extra column has been added to define whether the data from the transmitter or the channel is in control of the receiver output. Knowing whether the data or the channel is in control for a given communication channel is important. It shows the channel health (a new evaluation column) and reveals possibly new safety problems for the system using the transmission channel. The following new condition assessment definitions are:

- **Data True Positive** (*DTP*): The receiver output is correct, the detector outcome is correct and the receiver output is depending on the transmitter data. This condition is the best possible one. It shows us that the channel is in good health and that there is no immediate indication that the next transmitted information would be wrong.
- **Channel True Positive** (*CTP*): The receiver output is correct, the detector outcome is correct, but the output is depending on the channel and not the data. This condition means that the we have a 50% (if the data itself has a 50% chance to end up as a '1' or a '0') chance to end up with a True positive, if the EM disturbance, or something else enforces a digital '1' on the channel and the sender also happens to have sent a '1' we end up with this True Positive. If the sender would have send a '0' instead, and the detector did not detect it, we would end up with a False Negative. Hence, a Channel True Positive is as dangerous for the system's safety as a False Negative.
- **Data True Negative** (*DTN*): The receiver output is wrong, the detector outcome is correct (it detected an error while there is an error) and the data determines the receiver output. This condition can exist in the 2oo3 comparator example when for example the transmitter is hacked. It could also exist in some error detection/correction codes where the code algorithm is not able to calculate any output for a specific number of bit flips.
- **Channel True Negative** (*CTN*): The receiver output is wrong, the detector outcome is correct (it detected an error while there is an error) and the channel determines the receiver output. In this case an error occurred on the channel and the detector has detected this. This case reduces the availability and safety of the system and produces a warning to the system.
- **Data False Positive** (*DFP*): The receiver output is correct, the detector is wrong (it detected an error while there is no error) and the data determines the receiver output. An error is detected while there is no error, reducing the availability of the transmission channel since one does not know if the data is still valid. Although the data still determines the output, it is an indication that the channel's health may degrade in the future.
- **Channel False Positive** (*CFP*): The receiver output is correct, the detector is wrong (it detected and an error while there is none) but the channel determines the receiver output. Again, an error is detected while there is no error, reducing the availability of the transmission channel. Yet in this case, the channel determines the output indicating a bad channel health.
- **Data False Negative** (*DFN*): The receiver output is wrong, the detector did not detect the error but the output is determined by the data. Hence, the transmitter is either hacked or is interfered internally. A very dangerous situation, since the received data will be used without any warning.
- **Channel False Negative** (*CFN*): The receiver output is wrong, the detector did not detect the error and the output is determined by the channel. Hence, the channel is deciding the final outcome of the transmission channel yet the receiver does not know. Again a very dangerous situation.

It should be emphasized that the most dangerous situations are the ones where no warning is given (DFN,CFN) and where there is a possible fifty/fifty chance that the output would be correct (CTP). An ideal error detector would have zero False Positives and zero False Negatives. Given the new condition assessment definitions, it could be stated that an ideal detector has zero Channel True Positives, zero Data False Positives, zero Channel False Positives, zero Data False Negatives and zero Channel False Negatives. Of course, when using a specific detector it cannot make a difference between these different condition assessment definitions during operation. However, in the development of such detectors they provide vital information on the effectiveness of the detector. A detector could be developed that focusses on reducing the number of Channel True Positives.

The last column in Table II shows the new condition assessment definitions next to the old ones. It is clear that the old definitions, in some cases, indicate a good-(green) or medium safety/availability condition(orange) while they are actually a very severe situation (red). The new condition assessment definitions now show the actual severity of the situation in the transmission channel.

IV. EVALUATING MULTI LAYER ERROR DETECTION SCHEMES

The definitions defined in Section III are proposed to be used in a detector at the receiving end of a channel with data being sent from a transmitter. However, they could also be used to assess the condition of multiple layers of a error detectors. In Fig. 2 a communication scheme is presented which consists of different layers of the transmitter, channel, receiver, detector model. Each layer could have its own detection and/or correction mechanism. The channel is the medium through which the data of that layer is sent. This implies that the transmitters of the lower layers' are part of a higher layer under discussion.

The example shown in Fig. 2 is used to show the relevance of the new expanded condition assessment definitions. It also shows how the condition in one layer can be catched and resolved in a next layer. Although this example is not realistic setting, it shows that by layering multiple detectors, a system could be made safer and more available with a larger design confidence.

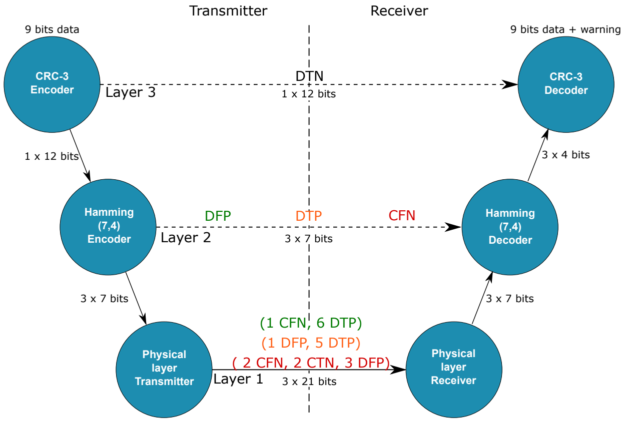

Fig. 2. Multiple layers of error detection

To be more specific, in Fig. 2 three different layers are shown. At layer 3, the transmitter and receiver/detector are defined as a CRC-3 encoder and decoder, respectively. Together they have the ability to detect bit errors. The channel, for layer 3, consists of the (i) Hamming(7,4) encoder, (ii) the physical layer transmitter, (iii) the physical channel, (iv) the physical layer receiver and (v) the Hamming(7,4) decoder.

The data itself comprises 9 bits and has three bits of the cyclic redundancy check [19] remainder, appended at layer 3, resulting in a total of 12 bits being transmitted over its channel. At layer 2 a Hamming encoder [20] is used. The Hamming coding method [20] is an error correction code that uses parity bits to determine if and possibly where a bit error has occurred. As shown in [15] a Hamming(7,4) (four data bits and three parity bits) has the ability to correct one bit error or detect two bit errors. However, it does not know whether a single error or two errors occurred. Hence a possible correction can still end up as a wrong output. When more than 2 bit errors occur in the Hamming(7,4), two possible outputs can be expected. The output can either be a detection and failed correction or no detection and a false negative as a result. Based on Section III, the failed correction can result in either a Data True Negative or Channel True Negative. The false negative, which occurs due to 3, 4 or 7 bit flips, will result in Channel False Negative, assuming that the bit flips are induced by or in the channel.

In the Hamming encoder, the 12 bits are divided into three groups of four data bits, on which three parity bits are appended. This results in three Hamming words, each consisting of 7 bits. These Hamming words are sent to the physical layer (layer 1) which in its turn sends the bits over a triple-redundant channel with e.g. time diversity, as described in [15], [21]. Each bit is sent 3 times across three different traces at three separate instances in time. A 2oo3 voter at the physical layer receiver then decides on the output. When a difference between the three traces exists a possible error is detected. As described in [9], this results in a drastic reduction of CFN due to a single frequency disturbance. However, as shown in [21] this is not flawless as multiple harmonics start to influence the channel differently. The channel (three physical traces) over which the 21 physical bits are sent, is the most vulnerable part of the fully layered communication system, since it has a higher chance to be affected by an external EM disturbance.

For each seven bits grouped per Hamming word at layer 1, the expanded assessment conditions definitions are given. In the first group (green), the first bit is corrupted resulting in a CFN while the others are a DTP. These 7 bits are given to the higher layer without any warning. At the second layer, the Hamming decoder can detect the CFN and correct the bit. However, it is not sure that there was only one or two faulty bits and hence raises a warning resulting in a DFP for the first Hamming word.

In the second group (orange), at the first bit, the voter detects a possible error resulting in a DFP. The other bits are a DTP. In this instance, the voter corrected the bit correctly. However, it is not sure and it sends a warning together with the 7 bits to the higher layer. At this layer, the Hamming decoder performs the Hamming decoding and concludes that the 7 bits are correct, resulting in a DTP. The third and last group of bits is interfered a lot more by an EM disturbance and results in two CFNs, two CTNs and three DFPs. This means that five bits (CTN and DFP) are corrected, and four bits are wrong (CTN and CFN). These 7 bits are given to the higher layer with a warning. At the next layer, the Hamming decoder performs the Hamming decoding and concludes that the 7 bits are correct, even though the Hamming word is incorrect resulting in the dangerous situation of a CFN.

All Hamming decoded bits are now sent to the CRC-3 decoder together with a warning of the first group. Although the first group does not contain an error, the last group does. The CRC-3 decoder is however, able to detect the errors of the last group, resulting in a DTN. This example shows that a multi-layered error detection scheme reduces the probability of a false negative propagating through the system. The third group of 7 bits resulted in a CFN, meaning it would be used without any indication that it is wrong. The voter from layer 1 detected several faults and tried to correct them. One can conclude that combining different layers of error detection schemes is beneficial when they are diverse and complementary. In this example, three different techniques are used based on a voter, parity and division. Combining detection schemes should avoid propagating false negatives through the system. This way, a higher level could focus more on improving the availability and trustworthiness of the system. An important component will be the different layers' warnings to see how the system could cope with uncertain data.

V. CONCLUSION

This paper discussed the old and new condition assessment definitions used for EMI detectors and EM diverse systems. It is shown that in some cases the old definitions indicate a safe condition of the transmission channel when this is actually only based on 'luck' and are possibly very dangerous. By introducing the new definitions, we can now perform a better analyses of the performance of EMI detectors for safety critical systems. They can also be used to indicate the propagation of possible conditions between multiple layers of error detection and correction systems. It is shown that the dangerous CFNs at a lower layer can be transformed to a DTN at the higher layers, going from a very dangerous situation to a bad, but safe situation. Results using these definitions are already shown in [22].

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