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Effectiveness of Forward Error Corrections Over Different Wired Communication Channels in Harsh Electromagnetic Environments

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***Abstract*—This paper presents the effectiveness of several forward error corrections in a harsh electromagnetic environment. A harsh electromagnetic environment consists of many reflections and unknowns which could negatively impact the functioning of the operational equipment or systems therein. Accordingly, four printed circuit boards with varying EMC designs are considered to emulate four single-trace communication channels. In addition, based upon the reflective characteristics of harsh electromagnetic environments, a Vibrating Intrinsic Reverberation Chamber is used to produce such an environment. It is found that in such a complex environment, with poor EMC-aware design, the reliability of the data transmission can be substantially decreased. A good EMC-aware design provides far better electromagnetic resiliency under similar conditions. Nevertheless, this design still can be affected under harsher electromagnetic environments. Furthermore, the results show that forward error corrections are able to significantly improve the electromagnetic resiliency of the communication channels. However, forward error corrections are not perfect. There are cases that a code word can get corrupted and turn into another valid code word. This type of error results in undetected corrupted data and is considered as the Achilles' heel of forward error corrections. Therefore, it can be concluded that even with both good electronic design and forward error corrections, the communication channels are not entirely safe. In this regard, other safety practices involving hardware-based and software-based techniques are required to limit the impact of electromagnetic disturbances on safety-critical or mission-critical systems in harsh environments.**

***Index Terms*—harsh electromagnetic environment, communication reliability, electromagnetic disturbance, forward error correction, resilience.**

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I. INTRODUCTION

Moving towards digital transformations, smart cities, and autonomous systems has led to an increase in the number of Electrical/Electronic and Programmable Electronic (E/E/PE) devices. Unfortunately, due to the design characteristics of these modern E/E/PE devices, in particular smaller voltage levels and feature size, they have become more vulnerable to Electromagnetic Disturbances (EMD) [1]. As a consequence, this could negatively impact the reliability of data transmission over the communication channels in these devices.

In a harsh electromagnetic (EM) environment which compromises of many reflections, EMD can induce voltages onto the communication channels and create bit-flips. Hence, the demand for mitigating the associated safety-related risks in E/E/PE devices has become of the utmost importance.

For decades, Error Control Techniques (ECT) have been developed and employed for controlling errors over noisy communication channels [2]. Forward Error Correction (FEC) is a subclass of ECT which is commonly implemented in the lower-layer of the protocol stack. FEC adds extra information to a data word and encodes it to a code word. This generates reduced dictionaries of code words. Later, this extra information is used during the decoding process to detect and correct the possibly corrupted data. In this regard, FECs have a capability to recover limited number of errors without a demand for retransmission.

FEC, however, has a major vulnerability. In some scenarios, code words can get corrupted in such a way that they turn into another valid code word. As a result, FEC cannot detect such corruptions and the decoder assumes that the received data is correct. From the safety viewpoint, these undetected corrupted data may lead to severe risks. Therefore, it is essential to reduce these undetectable corruptions to a level as low as reasonably practicable.

In previous studies, the effectiveness of several FECs were investigated against steady-state single-frequency EMD by means of our in-house developed simulation framework [3]–[5]. It was found that the majority of undetected corrupted data is produced owing to the repetitiveness in the generated code words.

This study takes one step further and considers a more realistic scenario to answer the following questions:

1) What is the impact of electronic design on the reliability of data transmission in harsh EM environments?
2) Are FECs sufficient to arm the communication channel in harsh EM environments?

Accordingly, three well-known FECs, including Reed-Muller codes [6], Hamming codes, and Triplication codes [3], are investigated under a harsh EM-environment. These codes are extensively implemented in telecommunication industry. Hamming codes are able to correct single-bit error, while Triplication and Reed-Muller codes have the capability to correct multiple-bit errors. Accordingly, this study carries out experiments on four dedicated designed printed circuit boards (PCBs) which mimic four single-trace communication channels.

There are various energy sources, such as Bluetooth, Wi-Fi, and Cellular, that are widely used in almost every environment, from homes and offices to safety-critical environments such as hospitals. In presence of these energy sources, the reflective characteristics of these environments could result in harsh EM environments. In this respect, this paper considers the hospital environment as an instance of a harsh environment since the risk and impacts are more severe in this case.

It is found that energy sources in hospital environments could intentionally or unintentionally generate EMD [7]. Considering the semi-reflective characteristic of the hospital environment, these energy sources could lead to extensive issues for the safety-critical or mission-critical equipments functioning in this environment. In this respect, this paper uses a Vibrating Intrinsic Reverberation Chamber (VIRC) to produce a harsh EM environment. The acquired responses from each PCB are then used in the considered EMD fault model to simulate the worst-case scenarios.

The remainder of this paper is organized as follows. Section II explains the experimental setup. Section III presents the response of each case study in the VIRC. Section IV uses the obtained information to investigate the effectiveness of FECs in a harsh EM environment. Finally, conclusions and future works are drawn in Section V

Fig. 1: An illustration of the VIRC setup used to mimic the hospital environment.

II. Experimental Setup

A. Vibrating Intrinsic Reverberation Chamber

This study uses a Vibrating Intrinsic Reverberation Chamber to produce a harsh EM environment. This reverberation chamber uses specific flexible walls made of conducting material [8]. In addition, there are varying angles among walls, floor and ceiling. In this regard, the VIRC is able to create a statistically uniform electromagnetic field without using a mechanical rotating mode stirrer. As mentioned, due to the associated risk and more severe impact of EMD in hospital environment, this paper uses hospital as an example of a harsh environment. It has been shown that hospital environments have a semi-reflective characteristic [9], [10]. Therefore, it is safe to assume that the VIRC could represent the similar conditions, as in a hospital environment, in terms of reflections [11], [12]. Accordingly, all measurements are carried out using a VIRC with a size of 150 cm $\times$ 120 cm $\times$ 100 cm as shown in Fig. 1.

B. Case Studies

Within this paper, four PCBs are presented to investigate the performance of different types of single-trace communication channels under a harsh EM environment. Accordingly, four PCB designs that emulate four independent single-trace communication channels are considered. These designs follow inconsistent EMC designs. In this way, it is possible to observe EM-diverse responses of these communication channels under a same harsh EM environment.

In all designs, a two-layer board is considered with a ground plane on the bottom layer and a microstrip on the top layer. The microstrip has a length of 10 cm and a width of 2 mm. All PCBs are fabricated with FR4 substrate. Note that the characteristic impedance of these designs is close to $50\,\Omega$. Furthermore, the connection between the traces and external hardware are established via SMA connectors.

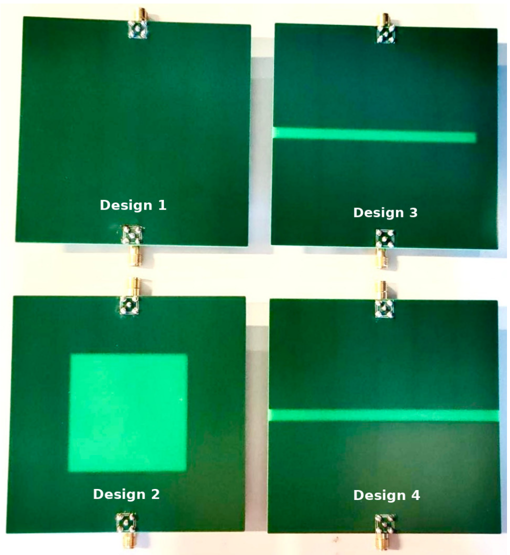

Fig. 2: The ground planes of the designed communication channels.

The following designs with four varied ground planes and an identical top layer are considered to mimic different communication channels. The ground planes of these designs are displayed in Fig 2.

- Design 1: This design follows good EMC design guidelines. The full ground plane at the bottom layer provides a proper return current path to the signal.
- Design 2: This design uses a square hole in the ground plane. This diverts the return current path to the outer edge of the hole.
- Design 3: This design uses a cut in the ground plane with a 1 cm connection at one edge. This diverts the return current path to the edge with a connection.
- Design 4: In this design, the ground plane is divided into two separate parts with no direct connection. This results in no direct return current path.

C. Measurement Setup

To perform the measurements, each design was separately placed in the VIRC. A tracking generator outside the VIRC was connected to a log-periodic broadband antenna inside the VIRC to generate an electric field. All traces were terminated with $50\,\Omega$ at one end, and connected to a spectrum analyzer at the other end. Note that the spectrum analyzer was synchronized to the tracking generator, and was calibrated to eliminate the losses of cables and connections. In this way, the responses of all designs were measured over the frequency range of 400 MHz to 2.5 GHz with a step of 2 MHz. These responses reveal the power level coupled into the traces in this particular VIRC. Correspondingly, these responses are used within this paper to calculate the induced voltage coupled into the traces over the specified frequency range. Furthermore, the aforesaid responses are used to give an overview of the radiated immunity of each design under the considered harsh EM environment.

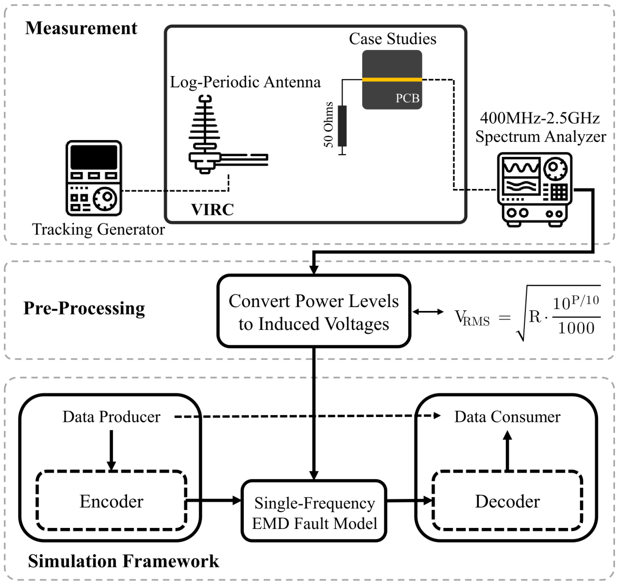

Fig. 3: Conceptual overview of the experimental setup.

D. Simulation Framework

This paper has employed the same fault model as used in [4], [5]. By default, this fault model uses a fixed induced voltage over a frequency range to generate steady-state single-frequency EMD. To achieve more realistic scenarios, the measured data in the VIRC is used to calculate the induced voltage at each frequency of the EMD. The representation of the simulated induced voltages is given in Equation (1). Furthermore, the conceptual overview of the experimental setup is demonstrated in Fig. 3.

$$\begin{cases} U_i = A \cdot \sin[(2\pi \cdot f_{\text{EMD}} \cdot t_i) + \phi] \\ t_i = \dfrac{i}{f_{\text{bit}}} \\ i \in [0, N-1] \\ \phi \in [0:359];\ \Delta\phi = 1 \text{ degree} \\ A = V_{\text{Peak}} = \sqrt{2} \times \text{Calculated Induced Voltages } (V_{\text{RMS}}) \\ N = \text{Code Word Length} \end{cases} \tag{1}$$

Additionally, the condition assessment definitions proposed by Claeys et al. [13], are applied to analyze the outcomes. Accordingly, eight categories are generated from the subsequent three questions:

1) Is the output data word correct? *Positive or Negative*
2) Based on the answer of question 1, is the detection outcome correct? *True or False*
3) Is the data in control or the channel in control? *Data or Channel*

Table I presents an overview of this category system. Note that this paper solely focuses on undetected corrupted data (i.e., shades of red) which includes Channel False Negative (CFN) and Channel True Positive (CTP). In these scenarios, the system is unaware of the corruption which could

TABLE I: AN OVERVIEW OF THE CONSIDERED CATEGORIES.

Category	Channel Status	Data Status	Detector Status	Label
Data True Positive	Data In Control	Uncorrupted	No Warning	
Data True Negative	Data In Control	Corrupted	Warning	
Data False Positive	Data In Control	Uncorrupted	Warning	
Data False Negative	Data In Control	Corrupted	No Warning	
Channel True Positive	Channel In Control	Uncorrupted	No Warning	
Channel True Negative	Channel In Control	Corrupted	Warning	
Channel False Positive	Channel In Control	Uncorrupted	Warning	
Channel False Negative	Channel In Control	Corrupted	No Warning	

result in critical failures. In case of a CFN, the channel turns the input data into another valid data, and FECs assume that all is right. In case of a CTP, however, the received data is correct, but out of pure luck. CTP happens when the data producer transmits a same value as the enforced value by the channel. In other words, if the data producer would have sent another data at that moment, then it would have ended up as a false negative. Thus, this category must be considered as dangerous as a CFN.

III. Radiated Immunity of the Communication Channels in Harsh EM Environments

Radiated immunity of the communication channels in safety-critical or mission-critical applications is of the utmost importance. In this regard, this paper focuses on the worst-case scenarios to analyze the behavior of the aforesaid designs against harsh EM environments. In the worst-case scenarios, the maximum power emitted by known and unknown superimposed energy sources is coupled to the victim device (i.e. the PCB designs in this case). Such scenarios may result in critical failures. Consequently, they could lead to severe harm to users, bystanders, and the environments. Correspondingly, the maximum value of the received power by each design is considered within this paper. Note that these maximum values are dependent to the input power of the VIRC.

A. Responses of Four Single-Trace Communication Channels in the VIRC Environment

Fig. 4 demonstrates the responses of four PCB designs. For more clarity, the input power is recalibrated to 0 dBm. As can be seen, designs 3 and 4 have higher power levels which indicate a higher power absorption by these two designs. This also indicates that designs 3 and 4 have a lower radiated immunity compared to designs 1 and 2. Simply put, less power is required to corrupt the data while it is transmitted via designs 3 and 4.

Accordingly, the induced voltages are calculated from these power levels via Equation (2). These calculated induced voltages are then used as the input of the EMD fault model.

$$V_{\text{RMS}} = \sqrt{R \cdot \frac{10^{P/10}}{1000}} \qquad (2)$$

Here, R is the characteristic impedance of the designs, P is the received power level, and V is the RMS value of the induced voltage in accordance to the considered concept.

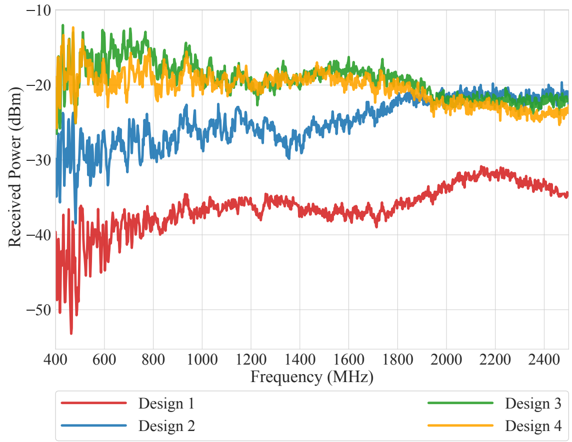

Fig. 4: Power received by the four PCBs, with the input power of 0 dBm.

TABLE II: INSTANCES OF THE POWER LEVELS PRODUCED BY SOME ENERGY SOURCES.

Energy Source	Subcategory	Power	Power level
Cellular	Power class 1 mobiles	2 W	33 dBm
	Power class 2 mobiles	500 mW	27 dBm
	Power class 3 mobiles	251 mW	24 dBm
	Power class 4 mobiles	125 mW	21 dBm
Bluetooth	Class 1	100 mW	20 dBm
	Class 2	25 mW	4 dBm
	Class 3	1 mW	0 dBm
Wi-Fi	2.4 GHz	100 mW	20 dBm
	5 GHz	200 mW	23 dBm

B. Overview of the Existing Energy Sources in the Hospital Environment

Table II lists examples of the power levels produced by some well-known energy sources [14], [15]. These technologies are extensively used in almost every environment. Some of these environments are safety-critical or mission-critical. Take hospital as an example. The risks and effects of EMD in such an environment is way more intense than in households or offices. Nowadays, almost everyone has a mobile phone. With that in mind, it is highly probable that hospital staff or visitors carry their phones to an environment with several functioning safety-critical equipment.

Furthermore, due to the semi-reflective characteristic of the hospital environment, other energy sources such as Bluetooth and Wi-Fi could add up to the existing field and make an even harsher EM environment. As a consequence, in the worst-case scenario, the emitted EMD from these energy sources can lead to critical failure in the victim device.

IV. Effectiveness of Forward Error Controls Against Single-Frequency Electromagnetic Disturbances

To investigate the impact of various energy sources on the reliability of data transmission in a harsh EM environment, two experiments are conducted using the four different PCB

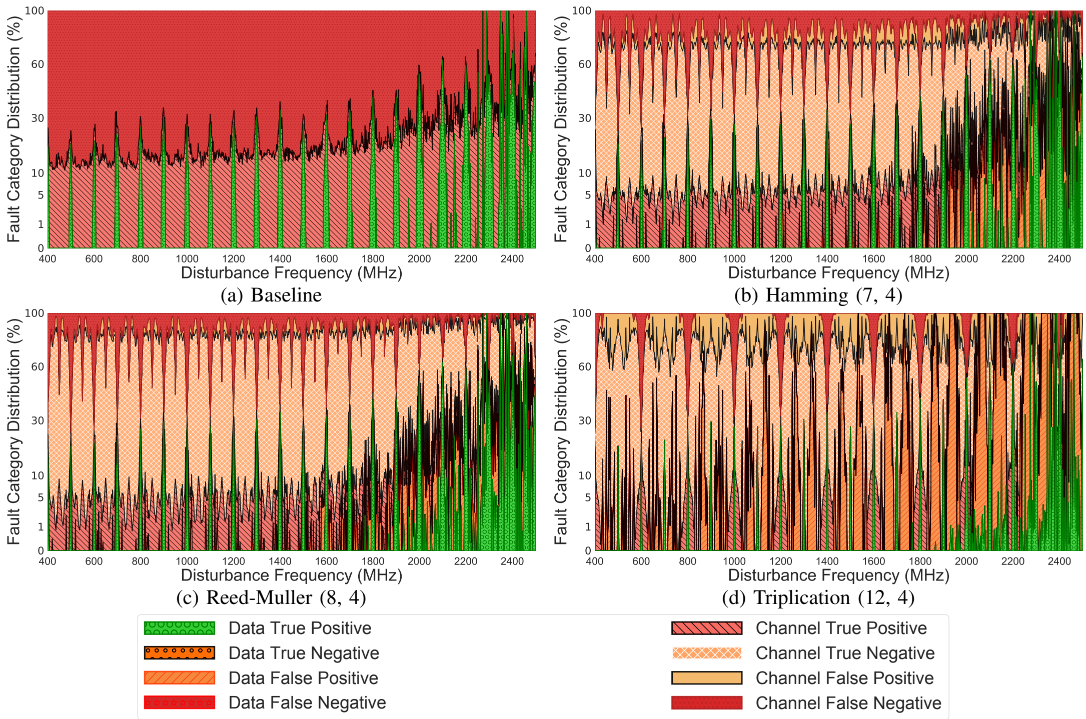

Fig. 5: The effectiveness of various FECs for data transmission using design 4 in the presence of an energy source equals to the Bluetooth class 1.

designs. First, data are transmitted without any added FEC to observe the impact of the communication design on the data transmission reliability in a harsh EM environment. In the second experiment data are transmitted by means of three different FECs. The purpose of this experiment is to investigate the effectiveness of FECs against single-frequency EMD. Furthermore, the outcomes of this experiment reveal the impact of combining a FEC and a specific communication design on the data transmission reliability under the considered setup. In this respect, sixteen experiments were carried out in presence of each energy source introduced in Table II of which the most important results are provided here.

Based upon the Equation (2) and the considered bit-flip threshold in the EMD Fault model (i.e., 0.5 V_{Peak} or 0.35 V_{RMS}), approximately 4 dBm at the end of the communication channels is required to generate a bit-flip. Since the setup elements are all linear, the power received by the PCBs can be scaled to any input power to investigate the impact of different power levels on the mentioned designs when exposed to the actual sources like Bluetooth or Cellular.

Accordingly, three well-known FECs, including Hamming (7, 4), Triplication (12, 4), and Reed-Muller (8, 4), are considered within this paper. By means of the EMD fault model, all possible data words with a length of four bits are transmitted using the mentioned FECs with a fixed bit-rate of 200Mbps. Subsequently, the input and output data words of these FECs are compared, and fault categories are generated. Fig. 5 shows the fault category distribution of data transmission via design 4 in the presence of an energy source equals to the Bluetooth class 1 (i.e., the power level of 20 dBm). In this respect, a bias of 20 dB is added to the measured responses to simulate the impact of this energy source. It should be noted that authors are aware of the fact that some of the introduced energy sources use modulation and operate within a certain frequency range. However, this paper has used a simplified model to represent and analyze the worst-case scenarios in harsh EM environments. Accordingly, single-frequency EMD are used to simulate the impact of such scenarios.

As can be seen, a significant portion of the received data in Fig. 5-a is undetected corrupted data (i.e., CFN and CTP). Note that the aforesaid spikes and the Data True Positive spikes (i.e., the green category) depend on the bit-rate frequency. Correspondingly, changing the bit-rate only shifts the spikes to other frequencies. Nevertheless, all FECs, notably the Triplication technique (i.e., Fig. 5-d), could significantly improve the EM-resiliency of the communication channels in terms of both CFN and CTP. Despite this improvement, the spikes of CFN and CTP still can be observed all over the considered frequency range.

The single-frequency EMD have a periodic pattern which could turn code words into another code word with repetitive (i.e., $[A, A, \cdots, A, A]$) or alternating patterns (e.g., $[A, A, B, B, \cdots, A, A, B, B]$ or $[A, B, A, B, \cdots, A, B]$). As these patterns are valid based on the initially generated dictionaries, FECs are unable to detect these errors [4], [5]. This explains why the Triplication approach outperforms the Hamming and Reed-Muller codes. The generated dictionary by the Triplication codes contains smaller number of code words with repetitive or alternating pattern. This, accordingly, results in fewer peaks of CFN or CTP. These outcomes are also true for all other FECs that generate code words with repetitive or alternating patterns. Therefore, it can be concluded that FECs with fewer number of repetitive or alternating code words have a better EM-resiliency against the single-frequency EMD.

It is worth noting that all designs remain unaffected (i.e., 100% Data True Positive) in presence of Bluetooth Class 2 or 3 under the considered setup. In addition, design 1 is the only design that remains unaffected in presence of all introduced energy sources in Table II. Nevertheless, energy sources above 37 dBm (i.e., generated by single energy source or superimposition of several energy sources) could lead to similar issues even for design 1. This is because this power level surpasses the specified threshold and result in bit-flips. This indicates that even with both good EMC-aware designs and FECs, the communication channels are not entirely safe. They can only provide EM-resiliency up to a certain level. Hence, supplementary hardware-based and software-based techniques, such as shielding and EM-resilient FECs, are required to increase the channel resiliency in the harsh EM environments.

V. Conclusion

This paper presented the effectiveness of several forward error corrections in a harsh EM environment. Four PCB designs with inconsistent EMC designs were considered within this paper to mimic four single-trace communication channels. This paper used VIRC to produce a harsh environment as both environments represent similar reflective characteristics. In addition, owing to the associated risks and more severe impacts of EMD in safety-critical environments, this paper considered hospital environments as an example.

In this respect, as the first step, the responses of each design were measured in the VIRC. Afterwards, the maximum values of the measured power levels were converted into induced voltages to represent the worst case scenarios. The calculated induced voltages then fed to the EMD fault model. Finally, the EMD fault model was employed to analyze the effectiveness of three well-known FECs, including Hamming codes, Reed-Muller codes, and Triplication codes, under the considered setup.

It is found that data transmission reliability can be degraded substantially over a communication channel with a poor EMC-aware design. A good EMC-aware design have a better EM-resiliency. Nevertheless, this design can also get adversely affected under harsher EM environments. In addition, this paper showed that FECs are effective tools to improve the EM-resiliency of communication channels. However, FECs are not perfect, and they are still vulnerable to undetected corrupted data. This is an extreme type of error which could not be detected by FECs. Consequently, undetected corrupted data can lead to critical failures.

Accordingly, this paper showed that even with both good EMC-aware designs and FECs, the communication channels are not completely safe. In this respect, further counter-measures including both hardware-based and software-based techniques are required to improve the EM-resiliency of communication channels in harsh electromagnetic environments such as hospitals.

In the future studies, new measurements will take place in the hospital environment, and they will be compared with the current findings. Moreover, more resilient FECs will be investigated to mitigate the number of undetected corrupted data during data transmission.

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