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# Exploring design diversity redundancy to improve resilience in mixed-signal systems

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ABSTRACT

Redundancy is the most popular technique to add fault tolerance at system level to electronic systems. Redundancy with hardware and software diversity of digital computers is currently employed in safety critical applications, as, for example, in spacecrafts and commercial aircrafts, to increase the reliability of such systems. This work presents a study of the design diversity redundancy technique in the context of mixed-signal systems, identifying the advantages and associated costs of applying this technique to subsystems with both analog and digital parts. The discussion is based on three case studies: two data acquisition systems and a low-pass filter, all of them prototyped in mixed-signal programmable platforms. In these systems, different combinations regarding the number of modules (double or triple modular redundancy) and specific issues related to the applied diversity modes are considered. Based on the results of fault injection campaigns by hardware emulation and one neutron irradiation test, the achieved reliability level of each studied system is discussed, as well as the tradeoffs of applying design diversity redundancy to mixed-signal systems.

## 1. Introduction

Modern electronic systems are subject to several sources of degradation and environmental perturbations that can generate physical defects and unintended electrical activity, which may lead to functional or structural faults, as well as hard or soft errors. Considering the submicron CMOS technologies, it is possible to cite various causes of faults at circuit level. In the early life of a given system, faults are mainly associated to manufacturing defects and incorrect designs [1,2]. However, significant defect sources may arise during the circuit lifetime that are usually associated to aging effects and environmental interactions. Examples of such defect sources are: thin oxide breakdown, caused by large electric fields in the insulator [3]; electromigration – the drifting of metal atoms due to the high current densities in the metal lines [4]; hot carrier injection into the oxide caused by high electric fields in the channel [5]; permanent or transient faults produced by radiation, such as alpha particles, cosmic rays and secondary neutron reactions [6,7]; abnormal electric activity caused by electromagnetic interferences [8], as well as electrostatic discharge [9] and other defects caused by an array of sources, like mechanical stress and corrosion, for example.

The techniques to protect the electronic circuits are often divided in device level, circuit level and system level and may be used separately or even together, in a single implementation.

Device and circuit level techniques are usually focused on preventing errors, and may not be always applicable or economically viable, since modifications at layout and circuit level are usually needed [10]. System level fault tolerance is specially recommended when recovery mechanisms are needed or when the access to device and circuit level methods are not available, as, for example, when employing commercial off-the-shelf (COTS) devices [11].

The most popular system level fault tolerance technique is the Triple Modular Redundancy (TMR), introduced in the 1950's by John von Neumann [12]. It is based on hardware redundancy and consists of triplicating the designed circuit, in a way that the outputs of the circuit copies feed a majority voter. If there is an error in one of the triplicated blocks, two of them are assumed to be operating properly and the majority value is chosen by the voter. TMR is a particular case of N-tuple modular redundancy, known as NMR [13], when N copies of the circuit are used to implement redundancy. The particular case when only two copies are used is known as Double Modular Redundancy (DMR) [14].

Design diversity has been employed in addition to modular redundancy to increase the fault tolerance of the final system [15] in presence of multiple fault scenarios. In this approach, the hardware and software elements used to perform multiple computations are not copies, but, instead, are independently designed to meet the requirements of the system. The interesting of using design diverse has increased due to the fact that complex system-on-chips (SoC) are nowadays more susceptible to multiple faults, and traditional redundancy may not be sufficient to mask multiple faults in mixed-signal designs.

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The authors in this work aim at discussing the relevant aspects of mixed-signal design diversity techniques, identifying the potentialities and the associated costs of the application of such strategy. The discussions rely on real data analysis from three case studies mixed-signal designs developed by our group, which consists of mixed-signal subsystems prototyped in programmable platforms. Two of these subsystems are data acquisition systems, one of them based on DMR with hardware diversity at the control circuit of the Analog-to-Digital Converters (ADC), implementing a Diverse-DMR (DDMR). The other data acquisition system implementation is based on Diverse TMR (DTMR) with hardware and time diversity. The third case study is a low-pass filter based on TMR with, hardware, level and domain diversity. These case study circuits were selected to exemplify the application of the technique, since they are interface blocks commonly present in many electronic systems. Furthermore, these subsystems allow the application of different diversity modes, as will be described in the remainder of the paper.

The paper is organized as follows: Section 2 presents a background of design diversity and it defines the types of implementations that can be used to employ design diversity redundancy to mixed-signal systems. Sections 3, 4 and 5 discuss each mixed-signal diversity implementation explored in this work and the obtained results for each case. Section 6 presents overall considerations, while concluding remarks are presented in Section 7.

## 2. Design diversity redundancy

Diversity has been used specially to mitigate common-mode faults, which occur when multiple copies of a redundant system suffer faults nearly simultaneously, generally due to a single cause [16]. Design diversity can be implemented in many different ways. Besides using different hardware copies (*hardware diversity*), the repetition of the computation with different clock rates can be considered as diversity implementation (also known as *time* or *temporal diversity*) [15]. Diversity can also be carried out by employing different design teams and design tools to the development of each system copy, in a way that commonalities are systematically avoided, or by using different architecture approaches. Thus, faults due to defective design or incorrect specification or modeling, will not produce similar errors in the majority of system modules [15,16].

The pioneers in the use of redundancy with diversity techniques were NASA (in spacecraft systems and military aircrafts) and the commercial air transport industry. To enable the use of digital computers on the Apollo missions to the moon, NASA made the Saturn V launch vehicle be controlled by an early triple redundant IBM computer [17]. The design and validation in spacecraft systems influenced the fly-by-wire flight control systems developed in the 1970's for military aircrafts. The basic F-8 mechanical control system, i.e., the mechanical links between the pilot and the control surface actuators, were completely removed with success [18].

The commercial air transport industry also was pioneer, presenting a classic example of redundancy with diversity. The Boeing 777 flight control computer is composed of three software/hardware variants developed for common specifications. Each of the variants is called a *lane*. The hardware for each lane is the same, except for the processor, since three different processors are used (AMD 29050, Motorola 68040 and Intel 80486). Each lane presents I/O, program and data memory that are not shared with the other lanes. The source code language for the three software variants is the same, except for some hardware dependent differences, but the parentage of the compilers is different [19]. Another example, the A320 from Airbus, uses four redundant computers on the flight control system. They consist of two different processors and four different softwares, made by two development teams [20]. This characterizes *software* or *program diversity*.

The above-mentioned examples consist of digital systems to which design diversity was applied. With the evolution of monolithic mixed-signal circuits and programmable analog and mixed-signal devices, a new paradigm on design diversity arises: *mixed-signal design diversity*. In this approach the redundant copies may be implemented in different levels and domains, when applicable: digital (software and hardware) and analog. Our research group was the pioneer on investigating mixed-signal (MS) design diversity that uses different domains to implement the system copies, and validating the mixed-signal redundant schemes by fault injection experiments (using hardware emulation) and radiation tests.

To proceed with the discussion presented in the next sections of this paper, it is useful to present two definitions, since no formal reference to these terms are available in the specialized literature. These definitions arise from the particular diversity modes that are possible to be applied in MS redundant systems.

**Definition 1.** We define as “level diversity” when at least one system copy performs its function by a software implementation while the other(s) are implemented purely by hardware.

**Definition 2.** We classify as “domain diversity” when there is at least an analog copy and a digital copy of the replicated blocks among the redundant modules.

Actually, domain diversity may be classified as a subgroup of hardware diversity, since, in this scheme, there is an analog HW copy and a digital HW copy. Level diversity may be seen as a composite redundancy form, derived from hardware and software diversity. This is because, even with a software implementation of the function among the replicated modules, this software runs on a specific hardware (a microprocessor, for example) that is different from the other hardware block(s), whose “program” is defined by a specific state machine.

Another diversity mode employed in this work is time diversity. The concept of time or temporal diversity is already widely explored to reduce errors in communication systems, by transmitting the same information in different times to avoid errors that may occur due to time dependent channel conditions, as, for example additive white noise [21]. In digital systems, a similar technique employed in redundant systems is known as time redundancy, which consists in introducing delays in the sampling clock of registers of the different copies of the circuit. This is usually added to TMR systems to cope with transient faults, since it is assumed that a transient fault that causes a temporary bit flip (which can be captured by a flip-flop), will vanish before being sampled by the replicated registers, whose clock edges are delayed [22]. The computation delay may also be added at macro level, which means that different processes are under execution in a given time frame since the time redundancy is added by delays between process execution [23], though running with the same clock frequency.

In the present work we explore time diversity by using different sampling rates in analog-to-digital converters, as will be discussed in one of the case studies presented in the remainder of this paper. This specific time diversity scheme allows employing an additional temporal voting, since redundant data is generated due to the diversity in the sampling rate.

Besides time diversity, the DDMR and DTMR systems studied in this work employ level, domain, and hardware diversity. Depending on the redundancy degree (double, triple or N-tuple) different combinations of these modes may be applied. Consequently, different voting schemes may be considered and specific synchronization blocks may be necessary to allow hardware and temporal diversity, as it will be discussed in the following sections.

## 3. Case-study mixed-signal system I: DDMR data acquisition system using level diversity

In this case study the implemented circuit is a data acquisition system composed by two Analog-to-Digital Converters (ADCs), in which the diversity is applied to the ADCs control circuits [24], as described