Self-Adaptive Single-Event Upsets Mitigation for Dependable Multiprocessing Systems

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***Abstract*—For safety-critical application in radiation-harsh environments, such as space applications, the static fault mitigation techniques based on the worst-case conditions are widely applied. However, this results in a resource overhead, since most of the time the system is over-protected. To overcome this issue, a dynamic self-adaptive platform is proposed here, which can collaboratively and efficiently mitigate Single Event Upsets (SEUs) on a highly dependable multiprocessing system. A low-cost on-chip SEU monitor network is proposed and integrated into this platform to ensure timely detection of high radiation levels and protection of sensitive circuits. A smart analysis unit drives the selection of multiprocessor operating modes according to the external environment and user/tasks requirements. Therefore, a dynamic trade-off between reliability, performance and power consumption in real-time can be achieved.**

***Keywords*— SEU mitigation, self-adaptive, SEU monitor, multiprocessing system**

I. INTRODUCTION

As technology scales, the radiation-induced effects, especially the Single Event Upsets (SEUs), are one of the major concerns for the design of modern nano-scale CMOS integrated circuits in space and aviation applications. SEUs, as transient faults in storage components, can be, for example, caused by high-energy particles which can pass through the sensitive region within a transistor and result in a change of state in the memory element. As a result of SEUs, a malfunction or complete failure of an electronic system may occur. Therefore, effective mitigation of the SEU effects is essential in mission-critical applications.

The main influence factor for the SEUs are the high-energy particles from cosmic radiation phenomena. These particles can directly affect electronic devices at high altitude, or indirectly by interacting with the atmosphere. These cosmological phenomena, known as Solar Particle Events (SPEs), can change the radiation environment with variable intensity of the particle flux over five orders of magnitude, thereby increasing the probability of SEUs. Since these high-level radiation phenomena can last for hours or even days, it is vital to be aware of the radiation condition in order to detect the abnormally of high radiation levels, and subsequently apply appropriate hardening measures.

Traditionally, a reliable design can be achieved by introducing fault tolerance and targeting the correct operation under the worst-case condition. The fault tolerance mechanisms can address the faults detection and even correction by adding redundancy in hardware, time, software or information to the system. However, this approach can also impose significant overhead in area/power consumption and performance penalties which is not unacceptable for many applications [1]. For example, Triple Module Redundancy (TMR) is a typical approach against soft errors. It can decrease the sensitivity of the system to soft errors by extending a single module with two identical replicas and a majority voter. However, an up to 400% power/area overhead is not acceptable for various resource-limited applications. Moreover, today's embedded systems are usually mixed-criticality systems, i.e. the requirements of the running applications with respect to reliability, performance, and power consumption could be dynamically adjusted during operation.

To overcome these limitations, this paper proposes a self-adaptive platform for multiprocessing systems, which are the backbones of the modern embedded systems. This platform utilizes the internal and external SRAMs to establish an SEU sensor network, which can monitor the external radiation condition and predict the potential large particle flux phenomena. The inherent advantage in hardware redundancy of multiprocessor systems is convenient for the deployment of reconfigurable/dynamic mechanisms, such as the core-level N-Module Redundancy (NMR), Adaptive Voltage Scaling (AVS), dynamic task scheduling, etc. Therefore, the use of the proposed platform in the multiprocessing system can enable the dynamic self-adaptive selection of the operating modes, providing optimal system reliability under variable radiation conditions during run-time.

II. PROPOSED SELF-ADAPTIVE PLATFORM

The proposed self-adaptive SEU mitigation platform is intended to be integrated into multiprocessing systems which contain reconfigurable/dynamic mechanisms. Fig. 1 shows the block diagram of the combination of the proposed platform with a flexible and highly dependable 4-core multiprocessing system which contains the core-level NMR mechanism [2]. This 4-core multiprocessing system has three operating modes: 1) in de-stress (and power-saving) mode, three of the cores are powered off, while only one core is actively executing instructions; 2) in fault-tolerant mode, two, three or all four cores simultaneously execute the same tasks in a Dual, Triple or Quadruple Modular Redundant (DMR, TMR, or QMR) fashion, respectively, in order to increase the error resilience; 3) in high-performance mode, all cores execute different

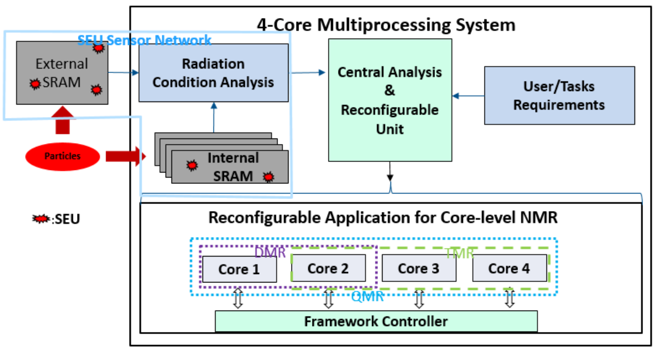

Fig. 1. Overview of the self-adaptive platform with 4-core multiprocessing system. The SEU sensor network can monitor the radiation particles and analyze the radiation environment. The appropriate core-level NMR operation mode can be decided according to the radiation environment and user/tasks requirements.

tasks. The objective of switching between different operating modes is to dynamically improve the reliability or enhance the performance by adjusting the "redundant" and "power off" status of the processing cores. Regarding the transient faults induced by radiation particles, the DMR enables detection of one core error output, TMR can mask one core error, and QMR has the ability to mask up to two erroneous cores simultaneously.

A. Sensor Network

The SEU sensor network is used to monitor space environment, quantify SEUs and classify the radiation level. The memory cells, especially SRAM cells, are much more sensitive than standard logic gates and very suitable to be used to detect the effect of radiation particles. In this 4-core multiprocessing system, each core has its own 32 KB scratchpad SRAM memory and also supports the external memory unit. Therefore, the 4-internal SRAMs in the proposed multiprocessing systems and the external SRAM can be utilized as SEU sensors.

The particle flux is measured with the memory by counting the number of flipping cells within one checking cycle. The sensor network was verified to detect the single and double bit errors as well as permanent faults in each SRAM memory words with a negligible cost and overheads compared to traditional stand-alone SEU sensors. By determining the Soft Error Rate (SER) of this SEU sensors, the external radiation condition can be evaluated. Moreover, the onset of SPE phenomenon can be predicted by evaluating the Mean Time To Upset (MTTU) of the sensors. The prediction of the SPE can let the system to respond appropriately in advance, in order to avoid the predicted large particle fluxes.

B. Control Unit

The decision tree for determining the optimal operation mode for this 4-core multiprocessing system is shown in Fig. 2. The quantification of reliability requirements for the system is based on the Safety Integrity Level (SIL), which is defined by the IEC 61508 standard and commonly referred by high-reliability requirements systems such as those in space

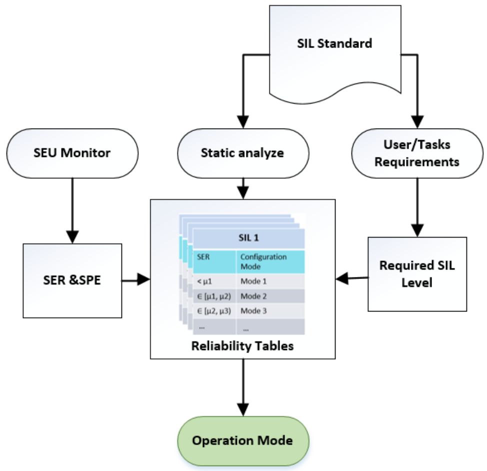

Fig. 2. Decision tree for determining the operation mode in the central analysis unit. The SIL standard is used here to quantify reliability requirements and establish an appropriate connection between the SERs from SEU sensor network with operation modes.

applications. In this standard, four SILs are proposed, with SIL 4 being the most dependable and SIL 1 as the least. The relationship between the SERs and the configuration modes under the constraint of SILs can be determined by static analysis. Four reliability tables can be formed to represent the connection between the SERs and operation modes under the different reliability requirements from each SIL. The system can launch a specific operating mode within a certain SERs range, in order to satisfy the SIL demand. Basing on the real-time SER information coming from the proposed monitor and the required SIL from the user/tasks requirements, the operating mode can be determined and launched according to these tables.

III. Conclusion

In this paper, we introduced a self-adaptive SEU mitigation platform for multiprocessing system. An SRAM-based SEU sensor network and a reconfigurable mechanisms control unit were presented. The optimal operating mode can be dynamically determined according to the SERs from the sensor network and user/tasks requirements, in order to realize the trade-off between reliability, performance and power consumption during run-time.

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