RADIATION EFFECTS ON ADVANCED MICROELECTRONICS FROM THE SPACE AND NUCLEAR WEAPON GENERATED RADIATION ENVIRONMENTS AND THEIR IMPACT ON SOFTWARE DEFINED RADIO (SDR) DESIGN

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ABSTRACT

This paper addresses radiation response issues associated with the deployment of Software Defined Radio (SDR) technology in natural space and nuclear weapons effects environments. This paper addresses the impact of these environments with respect to the electronic component technology likely to be employed in SDR applications along with a discussion of likely mitigation strategies. Dose rate, total ionizing dose (TID) and neutron effects will be considered for the nuclear weapons environment. The natural space radiation environment assessment will be based on trapped radiation in the van Allen belts, solar particle flux, and galactic cosmic rays and will consider TID and single-event effects (SEE). In terms of device response, exposure to either of these environments may cause parametric shifts in electrical performance, upset, latchup or possibly functional failure of the device under consideration. Because SDRs are likely to make use of state-of-the-art electronics such as FPGAs, DSPs, microcontrollers, SRAMs, SDRAM, and Flash Memory, special attention will be given to these technologies. The particular vulnerabilities of each of these device types with respect to radiation effects will be reviewed and discussed.

1. INTRODUCTION

Software defined radio (SDR) is an evolving technology that holds significant promise for military space and missile defense applications. One potential SDR application is in satellite and/or missile defense interceptor communications. SDR application on these types of platforms provides unique advantages over traditional "static" designs currently in use. Present-day deployed communications solutions tend to be point-source designs. In the case of space-based systems, these designs cannot be readily modified due primarily to the inaccessibility of on-orbit systems or, as in the case of ground based interceptor systems, the excessive cost associated with performing hardware upgrades. Furthermore, current design approaches do not lend themselves to multiple-system applications, thus driving non-recurring engineering (NRE) and deployment cost for developmental systems. The use of SDR solutions for deployed satellite and missile defense systems would be responsive to the issues outlined above. At the same time, SDRs would provide on-platform robustness to address evolving communications requirements and standards, potentially extending component lifetime, and allowing for improved system performance due to inherent adaptability to changes to the mission, threat, operational environments and/or performance requirements.

The hardware of a software-defined radio typically consists of an antenna, a RF front end, A/D and D/A converters, memory, DSPs, and FPGAs.

2. SPACE RADIATION ENVIRONMENTS

SDR application in space creates unique requirements that are not normally considered when developing a ground based communications system. This paper highlights the impact of ionizing radiation found in the natural space, as well as radiation created from nuclear exoatmospheric detonations, on SDR design.

A satellite's effective lifetime ranges from 5-10 years. Satellite communication links tend to be point source designs, i.e., a fixed design that is developed for a specific purpose. Due to the very nature of operation it is expensive and nearly impossible to make upgrades on orbit except in the most extreme circumstances. Implementing the SDR architecture in satellite communications (satcom) offers satellite designers an added degree of freedom with the ability to reconfigure the communication link remotely to incorporate new communication standards and increase link efficiency. Unique requirements exist for satellites depending on whether the asset is of commercial or military origin. Military space assets have radiation survivability requirements, while many commercial space assets are COTS based systems that don't include any radiation hardening requirements due to the perceived cost of hardening the system.

2.1 Natural Space Radiation

Natural space radiation is composed of cosmic background and solar radiation. The cosmic background radiation consists of high energy heavy ions. Solar radiation is cyclic (11 year solar cycle) in nature with increased intensity of radiation generated from solar flares on the surface of the sun. [1] Solar ionizing radiation is typically high energy protons and x-rays, protons being the majority. A graphic representation of the solar cycle is provided in Figure 1 below. SDR application in space can occur in two primary roles, as a short term communications payload for launch vehicles and missile interceptors, or a long term payload for satellites and deep space vehicles. Whether the mission is short term or long term, unique space radiation requirements exist for the SDR.

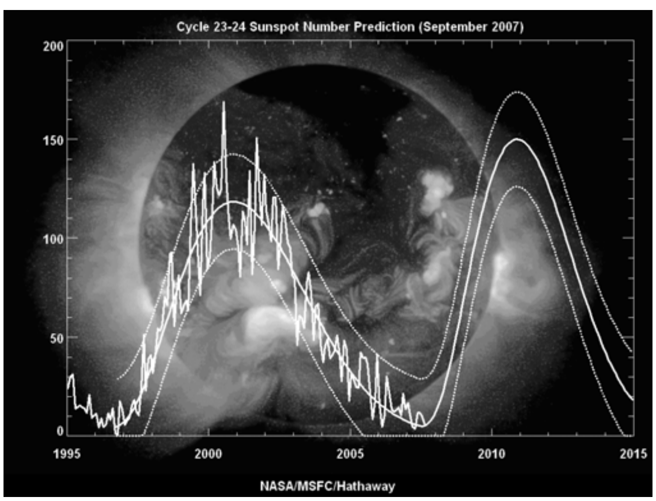

Figure 1. Graphical representation of the solar cycle provided by NASA/MSFC [2]

The primary effects of the natural space radiation environment that are of concern to deployed satellites are single event effects (SEE) and total ionizing dose (TID) effects. These ionizing radiation effects can be detrimental to mission success and lifetime if not managed throughout the design process and production of a satellite. Single event effects describe a variety of events caused by high energy ions interacting with a semiconductor such as single event upsets (SEU), single event latchup (SEL), single event burnout (SEB), and single event functional interrupt (SEFI). Single event effects are well documented in literature.

Launch vehicles and missile interceptors have a shorter mission lifetime than satellites, but have similar requirements due to the space environment. Do to the brief mission, launch vehicles and missile interceptors are most susceptible to single event effects due to the natural space radiation environment.

2.2 Nuclear Weapon Generated Radiation

The threat of nuclear weapons on space assets is well defined, and can be found in open literature. [3], [4] Unlike natural space radiation, exoatmospheric radiation generated by nuclear weapons is not easily managed due to the extreme intensity and complex radiation environment created by the nuclear weapon. A notional radiation environment caused by the detonation of a nuclear weapon in the space is shown in Figure 2 below.

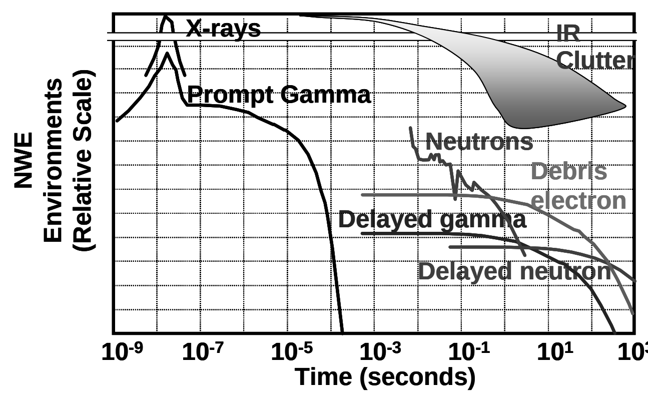

Figure 2. Nuclear Weapon Radiation Environment vs. Time

The nuclear weapon radiation environment lasts from tens of seconds to many days. A nuclear weapon radiation environment can be broken into three categories: prompt, delayed, and persistent, each of which causes unique failure mechanisms in integrated circuits. From Figure 2, in a matter of nanoseconds, intense prompt gamma rays and x-rays arrive at the speed of light causing massive disruption to all integrated circuits. This disruption is called a dose rate upset. These effects are a result of the interaction of the x-rays and prompt gamma rays generated by the detonation with the semiconductor lattice. Intense current pulses (called photocurrents) are created through the physical interactions of the photoelectric effect and Compton scattering in the semiconductor material. These photocurrents are of significant concern and their ramification on integrated circuits will be detailed in Section 3. Delayed nuclear radiation typically begins arriving in less than a second and includes neutrons and electrons, as well as delayed gamma rays. The neutrons are of most concern to integrated circuits (IC), particularly digital ICs. Digital ICs are highly susceptible to neutron induced upsets (NIU). NIU is similar to SEE in results, but different in mechanisms. Neutrons also cause displacement damage in the semiconductor lattice which degrades the operational efficiency of an IC by slowly damaging the device until it begins operating out of specification. Delayed electrons tend to persist for a long period of time (days/months) after a nuclear detonation in the exoatmosphere. This is described as persistent radiation. Persistent radiation pumps the radiation belts around the Earth and increases the overall total ionizing dose that a system in space would encounter. While a satellite may be designed to operate for 5-10 years in orbit, a nuclear weapon detonation in space would degrade the operation and drastically shorten the lifetime of a satellite, thereby, critically disrupting commercial, civil, and military satellite operations for years. A nuclear weapon detonation in orbit can also affect launch vehicles and missile interceptors by interrupting critical tracking, trajectory and communication functions, thereby disrupting the short time line these systems are in operation and possibly leading to mission failure.

3. MICROELECTRONIC DEVICE RESPONSES

In this section, the response of microelectronic devices to ionizing radiation will be briefly discussed. It should be noted that a wealth of knowledge exists in the radiation effects community through refereed journals such as the Journal of Radiation Effects, Research and Engineering, and the IEEE Nuclear and Plasma Science Society, Transactions on Nuclear Science as well as numerous published books. [5,6]

This section will begin with a discussion of the radiation response to the natural space radiation environments effects on integrated circuits. Following this overview will be a discussion on the impacts and effects of the nuclear weapon radiation environment on integrated circuits.

3.1 Natural Space Radiation Effects

As described in Section 2.1, there are two primary effects on integrated circuits due to the natural space radiation environment, SEE and TID. Since both TID and SEE are from ionizing radiation, it is important to address the difference between the two with respect to design and analysis. TID is a long-term failure mechanism versus SEE which is an instantaneous failure mechanism.

SEEs are the result of a single energetic atom typically from the cosmic background or high energy protons from solar flares. An SEE occurs when the charged particle loses energy by ionizing the semiconductor through which they pass, leaving behind a wake of electron-hole pairs. This wake of electron-hole pairs creates a disparity in the static state causing currents to flow which can cause multiple types of errors. SEE errors are categorized as single event upsets (SEU), single event transients (SET), single event latchup (SEL), and single event burnout (SEB). Single event effects are a major concern for SDR design.

SEUs are transient soft errors, and are non-destructive. A reset or rewriting of the device results in normal device behavior thereafter. An SEU may occur in analog, digital, or optical components, or may have effects in surrounding interface circuitry. SEUs typically appear as transient pulses in logic or support circuitry, or as bit flips in memory cells or registers.

SETs in a linear device are caused by the generation of charge by a single particle (proton or heavy ion) passing through a sensitive node in the linear circuit. The SET consists of a transient voltage pulse generated at that node that propagates to the device output, where it appears as the same voltage transient, an amplified version of this transient, or a change in the logical output.

SELs are hard errors, and are potentially destructive (i.e., may cause permanent damage). The SEL results in a high operating current, above device specifications. The latched condition can destroy the device, drag down the bus voltage, or damage the power supply. Typically, the concern is latchup caused by heavy ions. However, latchup can be caused by protons in very sensitive devices. An SEL is cleared by a power off-on reset or power cycling of the device. If power is not removed quickly, catastrophic failure may occur due to excessive current flow and heating, leading to metallization or bond wire failure. SEL is temperature dependent: the threshold for latchup decreases at high temperature, and the cross section increases as well.

SEB is a condition that can cause device destruction due to a high current state in a power transistor. SEB causes the device to fail permanently. Specific types of SEB include burnout of power MOSFETs, gate rupture, frozen bits, and noise in CCDs (charge-coupled devices). SEB susceptibility has been shown to decrease with increasing temperature.

TID is mostly due to electrons and protons and can also result in device failure. In low earth orbit (LEO), the main dose source is from electrons and protons (inner belt); in geostationary earth orbit (GEO), the primary source is from electrons (outer belt) and solar protons. Long-term exposure can cause integrated circuit threshold shifts, increased leakage current and power consumption, timing changes, and decreased functionality.

3.2 Nuclear Weapon Radiation Effects

As stated in Section 2.2, nuclear weapon radiation effects in integrated circuits are dose rate effects, total ionizing dose, neutron induced upsets, and neutron displacement damage.

Dose rate effects are categorized as dose rate upsets, dose rate latchup, and dose rate burnout. As mentioned above, dose rate effects occur by the intense photocurrents caused by the interaction of the gamma rays and x-rays of the nuclear detonation with the electronic component. These photocurrents can range from milliamperes to many amperes in intensity. Most integrated circuits are not designed to handle these current levels even in ultra short durations (tens of nanoseconds). Devices which are sensitive to the generated currents will, at the least, upset and lead to data corruption to the extreme of latchup and, even worse, burnout. The major concern for the SDR design is latchup and burnout. Devices that latchup must have the input voltage reduced below the holding voltage of the circuit. This resets the device and releases the latchup. For certain devices latchup can lead to permanent catastrophic failure, referred to as a device burnout or dose rate burnout.

Neutron effects from a nuclear weapon detonation are neutron induced upsets (NIU) and neutron displacement damage. Digital integrated circuits are particularly sensitive to NIU. A NIU is a single event effect caused by a neutron, a subatomic particle that has no charge. Unlike protons and electrons which interact with the semiconductor material via ionization, NIUs are caused when a neutron directly impacts an atomic nucleus of the semiconductor. The neutron induces a nuclear reaction in the atomic nucleus yielding a radioactive isotope that must decay to a stable atom species. This decay process yields reaction products such as protons, beta particles (electrons), and alpha particles. These secondary particles create ionization similar to those of heavy ion single event effects, leading to transient upsets like those witnessed via SEE from external heavy ions and protons.

In a subset of this effect, the atomic nucleus that is impacted by the neutron will also have some energy converted to mechanical energy which causes the atomic nucleus to recoil, damaging the semiconductor lattice. If the flux of neutrons is high as found in a nuclear weapon detonation, the integrated circuit operation will degrade due to this recoil damage. This damage is termed neutron displacement damage. The damage is evident similar to the total ionizing dose effects, including threshold shifts, increased leakage current and power consumption, and decreased functionality.

In the case of nuclear weapon radiation, TID is heavily affected by the gamma ray and x-ray environment. The dose of ionizing radiation received from a nuclear weapon is prompt and extreme in magnitude compared with the natural space environment.

4. IMPACT ON SDR DESIGN

The primary benefit to SDR's is the ability to reconfigure the unit. Maintenance operations allow the ability of being able to simply update waveforms and protocols without redesigning and/or de-installing the radio. During normal operation, SDR's allow the ability to dynamically reconfigure operational parameters as mission criteria changes. In order to implement this level of reconfigurability requires a higher level of software components and processing power than in previous systems. Unfortunately, in the context of a radiation environment, this makes the SDR's more susceptible to the effects of radiation than ever before. To achieve these design criteria for space applications, unique requirements will need to be considered in the development and production of a SDR for exoatmospheric application.

The unique space applications described in this paper are satellites, launch vehicles, and missile interceptors. Each application has unique requirements beyond normal operating requirements that must be defined to ensure operation and survival in the natural or hostile radiation environment.

In the simplest of forms, a SDR is comprised of an antenna, RF interface, A/D and D/A converters, digital signal processors (DSP), field programmable gate arrays (FPGAs), and memory. Each of these devices will have a specific response to ionizing radiation that must be accounted for and designed into the SDR operating margins. This process can begin with analysis at the onset of a design to ensure appropriate part selection that will meet ionizing radiation requirements.

There will be different impacts on SDR design depending on the radiation environment. Satellites will have requirements that must manage the single event effects and total ionizing dose effects for the 5-10 year lifetime of the system. The requirements will vary depending on whether this is a military or a commercial asset. Military satellites may have additional requirements to manage any threats from possible nuclear weapon detonation in the exoatmosphere. Launch vehicles and missile interceptors will have different requirements. The mission life for both is significantly shorter than that of a satellite. Therefore, both may not be as susceptible to total ionizing dose effects. Military assets tend to have higher requirements in radiation due to the criticality of its mission. Commercial entities tend not to be concerned with planning for nuclear war, while the military must take this into consideration when designing systems.

Amtec Corporation has developed a methodology to assess the radiation survivability of systems such as SDRs in radiation environments. The survivability assessment includes an evaluation of piecepart/component hardness relative to total ionizing dose (TID), dose rate, neutron, solar and galactic particles, and electromagnetic pulse effects. Piecepart/component survivability issues to be considered include device performance degradation/failure due to accumulated ionizing dose; data corruption due to dose rate effects or single event effects (SEE); latch-up due to dose rate effects or SEE; burnout due to dose rate, SEE, or a sustained latch-up condition. Amtec's proprietary Hardness Engineering Assessment Tool (HEAT™) is used to guide these evaluations, identify susceptible components and assess the estimated probability of survival (Ps) or margin for each piecepart/component evaluated along with an overall system Ps. Developed to support ionizing radiation hardening efforts by Amtec personnel, HEAT™ allows trained Amtec survivability engineers and scientists to be able to model the system topology, describe the components and materials, apply the required radiation environments, transport those environments, perform assessments and apply mitigation techniques. Modifications needed to achieve an effective hardening solution in an SDR design can be developed and implemented into these assessments.

Amtec Corporation and Rockwell Collins, Inc are currently applying the HEAT™ methodology in one of Rockwell Collins designs for the Missile Defense Agency (MDA).

5. MITIGATION STRATEGIES

Key to the mitigation of radiation induced effects in a SDR is an understanding of final system implementation. There are multiple ways to mitigate radiation induced effects. Knowledge of the operating condition is principal in many of the decisions that are required during mitigation studies. System architecture to include intrinsic shielding must be well understood. First and foremost, analysis must be completed to determine devices performing poorly in the radiation environment requirements. Output of this analysis is used to determine appropriate methods to improve the operation of the SDR in the radiation environment. Parts/components requiring replacement can be identified along with other hardening strategies and mitigation approaches to ensure a SDR design that operates as it is intended in the radiation environment requirements.

Natural space radiation, TID effects may be mitigated using radiation hardened devices and added shielding. Electrons and low energy protons can be partially mitigated with shielding. For higher energy particles and for missions that have intense radiation survivability requirements such as nuclear weapon radiation effects, radiation hardened devices may be required.

Digital ICs that are susceptible to single event effects can be mitigated using strategies that range from parts replacement, Error Detection and Correction (EDAC) implementation, triple mode redundancy (TMR), incorporation of radiation hardened devices, and other mitigation strategies required to achieve the objective radiation hardness survivability.

SDRs that are required to operate through a nuclear radiation environment (such as a launch vehicle or missile interceptor) may require a circumvention process to manage the effects of the prompt radiation and still carry out its mission. Circumvention is the process of storing mission critical information in hardened memory, shutting a system down, and then restarting and restoring the system to its previous state after a short period of time. Due to the intense ionizing radiation environment, circumvention tends to be the most economical solution to ensuring mission success. It is cost prohibitive to design a complete system with radiation hardened devices, as well as impractical since most of these devices are built in old technology that does not meet the performance requirements that a modern system would need.

6. CONCLUSIONS

The technical advantages of using SDRs in space applications provide flexibility for both commercial and military entities to ensure enhanced capabilities as waveforms and protocols improve. Technical challenges must be overcome with respect to the unique ionizing radiation environments present to implement SDRs into space applications. Specific to these challenges is the mitigation of ionizing radiation on advanced integrated circuits that would comprise the SDR. Through thoughtful analysis and design, proper mitigation strategies can be developed and implemented to ensure SDR operation in the unique radiation requirements of space.

7. REFERENCES

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