

Soft Error Considerations for Computer Web Servers

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***Abstract** – Soft errors are caused by cosmic rays striking sensitive regions in electronic devices. Termed as single event upset (SEU), in the past this phenomenon mostly affected the high altitude systems or avionics. The small geometries of today's nanodevices and their use in high-density and high-complexity designs make electronic systems sensitive even to the ground-level radiation. Therefore, large computer systems like workstations or computer web servers have become major victims of single event upsets. Given that the idea of cloud computing is an unavoidable trend for the next generation internet, which might involve almost every company in the IT industry, the urgency and criticality of the reliability rise higher than ever. This paper illustrates how soft errors are a reliability concern for computer servers. The soft error reduction techniques that are significant for the IT industry are summarized and a possible soft error rate (SER) reduction method that considers the cosmic ray striking angle to redesign the circuit board layout is proposed.*

I. Introduction

The term single event upset (SEU) refers to a change in the state of a circuit caused by high energy alpha particles or neutrons striking a sensitive area in a microelectronic device. Until few years ago, this was only a concern for high-altitude avionics. It has become a significant electronic reliability issue for contemporary ground-based electronics. SEUs are also referred to as soft errors.

The single event upset phenomenon has been extensively studied by electrical, aerospace, nuclear and radiation engineers for almost half a century. Ground level strikes were observed and recorded in error logs for computer systems containing large amounts of random access memory. This provided a solid evidence of SEUs [15]. In the period 1954 through 1957 failures in digital electronics were reported during the above-

ground nuclear tests. These were treated as electronic anomalies in the monitoring equipment because they were random and their cause could not be traced to any hardware fault [24]. Perhaps the first paper postulating the role of cosmic rays on electronics is by Wallmark and Marcus [22]. These authors predicted that cosmic rays would start upsetting microcircuits due to heavy ionized particle strikes when feature sizes become small enough. The main sources of radiation environment within the interest of avionics and electronics at the terrestrial level are listed below [4]:

- Proton and electrons trapped in the Van Allen belts [8]¹.
- Heavy ions trapped in the magnetosphere.
- Cosmic ray protons and heavy ions.
- Protons and heavy ions from solar flares.

The radiation levels strongly depend on the activity of the sun, varying over an eleven year cycle. At the terrestrial level, when cosmic particles collide with atoms in the atmosphere, they create cascades or showers of neutrons and protons, which in turn may interact with sea-level electronics. In addition, alpha particles from package impurities can be another major source of terrestrial SEUs.

Non-environmental conditions, like loose connections, aging components, power supply noise, resistance and capacitance variations, etc., may not affect the sub-micron semiconductor reliability due to advances in the design and manufacturing technology and can be ignored. However, errors caused by cosmic rays and alpha particles remain the dominant errors in electronic systems [23]. The presence of alpha-particles can be greatly reduced by removing the radioactive impurities from the package material. Shielding is an alternative approach. However, shielding against neutrons is harder to achieve because

¹The radiation belts are regions of high-energy particles, mainly protons and electrons, held captive by the magnetic influence of the Earth (Source: NASA Thesaurus).

TABLE I. Commodity flash memory reliability requirements.

Year	2007	2010	2013	2016
Density (megabit)	1024	2048	4096	8192
Maximum Data Rate (MHz)	166	200	250	300
MTTF (hours)	4020	4654	5388	6237

there are still no effective absorbents found. For example, to completely eliminate cosmic particles by shielding, more than 10 feet thick concrete should be used [20]. Mason predicted that failures caused by neutron strikes will be the dominant soft failure mechanism of programmable logic [12]. Nanotechnology microelectronic systems are more vulnerable to soft errors when they contain densely packed components. For the ground level electronics, the computer web server would become a major victim of SEUs as we will discuss in Section II. The internet is one of the most important evolutions of the 20th century. People from different continents are seamlessly connected by e-mails, instant messengers, blogs, online-communities, IP-phones and web meetings. Internet changes the way human lives. The number of web servers skyrockets every year. From a *Netcraft Ltd.* web server survey, there were more 230 million web sites around the world by November 2009, up from 168 million in early 2008 [13]. The downtime of a server will cause previously unimagined inconveniences, which sometimes may be critical. Take e-commerce for example. According to *ComScore, Inc.*, during 2007 holiday season from November 1 to December 31 the e-commerce shopping surpassed \$29 billion in sales, which makes a 19 percent gain over the same period in 2006. Such growth is expected to continue [10].

The closeness relationship between human life and internet, as well as the business, requires high reliability in web servers. The web server reliability and the continuous availability of the data on demand are the lifelines for the high traffic sites.

In this paper we discuss how the soft error could become a reliability nightmare and then summarize soft error reduction techniques used in the IT industry. In Sections II and III, the newly emerging problems caused by the technology trends and widely used soft error protection techniques are analyzed. A possible reliability improvement technique based on how cosmic ray striking angle affects the soft error rate (SER) is proposed in Section IV .

TABLE II. Typical server system reliability goals.

Error Type	System MTBF Goal
SDC (Silent Data Corruption)	1000 years (114 FIT)
DUE for system crash	25 years
DUE for application crash	10 years

II. Why Soft Error Is a Concern

Increasing Reliability Requirements. The ITRS (International Technology Roadmap for Semiconductors), predicts in its difficult test challenges report that the commodity flash memory has increasing reliability requirements, as shown in Table I. The maximum data rate and density will increase faster, putting stress on the reliability requirements. Recent study shows the soft error rate of a low-voltage embedded SRAM can easily be 1000 FIT/Mbit [1]. For FIT and other reliability related terms, see footnote below².

Generally speaking, a computer that is used as a web server by an Internet Service Provider (ISP) with basic mailing and customer site hosting services should have at the minimum the following characteristics:

- Dual Intel XEON or AMD Dual core processor.
- RAID 5 1/2 TB disk.
- 4 GB Error-Correcting Code (ECC)RAM.
- Linux or FreeBSD UNIX operating system.

Services such as a Firewall, Web, FTP, RADIUS (an AAA - authentication, authorization, and accounting - protocol for controlling access to network resources) server, gaming, etc., may be needed, so the actual requirements for an ISP server will be more stringent and complex than what is mentioned above. The SEU induced errors can be categorized into four types for an electronic system depending on how the system responds to the error [14]: 1) masked error, i.e., the error is tolerated by the system; 2) correctable errors, i.e., the error is detected and successfully corrected; 3) detected uncorrectable errors (DUE); and 4) silent data corruption (SDC), i.e., the non-detectable error corrupts the system. Typical server system data corruption target is around 1000 years MTBF in Table II [2], but it is a significant challenge to achieve this goal in a cost-effective way.

Cloud Computing Era. Cloud, recognized as Internet's next generation, has benefits of centralizing the

²FIT: Failure In Time, 1FIT=1 fail in 10⁹ hours; 1 year MTTF=109/(24*365)FIT=114,155 FIT; MTTF is Mean Time to Failure, MTTR is Mean Time to Repair, MTBF is Mean Time Between Failures = MTTF + MTTR.

infinite resource and its enterprise users do not own the physical infrastructure to reduce capital expenses. It provides enterprise customers the ability to use one or many (sometimes thousands) servers and run a geophysical modeling application on the most powerful systems available anywhere with full support of the operating systems, Apache, a MySQL database, PHP and lots of other application softwares, APIs and services. It also has the capacity to store and secure huge amounts of data that is accessible only by authorized applications and users. Cloud computing builds on the established trends to reduce the cost of the delivery of services while increasing the speed and agility with which services are deployed [21]. Given that cloud is an inevitable trend, IT leaders such as *Amazon*, *AT&T*, *Google*, *Microsoft*, *Sun* and *HP* are making tremendous investments on it and consider their cloud infrastructures as their competition strength. Taking Sun Microsystems for an example, the heart of Sun's cloud is located close to Las Vegas, Nevada. The comprehensive cloud product package is yet to be released but the mega *Switch Communication SuperNAT* data center stores critical government information, patients' medical records, and many of fortune 500 companies' most important data [19]. This data center is vast and some of its specifications are listed below.

- 407,000 square feet of space.
- 7,000+ cabinets.
- 250 MVA Switch owned substation.
- 30,000 tons of system and system cooling.
- Designed for 1500 watts per sq. ft. density.

III. Soft Error Reduction - Industry Practices

Server system designs from different manufacturers vary in their architectures. However, traditional error checking mechanisms including error correction codes (ECC) or error detection and correction (EDAC) codes, parity, and redundancy, e.g., triple modular redundancy (TMR), are extensively used to meet high reliability, availability and serviceability (RAS) requirements [3], [6]. As an industrial case study consider the *HP Integrity non-stop NS16000* server [5]. This server has the capability to grow with linear scalability from 2 to 4,080 processors and up to 65 TB of main memory. Providing the announced seven-9s (99.99999%) level of availability, the fault tolerant hardware techniques can be summarized as follows:

- *ServerNet*: High bandwidth and low latency optical fabric connection with error detection and isolation capability. The routers are self-diagnosing and data are subjected to a 32-bit cyclic redundancy code (CRC).
- Parity checks and ECC are used in the main memory and cache and parity checks are employed in buses and caches on the logic board.
- For disk subsystem, parity checks and end-to-end checksum are employed.

Note that these techniques protect the systems from both hard errors and soft errors. The error tolerance of storage devices are discussed because of their extensive usage in industrial applications.

a) Memory: Soft errors caused by alpha particles or cosmic rays are not generally repeatable because they are caused by erroneous charge storage rather than by permanent hardware faults. So, soft errors in a memory may be corrected by rewriting the erroneous memory cell with correct data if the error is detected. The failure to correct a soft error in memory may potentially cause a serious system crash. Memory soft errors are generally categorized as either single-bit or multi-bit errors. A single bit error can be detected and corrected by standard error correction codes (ECC). However, when more bits than one are affected simultaneously by cosmic rays, standard ECC may not be sufficient. ECC may be able to detect multi-bit errors, but may not be able to correct them depending on the nature of the ECC implemented. In some cases, the ECC may not even be sufficient to detect the multi-bit errors. Recovery of memory from multi-bit errors will require more complex means [17].

b) RAID: Modern computer server systems require large capacity mass data storage devices. The web servers provide text, graphics, sound and video on demand and, typically, such server systems require access to databases stored on rotating rigid magnetic disk drives. The considerable number of storage devices increases the probability that server systems might fail. A RAID (*Redundant Arrays of Independent Disks*) disk drive is commonly used in such applications. RAID has the capability to reconstruct data stored on any single disk drive if there is a failure of that disk from the data stored on other disk drives [16].

The disk drive normally has on-board soft error recovery procedures for recovering data. Because different data types stored on a disk drive have different characteristics. For example, every single bit is potentially of critical important for alphanumeric data while for multimedia

data like audio and video the corruption of a single bit, or even several bits, is likely to be negligible because the consequences may not be severe. So, if each disk can independently allocate data of different types, different data redundancy strategies may be selected based on the type of data stored on a disk. For example, if a disk drive is selected to store multimedia data, the soft error recovery can even be disabled to reduce the cost [16].

c) *System software level handling:* There are two main types of event handlers at the software level to deal with the unexpected interruptions or errors in web servers, namely, service event handlers and host event handlers. Event handler commands are executed whenever a host or service state change occurs. Thus, handler commands will be executed when a service or host:

- 1) is in a “soft” error state.
- 2) initially goes into a “hard” error state.
- 3) recovers from a “soft” or “hard” error state.

In general, RAS requirements for high performance computer servers are very stringent and some existing techniques may not be sufficient. Besides, the cost of high reliability may become too high to be acceptable. For example, extensive use of TMR structure can lead to excessive cost. For the logic in a microprocessor, the SEU-induced transient pulse duration may span more than one clock cycle of operation and such long duration faults may cause errors in two adjacent bits at the circuit output for which new fault tolerance solutions at system level must be devised [11].

Hard errors are distinguishable from soft errors through “error log” reports because hard errors are repeatable. It is necessary to find out the root causes of the so-called “soft errors” detected and recorded in the server “error log” through some debugging process. To distinguish between soft errors caused by non-environmental factors and cosmic rays and the intermittent errors caused by environmental factors, experiments on soft error testing at different altitudes are necessary. This is required so that soft error protection techniques can be devised. However, such results at this time are still largely unavailable.

A potential solution, a soft error oriented hardware layout server system is discussed in the next section.

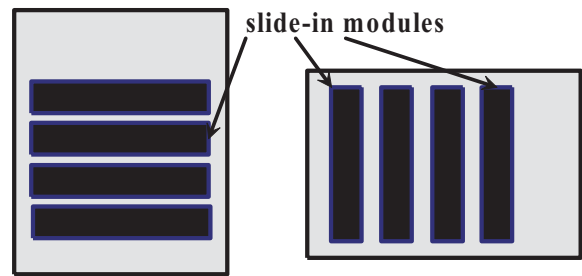


Fig. 1. Horizontal and vertical slide-in modular design for web storage and servers.

IV. A Potential Solution: Hardware Re-Alignment

A. The Proposed Solution

A preliminary experiment [9] carried out on an *ask.com* search engine and a set of office desktop computers gives an opportunity to improve soft error tolerance through a potentially new approach. The experimental results suggest that the memory soft error rate (SER) in real production systems are much lower than those reported by previous studies. The reason cited for this low SER is the use of memory DIMMs (*dual in-line memory modules*) in the system that were plugged perpendicular to the horizontal plane while the main source of cosmic rays lies straight above. This result provides a possible SER reduction method.

The ubiquitous rack-mounted server is the most popular layout style for server systems. A rack is a metal frame that contains bays designed to hold pieces of the server computer. The vertical rack spaces between stacks are in rack units, commonly known as “U-space” (a “U” equals 1.75 inches). What is more, the contemporary large computing systems are designed in a configurable fashion which gives customer opportunity to buy separately shipped add-on FRUs (*Field Replaceable Units*) to upgrade the base system. These add-on modules are normally slide-in cards with modular electronic circuit on printed circuit boards. Electronic circuits on the card provide either interfacing modules or storage drawers. There are two types of add-on cards in term of the slide-in direction. Figure 1 shows the vertical and horizontal add-on card designs.

A comprehensive understanding of how soft error occurs will help improve the existing protection method. First, the ground-level cosmic ray characteristics are discussed. At sea level, the nucleon flux contains 94%

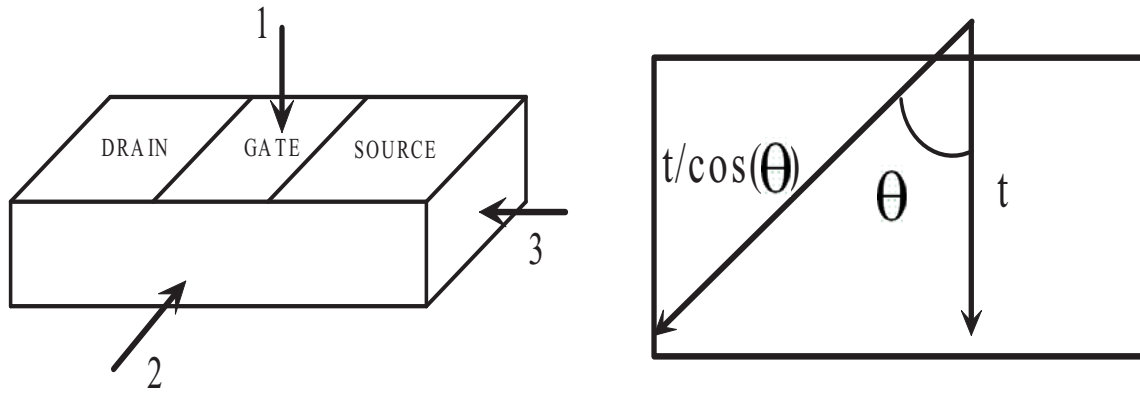


Fig. 2. Three perpendicular orientations for exposing a transistor and particle angle of incidence.

neutrons, 4% pions, and 2% protons, along with relative variations in neutron flux with latitude, altitude, diurnal time, earth's sidereal position, and solar cycle. The earth's magnetic field plays a role of providing a shield against charged particles everywhere except for particles entering vertically at poles. As galactic cosmic ray particles near earth, the magnetic field interacts with the particle's charge and bends the particle's trajectory [25]. Therefore, at sea level, the particles potentially causing soft errors strike the electronics with varying angle to the horizontal plane. One may argue that the angle of these particles is uniquely distributed so the soft errors are unavoidable for electronics because of the interaction with earth's atmosphere. However, the measurement results on the angular distribution for ground-level cosmic particles are yet to be published. The major reason is that such data varies significantly with location and time of measurement.

There is a minimum distance that a particle must travel into the material of the device before sufficient energy is deposited to cause an SEU. So the particle's angle of incidence from the normal to the surface of the device is important. Similar to the refraction of a beam when traversing from one matter to another, as the incidence angle deviates from the normal, the path length traversed by the radiation increases. The angle of incidence at which upsets occur for a given particle LET³ is known as the critical angle θ_c [7]:

$$\cos(\theta_c) = LET/LET_c \quad (1)$$

where LET_c is critical LET. LET_c is smaller than

³Linear Energy Transfer. LET is a measure of the energy transferred to the device per unit length as an ionizing particle travels through the material.

LET_{th} ⁴. The particles that produce upsets are incident at angles between θ_c and $\pi/2$. Therefore, two possible cases exist:

- 1) $LET > LET_c$: all striking incident angles will produce upset.
- 2) $LET < LET_c$: then there is a critical angle, θ_c , above which upsets occur.

Figure 2 is a schematic view of an MOSFET transistor. It shows three mutually perpendicular directions of exposure to cosmic rays. The direction labeled 1 is traditionally considered for SEU testing at normal incidence. Directions 2 and 3 represent exposures at grazing incidences and their path lengths through the sensitive volume tend to be longer when protons are incident parallel to the longest dimension of the sensitive volume for proton induced SEUs [18]. Particles incident at an angle (θ) have a path that is $1/\cos(\theta)$ times longer than the path at normal incidence, thus they produce more ionization charge.

B. The Challenges

The proposed method provides a potential direction for hardware layout design for next generation server architectures. However, there are several challenges to be handled before making this practical. Major concerns related to the changes in hardware layout are listed below:

- 1) The particle angle distribution measurement data is hard to obtain because it varies depending on locations, season, and even date. However, establishing an yearly measurement record should help.

⁴ LET_{th} is LET threshold, defined as the minimum LET to cause an upset at a given environmental background.

2) For changes in the hardware layout for soft error protection, following issues arise:

- Heating issues may arise and the airflow architecture needs to be redesigned.
- With the proposed layout redesign, the system needs better vibration proof design.
- The increased complexity of system design and cost.

In summary, with a proper understanding of local ground level particle orientation and energy distribution, if the circuit boards of the server system are appropriately oriented, then the SEUs caused by particles with LET smaller than the critical LET would be greatly reduced. However, re-arranging and placing the circuit boards will not be able to totally eliminate SEU.

V. Conclusion

In this paper, the essential features of soft errors in modern web servers are presented and commonly used industrial error tolerance techniques for web servers are summarized. In addition, a possible SER reduction technique for a conventional hardware server systems is presented and the feasibility and challenges are discussed. The effectiveness of the proposed design orientation to reduce soft errors in large computing systems needs further investigations and gathering of data to prove effectiveness. A simple experimental set up can monitor the soft error log files for two functionally identical web servers, one with vertical and the other with horizontal fully loaded add-on cards. The measured soft error data will help understanding how hardware architecture will affect soft errors. Also, the ground level particle striking angle distribution measurement data should be established to support the proposed theory in this paper.

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