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Acronyms

- Combinatorial logic (CL)
- Commercial off the shelf (COTS)
- Complementary metal-oxide semiconductor (CMOS)
- Device under test (DUT)
- Edge-triggered flip-flops (DFFs)
- Error rate (\(\lambda\))
- Error rate per bit (\(\lambda_{bit}\))
- Error rate per system (\(\lambda_{system}\))
- Field programmable gate array (FPGA)
- Global triple modular redundancy (GTMR)
- Hardware description language (HDL)
- Input – output (I/O)
- Intellectual Property (IP)
- Linear energy transfer (LET)
- Mean fluence to failure (MFTF)
- Mean time to failure (MTTF)
- Operational frequency (fs)
- Personal Computer (PC)
- Probability of configuration upsets (\(P_{configuration}\))
- Probability of Functional Logic upsets (\(P_{functionalLogic}\))
- Probability of single event functional interrupt (\(P_{SEFI}\))
- Probability of system failure (\(P_{system}\))
- Processor (PC)
- Radiation Effects and Analysis Group (REAG)
- Reliability over time (R(t))
- Reliability over fluence (R(\(\Phi\)))
- Single event effect (SEE)
- Single event functional interrupt (SEFI)
- Single event latch-up (SEL)
- Single event transient (SET)
- Single event upset (SEU)
- Single event upset cross-section (\(\sigma_{SEU}\))
- Xilinx Virtex 5 field programmable gate array (V5)
- Xilinx Virtex 5 field programmable gate array radiation hardened (V5QV)
Problem Statement

- Conventional methods of single event upset (SEU) analysis are not effective for characterizing error rates ($\lambda$) or mean time to failure (MTTF) for complex systems implemented in field programmable gate array (FPGA) devices.

- The problem boils down to extrapolation and application of SEU data to characterize system performance in radiation environments.
Abstract

- We are investigating the application of classical reliability performance metrics combined with standard SEU analysis data.
- We expect to relate SEU behavior to system performance requirements...
  - Example: The system is required to be 99.999% reliable within a given time window. Will the system’s SEU response meet mission requirements?
  - Our proposed methodology will provide better prediction of SEU responses in harsh radiation environments.
Background
(Traditional Method for SEU Calculations)

- Conventional goal: Convert SEU cross-sections ($\sigma_{SEU}$: cm$^2$/particles) to error rates ($\lambda$) for complex systems.

- Common methods of SEU analysis include the following steps:
  - Perform SEU accelerated radiation testing across ions with different linear energy transfers (LETs) to calculate $\sigma_{SEU}$s per LET.
  - Given $\sigma_{SEU}$ (per bit) use an error rate calculator (such as CRÈME96) to obtain an error rate per bit ($\lambda_{bit}$);
  - Multiply $\lambda_{bit}$ by the number of used memory bits (#UsedBits) in the target design to attain a system error rate ($\lambda_{system}$).

\[
s_{SEU} = \frac{\text{#errors}}{\text{fluence}} \quad \lambda_{system} = \frac{\text{#errors}}{\text{time}}
\]
Background

FPGA SEE Susceptibility

- $\sigma_{\text{SEU}}$ (per category) are calculated from SEE test and analysis.
- Traditionally, global route contributions have been ignored.
- FPGAs vary and so do their SEU responses. However, the dominant $\sigma_{\text{SEU}}$ are usually per bit (configuration or functional logic).
- After the dominant $\sigma_{\text{SEU}}$ is determined, we multiply the calculated $\lambda_{\text{bit}}$ by the number of used bits (configuration or functional logic).

\[ P(\text{fs})_{\text{system}} = \mu P_{\text{Configuration}} + P(\text{fs})_{\text{functionalLogic}} + P_{\text{SEFI}} \]

Design $\sigma_{\text{SEU}}$
Configuration $\sigma_{\text{SEU}}$
Functional logic $\sigma_{\text{SEU}}$
SEFI $\sigma_{\text{SEU}}$

SEU cross section: $\sigma_{\text{SEU}}$
Error rate: $\lambda$
Technical Problems with Current System Analysis Method (1)

- Multiplying each bit within a design by $\lambda_{bit}$ is not an efficient method of system error rate prediction.
  - Works well with memory structures... but...
  - Complex systems do not operate like memories.
  - If an SEU affects a bit, and the bit is either inactive, disabled, or masked, a system malfunction might not occur.
  - Using the same multiplication factor across DFFs will produce extreme over-estimates.
  - To this date, there is no accurate method to predict DFF activity for complex systems.
  - Fault injection or simulation will not determine frequency of activity.

$\lambda_{system} < \lambda_{bit} \times \#UsedBits$
Technical Problems with Current System Analysis Method (2)

- There are a variety of components that are susceptible to SEUs (clocks, resets, combinatorial logic, flip-flops (DFFs, etc…)).
  - Various component susceptibilities are not accurately characterized at a per bit level.
  - Design topology makes a significant difference in susceptibility and is not characterized in error rate calculators (e.g., CREME96).

Error rates calculated at the transistor-bit level are estimated at too small of granularity for proper extrapolation to complex systems.
Let’s Not Reinvent The Wheel… A Proven Solution Can Be Found in Classical Reliability Analysis

- Classical reliability models have been used as a standard metric for complex system performance.
- The analysis provides a more in depth interpretation of system behavior over time by using system-level MTTF data for system performance metrics.

\[ R(t) = e^{-t/\text{MTTF}} \quad \text{or} \quad R(t) = e^{-\lambda t} \]

Theory is already developed, proven, and should be in our hands!
A Comparison of Reliability and SEU Analyses

• Classical reliability models are measured across time.
  – This is because most of the failures that can affect performance in classical studies are due to wear-out mechanisms, or corner-case design bugs.
  – For each case, time to failure is a key measurement factor.

• When evaluating SEU susceptibility, during radiation testing, particle fluence is the key variable for system failure as opposed to time.
  – Missions required to operate in space environments will be susceptible to fluences ($\Phi$ particles/(cm$^2$)) of ionizing particles.
  – As a metric of SEU susceptibility, $\sigma_{\text{SEU}}$s are calculated across fluence.

• Goal: In order to better characterize SEU susceptibility for complex systems, we would like to analyze given $\sigma_{\text{SEU}}$s per bit and $\sigma_{\text{SEU}}$s per system.
Mapping Classical Reliability Models from The Time Domain To The Fluence Domain

- The exponential model that relates reliability to MTTF assumes that across time (disregarding infant mortality and wear-out):
  - Failures are random.
  - Error rate is constant.
  - $MTTF = 1/\lambda$.

- For a given LET (across fluence):
  - SEUs are random.
  - $\sigma_{SEU}$ is constant.
  - $MFTF = 1/\sigma_{SEU}$.

- Hence, mapping from the time domain to the fluence domain is straightforward:
  - $t \Leftrightarrow \Phi$
  - $MTTF \Leftrightarrow MFTF$
  - $\lambda \Leftrightarrow \sigma_{SEU}$

$R(t)=e^{-t/MTTF}$ or $R(t)=e^{-\lambda t}$

Parallel between time and fluence.

$\sigma_{SEU} = \#\text{errors/fluence}$

$\lambda_{system} = \#\text{errors/time}$
Use of Environment Data

- Typical (heavy-ion) environment data is expressed in particle flux across LET.
- In many cases, missions want to know what is the reliability of a system, within a given a time window.
- When analyzing SEU system behavior, this can also be interpreted as: what is the reliability given a window of particle fluence.

\[ \text{Flux} : \frac{\text{particles}}{(\text{cm}^2 \cdot \text{day})} \]

Example

- **Mission requirements:**
  - The FPGA shall contain an embedded microprocessor.
  - Decision shall be made to select a Xilinx V5QV (approximately $80,000 per device) or a Xilinx V5 with embedded PowerPC (less than $2000.00) per device.
  - FPGA operation shall have reliability of 3-nines (99.9%) within a 10 minute window.

- **Proposed methodology:**
  - Create a histogram of particle flux versus LET for a 10-minute window of time for your target environment.
  - Calculate MFTF per LET (obtain SEU data).
  - Graph \( R(\Phi) \) for a variety of LET values and their associated MFTFs. \( R(\Phi) = e^{\Phi/MFTF} \)
  - For selected ranges of LETs, use an upper bound of particle flux (number of particles/cm^2•10-minutes), to determine if the system will meet the mission’s reliability requirements.
Flux versus LET Histogram for A 10-minute Window

Geosynchronous Equatorial Orbit (GEO)
100-mils shielding
## Histogram Actuals: For Reference

**Frequency distribution of LET (MeV-cm²/mg)**

<table>
<thead>
<tr>
<th>LET (MeV-cm²/mg)</th>
<th>Flux (particles/(cm²•10 minutes))</th>
<th>Cumulative Flux Count (particles/(cm²•10 minutes))</th>
<th>Percent</th>
<th>Cumulative Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 To 0.07</td>
<td>3,068.53038</td>
<td>3,068.53038</td>
<td>0.99352</td>
<td>0.99352</td>
</tr>
<tr>
<td>0.07 To 0.1</td>
<td>4.55258</td>
<td>3,073.08297</td>
<td>0.00147</td>
<td>0.99499</td>
</tr>
<tr>
<td>0.1 To 1.8</td>
<td>15.17444</td>
<td>3,088.2574</td>
<td>0.00491</td>
<td>0.9999</td>
</tr>
<tr>
<td>1.8 To 3.6</td>
<td>0.22905</td>
<td>3,088.48645</td>
<td>0.00007</td>
<td>0.99998</td>
</tr>
<tr>
<td>3.6 To 20</td>
<td>0.06566</td>
<td>3,088.55212</td>
<td>0.00002</td>
<td>1.</td>
</tr>
<tr>
<td>20 To 40</td>
<td>0.00093</td>
<td>3,088.55304</td>
<td>2.99929E-7</td>
<td>1.</td>
</tr>
<tr>
<td>40 and over</td>
<td>2.94342E-7</td>
<td>3,088.55304</td>
<td>9.5301E-11</td>
<td>1.</td>
</tr>
</tbody>
</table>
MFTF versus LET for the Xilinx V5 MicroBlaze Soft Processor Core and the Xilinx V5QV embedded PowerPC Core

\[ \text{MFTF} = \frac{1}{\sigma_{\text{SEU}}} \]

- V5QV: MicroBlaze with Cache Enabled
- V5: PowerPC

Reliability across Fluence at \( \text{LET}=0.07 \text{MeV} \cdot \text{cm}^2/\text{mg} \) And Below

- **V5QV:** no system errors were observed below \( \text{LET}=3.6 \text{MeV} \cdot \text{cm}^2/\text{mg} \). Total fluence > \( 5.0 \times 10^8 \) particles/cm\(^2\).

- **PowerPC:**
  - System errors were observed with a MFTF=\( 1 \times 10^7 \) particles/cm\(^2\) at an LET=\( 0.07 \text{MeV} \cdot \text{cm}^2/\text{mg} \).
  - No systems errors were observed at an LET=\( 0.01 \text{MeV} \cdot \text{cm}^2/\text{mg} \) with a Total fluence > \( 5.0 \times 10^8 \) particles/cm\(^2\)
Reliability across Fluence up to LET=0.07 MeV•cm²/mg – Low Bound Analysis

Binned GEO Environment data shows approximately 3000 particles/(cm²•10-minutes), in the range of 0.0MeV•cm²/mg to 0.07MeV•cm²/mg. We are using MFTF for 0.07MeV•cm²/mg to upper bound this bin.

Reliability at 3000 particles/(cm²•10-minutes) > 99.999% for the PowerPC design implementation.
Reliability across Fluence up to LET=0.1 MeV\cdot cm^2/mg

Binned GEO Environment data shows approximately 5 particles/(cm^2\cdot 10\text{-}minutes), in the range of 0.07 MeV\cdot cm^2/mg to 0.1 MeV\cdot cm^2/mg. We are using MFTF for 0.1 MeV\cdot cm^2/mg to upper bound this bin.

\[ R(\Phi) = e^{\Phi/1.0 \times 10^5} \]

We fall below 99.99% at approximately 10 particles/cm^2!

Reliability at 5 particles/(cm^2\cdot 10\text{-}minutes) > 99.99\% for the PowerPC design implementation.
Reliability across Fluence up to LET=1.8 MeV•cm$^2$/mg

Binned GEO Environment data shows approximately 15 particles/(cm$^2$•10-minutes), in the range of 0.1MeV•cm$^2$/mg to 1.8MeV•cm$^2$/mg. We are using MFTF for 1.8MeV•cm$^2$/mg to upper bound this bin:

\[ R(\Phi) = e^{\Phi/6.0 \times 10^4} \]

We fall below 99.99% at approximately 6 particles/cm$^2$!

Reliability at 15 particles/(cm$^2$•10-minutes) > 99.9% for the PowerPC design implementation. This is the most susceptible bin for the system.
Reliability across Fluence up to LET=3.6MeV•cm²/mg

Binned GEO Environment data shows approximately 0.23 particles/(cm²•10-minutes), in the range of 1.8MeV•cm²/mg to 3.6MeV•cm²/mg.

Within this LET range, reliability at 0.23 particles/(cm²•10-minutes) > 99.999% for both design implementations.

\[ R(\Phi) = e^{\Phi/3.0 \times 10^6} \]

\[ R(\Phi) = e^{\Phi/1.2 \times 10^3} \]
Reliability across Fluence at LET=40MeVcm\(^2\)/mg

Binned GEO environment data shows approximately 0.07 particles/(cm\(^2\)•10-minutes), in the range of 3.6MeV•cm\(^2\)/mg to 40.0MeV•cm\(^2\)/mg.

V5QV: MFTF= 7.0×10\(^5\)
PowerPC: MFTF = 2.8×10\(^2\)

\[ R(\Phi) = e^{\Phi/7.0 \times 10^5} \]
\[ R(\Phi) = e^{\Phi/2.8 \times 10^2} \]

We fall below 99.99% at approximately 0.02 particles/cm\(^2\)!

Within this LET range, reliability at 0.07 particles/(cm\(^2\)•10-minutes) > 99.9% for both design implementations. We can refine by analyzing smaller bins.
Example Conclusion

• Using the proposed methodology, the commercial Xilinx V5 device will meet project requirements.
• In this case, the project is able to save money by selecting the significantly cheaper FPGA device and gain performance because of the embedded PowerPC.
Conclusions

• This study transforms proven classical reliability models into the SEU particle fluence domain. The intent is to better characterize SEU responses for complex systems.

• The method for reliability-model application is as follows:
  – SEU data is obtained as MFTF.
  – Reliability curves (in the fluence domain) are calculated using MFTF; and are analyzed with a piecemeal approach.
  – Environment data is then used to determine particle flux exposure within required windows of mission operation.

• An example is provided to illustrate the strength of the proposed SEU characterization methodology.

• This is preliminary work. There is more in the plans.

  This methodology expresses SEU behavior and response in terms that missions understand via classical reliability metrics.
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