Bridging methodology from component to system-level for the assessment of radiation effects in digital systems

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RADSAGA Final Conference and Industrial event

Israel DA COSTA LOPES, RADSAGA ESR 13, Work Package #3
Presentation outline

- Introduction and motivation
- Case study and instrumentation development
- Radiation experiments
- Bridging methodology development
Radiation environments and applications

- **Applications**
  - Geostationary Orbit (GEO)
    - Telecommunication Satellites
  - Low Earth Orbit (LEO)
    - International Space Station (ISS)
  - Aviation
    - Commercial Airplanes
  - Ground and Accelerators
    - Autonomous cars
    - Hospitals and accelerators

- **Environments**
  - Space
    - Mainly protons
    - Heavy-ions
    - X-rays, gamma-rays, etc.
  - Atmospheric
    - Mainly neutrons and protons
  - Accelerators
    - Ex: High energy Hadrons

- Which kind of digital systems can be exposed in those applications?
Digital system and component definitions

- Systems can be classified in different ways:
  - Application dependent
  - RADSAGA context system definition
  - Different system classes are proposed

- In this work:
  - Component defined as an Integrated Circuit (IC)
  - System defined as an assembly of components
  - New trend on embedded digital systems
    - System-on-modules
    - Typical Embedded System components

- How to assure the radiation hardness of those systems?

<table>
<thead>
<tr>
<th>Class</th>
<th>Systems considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra Small</td>
<td>SoC, System-in-package and Package-on-Package</td>
</tr>
<tr>
<td>Small</td>
<td>Typical small-form-factor SoM</td>
</tr>
<tr>
<td>Medium</td>
<td>Typical two-sided SBC</td>
</tr>
<tr>
<td>Large</td>
<td>Cubesat-like small system</td>
</tr>
<tr>
<td>Extra Large</td>
<td>50cm x 50cm box (Maximum size)</td>
</tr>
</tbody>
</table>

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Motivation: Transition between component to system-level approach

<table>
<thead>
<tr>
<th></th>
<th>Component-level approach</th>
<th>System-level approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct obtention of system reliability</td>
<td>😞</td>
<td>😊</td>
</tr>
<tr>
<td>Total cost</td>
<td>😞</td>
<td>😊</td>
</tr>
<tr>
<td>Component observability</td>
<td>😊</td>
<td>😞</td>
</tr>
<tr>
<td>Reusability of results</td>
<td>😞</td>
<td>😞</td>
</tr>
</tbody>
</table>

- Re-use component-level RHA knowledge and methods
- Re-use component-level data
- Make the system-level approach more reliable
- Facilitate the cultural transition
Case study objectives

- To develop a RHA methodology case study for providing component and system-level data:
  - Select a representative **Hardware system**
  - Develop a **case study** on the **target hardware**
  - Design an **experimental setup**

- **Selected hardware system:**
  - Commercial Industrial **System on modules (SoM)**
  - Requires a **Carrier board** for external interfaces
  - Based on Programmable System-on-Chips
  - Also include external memories, transceivers and power regulators
Target Hardware

SoM generations from Enclustra

- **Z7 SoM**
  - Based on 28nm Planar Zynq7000 SoC

- **ZU+ SoM**
  - Based on 16nm FinFET ZynqUltrascale+ SoC

- **Samsung DDR3 DRAM**
  - 1GB capacity
  - 2.1Gb/s/pin rate

- **ZU+ SoM block diagram**
  - ZynqUltrascale+ block diagram

- **Spansion NOR Flash**
  - 64MB capacity
  - 80Mb/s data rate

- **Micron DDR4 DRAM**
  - 2GB capacity
  - 3.2Gb/s/pin rate

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Representative application of an aerospace embedded digital system
### Instrumentation Level (IL) functions:

- **IL0**
  - Application output (PWM) checksum
  - Watchdogs for control flow verification

- **IL1**
  - External memories (DDR and Flash) built-in ECCs
  - Intermediate steps (AES, FIR…) checksum

- **IL2**
  - Internal memories observability (OCM, and PL FIFO) built-in ECC
  - Exception abort status reporting (cache)
TID IP-core and code-instrumentation

- TID instrumentation for monitoring parametric degradation:
  - **PL:**
    - RO IP-core for sensing gate delay variations
    - Configurable RO lengths and feedback
  - **PS:**
    - Software for measuring the RO frequencies

**Implementation results**

<table>
<thead>
<tr>
<th></th>
<th>Z7</th>
<th>ZU+</th>
</tr>
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<tbody>
<tr>
<td>Number of ROs</td>
<td>27</td>
<td>21</td>
</tr>
<tr>
<td>RO length</td>
<td>1024, 3000</td>
<td>1500</td>
</tr>
<tr>
<td>RO frequency at 78°C(kHz)</td>
<td>1900, 580</td>
<td>2000</td>
</tr>
</tbody>
</table>
Experiment objectives and timeline

- **Objectives:**
  - To obtain component-level and system-level data:
    - To irradiate the entire system containing different package thicknesses
  - To validate the instrumentation layer:
    - Error capturing capability
    - Observability increase

- **Experiment motivations:**
  - Atmospheric neutrons
    - High penetration and atmospheric representation
  - 184MeV protons
    - High penetration and space representation
  - X-ray experiment
    - Localized and fast experiments
  - Laser experiments
    - Get insight on the SoC components
Facility parameters:
- **Facility**: KVI-CART in Netherlands
- **Spectrum**: 184MeV
- **Flux**: 1-3E+06 p/cm²/s

Test methodology:
- **Beam layout**:
  - Z7: Two Z7 SoMs in parallel (one partially)
  - ZU+: Single SoM

Result summary:
- Lack of observability on analog parts and power regulators
- AES SEFI has the lowest cross-section in both technologies
- No external memory MBU observed (Flash and DDR)
- Exception aborts observed
- Most of events observed thanks to the IL0 and IL1
X-ray experiment

- **Facility parameters:**
  - **Facility:** PRESERVE facility at IES
  - **Spectrum:** <300KeV photons
  - **Dose rate:** 8.33 rad/s

- **Test methodology**
  - **Beam layout:**
    - Only one group of ROs was irradiated

- **Z7 vs ZU+ comparison summary**

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<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>Spatial variability</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Maximum Recovery</td>
<td>&lt;40%</td>
<td>&gt;90%</td>
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<td>~-4pS</td>
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<td>Dose resistance</td>
<td>&gt;430krad</td>
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**Test setup picture**

**Beam layout schematic**

**DUT**

**Z7 vs ZU+ worst case delay**

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**Zynq7000**
- 50Krad
- 100Krad
- 300Krad

**ZynqUltrascale+**
- 50Krad
- 100Krad
- 300Krad
Laser experiments

- Facility parameters:
  - Facility: IES SPA laser facility
  - Spectrum: 189-310 pJ
  - Equivalent LET: 19-32 MeV/mg/cm²
  - Flux: 10-20 pulses per second

- Test methodology:
  - Samples: Baredie Z7 and ZU+ SoCs
  - Regions of Interest (ROI):
    - SoC PL and PS resources

- Result summary:
  - Z7
    - High error counts and cross-sections
    - Exceptions mainly generated by caches
    - Checksum Errors and SEFIs observed
    - BRAM errors not detected by FIFO ECC
  - ZU+
    - Only timeouts observed in the PL and PS

Z7 Laser vs Proton results

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System-level test guidelines

- **Experiment preparation**
  - The test plan should predict possible issues during the experiment
  - Reliability on the experimental setup depends on adequate protocols
  - Flexible benchmark for increasing system exposition (workload, memory usage…)
  - To validate the instrumentation is essential

- **Experiment execution**
  - Dynamic reporting
  - Increase system exposition
  - Increase observability level
  - Increase radiation level

![Experiment decision making Flowchart](image-url)
Bridging methodology: System analysis

- System analysis
- System instrumentation and test plan elaboration
- Radiation tests and data analysis
- System reliability calculation

System analysis

1. Hardware system
2. Architecture analysis
3. Code analysis
4. Components usage
5. Criticality analysis
6. Critical components
7. Inputs
8. Process
9. Outputs

- Source code
- Executable files
- Datasheet
- Schematic

- Severity
- Exposure
- Probability of failure
Bridging methodology: System Instrumentation and Test plan

- **System analysis**
- **System instrumentation and test plan elaboration**
- **Radiation tests and data analysis**
- **System reliability calculation**

**Instrumentation and Test plan**

- **Critical components**
  - Data Available?
  - no
  - Instrumentation for testing
    - Instrumented Application
      - Test plan elaboration
      - Test plan

- **Components usage**

**Mission requirements**

- High penetration beam selection
  - E.g. 200MeV protons
- Smart beam layout:
  - Parallel irradiation (atmospheric neutrons)
  - Masking possibilities

**Software instrumentation**

- Embedded checking mechanisms
- Custom verification code

**IP-core instrumentation**

- Program Tracer decoder
- Test structures

**Minor Hardware modifications**

- Shunt resistor

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Bridging methodology: System-component correlation

- System analysis
- System instrumentation and test plan elaboration
- System reliability calculation
- System-level data
  - Cross-sections
  - Parametric degradation
- Instrumented Application
- Hardware system
- Component-level Benchmark

System-component correlation

- Components usage
- Comparison of SEE cross-sections or degradation
- Probability of possible root causes
- Component-level events propagated to system-level events
- Component-level events masked
- Fault injection at component-level

Requirements:
- Requires high observability

- Laser fault injection
- Software fault injection
- PL partial reconfiguration
Bridging methodology: System reliability calculation

- Fault propagation simulation
  - e.g. SEAM tool
- SEE and dose calculation
  - e.g. OMERE tool

System reliability calculation

- Component-level data
  - Cross-sections
  - Parametric degration
- Components usage
- System-level data
  - Cross-sections
  - Parametric degration
- Mission requirements
  - Environment
  - Duration
- Component-level reliability data

Fault propagation modeling

SEE rate calculation

Transmitted LET spectrum

Degradation during the mission

Inputs
Process
Sub-processes
Outputs

System-level reliability prediction

SEE sensitivity variation
- Coupled effects

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Bridging methodology summary

- **Decisive steps:**
  - Adding instrumentation for increasing observability
  - Combining both component and system-level data for calculating system-level reliability

- **Methodology limitations**
  - Requirement of final application
  - Hardware documentation requirement
  - Critical vs non-critical error classification

- **Case study limitations**
  - Lack of observability on analog parts
  - Limited number of events

- **Case study improvements**
  - Automated instrumentation addition
  - Cross-platform instrumentation library
## Case study event rate estimation

- **Data used for the calculations:**
  - Component-level cross-section from literature multiplied by bits used
  - System-level cross-sections extracted from 184MeV protons experiments
- **Rate calculation at OMERE for LEO ISS mission**
  - Combination of component and system-level data
- **Optimistic estimation** could validate a short mission (0.25 years)
- **Conservative estimation** would not validate short mission
  - Based on safety margins

### SEE rate prediction

<table>
<thead>
<tr>
<th>Predictions</th>
<th>SoM</th>
<th>Event</th>
<th>SEE rate (events/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optimistic</strong></td>
<td>Z7</td>
<td>Soft failures</td>
<td>2.47E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard failures</td>
<td>7.12E-06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resettable failures</td>
<td>6.63E-03</td>
</tr>
<tr>
<td></td>
<td>ZU+</td>
<td>Soft failures</td>
<td>2.91E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard failures</td>
<td>5.51E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resettable failures</td>
<td>1.14E-03</td>
</tr>
<tr>
<td><strong>Conservative</strong></td>
<td>Z7</td>
<td>Soft failures</td>
<td>4.94E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard failures</td>
<td>2.85E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resettable failures</td>
<td>1.99E-02</td>
</tr>
<tr>
<td></td>
<td>ZU+</td>
<td>Soft failures</td>
<td>5.82E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard failures</td>
<td>1.65E-02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resettable failures</td>
<td>3.41E-03</td>
</tr>
</tbody>
</table>
The possibility of a Bridging RHA methodology from component to system-level was investigated

A digital System-on-module case study including additional instrumentation were developed

Neutron, 184MeV protons, X-ray and laser radiation experiments were conducted for accumulating data

The lessons learned and experience acquired during the system-level experiments was shared

Available component-level tools, data and methods were used for developing a bridging methodology

The challenging comprehension of fault propagation in SoCs could be explored thanks to the instrumentation and laser testing

Several paths were identified for improving the proposed methodology:
  - Standardization, portability and automation of the instrumentation

The question of predicting system-level SEE rate is still a challenging task:
  - A first-step was taken towards the objective
  - Extension of the proposed methodology
    - Different systems, technologies and instrumentations approaches
    - The inclusion of coupled-effects on the SEE rate prediction