Accurate Analysis of SET effects on Flash-based FPGA System-on-a-Chip for Astrophysical Applications

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Luca Fossati
Luca Sterpone
Outline

- SET effects on Flash-based FPGAs
- Single Event Transient Analysis (SETA) tool
  - Analysis
  - Mitigation
  - Experimental results
- Conclusions and future activities
SET effect

Solar Energetic Particles
(Solar Particle Events or Coronal Mass Ejections)
SET effect

Radiation particles: Heavy ions, neutrons, protons
A Single Event Transient (SET) is generated by the injunction of charge collection.

- A charged particle crosses a junction area.
- It generates an amount of current, provoking a “glitch.”
- SET can be indistinguishable from normal signal and exist for notable distances.

**SET width**
**SET amplitude**
**Rise $\Delta V/\Delta T$**
**Fall $\Delta V/\Delta T$**
SET effect

Generation of the radiation-induced phenomena
SET effect

Generation of the radiation-induced phenomena
SET effect

- Analysis and mitigation of the SEE on Flash-based FPGAs
  - Type and radiation incidence angle
  - LET
  - Technology

![Diagram showing particle strikes on Flash-based FPGAs]
Circuits on Flash-based FPGAs

Flash configuration memory

FPGA array
Circuits on Flash-based FPGAs

Flash configuration memory

FPGA array

Configuration process
SET scenario

- Considering a place and route design on FPGA
  - Fixed logic cells
  - Defined number of routing segments

Source of SET
SET scenario

- Considering a place and route design on FPGA
  - Fixed logic cells
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SET scenario

- Considering a place and route design on FPGA
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SET Propagation through gates

Fist Region: \( \text{If}(\tau_n < k*tp) \text{ then } \tau_{n+1} = 0 \)

Second Region: \( \text{If } (\tau_n > (k+3)*tp) \text{ then } \tau_{n+1} = \tau_n + \Delta tp \)

Third Region: \( \text{If } ((k+1)*tp < \tau_n < (k+3)*tp) \text{ then } \tau_{n+1} = (\tau_n^2 - tp^2)/\tau_n + \Delta tp \)

Fourth Region: \( \text{If } (k*tp < \tau_n < (k+1)*tp) \text{ then } \tau_{n+1} = (k+1)*tp(1 - e^{(k - (\tau_n/tp))}) + \Delta tp \)

For a 1→0→1 transition \( \Delta tp \) is defined as:
\[ \Delta tp = tpHL - tpLH \]

For a 0→1→0 transition \( \Delta tp \) is defined as:
\[ \Delta tp = tpLH - tpHL \]

Source of SET
Propagatiob through gates
Propagation through routing
SET classification on FFs or IOs
SET Propagation through gates

Fist Region: If $\tau_n < k*tp$ then $\tau_{n+1} = 0$

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For a $1\rightarrow 0\rightarrow 1$ transition $\Delta tp$ is defined as:

$\Delta tp = tp_{HL} - tp_{LH}$

For a $0\rightarrow 1\rightarrow 0$ transition $\Delta tp$ is defined as:

$\Delta tp = tp_{LH} - tp_{HL}$

Source of SET

Propagation through gates

Propagation through routing

SET classification on FFs or IOs
SET Propagation through routing

- Source of SET
- Propagation through gates
- Propagation through routing
- SET classification on FFs or IOs

[Sterpone et al, RADECS 2014]
SET Propagation through routing

Gate to Gate Broadening Coefficients

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FFs maximal broadening pulses

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[Sterpone et al, RADECS 2014]

Propagation Induced Pulse Broadening

Source of SET

✓ Propagation through gates

SET classification on FFs or IOs
SET Propagation through routing

Propagation Induced Pulse Broadening

Gate to Gate Characterization

Source of SET

- Propagation through gates
- Propagation through routing
- SET classification on FFs or IOs

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A tool has been developed:

- Single Event Transient Analyzer (SETA)

Source of SET
- Propagation through gates
- Propagation through routing
- SET classification on FFs or IOs
SETA tool

- Netlist
- Constraints
- Physical Design Description (PDD)
- Gate PIPB Characterization

Source of SET
- Propagation through gates
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SETA tool

- Netlist
- Constraints
- Physical Design Description (PDD)
- Sensitive nodes selection
- Gate PIPB Characterization

Source of SET
- ✓ Propagation through gates
- ✓ Propagation through routing
- SET classification on FFs or IOs
**SETA tool**

- **Netlist**
- **Constraints**
- **Physical Design Description (PDD)**
- **Sensitive nodes selection**
- **SET propagation**

**Gate PIPB Characterization**

- **Source of SET**
  - Propagation through gates
  - Propagation through routing
  - SET classification on FFs or IOs
SETA tool

Netlist

Constraints

Physical Design Description (PDD)

Sensitive nodes selection

SET propagation

Gate PIPB Characterization

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✓ Propagation through gates
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Source of SET
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**SETA tool**

- Netlist
- Constraints

**Physical Design Description (PDD)**

- Sensitive nodes selection
- SET propagation

**Gate PIPB Characterization**

- Propagation is performed up to “terminal” nodes (IOs / FFs)

Source of SET

- Propagation through gates
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SETA tool

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Netlist

Physical Design Description (PDD)

Sensitive nodes selection

SET propagation

Constraints

Gate PIPB Characterization

SET classification on FFs or IOs

Source of SET

✓ Propagation through gates

✓ Propagation through routing

✓ SET classification on FFs or IOs
The classification identifies the number of SET:

- Totally filtered
- Partially filtered
- Equally propagated
- Broadened
SETA results – EUCLID project

Combinational Path - Single Event Transient sensitivity

Filterged: Filtered, Partially Filtered: Partially Filtered, Equal: Equal, Broadened: Broadened
SETA results – EUCLID project

- Analysis of the integral fluency expected for the duration of the mission: expected EUCLID duration is 6.25 years
- Linear Energy Transfer distribution calculated using CREME96

![CREME 96 LET Spectra](image)

<table>
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<tr>
<th>Resource</th>
<th>SET Normalized cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routing Segment</td>
<td>1.31E-10</td>
</tr>
<tr>
<td>VersaTile</td>
<td>2.60E-08</td>
</tr>
</tbody>
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SETA results – EUCLID project

Transient Error cross-section per module

Circuit module
SETA results – EUCLID project

**Combinational Path - Single Event Transient sensitivity**

- **Total number of analyzed SET**
- **Type of SET per injected pulse**
SELECTIVE GUARD GATE (GG) MAPPER

Inserting a GG logic structure in the input of the selected FF

[Sterpone and Du, IEEE ETS 2014]
SET: mitigation solution 1

- Selective guard gate (GG) mapper
  - Inserting a GG logic structure in the input of the selected FF

Filtering estimated on the basis of the SETA report
SET: mitigation solution 2

- Accurate placement acting on the critical paths
- Distance between gates is modified in order to maximize the electrical filtering effect

\[ \Delta T_{\text{tot}} = \Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 \]
Accurate placement acting on the critical paths

- Distance between gates is modified in order to maximize the electrical filtering effect

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Accurate placement acting on the critical paths

Distance between gates is modified in order to maximize the electrical filtering effect

\[ \Delta T_{\text{tot}} = \Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 \]
SET: mitigation results

RISC average 0.83 ns SET sensitivity - A3P250 array 48 128

Average SET sensitivity

Different place and route constraints
SET: mitigation results

Average SET sensitivity

Different place and route constraints

Original RISC circuit

Post SETA RISC circuit

RISC average SET sensitivity on A3P250 array 48 128
SET: mitigation results

Effective mitigation of SET

Different place and route constraints
SET: mitigation radiation test results

- Heavy ions test performed at the Cyclotron of the Université Catholique de Louvain (UCL)
  - Kripton ion with a fluence of 3.04E8 (particles)
  - Average flux 1E4 (particles/sec)
  - RISC working frequency of 20MHz on ProASIC3 A3P250

<table>
<thead>
<tr>
<th>RISC processor version</th>
<th>SEE Cross-section [MeV cm²/mg]</th>
</tr>
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<tbody>
<tr>
<td>Unhardened</td>
<td>1.45E-9</td>
</tr>
<tr>
<td>Full TMR + GG</td>
<td>6.37E-10</td>
</tr>
<tr>
<td>Our Approach</td>
<td>3.12E-12</td>
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SET: in conclusion...

- SETA tools are available
  - Effective analysis of SET propagation
  - Effective overall SET mitigation
SET: in conclusion...

- SETA tools are available
  - Effective analysis of SET propagation
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Very Good
SET: in conclusion...

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X Source of SET
✓ Propagation through gates
✓ Propagation through routing
✓ SET classification on FFs or IOs
Physical Design Description

- The circuit is modeled as a graph
  - Cell functionality
  - Routing model
SET generation phenomena

- Particle hitting a sensitive node
  - Generate a SET pulse
  - Propagates through the logic
SET generation phenomena

- SET generation is related to
  - Linear Energy Transfer (LET)
  - VersaTile architecture
  - Technology

[Azimi, Du, Sterpone, Micro Rel, 2015]
[Azimi and Sterpone, IEEE DDECS 2016]
Why SET generation?

- The type of source SET is mandatory to understand the exact type of propagation
  - Mitigation GG insertion is related to SET length
- It is necessary to establish the absolute SET count
  - Calculation of the realistic IOs/FFs error rate for the whole space mission duration
Why SET generation?

Combinational Path - Single Event Transient sensitivity

Filtered  Partially Filtered  Equal  Broadened
Identification of source SET length

Effective source SET designer must care
Identification of effective SET counts

Combinational Path - Single Event Transient sensitivity

Effective source SET designer must care
Thank you!

- luca.sterpone@polito.it