An Analysis of Heavy-Ion Single Event Effects for a Variety of Finite State-Machine Mitigation Strategies

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Acronyms

- Device Under Test (DUT)
- Edge-triggered flip-flops (DFFs)
- Error Correction and Detection (EDAC)
- Finite state machine: (FSM)
- Field programmable gate array (FPGA)
- Input – output (I/O)
- Linear energy transfer (LET)
- Localized triple mode redundancy (LTMR)
- Low cost digital tester (LCDT)
- Probability of logic masking ($P_{\text{logic}}$)
- Radiation Effects and Analysis Group (REAG)
- Single event transient (SET)
- Single event upset (SEU)
- Single event upset cross-section ($\sigma_{\text{SEU}}$)
FSMs Implemented in FPGAs Targeted for Critical Applications

• FSMs are used to control operational flow in FPGA devices.

• Because of their ease of interpretation, FSMs simplify the design and verification process and consequently are significant components in a synchronous design.

• By definition, the current state of an FSM is stored in DFFs.

• Significance: can be detrimental to system operation if an FSM were to change its state due to an SEU in one of its DFFs.
Motivation: FSM Mitigation and SEU Testing

• Techniques have been employed to FSMs that either:
  – correct the current state of an FSM,
  – detect incorrect state transition, or
  – Auto-transition to a new state if an un-mapped state is reached (“safe state-machine” which is very UNSAFE).

• Currently no heavy-ion or proton SEU studies have been performed that measure the efficacy of any of these mitigation approaches.
Overview

• Define FSMs and various mitigation strategies that can be applied to them.

• Discuss Goal of SEU testing: to investigate mitigation efficacy while varying frequency and giving attention to global route SEEs.

• Discuss a scheme that can be used to test the efficacy of SEU FSM mitigation strategies and provide corresponding SEU test data

We used the Microsemi ProASIC3 and the Virtex-5QV as DUTs. Data presented is from the ProASIC3 SEU testing.
Synchronous FSMs and SEUs

- A synchronous FSM is designed to deterministically transition through a pattern of defined states.
- A synchronous FSM utilizes DFFs to hold its current state, transitions to a next state controlled by a clock edge and combinatorial logic, and only accepts inputs that have been synchronized to the same clock.
- FSM SEUs can occur from:
  - Caught data-path SETs
  - DFF SEUs
  - Clock/Reset SETs
Mapping States into DFFs

- Each state of an FSM must be mapped into some type of encoding (pattern of bits) stored in DFFs.
- Once the FSM state is mapped into a DFF state, it is considered a defined (legal) state.
- Based on the number of DFFs used (N), the total number of available DFF state mappings is $2^N$.
- Unmapped DFF states are considered illegal states.
  
  $2^3 = 8$ available DFF states
  
  5 out of the 8 states are mapped
  
  3 out of the 8 states are unused.

- Other encoding schemes can be employed that use more than 3 DFFs.
5-State FSM Binary Encoding Example

**Example of an FSM used to control a peripheral device**

An SEU can change current state and cause a catastrophic event.
EDAC: Corrective FSM Mitigation

• Corrective FSM mitigation (as defined in this presentation) is a scheme that masks and corrects SEUs so that incorrect FSM state transitions do not occur

• Scope of presentation focuses on two corrective mitigation approaches:
  – Localized triple modular redundancy (LTMR)
  – Hamming Code-3

• Auto transitioning (“safe state-machine”) is a reaction to a small subset of incorrect transitions (unmapped states). They do not protect against incorrect transitioning and are not in the scope of this presentation
Adding Corrective Mitigation

• LTMR: Triplicate each DFF and use a majority voter.
  – The triplication + voter is treated as one DFF
  – Encoding doesn’t change
  – Resultant FSM has 3 times the number of DFFs than the original encoding scheme.
  – Combinatorial logic (not including the voters) does not change

• Hamming Code-3: requires a new encoding scheme.
Binary versus LTMR FSMs

Binary implementation

Outputs

Next State

Current State

Clock

LTMR implementation: only change is each DFF is triplicated. Majority voter is used across the triplication.

Outputs

Next State

Current State

Clock

Synchronous LTMR FSMs and SEUs

- Triplication plus majority voter protects against SEUs in DFFs
- No mitigation in Data-path, consequently, data-path SETs can get caught by DFFs
- If global routes (clocks and resets) are not hardened, then SETs can global affect DFF states
FSM Fault Tolerance: 5-State Conversion to a Hamming Code-3 FSM

Hamming Code-3 FSM Diagram for a 5 Base-State FSM: Would need 5*7=35 FSM states to be represented... 6 DFFs

A closer look at a base-state (state 0) and its companion-states

SEU Testing of FSMs: Efficacy of mitigation while investigating how frequency and global routing affect FSM $\sigma_{\text{SEUs}}$

LETs lower than 10MeV*cm$^2$/mg are used. Otherwise, global route SEUs dominate.
ProASIC3 SEU Heavy-Ion Test Structures:

- No error detection and correction: 8-bit Binary Encoding:
  - 256 FSM states total
  - Binary: 1 DFF per bit requires 8 DFFs

- Local triple modular redundancy (LTMR): 8-bit Binary Encoding:
  - 256 FSM states total
  - LTMR: 3 DFFs per bit requires 24 DFFs

- Hamming Code-3: 5-bit encoding:
  - 32 FSM states total
  - Hamming Code-3 must represent all states plus their companion states and requires 9 DFFs

For statistical analysis, a large number of each of these FSMs are implemented.
ProASIC3 FSM Heavy-Ion SEU General Test Structure Diagram

REAG Counter Array concept is used. FSMs replace Counters.

200 of the same type of FSM

Size of FSM

SNAP SHOT Array

FSM 0
FSM 1
FSM 196
FSM 197
FSM 198
FSM 199

ProASIC3 Heavy-Ion FSM SEU Testing

**SEU cross-sections per FSM. Scale is Log-Linear**

**SEU cross-sections for global routes: (clocks and resets). Scale is linear-linear**
Novelty of SEU FSM Results

• The efficacy of previous EDAC+FSM studies was proven by means of theory or by fault injection in soft-configuration SRAM Based FPGAs. Problems:
  – Theory doesn’t take into account data-path SETs and global route upsets
  – EDAC implementations with FSMs are not worth-while schemes in soft configuration devices. This cannot be uncovered using fault injection because global route SETs and frequency response cannot be fully investigated with fault injection.
  – In general, previous studies have no regard to LET (size of SET), global routes, or frequency of operation

• This is the first study to investigate FSM SEU response to heavy-ions while taking into account frequency, SETs, and global routing effects.
Conclusions

• Utilizing the Snap-Shot test scheme has shown to be a reliable approach for investigating FSM SEEs.

• Analysis of non-mitigated FSM data shows that it cannot be assumed that the FSM-$\sigma_{SEU}$s will increase across frequency.
  – Well mitigated (e.g., LTMR and Hamming-3) FSM-$\sigma_{SEU}$s increase across frequency
  – Non-mitigated FSM-$\sigma_{SEU}$s decrease across frequency

• Well-mitigated FSM-$\sigma_{SEU}$s will be lower than non-mitigated FSM-$\sigma_{SEU}$s

• Global routing:
  – A trade should be made prior to deciding whether to use mitigation because the global routing SEUs may be significant enough to erase the gains from additional mitigation circuitry
  – At lower frequencies, mitigation will reduce global routing $\sigma_{SEU}$s