Configuration Scrubbing and Mitigation Approaches for the Zynq System-on-Chip

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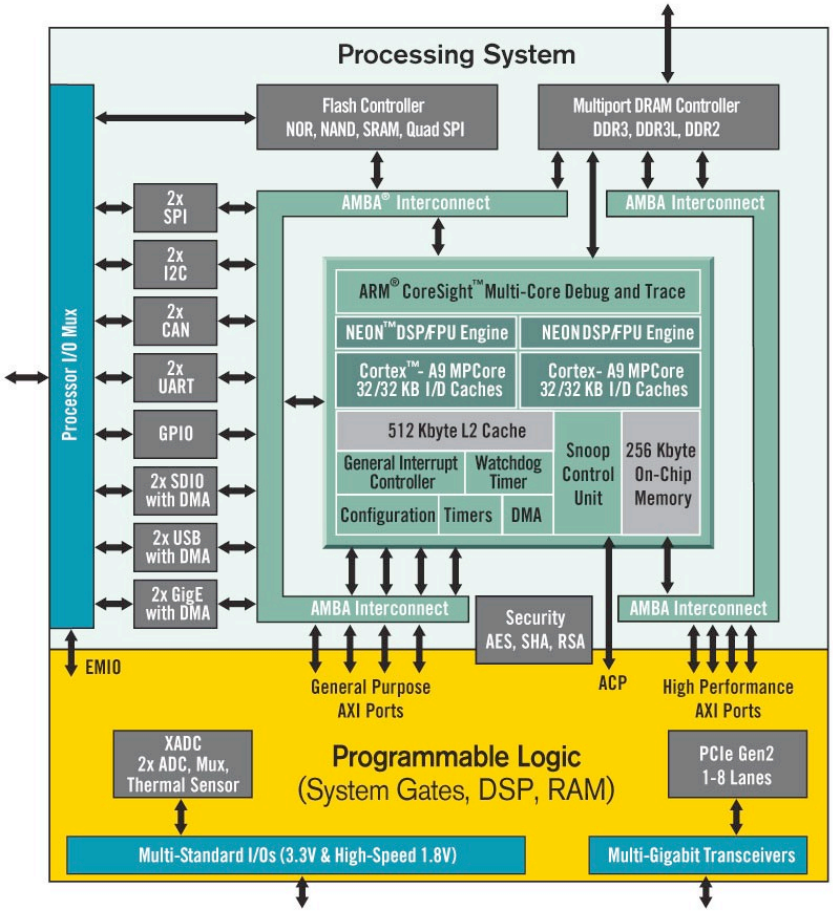
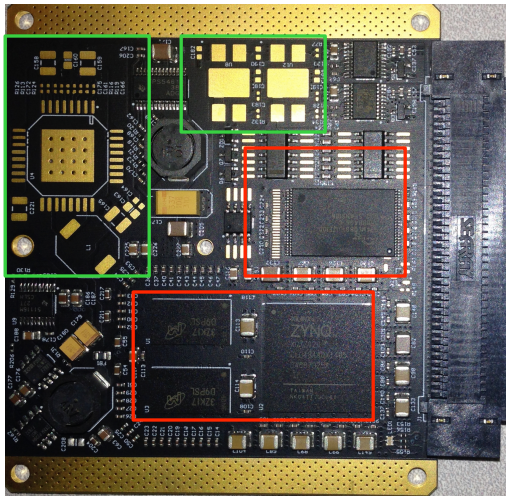
Zynq All-Programmable SOC

- Processor Resources
  - *Dual ARM A9 cores*
  - *NEON FPU Engine*
  - *L1/L2 Cache + Shared Memory (OCM)*
- I/O Resources
  - *SPI, I²C, CAN, UART, Flash, USB, GPIO, GigE, etc.*
  - *PCIe, DDR controller*
- Programmable Logic
  - *350K logic cells*
  - *545 BRAM (36 Kb blocks)*
  - *900 DSP slices*
  - *350 I/O pins*



CHREC Space Processor (CSP)

- Zynq-Based CubeSat Processing board
  - *Developed at University of Florida, CHREC*
  - *1U CubeSat form factor – 10cm x 10cm*
  - *Hybrid COTS/RadHard device support*



COTS
- Zynq-7020 hybrid SoC
  - *Dual ARM A9/Neon cores*
  - *Artix-7 FPGA fabric + hard IP*
- DDR3 memory

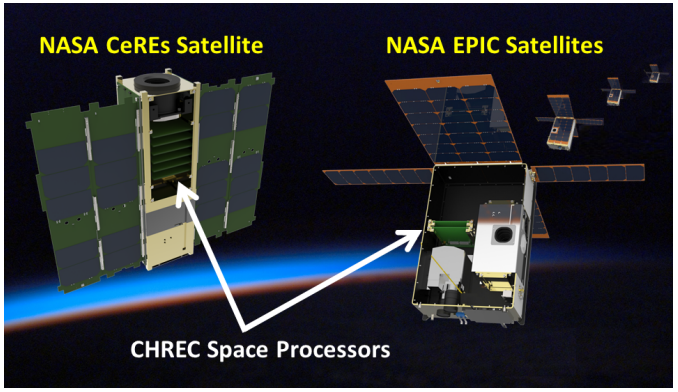
RadHard
- NAND flash
- Power circuit
- Reset circuit
- Watchdog unit

"CSP: A Multifaceted Hybrid Architecture for Space Computing", Proc. of the AIAA/USU Conf. on Small Satellites, Logan, UT, Aug. 2-7, 2014.

CSP Scheduled Deployment

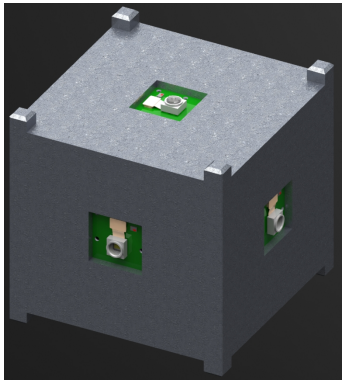
NASA technology mission:
STP-H5/ISEM on ISS

- Two CSPv1's working in tandem
- SpaceWire, camera
- Reconfiguration control
- Anticipate launch: imminent



NASA science mission:
CeREs Cubesat

- Heliophysics experiment in LEO orbit
- One CSPv1 computer for on-board data processing

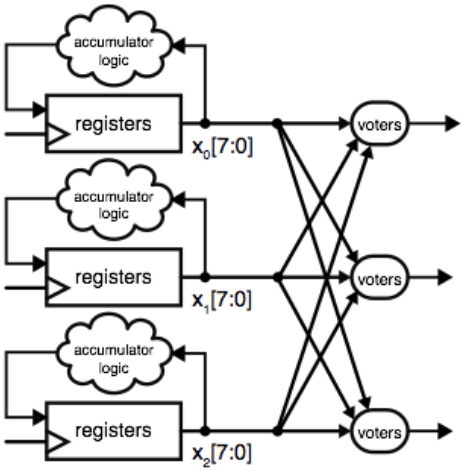


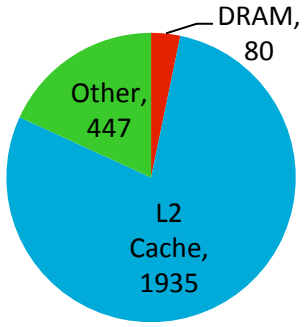
NASA Undergraduate student Instrumentation Project (USIP):
BYU Passive Inspection CubeSat (PICS)

- Passive spacecraft inspection
- Spherical camera (6 faces)
  - Data logging, compression
- CSP controls camera & power system
- Command and control
- Anticipated launch: Dec 2017

SEU Mitigation Techniques

- FPGA
  - *Triple Modular Redundancy*
  - *Configuration Scrubbing*
  - *ECC/Memory Scrubbing*
- Processor (Linux O/S)
  - *Hardware watchdog timer*
  - *DDR ECC enabled (SECDED)*
  - *Memory scrubbing*
  - *Active cache management*





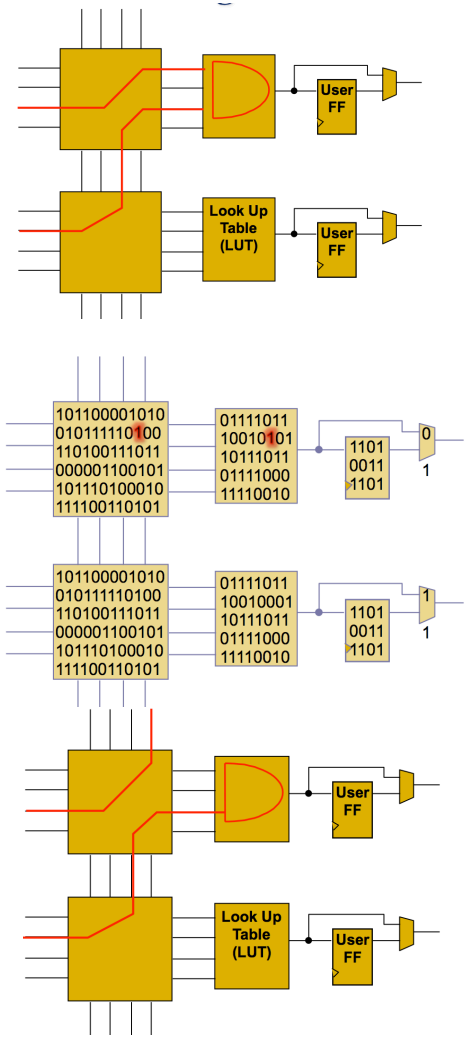
Most failures are due to memory system

Demo Tonight: TMR and Fault Injection

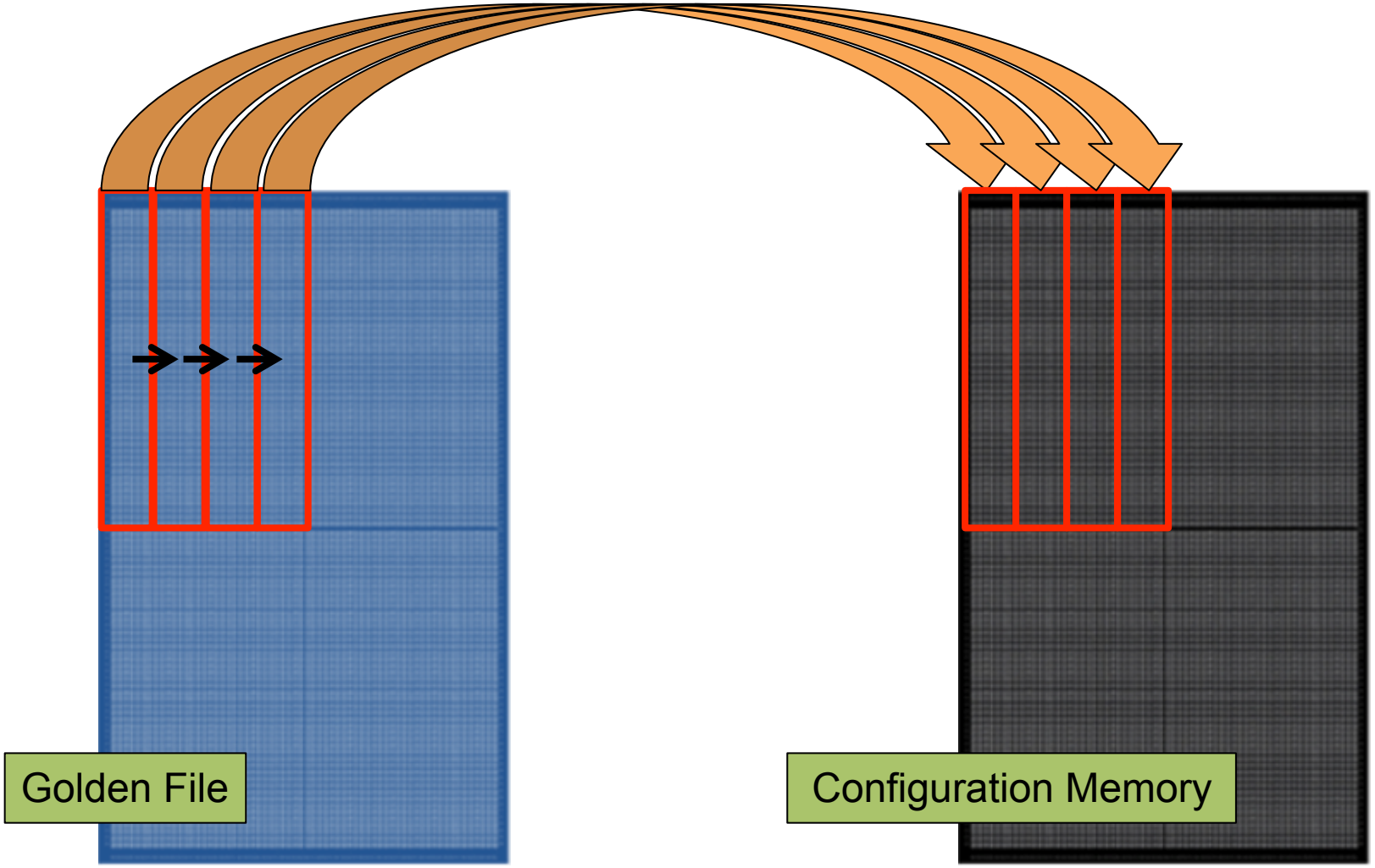
Wednesday Presentation: BL-TMR Tools and Results

Configuration Scrubbing

- Configuration memory should remain static
- Upsets in configuration *change* design
- Repair mechanism needed for configuration upsets
  - *Return configuration memory to original state*
  - *Process called "configuration scrubbing"*
- Configuration Scrubbing Responsibilities
  - *Periodically check the memory to detect upsets*
  - *Overwrite (correct) those locations in memory where upsets are detected*
- Many approaches for configuration scrubbing
  - *Blind Scrubbing*
  - *Readback Scrubbing*
  - *Hybrid Scrubbing*
  - *External vs. Internal Scrubbing*

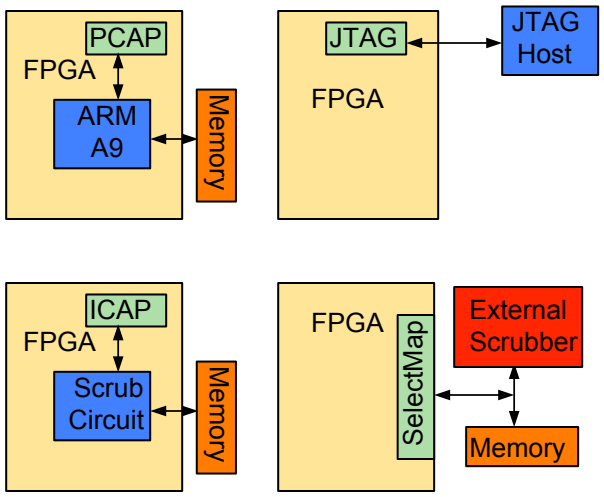


Scrubbing Example



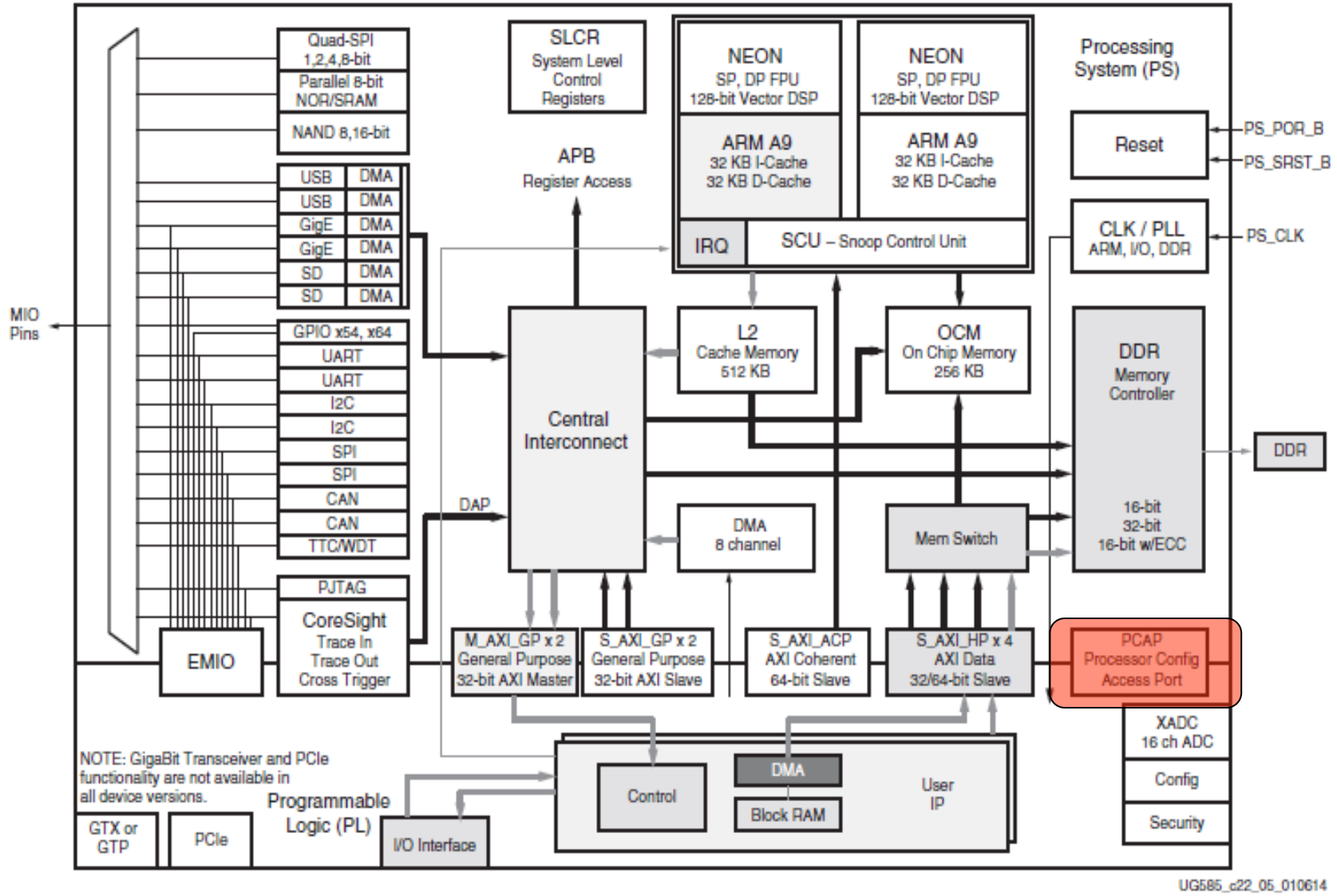
Configuration Interfaces

- Configuration scrubbing performed using *configuration Interfaces*
  - *Interface for loading configuration data*
  - *Read configuration data (readback)*
- Available Configuration Interfaces
  - *JTAG – serial external I/F*
  - *ICAP – parallel internal I/F*
  - *SelectMap* – parallel exteral I/F*
  - *PCAP – processor internal I/F*



*Not available on Zynq devices

Processor Config Access Port (PCAP)



PCAP DMA Bridge

- Accessible from the Zynq processor
  - *AXI Bridge/DMA Interface*
  - *Transfer data between DDR and FPGA*
  - *Interrupt Support*
- Configuration Operations
  - *DMA transactions*
    - Setup DMA registers
    - Issue DMA transfer
  - *Configuration*
    - Write to TxFIFO
  - *Readback*
    - Read from RxFIFO

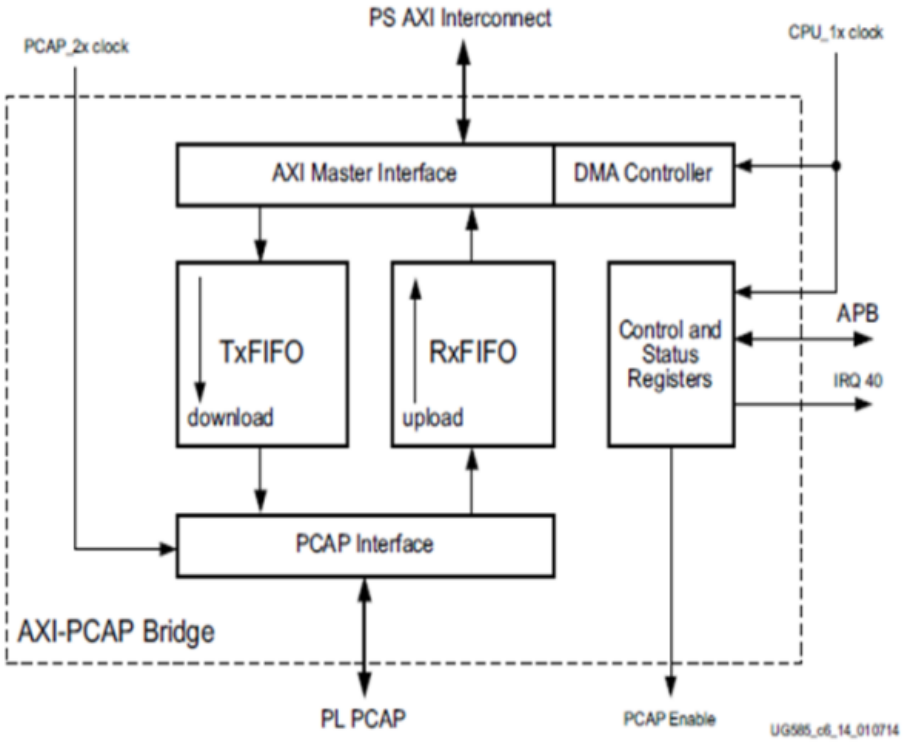
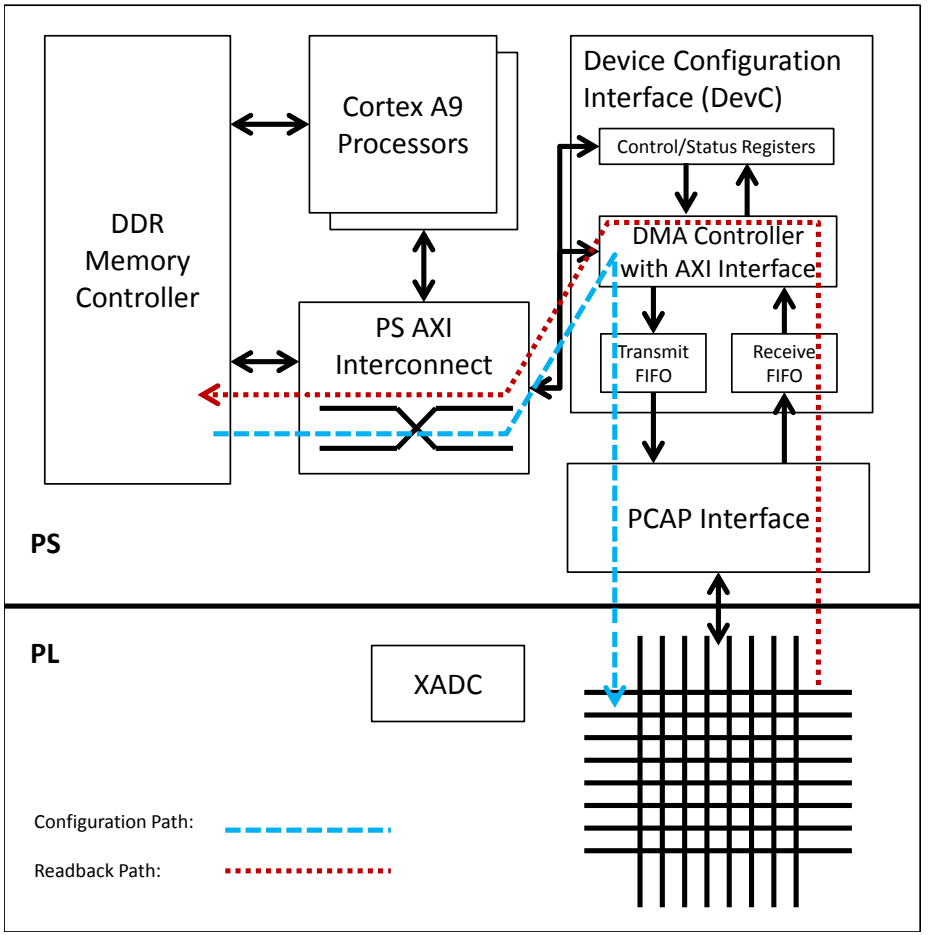


Figure 6-14: **AXI-PCAP Bridge**

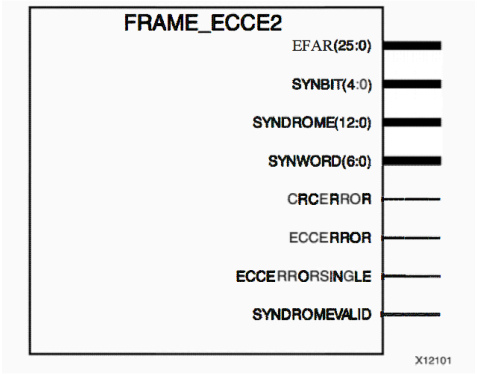
PCAP Requirements

- Atomic operations
  - *All configuration operations handled in one DMA transfer*
  - *Must manage DMA controller carefully*
- Readback
  - *Sufficient bandwidth to capture readback data*
  - *Break up into smaller readback packets*
  - *Manage PCAP Clock*

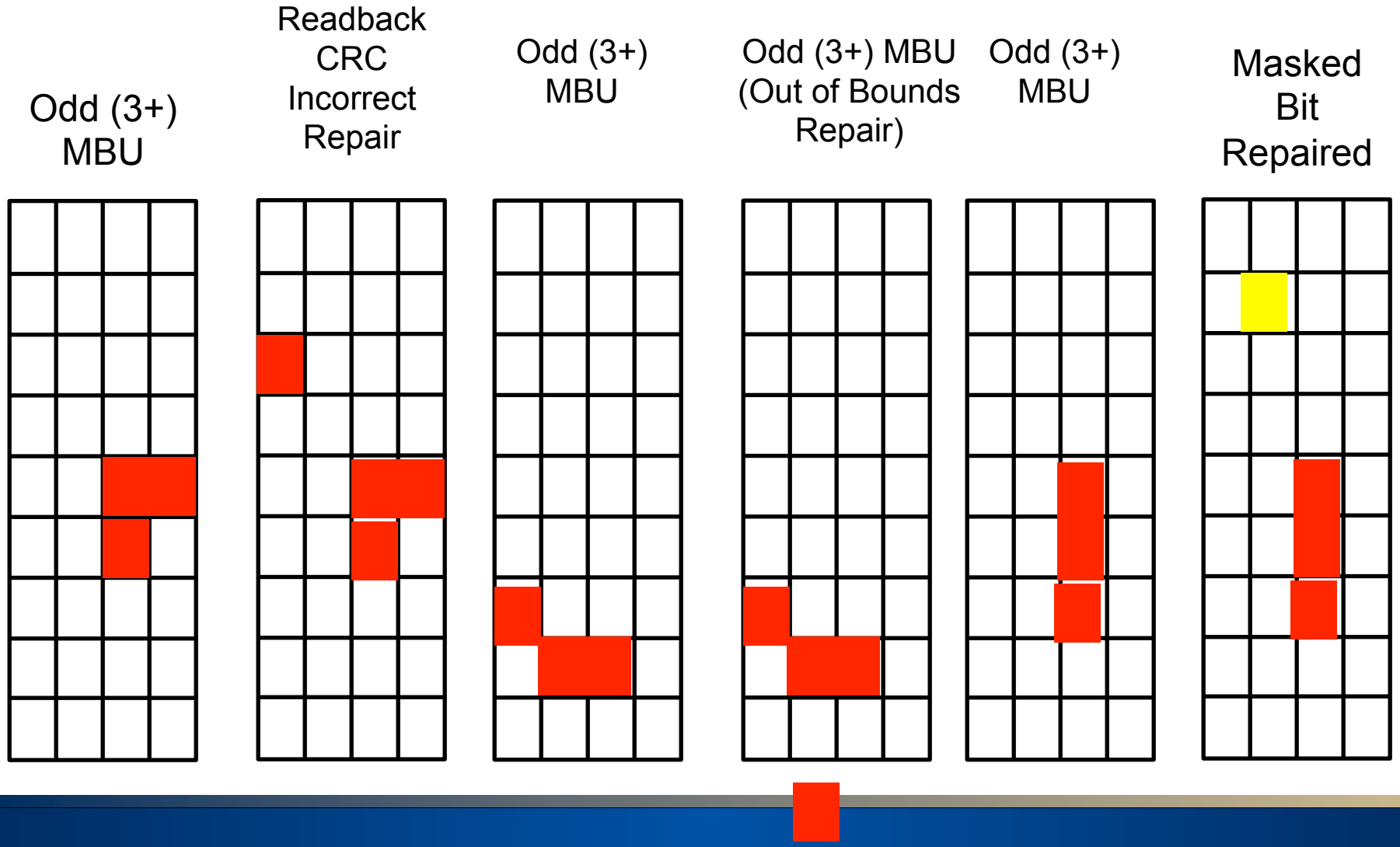


7-Series Internal Scan

- Automatically detect and correct SEUs
  - *Internal hardware implements SECDED*
  - *Continually reads configuration frames*
  - *Fast detection and correction speeds*
- Exploits the FrameECC interface
  - *Decodes Frame ECC word*
  - *Detects double errors*
  - *Identifies location of single errors (repair)*
- Limitations
  - *Cannot correct multi-bit upsets (MBUs)*
  - *May insert errors when repairing odd upsets*
    - 3 or more upsets (3,5,7, etc.)
  - *May try to repair upsets in "empty" location*
    - "Out of bounds" upset, "masked" bits
- Global CRC: Used to detect global bitstream errors



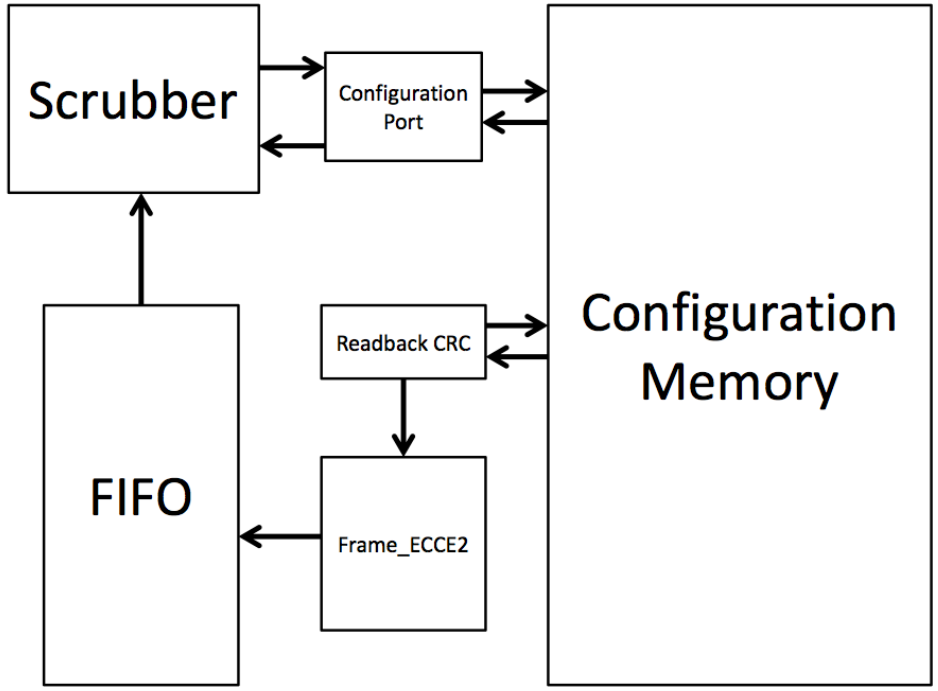
Incorrect Scrub Examples



Hybrid Scrubbing

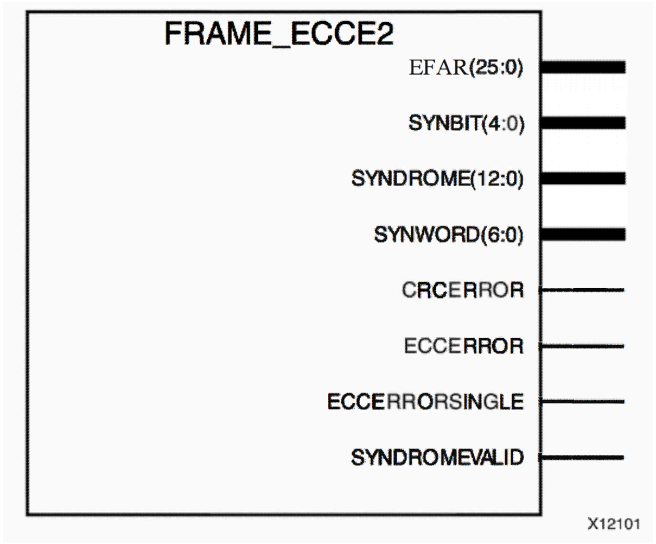
- Combine benefits of multiple approaches
  - *Internal Scan:* *High Speed*
  - *External Scrub:* *Correct MBUs*

	SBUs	MBUs
Detection	RCRC	RCRC
Correction	RCRC	External Scrubber



FRAME_ECC Packet Logging

- Error condition can be inferred from error signals
- Log error events
  - *syndrome_valid*
  - *Non-zero syndrome*
- History of error packets needed to determine error type

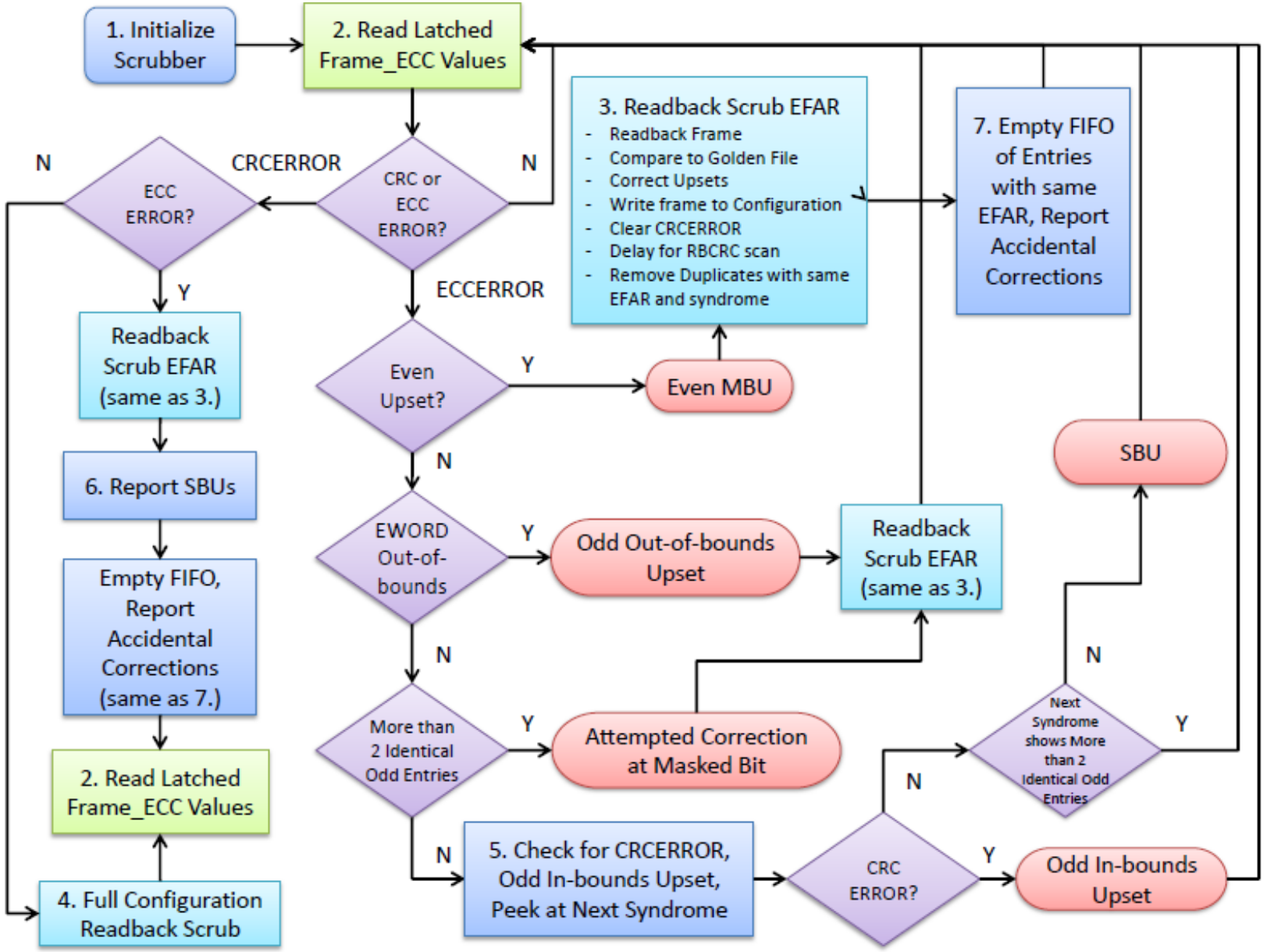


Error Event Types

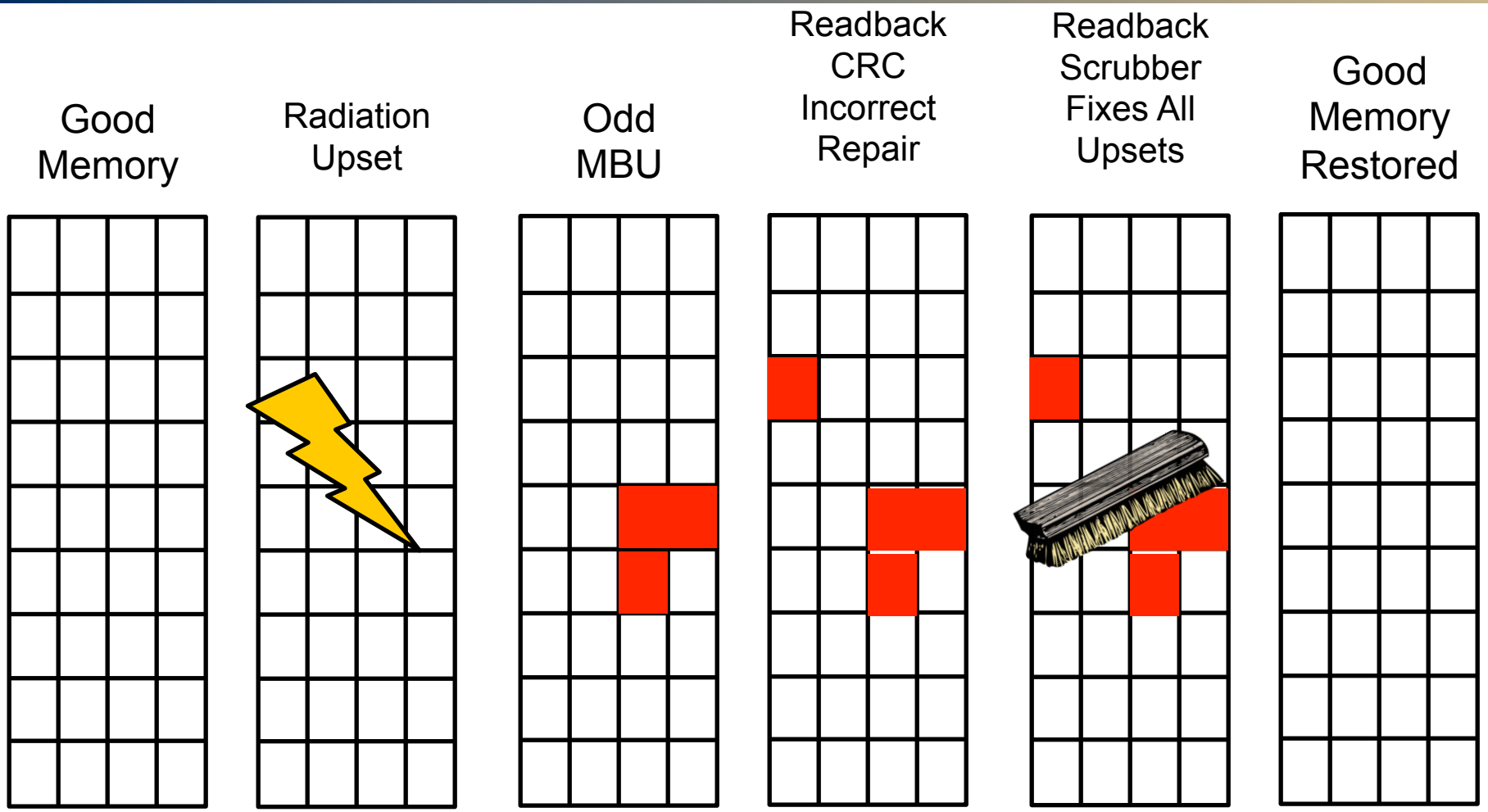
- SBU and Odd-Numbered "In Bounds"
  - *First packet detects upset*
  - *Second packet fixes upset*
- Odd Numbered "out of bounds"
  - *First packet detects upset*
  - *Second tries to fix upset*
  - *Continuous upset packets (since it can't be fixed)*
- Even numbered/Masked bits
  - *First packet detects upset*
  - *Continues to generate packets (since it isn't fixed)*

Type of Upset	FRAME_ECCE2 Batches Generated
SBU	2
Even-Numbered MBU	∞
Odd-Numbered In-Bounds MBU	2
Odd-Numbered Out-of-Bounds MBU	∞
Odd MBU Correction at Masked Bit	∞

Hybrid Scrubber Flowchart



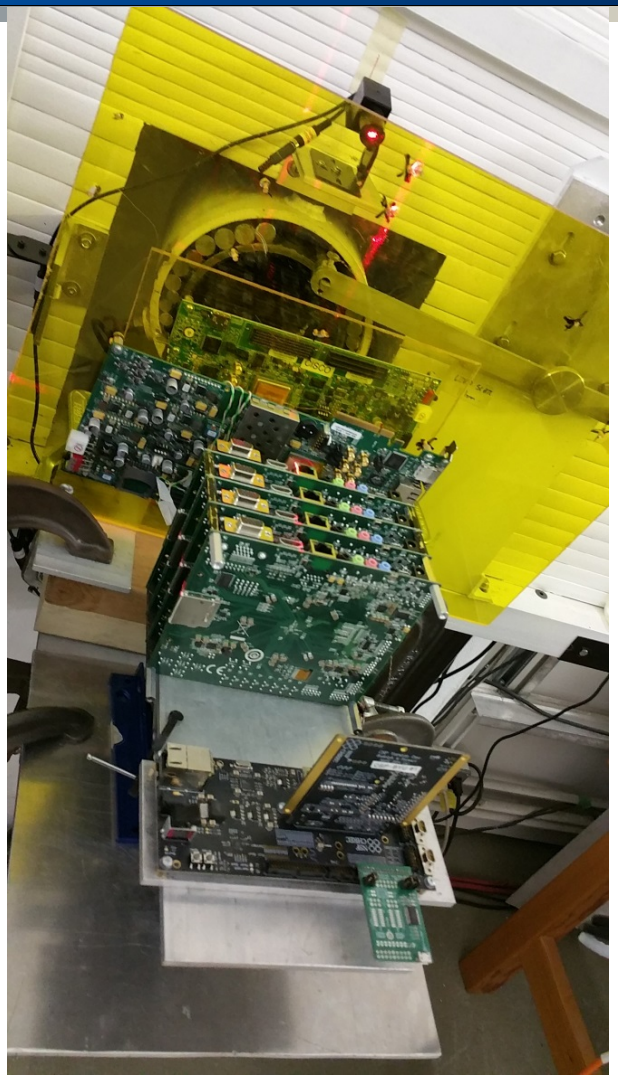
Example



Odd In-Bounds Multi-Bit Upset

Radiation Beam Test Setup

- Radiation Tests
  - *Neutrons*
  - *Protons*
  - *Heavy-Ions*
- Facilities
  - *TRIUMF (Neutrons)*
  - *LANSCE (Neutrons)*
  - *TSL (Protons)*



Hybrid Scrubber Log Excerpt

Frame_ECC 0: 8B21176B
Frame_ECC 1: 60400A9C

13176.651231 : SBU corrected @ FRAD: 400A9C Word: 33 Bit: 11

****
13176.742754 : CRC HIGH: Multi-Bit Upset! Syndrome: 1

13176.776186 : Scrubbing FRAD: 400A9D...
13176.776914 : FAULT DETECTED! FRAD: 400A9D Word: 33 Bit(s): 10 11
13176.777756 : Word: 33 | Expected: 0 Actual: C00
13176.782169 : Scrubbing of FRAD: 400A9D Finished with 2 Upsets !

Clearing CRC latch ! After Scrub, CRC = 0

Test Results—Hybrid Scrubber

Number of Upsets in a Frame	Occurrences
1	4,239
2	326
3	133
4	41
5	3
6	7
7	2
8	1
14	1
16	1
Total Upsets Corrected	5,563
Readbacks	69
Reboots	281
Even → Odd Upset Scenario	71
Odd out-of-bounds Upsets	0
Masked Bit Upsets	0
Total Runtime	152,168.03 seconds

Performance—Hybrid Scrubber*

Upset Type	Detection	Correction	Total Scrubbing
SBUs	8.02 ms	4.5 us	8.024 ms
Two-Bit	8.02 ms	1.86 ms	13.38 ms
Odd MBUs	16.04 ms	1.86 ms	21.40 ms
Even MBUs	8.02 ms	1.86 ms	13.38 ms
Full Readback Scrub	1.82 s	1.86 ms	1.822 s

*all measurements performed on xzc07020 board

Questions?

"Xilinx 7-Series Configuration Scrubbing Architectures for High-Reliability FPGA Systems ", Aaron Stoddard, MS Thesis, Brigham Young University, December 2015