Design of a radiation-tolerant multi-band radio system for new space applications

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Outline

1. Background and Motivation
2. Design Challenges for Space Application
3. Development and Design Approach
4. Radiation Effects on Critical System Parts
5. System-Level Verification
6. Conclusion and Outlook
Background & Motivation
A SDR usually define the signal processing in software, implemented on an DSP or FPGA.
RF Front-End mostly untouched and tailored to specific application requirements.

State-of-the-art SDR system

- DSP/FPGA
- ADC
- DAC
- RF Front-End
- Antenna(s)

- LNA
- PA
- Mixer
- Filter
- ...

Languages for implementation:
- C/C++
- GNU/Python
- VHDL/Verilog
State-of-the-art SDR in space applications

- SDRs are already established
- Commonly used for single applications / units
- Limited in operational frequency band

High reliability:
- High mass and mechanical dimensions
- High costs
- Long lead-times
- High power consumption

Low reliability:
- No radiation effect background
- Low frequency range (< S-Band)
- Non-conformances to mission ICD

Source: Frontier Radio platform by JHU/APL
A new approach with software-defined RF Front-End

- The highly integrated RFIC (AD9361) combines most of the RF Front-End properties and the ADC/DAC
- Allows a multi-band operation (70MHz-6GHz) reconfigurable by software

**Diagram:**
- RFIC (AD9361)
  - ADC
  - DAC
  - RF Front-End
  - Antenna(s)

- DSP/FPGA
- C/C++
- GNU/Python
- VHDL/Verilog

- LNA
- (PA)
- Synthesizer
- Mixer
- Filter
- ...
RFIC (AD9361) Overview

### Description

<table>
<thead>
<tr>
<th>Description</th>
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What is the motivation and intention?

• A small, integrated, design/unit that allows simple, fast and cost-efficient re-use and modification
• Independencies from frequency band limitations for TM&TC (VHF, UHF, L S/C-Band, ...)
• Scalable design that keeps their specification (size, power consumption and performance)
• Something between low- and high reliability classes

Moreover:
• A single radio platform for multiple applications (two/three/four in one)
• Reconfiguration and operation of multiple applications (e.g. TM&TC or/and ADS-B or/and AIS or/and Spectral Monitoring)

➢ **Better utilization of given resources (size, weight, power, ...)**
Design Challenges for Space Application
Classic Space Missions vs. CubeSats Missions

- So far we had two types of space missions:
  - High-Reliability missions (e.g., Telecommunication, Human spaceflight)
  - Low-Reliability missions (e.g., CubeSats mostly driven by Universities)

- Gap between both types is huge
  - Technology level being used (+10 years)
  - Quality assurance
  - Size
  - Costs

- CubeSats mission becoming more interesting for commercial use (e.g., StarLink, OneWeb)

- For NewSpace, COTS is unavoidable

Example: CubeSat missions by type

https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database
What to keep in mind when using COTS

<table>
<thead>
<tr>
<th>STRENGTHS</th>
<th>WEAKNESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>• functional performance</td>
<td>• empirical design approach</td>
</tr>
<tr>
<td>• latest technologies</td>
<td>• limited technology insight</td>
</tr>
<tr>
<td>• availability on stock</td>
<td>• testability of devices</td>
</tr>
<tr>
<td>• fast proof-of-concept</td>
<td>• up-screening efforts (RHA, RLAT)</td>
</tr>
<tr>
<td>• competitive market</td>
<td>• poor control of supply chain</td>
</tr>
<tr>
<td>• low (initial) costs</td>
<td>• profound design expertise required</td>
</tr>
<tr>
<td>• ITAR free</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OPPORTUNITIES</th>
<th>THREATS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• innovative system designs</td>
<td>• absence of adequate components</td>
</tr>
<tr>
<td>• obsolescence strategies</td>
<td>• short product lifecycle (EOL / PCN)</td>
</tr>
<tr>
<td>• growing experience</td>
<td>• unpredictable process variability</td>
</tr>
<tr>
<td>• repackaging</td>
<td>• residual risk</td>
</tr>
<tr>
<td>• dual-use as fallback</td>
<td></td>
</tr>
</tbody>
</table>
Making such state-of-the-art technologies available for space, in a sufficient way, is the biggest challenge due to:

- Unknown reliability characteristics for space
- Harsh environment in space
  - Thermal stress
  - Vacuum condition
  - Radiation (TID, SEE)
  - Atomic oxygen

- Trade-off between cost, efficiency and reliability -> Fault-Tolerant Design!
Development and Design Approach

Knowledge for Tomorrow
Fault-Tolerant Approaches for System Development

1. Reliability prediction analysis
2. Analysis of radiation data bases and test data on COTS components with suitable candidates for the GSDR system design
3. Selection of well-known devices with certain product traceability
4. Radiation testing of selected “unknown” devices (e.g. AD9361)
5. RadHard or Rad-Tolerant alternatives
6. System-level mitigation on expected effects:
   - Redundancies, voting
   - Latchup-protection
   - OVP (SET)
   - Configuration scrubbing
   - EDAC mechanisms
   - Usage of watchdogs
   - Safe system-reset (e.g., prevent eFuse setting corruption)
7. Testing on system-level to verify the hardening strategies (e.g. radiation)
Fault-Tolerant System Design (Hardware)

Separation into functional blocks of the system design

• Power regulation
  ▪ Highest priority of reliability
  ▪ If one device fails, the system fails
  ▪ Certain devices have been already tested under irradiation
  ▪ However, RadHard solutions shall be considered (even if they are expensive and requires more space on the PCB)

• Memory resources
  ▪ Critical if they fail completely (partly loss acceptable, e.g., some blocks are not readable/writeable)
  ▪ Radiation test data available on COTS devices
  ▪ Radiation tolerant NAND flash available
  ▪ Radiation tested DDR3 SDRAM
Fault-Tolerant System Design (Hardware)

- **Clock sources**
  - Medium critical level (drift in the frequency compensable)
  - Radiation tolerant solutions available
  - Using mil-qualified oscillators, with radiation test data available

- **Baseband processor**
  - No RadHard solution available for this design requirements
  - Many researches on radiation effects of used Zynq SoC
  - Mil-Spec solution available (packaging etc.)

- **RF Transceiver**
  - Bottleneck device in the system
  - No radiation test data available
  - No RadHard or Rad-Tolerant alternative available
  - **Own investigations are required**
Fault-Tolerant System Design (Software)

- Operational concept
  - Tailored, light-weight, Linux-based ram-filesystem as OS
  - Applications basically described in HDL
  - OS captures and stores the payload application data and performs background operations (e.g. health-monitoring tasks)
  - Re-Configuration by loading application-bitstreams into PL

- Reliability assurance
  - Configuration- and boot files stored into radiation tolerant NAND flash devices
  - Backup partitions and redundant memory resources for sensitive data
  - Multi-Boot operation with fall-back solutions
  - Complex SW-architecture for system-health-monitoring (watch-dogs, SEL detection, configuration scrubbing, ...)

[Image of a map and the GSDR logo]
Radiation Effects on Critical System Parts
Source of Radiation

- The Sun
  - High dynamic magnetic field
  - Change of magnetic field every 11 years
  - Source and Modulator for Radiation
  - Solar Flares
  - Coronal Mass Extraction (100B Tons of Plasma)
  - Protons and Heavy Ion Particles, x-ray and gamma ray
Source of Radiation

- Galactic Cosmic Rays
  - 87% Hydrogen, 13% Helium, 1% Heavy Ions (e.g., Xenon)
  - Very High Energies (>10E20 eV)
  - Isotropic direction (comes from everywhere)
  - Lower Energies are shielded by Earth magnetic field
  - Shielding depending on the sun activity
  - Mainly Heavy Ion, less Protons

- Radiation belts of Earth
  - Trapped Protons
  - LEO missions are affected
Radiation Effects

- Displacement Damages
- Ionization
  - Accumulated Dose Effects
  - Single Event Effects
Accumulated Dose Effects

- Often calls Total Ionizing Dose (TID) effects
- Mainly affects the Isolator (SiO2)
- Metals and Semiconductors are immune
- Optical effects (blurred lances)
- Drifts in the devices parameters (e.g. output voltages or oscillator frequency)
- Shielding is effective
Single Event Effects

- Particle Effects in the semiconductor
- Sources: Electrons, Neutrons, Protons and Heavy Ions
- Particle Energy is disposed to the semiconductor
- Destructive and Non-Destructive SEEs
  - SEL, SEB, SEGR
  - SEU/MBU, SET,
Radiation Testing on AD9361
Reminder: AD9361 Overview

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**HOW TO TEST SUCH A INTEGRATED AND COMPLEX DEVICE?**
Total Ionizing Dose Effects Testing

- AD9361 is installed on daughterboard (blue) and is not surrounded by other sensitive devices (good DUT isolation)
- Carrierboard interfaces DUT and allows data access and controlling (shielded by lead bricks)
TID test parameters

- Co-60 Source of HZB (Potsdam) and X-Ray machine from CERN
- Three tests in total
  - 2015:
    - Target dose: 25 krad(SiO2)
    - Dose rate: 0.5 to 3.5 krad(SiO2)/h
    - Samples: 1
  - 2018:
    - Target dose: 200 krad(SiO2)
    - Dose rate: 11.5 krad(SiO2)/h
    - Samples: 2
  - 2019: X-Ray Test
    - Target dose: 80 Mrad(SiO2)
    - Dose rate: 4.1 Mrad(SiO2)/h
    - Samples: 2
TID test procedure

Two test configurations are considered:

1. During irradiation a continuous live test is performed in which a sinewave is transmitted and received on a specific transceiver configuration (e.g. carrier frequency, sample rate etc.).
2. In frequently intervals of approx. 15krad(Si) a detailed performance test is executed to evaluate the function of the device and degradation effects in different stages.
TID performance test (1)

• Current conditions under different ENSM stages
  Analysis of current conditions for different state machine modes to evaluate
general degradations (e.g., increased current level).

• Automatic gain control performance
  Evaluation of the receiver’s automatic gain control (AGC) by transmitting a
sinewave on different power levels (attenuated by the reference transmitter
output) to the DUT. The receiver AGC selected gain levels and the digitized
signal strength are recorded.

• Manual gain
  Transmission of a fixed, low power sinewave tone to the DUT receiver input
and progressively increase of the manual gain of the receiver (in 1dB steps)
to evaluate the digitized signal strength.
TID performance test (2)

• RX filter frequency response
A narrow receiver RF filter bandwidth of 200kHz is selected. A fixed amplitude sinewave is transmitted on different carrier frequencies inside and outside of the filter bandwidth (in 10kHz steps). The receiver’s gain is fixed to avoid overdrive effects. The detected peak in the frequency spectrum of the receiver is captured and recorded for every selected carrier frequency. The results show the bandwidth shape and frequency response.

• TX attenuation
The reference receiver is set to a fix gain configuration. The DUT transmits a sinewave tone on a dedicated carrier frequency and adjusts the TX attenuation in 2dB steps to evaluate the attenuation behavior under radiation. The signal received by the reference transceiver is digitized to detect the expected peak of the signal in the frequency spectrum for each selected attenuation value of the DUT’s transmitter.
TID performance test (3)

- **TX intermodulation**
  A 1MHz and 2MHz sinewave tone are transmitted on different carrier frequencies to the reference receiver device. With the increased output power, the reference receiver observes and records intermodulation products (3rd and 5th order) without being affected by overdriving the receiver’s amplifier. The intermodulation distances (IMD) are then evaluated.
TID performance test (4)

- TX local oscillator leakage
  A constant sinewave is transmitted on different carrier frequencies and is received by a fix-gain configured reference receiver. With the captured IQ data, the signal power on the expected frequency and the DC power level is calculated. The difference between those values is defined as local oscillator leakage (LOL).

Source:
Current conditions for different ENSM modes

- Different ENSMs observed
- 0krad(Si), 95krad(Si) and 180krad(Si)
- No changes in current levels observed
- Change sequences drifting, this is not based on radiation effects
RX AGC performance

- The maximum level of amplification and the amplitude vs. attenuation function depends on the narrow RF matching of the FMCOMMS-2 board.
- In all cases, we did not observed the AGC gain control does not deviate critically with increased TID level.
RX manual gain

- We observed, as already seen for the AGC, the gain factor of the amplification stage in the receiver is not affected by radiation.
- For RX2 there is a slightly different performance in low power levels (deviating amplitudes) which is expressed by mismatches in the front-end.
RX filter and bandwidth response
The attenuation shows an almost linear function for any selected carrier frequency and is not being affected by the exposed radiation dose.
The peak level for the fundamental tone, the 3rd and the 5th intermodulation product are shown vs. the selected TX attenuation on a carrier frequency of 1.6GHz and 2.4GHz.

As can be seen, the IMD for the 3rd and the 5th peak to the fundamental tone do not deviate with increased TID level.
To evaluate the LOL of the DUT’s transmitter, the distance between the received DC signal level and the expected transmitted sinewave level is calculated.

We did not observe critical changes in the function depending on the obtained TID.
Single Event Effects Testing

- Single Event Effects testing performed under Proton and Heavy Ion
  - Proton: up to 200 MeV (@KVI, Groningen, NL)
  - Heavy Ion: up to 65 MeV.cm²/mg (@ UCL, Leuven la neuve, BL)
- Test Board has been developed for this purpose
- AD9361 was required to “open” the device package
- Two Samples tested
SEE Test Procedure

Start

Boot Initial Configuration

Beam Shutter Disabled

Beam Shutter Enabled

Start Monitoring Task

SEL?

yes

no

yes

no

Start IQ Data capturing

Capture IQ Data on RX 1&2 and dump via ethernet

no

yes

Stop Script?

End

Start sinewave Transmission

Dump sinewave file to TX 1&2

no

yes

Stop Script?

End

Register SEU?

yes

no

yes

no

run

Fluence Achieved?

yes

no

no

Re-Init successful?

yes

no

A) Re-Config
B) Re-Init

Run Stop Script

End

yes

yes
Single Event Effects Testing

- Various types of errors
  - SELs
  - SEUs, MBU in functional register configuration
  - SEFIs that required a re-configuration or re-initialization
  - IQ Data corruption (soft and hard)
Single Event Effects Testing

Soft: SEU in ADC

Soft: Event in PLL

Hard: Loss of IQ data
Single Event Effects Testing

- No destructive event
- Very good SEE response
- Many SEUs, oft not critical
- Mainly recovered by re-configuration
- IQ Failures: 50% hard; 50% soft
- Hard IQ Failure recovered by re-initialization
- GEO and LEO reference mission
  - Nom.: YEARS for failure
  - Worst: DAYS for failure
- Results presented for Heavy Ions
- Proton response much lower (in order of > 10 events)

<table>
<thead>
<tr>
<th>Orbit</th>
<th>SEE type</th>
<th>Heavy Ion SEE Rate [failure/device/day]</th>
<th>Years for failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO</td>
<td>SEU</td>
<td>3.98×10^{-4}</td>
<td>6.88</td>
</tr>
<tr>
<td>GEO</td>
<td>SEU</td>
<td>1.17×10^{-3}</td>
<td>2.34</td>
</tr>
<tr>
<td>LEO</td>
<td>SEFI re-config.</td>
<td>2.22×10^{-5}</td>
<td>123</td>
</tr>
<tr>
<td>GEO</td>
<td>SEFI re-config.</td>
<td>6.43×10^{-5}</td>
<td>43</td>
</tr>
<tr>
<td>LEO</td>
<td>Hard TX IQ SEFI</td>
<td>1.26×10^{-5}</td>
<td>217</td>
</tr>
<tr>
<td>GEO</td>
<td>Hard TX IQ SEFI</td>
<td>3.77×10^{-5}</td>
<td>73</td>
</tr>
<tr>
<td>LEO</td>
<td>Hard RX IQ SEFI</td>
<td>1.55×10^{-5}</td>
<td>176</td>
</tr>
<tr>
<td>GEO</td>
<td>Hard RX IQ SEFI</td>
<td>4.64×10^{-5}</td>
<td>61</td>
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Nominal condition

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</thead>
<tbody>
<tr>
<td>LEO</td>
<td>SEU</td>
<td>3.06×10^{0}</td>
<td>7.78</td>
</tr>
<tr>
<td>GEO</td>
<td>SEU</td>
<td>1.33×10^{1}</td>
<td>1.8</td>
</tr>
<tr>
<td>LEO</td>
<td>SEFI re-config.</td>
<td>2.02×10^{-1}</td>
<td>120</td>
</tr>
<tr>
<td>GEO</td>
<td>SEFI re-config.</td>
<td>8.79×10^{-1}</td>
<td>27.4</td>
</tr>
<tr>
<td>LEO</td>
<td>Hard RX IQ SEFI</td>
<td>6.50×10^{-2}</td>
<td>370</td>
</tr>
<tr>
<td>GEO</td>
<td>Hard RX IQ SEFI</td>
<td>2.84×10^{-1}</td>
<td>85</td>
</tr>
<tr>
<td>LEO</td>
<td>Hard TX IQ SEFI</td>
<td>6.19×10^{-2}</td>
<td>387</td>
</tr>
<tr>
<td>GEO</td>
<td>Hard TX IQ SEFI</td>
<td>3.11×10^{-1}</td>
<td>77</td>
</tr>
</tbody>
</table>

Worst case
System-Level Verification
Radiation Testing on System-Level

- For TID Effects: Co60-Source can be used (no limitation in space)
- For SEE: Particle accelerators have only a narrow beam (20-100mm dia)
- How to test on system-level that exceed the narrow beam?
  - Local irradiation (single devices or groups of the system)
  - Failure propagation unclear
  - What about multi-point of failures?
  - Possible solution:
    **CERN High Energy Accelerator Mixed-Field Facility (CHARM)**
    - Use of 24GeV PS Proton beam
    - Metal target used (copper)
    - Mixed field of particles
      - Neutron, Protons, Electrons
      - No Heavy Ions

[Diagram of CERN High Energy Accelerator Mixed-Field Facility (CHARM)]
Radiation Testing on System-Level

- Two SUTs in a complex setup due to limited RF interfaces

**On system-level**
- Potential destructive events due to high current and voltage states
  - Sub-voltage latch-up detection and detection
  - Overvoltage detection and protection
- Single event failure interrupt
  - System-Watchdog executes reset if heart-beat disappears
  - Time-Out of command response (power-cycle)
  - Soft-Watchdog (on program/application level)

**On component-level**
- RF-Transceiver deep failure mitigation
- NAND Flash supervisory (Boot device)
Radiation Testing on System-Level

- System(s) run with multiple tasks on request
  - HK-Data, RF-Data aq., Spectrogram, ...
- No degradation of voltage and current due to TID
- No SELs or destructive failures
- Ability to perform self-recovery
  - 100% recovery from failure to valid system operation
  - No interrupted boot-processes observed (process takes ~15sec)
- 95% of all failures were system crashes (Zynq+DDR3)
- No invalid data on boot devices (NAND Flash)
- Data fly-by storage on SD-Card critical (SD-Card broken)
  - SUT#2 (partially) not able to response on requested tasks
Radiation Testing on System-Level

- RF Transceiver has been irradiated to Proton (max. 190MeV)
  - Low SEU rate in configuration registers
  - Very low SEFI rate
  - No SEFI seen in CHARM, only minor SEUs

- Zynq+DDR3 has been irradiated by proton (max. 190MeV)
  - Same configuration and software were used as in CHARM
    (only exception: SD-Card was not used for intermediate data storage)
  - No RF-board in use (no RF data captured)
  - Fluence: $5.0 \times 10^8 \#$/cm$^2$
  - Comparable saturation of cross-section
    - $\sim 2.6 \times 10^{-8}$ cm$^2$/device (proton)
    - $2.451 \times 10^{-8}$ cm$^2$/device (CHARM)
Conclusion and Outlook
Conclusion

- Commercialization of space (NewSpace) tolerates more risk and use new technologies that are not qualified for space, nor radiation hardened by the manufacturer
- Be aware when use COTS components in your space application
- A hybrid approach of RadHard and cots devices is a good solution to increase the performance capabilities and be cost-efficient and reliable
- Radiation effects testing is getting more and more complicated due to the complexity of modern devices
- Radiation testing on system-level is quite new and is an very good approach for testing new developed systems which are using COTS devices, where typically each devices needs to be investigated separately
Thank you for your attention