学校编码：10384　　分类号＿＿＿密级＿＿＿
学号：23320100154052　　UDC＿＿＿

厦门大学

博士学位论文

卫星通信系统星上处理抗辐照关键技术研究

Research on Anti-radiation Techniques for On-board Processing of Satellite Communication Systems

杨文慧

指导教师姓名：　王京　教授

专　业　名　称：　通信与信息系统

论文提交日期：　2013 年 10 月

论文答辩时间：　2013 年 12 月

学位授予日期：2013　年　　月

答辩委员会主席：＿＿＿＿＿＿

评　　阅　　人：＿＿＿＿＿＿

2013 年 12 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果，均在文中以适当方式明确标明，并符合法律规范和《厦门大学研究生学术活动规范（试行）》。

另外，该学位论文为（　　）课题（组）的研究成果，获得（　　）课题（组）经费或实验室的资助，在（　　）实验室完成。（请在以上括号内填写课题或课题组负责人或实验室名称，未有此项声明内容的，可以不作特别声明。）

声明人（签名）：

年　　月　　日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

（　　）1.经厦门大学保密委员会审查核定的保密学位论文，于　　年　　月　　日解密，解密后适用上述授权。

（　　）2.不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年　　月　　日

摘要

太阳活动导致太空中存在着大量的放射性粒子，这些放射性粒子对电路系统产生的辐射会使得卫星系统发生各种单粒子事件（Single Event Effect, SEE），从而造成计算数据或控制逻辑发生错误，严重影响系统的稳定性。随着半导体工艺的不断发展，器件尺寸不断降低，电路系统对辐射的敏感性日益增加。多载荷处理式卫星（On-Board Processing, OBP）通信系统中，辐射问题愈发显著。

三模冗余（Triple Modular Redundancy, TMR）是传统的星载平台容错方法，其原理简单易实现，具备较强的可靠性，在可信计算领域被广泛应用。但其开销巨大，严重制约了高复杂度星载信号处理算法的实现。因此，开发一种低开销、高可靠性的容错方法已经成为现代星上处理技术的重中之重。

本文针对低开销、高可靠性的抗单粒子翻转（Single Event Upset, SEU）方法展开研究，贡献主要包括以下几个方面：

1. 针对传统三模冗余开销大的问题，提出一种基于剩余码的三模冗余抗辐照技术，该技术将三模冗余两两检测的结构转化为将其中一模退化为用余数系统实现，并对另外两模进行检测的新结构，使得三模冗余开销降低至约两模。
   a. 分析余数系统在线性系统中应用的普适性；设计双模备份结合剩余码的单采样判决系统（Single-Sample Checking based Dual Modules plus Checking module based on Residue Code, SSC-DM-CRC），其面积开销和可靠性均随余数基的增大而增加。针对 SSC-DM-CRC 系统在小模数条件下漏检率高的问题，我们提出了一种双模备份结合剩余码的多采样判决系统（Multi-Sample Checking based Dual Modules plus Checking module based on Residue Code, MSC-DM-CRC），该系统的决策逻辑中采用循环判决，在采用相同的模数时，可在不大幅增加 SSC-DM-CRC 系统面积开销的同时，有效降低漏检率。
   b. 首次揭示余数检错过程中漏检问题的存在，针对线性系统构建故障模型，对漏检率数值做出理论分析。
   c. 设计了一种基于仿真的故障注入方法。

2. 提出一种高层次综合（High Level Synthesis, HLS）与剩余系统相结合的低开销抗辐照技术。该系统较 SSC-DM-CRC 和 MSC-DM-CRC 系统而言，漏检率得到了大幅降低，与此同时，面积开销也实现了一定程度的下降。
   a. 设计了一套基于资源约束的 ASAP（As Soon As Possible）调度算法，用于目标系统在面积与延时之间做出合理折衷。
   b. 设计一种双模备份结合多剩余系统联合检测的判决系统，
3. 电路屏蔽效应使得部分电路节点对单粒子翻转免疫，而前两种抗辐照方法没有利用电路本身的屏蔽效应，对这些形成过保护。为此，我们提出一种基于 HLS 的多级抗 SEU 技术。该技术针对目标系统中不同敏感度的子模块，采用不同的抗辐照方法，并利用 HLS 进一步缩减面积开销。
   a. 设计一套电路节点平均敏感度估算算法，用来计算每个电路内部节点对放射性粒子的敏感程度。
   b. 根据电路屏蔽效应提出一种基于加权平均面积的子模块敏感度分析方法，分别对目标设计中敏感、次敏感和不敏感三类子模块采取电路级抗辐照、门级抗辐照和不保护的措施。

关键词：卫星通信；抗辐照；单粒子翻转；三模冗余；低开销

Abstract

Sun activities produce large amount of high energy particles in the space environment, which radiate the circuit system in communication satellites.The radiation may generate varies kinds of Single Event Effects (SEE), which incur erroneous data or wrong control logic, damaging the system reliability greatly. With the development of semiconductor technologies, the size of device keeps decreasing, making the circuit system more sensitive to the radiation. The radiation problem is much more notable in the on-board processing satellite communication systems.

Triple Modular Redundancy (TMR) is a commonly-used on-board fault-tolerant method for its simplicity and high reliability in trusted computing. However, it restricts the implementation of high complexity on-board DSP units because of its high cost. Therefore, fault-tolerant methods with the low cost and high reliability are urgently required.

Researches of this article focus on the fault-tolerant method with low cost and high reliability. Main contributions of this article are concluded as follows.

1. To reduce the area overhead of traditional TMR, this paper proposes a anti-radiation structure based on residue code and TMR, which has one module implemented by residue systems to check the other two modules and makes the overhead almost as much as that of DMR.
   a. The residue systems' universality for linear systems is analyzed; Single-Sample Checking Dual Modules plus Checking module based on Residue Code (Single-Sample Checking based Dual Modules plus Checking module based on Residue Code, SSC-DM-CRC), whose area overhead and reliability increase with the increase of modulus, is designed. To reduce the high fault missing rate under small modulus in the SSC-DM-CRC system, we propose a Multi-Sample Checking Dual Modules plus Checking module based on the Residue Code (Multi-Sample Checking based Dual Modules plus Checking module based on Residue Code, MSC-DM-CRC) system, using the cyclic decision logic to reduce the fault missing rate without increasing area overhead greatly.
   b. The fault missing problem of residue error detection is pointed out for the first time; the fault model for linear systems is constructed to analyze the fault

missing rate theoretically.

c. A fault injection method based on software platform is given.

2. A hybrid anti-radiation method using HLS and residue code, which reduces the fault missing rate greatly and cuts down the area overhead to some extent, compared with SSC-DM-CRC and MSC-DM-CRC systems, is proposed.
   a. A suit of resource-limited As Soon As Possible (ASAP) scheduling algorithm is designed, to seek a proper tradeoff between area and delay.
   b. A Dual-Module Redundancy Multi-Residue Detection (DMR-MRD) system is proposed.
3. Due to the circuit masking effect, some circuit nodes are immune to SEU, butthey are protected in the two methods above, which is unnecessary for those nodes. Therefore, a multi-layer SEU-tolerant technique based on HLS, utilizing specific anti-radiation method for different modules according to their sensitivities, to reduce the system overhead, is introduced.
   c. An algorithm for estimating the sensitivity of inner circuit nodes is designed.

d. A sensitivity analysis method using the concept of weighted area-mean-value is proposed. To minimize the area overhead, different strategies are applied to those modules, that is, circuit level protection is applied to the sensitive modules, gate level protection is used for the semi-sensitive modules, and the insensitive modules are unprotected.

Keywords: Satellite communication; Anti-Radiation; Single event upset; Triple modular redundancy; Low cost

缩 略 词

AceS: ASIA cellular satellite

ADC: analog-to-digital converter

AIF: adder input fault

ASAP: as soon as possible

BP: bent pipe

BPSK: Binary Phase Shift Keying

CCSDS: consultative committee for space data systems

CMOS: complementary metal oxide semiconductor

CRT: Chinese remainder system

DAC: digital-to-analog converter

DBF: digital beam forming

DFG: data flow graph

DM-CRC: dual modules plus checking module based residue code

DSP: digital signal processing

DWC-CED: duplication with comparison combined with concurrent error detection

EDAC: error detection and correction

FFT: fast Fourier transformation

FIR: finite impulse response

GPS: global positioning system

HLS: high-level synthesis

HWIFI: hardware-implemented fault injection

LANL: Los Alamos national library

LEO: low earth orbit

LET: linear energy transfer

MAC: multiply-accumulate

MIF: multiplier input fault

MSC-DM-CRC: multi-sample checking DM-CRC

MUOS: mobile user objective system

NASA: national aeronautics and space administration

OBP: on-board processing

OFDM: orthogonal frequency division multiplexing

QPSK: quadrature phase shift keying

QAM: quadrature amplitude modulation

RNS: residue number system

RRNS: redundant residue number system

SEE: single event effect

SEL: single event latch

SEU: single event upset

SOI: silicon-on-insulator

SRAM: static random access memory

SSC-DM-CRC: single-sample checking DM-CRC

SWIFI: software-implemented fault injection

TDD: time division duplexing

TMR: triple modular redundancy

VLSI: very large scale integration

WDT: watchdog timer

WGS: wideband global SATCOM system

目 录

Contents