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The role of fault management in the embedded system design

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THE ROLE OF FAULT MANAGEMENT IN THE EMBEDDED SYSTEM DESIGN

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Abstract

In the last decade, the world of telecommunications has seen the value of services definitively affirmed and the loss of the connectivity value. This change of pace in the use of the network (and available hardware resources) has led to continuous, unlimited growth in data traffic, increased incomes for service providers, and a constant erosion of operators' incomes for voice and *Short Message Service* (SMS) traffic.

The change in mobile service consumption is evident to operators. The market today is in the hands of *over the top* (OTT) media content delivery companies (Google, Meta, Netflix, Amazon, etc.), and *The fifth generation of mobile networks* (5G), the latest generation of mobile architecture, is nothing other than how operators can invest in system infrastructure to participate in the prosperous service business.

With the advent of 5G, the worlds of cloud and telecommunications have found their meeting point, paving the way for new infrastructures and services, such as *smart cities*, *industry 4.0*, *industry 5.0*, and *Augmented Reality (AR)/Virtual Reality (VR)*. People, infrastructures, and devices are connected to provide services that we even struggle to imagine today, but a highly interconnected system requires high levels of reliability and resilience.

Hardware reliability has increased since the 1990s. However, it is equally correct to mention that the introduction of new technologies in the nanometer domain and the growing complexity of on-chip systems have made fault management critical to guarantee the quality of the service offered to the customer and the sustainability of the network infrastructure.

In this thesis, our first contribution is a review of the fault management implementation framework for the radio access network domain. Our approach introduces a holistic vision in fault management where there is increasingly more significant attention to the recovery action, the crucial target of the proposed framework. A new contribution underlines the attention toward the recovery target: we revisited the taxonomy of faults in mobile systems to enhance the result of the recovery action, which, in our opinion, must be propagated between the different layers of an embedded system (hardware, firmware, middleware, and software). The practical adoption of the new framework and the new taxonomy allowed us to make a unique contribution to the thesis: the proposal of a new algorithm for managing system memory errors, both temporary (soft) and permanent (hard)

The holistic vision of error management we introduced in this thesis involves hardware that proactively manages faults. An efficient implementation of fault management is only possible if the hardware design considers error-handling techniques and methodologies. Another contribution of this thesis is the definition of the fault management requirements for the RAN embedded system hardware design.

Another primary function of the proposed fault management framework is fault prediction. Recognizing error patterns means allowing the system to react in time, even before the error condition occurs, or identifying the topology of the error to implement more targeted and, therefore, more efficient recovery actions. The operating temperature is always a critical characteristic of embedded radio access network systems. Base stations must be able to work in very different temperature conditions. However, the working temperature also directly affects the probability of error for the system. In this thesis, we have also contributed in terms of a machine-learning algorithm for predicting the working temperature of base stations in radio access networks — a first step towards a more sophisticated implementation of error prevention and prediction.

Sammanfattning

Under det senaste decenniet har telekommunikationsvärlden sett värdet av tjänster definitivt bekräftats och förlusten av anslutningsvärdet. Denna taktförändring i användningen av nätverket (och tillgängliga hårdvaruresurser) har lett till en kontinuerlig, obegränsad tillväxt i datatrafik, ökade inkomster för tjänsteleverantörer och en konstant urholkning av operatörernas inkomster för röst och *Short Message Service* (SMS) trafik.

Förändringen i konsumtionen av mobiltjänster är uppenbar för operatörerna. Marknaden idag är i händerna på *over the top* (OTT) företag för leverans av mediainnehåll (Google, Meta, Netflix, Amazon, etc.), och *The fifth generation of mobile networks* (5G), den senaste generationen av mobil arkitektur , är inget annat än hur operatörer kan investera i systeminfrastruktur för att delta i den välmående serviceverksamheten.

Med tillkomsten av 5G har moln- och telekommunikationsvärldarna hittat sin mötesplats och banat väg för nya infrastrukturer och tjänster, såsom *smarta städer*, *industry 4.0*, *industry 5.0*, och *Augmented Reality (AR)/Virtual Reality (VR)*. Människor, infrastrukturer och enheter är anslutna för att tillhandahålla tjänster som vi till och med kämpar för att föreställa oss idag, men ett mycket sammankopplat system kräver höga nivåer av tillförlitlighet och motståndskraft.

Hårdvarans tillförlitlighet har ökat sedan 1990-talet. Det är dock lika korrekt att nämna att introduktionen av ny teknik inom nanometerområdet och den växande komplexiteten hos on-chip-system har gjort felhantering avgörande för att garantera kvaliteten på den tjänst som erbjuds kunden och hållbarheten i nätverksinfrastrukturen .

I den här avhandlingen är vårt första bidrag en översyn av ramverket för implementering av felhantering för domänen för radioaccessnätverk. Vårt tillvägagångssätt introducerar en holistisk vision inom felhantering där det blir allt mer betydande uppmärksamhet på återställningsåtgärden, det dominerande steget i det föreslagna ramverket. Ett nytt bidrag understryker uppmärksamheten mot återställningsmålet: vi tittade på taxonomin för fel i mobila system för att förbättra resultatet av återställningsåtgärden, som, enligt vår åsikt, måste spridas mellan de olika lagren i ett inbäddat system (hårdvara, fast programvara , mellanprogram och programvara). Det praktiska antagandet av det nya ramverket och den nya taxonomin gjorde det möjligt för oss att ge ett unikt bidrag till avhandlingen: förslaget om en ny algoritm för att hantera systemminnesfel, både tillfälliga (mjuka) och permanenta (hårda)

Den holistiska vision av felhantering som vi introducerade i denna avhandling involverar hårdvara som proaktivt hanterar fel. En effektiv implementering av felhantering är endast möjlig om hårdvarudesignen tar hänsyn till felhanteringstekniker och metoder. Ett annat bidrag från denna avhandling är definitionen av felhanteringskraven för hårdvarudesignen för det inbyggda RAN-systemet.

En annan primär funktion hos det föreslagna felhanteringsramverket är felprediktion. Att känna igen felmönster innebär att tillåta systemet att reagera i tid, även innan feltillståndet inträffar, eller att identifiera felets topologi för att implementera mer riktade och därför mer effektiva återställningsåtgärder. Driftstemperaturen är alltid en kritisk egenskap hos inbyggda radioaccessnätsystem. Basstationer måste kunna arbeta under mycket olika temperaturförhållanden. Arbetstemperaturen påverkar dock direkt sannolikheten för fel för systemet. I den här avhandlingen har vi också bidragit med en maskininlärningsalgoritm för att förutsäga arbetstemperaturen för basstationer i radioaccessnätverk - ett första steg mot en mer sofistikerad implementering av felförebyggande och förutsägelse.

To my family

Acknowledgment

Life is becoming. It may be why I keep looking.

Once, while presenting one of my novels, a person of the audience asked me how an engineer could have the imagination to write books. I replied that there is the same motivation behind my work and my novels: curiosity.

Doing research and writing books, ultimately, is nothing more than curiosity. The starting point is the same: a series of questions to which we would like to give answers. Then, you need passion, commitment, patience, study, and technique to season the journey. Having a group of people who never stop supporting you (and putting up with you!) makes it a fantastic experience. This unique and priceless gift is already valid value of the research, at least as much as the final result. For this reason, I'd like to thank those who accompanied me on this journey towards my licentiate.

First of all, my family, my wife **Raffaella**, and my daughter **Anastasia**, who, with daily gestures, made my development possible.

Thanks to **Ericsson AB**, which believed in the value of my growth and supported me in this adventure; **Anders Caspár**, director of external relations with universities, who is always available and present; **Pär Asplund**, my department manager and **John Grenholm**, my section manager, for believing in me, encouraging and supporting me in every circumstance. Many thanks to **Marcus Jägemar**. He pushed me toward the industrial Ph.D. experience, and since then, he has always remained by my side. As a supervisor, as a colleague, and as a good friend. Thanks to **all my colleagues**, who shared a thousand ideas and just as many coffees with me. Citing them all would be impossible, but working with them was fundamental to my research. Special thanks to **Alf Larsson**, internal supervisor, who has always contributed to my research, and **Elisabeth Larsson**, a solid point of reference for fault management.

Thanks to **Mälardalens Universitet** for welcoming me into its family. To **Daniel Sundmark** and **Thomas Nolte**, my tireless supervisors. To all the teachers with whom the technical discussion was constructive, the administrative staff, and the Ph.D. students, thank you for the network of support and friendship, with a special mention to **Shammona Imtiaz** and **Bahar Houtan**.

The future, it's just another journey to begin.

Carlo Vitucci
Västerås, April, 2024

List of Publications

Papers included in this thesis[1]

Paper A: Carlo Vitucci, Daniel Sundmark, Marcus Jägemar, Jakob Danielsson, Alf Larsson, Thomas Nolte *A Reliability-oriented Faults Taxonomy and a Recovery-oriented Methodological Approach for Systems Resilience.* In Proceeding IEEE 46th Annual Computers, Software, and Aplications conference (COMPSAC 2022).

Paper B: Carlo Vitucci, Daniel Sundmark, Marcus Jägemar, Jakob Danielsson, Alf Larsson, Thomas Nolte *Fault Management Framework and Multi-layer Recovery Methodology for Resilient System.* In the 6th IEEE International Conference on System Reliability and Safety (ICSRS 2022).

Paper C: Carlo Vitucci, Daniel Sundmark, Marcus Jägemar, Jakob Danielsson, Alf Larsson, Thomas Nolte *Fault Management Impacts on the Networking Systems Hardware Design.* In Proceeding IEEE 49th Annual Conference of the Industrial Electronics Society, IES (IECON 2023)

Paper D: Carlo Vitucci, Daniel Sundmark, Jakob Danielsson, Marcus Jägemar, Alf Larsson, Thomas Nolte *Run Time Memory Error Recovery Process in Networking System.* In the 7th IEEE International Conference on System Reliability and Safety (ICSRS 2023).

[1]The included papers have been reformatted to comply with the thesis layout.

Paper E: Selma Rahman, Mattias Olausson, Carlo Vitucci, Ioannis Avgoileas *Ambient Temperature Prediction for Embedded Systems Using Machine Learning.* In the 8th International Conference on Engineering of Computer-based Systems (ECBS 2023).

Related publications, not included in this thesis

Paper X: Carlo Vitucci, Alf Larsson. *Flexible 5G Edge Server for Multi Industry Service Network.* In International Journal on Advances in Networks and Services, vol. 10, no3& 4, 2017.

Contents

I

Thesis

Chapter 1

Introduction

The interest in the fault control of a system's hardware is certainly not new: dr. Grace Hopper is often credited for reporting the first bug in the computer world on September 9, 1947 (Figure 1.1). Research for fault management frameworks and models went hand in hand with introducing new technologies.

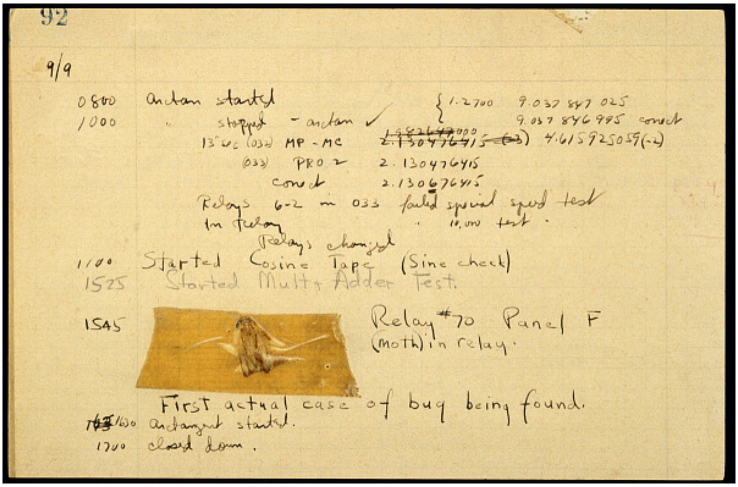

Figure 1.1. The iconic first bug reported in a log book. Smithsonian National Museum of American History

Most fault management models have identified this discipline's three fundamental pillars in the supervision, localization, and recovery of an error condition. Above all, recovery has acquired increasing importance because it has emerged that the true objective of fault management is not the identification of a fault but its management aimed at restoring a full or partial working mode condition in order to minimise the service downtime.

The purpose of a telecommunications system is to allow communication through a radio and network systems. From the beginning of the 90s, when the first digital communication system called `Global System` for `Mobile` (GSM) was born, to today, the type of traffic has changed drastically: network connects more and more devices, and the usage of mobile phones switched more and more from voice to services traffic. The data traffic generated exceeded the volume of voice traffic in the second quarter of 2009 [1, 2]. Since 2014, voice traffic has become a negligible component of the traffic volume generated [3]. Despite this exponential growth of data, the physical capacity of the network is not (any longer) the cash cow of the service. The business is dominated by the giants of media content delivery (like Netflix, Google, or Meta), while the profits of the network operators have consistently decreased. Most of the world's popular apps, social media sites, and music or video streaming services depend on connectivity that works anywhere and anytime (see Figure 1.2).

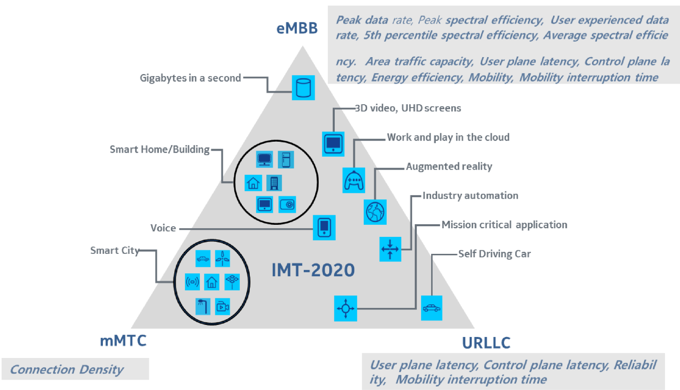

Figure 1.2. The 5G key performance requirements for service flexibility [4].

Figure 1.3. The 5G infographic representation [9].

The operators' need to find new business opportunities to keep their business sustainable [5]. 5G is the answer to the operators' need. The technology focuses to manage an interconnected world thanks to the meeting between wireless telecommunications and the cloud [6]. Automotive, factories, accessories, and shops will all be connected to develop services not even imaginable until yesterday [7]. The networking development has moved this paradigm to the world of connectivity, where everything is interconnected *...to everything, everywhere, and every time...* [8]. Figure 1.3 shows the useful 5G info-graphic from the European Commission [9] that helps to understand the business behind the need for the new telecommunication system.

The reference infrastructure reflects the level of connectivity required. In the mobile network , the radio system provides connectivity to a plethora of devices of different types to which to offer various services in terms of characteristics and performance: from the Internet of Things (IoT) networks with which to connect devices, sensors, and fabrics for the implementation of the industry4.0, audio and video streaming services for users, remote control of urban facilities, such as water, electricity and gas, and communication for and between vehicles (M2M, X2M, etc.). Services can feature caching capabilities in the Radio Access Network (RAN) to increase service usability or access distributed services across core and data center nodes. The whole network must be able to count on a reliable systems to set up the various distributed services. And be reliable means be a more **resilient system**.

Thesis outline

The thesis consists of two parts. Part I starts with presenting the overall research goals including the research approach and research method in Chapter 2. For a better reading experience, definitions and related works are presented next in Chapter 3. Followed by the research methodology, results are presented in Chapter 4 to explain the contributions made through the published papers. Towards the end of Part I, a conclusion is presented along with prospective future work in Chapter 5.

Finally, the included papers are presented in Part II of the thesis.

Chapter 2

Research Overview

In this chapter, a brief description of the problem overview and research goals is provided. The chapter then continues to present the research method used to achieve the goals.

2.1 Problem Overview

In chapter 1, we have arrived to the conclusion that the next generation network must count on more *resilient systems*. Understanding what a resilient system is helps identify what we need to improve the system's resiliency.

Figure 2.1 on the left shows the resilience triangle that describes and measures the system's resiliency. t_{f1} is the faulty event occurrence time and t_{r1} is the time when the system fully recovered by the fault event and is working again at the full functionality ratio F_f. if F_m is the minimum reduced functionality rate caused by a faulty even at the time $t_m T_{f1}$, then the measure of the system resilience is the area of the so-called *Resilience Triangle*:

$$\mathrm{A}_{\mathrm{TheoreticalResilience}} = \frac{1}{2}(T_{r1} - T_{f1})(F_f - F_m) \tag{2.1}$$

This thesis introduces a new method for the resilience calculation. It considers three factors: the *System Resistance*, that is the capacity of the system to mask and promptly react on a faulty event: the *System Recoverability*, that

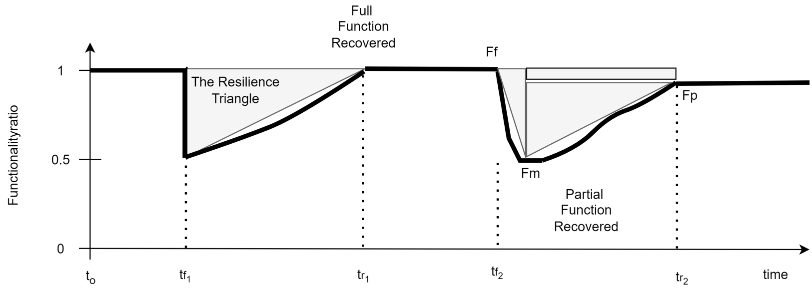

Figure 2.1. The Resilience Triangle. On the left, the theoretical definition and on the right a more realistic representation of system reaction to a fault event

is the capacity of the system to recover from a faulty event, and the *System dynamism*, that is the capacity of the system to continue to work under degraded functionality condition. Figure 2.1 on the right shows the contribution of the three factors as calculated by the thesis. the new proposed method compared to other (see Dong et al. [10], as example) has the advantage of tending towards the theoretical value.

$$\begin{aligned} \mathrm{A}_{\mathrm{RealisticResilience}} &= \tfrac{1}{2}(t_m - t_{f2})(F_f - F_m) + \\ &= \tfrac{1}{2}(t_{r2} - t_m)(F_p - F_m) + (t_{r2} - t_m)(F_f - F_p) \end{aligned}$$

$$\lim_{F_p \to F_f} A_{RealisticResilience} = A_{TheoreticalResilience} \tag{2.2}$$

Therefore, if it is true that we need to increase the system's resilience, our goal becomes reducing the area of the triangle of resilience. By definition, it is possible in two modes:

- reducing the impact of a fault on the system's functionalities;
- reducing the fault recovery time.

The system function that can reduce the area of the resilience triangle, either by reducing the impact of a fault or by reducing the recovering time, is the fault management. Fault management is a system function that aims to detect, locate, and recover possible fault conditions in the system [11]. The need to design a telecommunication system with dedicated fault management support has been well-known since the early life of networking [12, 13, 14, 15]. The term *correctness* indicates the ability of a system to operate following the requirements. But there is a cost for verifying the system correctness in run-time. It requires the addition of knowledge of its *correctness model*, which entails disadvantages, such as higher resource utilization, increased design complexity, and reduced maintainability. In a RAN embedded system, the mentioned disadvantages would have unacceptable drawback in network performance.

The difficulty of an efficient fault management policy increased hand to hand with the complexity of interconnected systems. The intrinsic quality of the hardware components has undoubtedly increased, and the trend doesn't face a turnaround [16]. Yet, the failures of hardware components have a higher cost. Patches can always fix software bugs, but board replacement is the only way to cope with a hardware device in a failure state. The hardware repair process is costly: maintenance activities on-site, packaging, expedition, board analysis, and test to confirm the failure condition diagnosis for the component, and, when possible, faulty hardware replacement. If an intrinsic component quality could be acceptable for straightforward, simple, and isolated embedded systems, it is no longer sufficient in the case of complex and interconnected systems. In telecommunication networks, multi-chip packages, robotics, automotive, and, more generally speaking, in an increasingly widespread distributed system, the hardware devices must work and inter-work properly, react to external disturbances promptly, and stand as long as possible. Therefore, maintaining a low value for the system's failure rate (and high reliability) is no longer just a problem of component quality but of the ability to detect, manage and correct a fault before it becomes a failure condition. A network design aimed at building resilient systems thanks to an efficient fault management implementation is the only way to prevent network operators from seeing their business model compromised by poor quality of experience and exponential increase in OPEX.

2.2 Research goals

Since the fault management is so crucial for the resiliency of the system, our work focuses on **revising design and implementation principles of fault man-**

agement in current and next-generation Radio Access Network boards to:

- minimize the fault impact on system's functionalities;
- reduce the fault recovery time;
- reduce the maintenance cost of radio access network infrastructure;
- increase the end user's quality of experience.

Design for Fault Management

A multi-technologies solution cannot be efficient if each layer doesn't consider the fault management impacts during implementation phase. In an embedded system, it is easily possible to perform a software update. With particular mechanisms and the proper attention to system security, it is also possible to consider changing the firmware. However, a hardware update is not a choice. If the hardware design is unsatisfactory, we must rethink the product and deliver a new hardware version with better performance than the old one. Fault management design makes no exception. The fault management solution for the system can only be correct if the hardware design of the product has considered what it means for the hardware to efficiently and effectively implement the fault management function. That is, there are fault management requirements for the hardware design. The task of this thesis is to define those requirements.

RG1 – Examine the impact of early-stage hardware design on the efficacy and efficiency of fault management, particularly focusing on fault management hardware requirements

Do the right thing in the right time

Fault management is a system function, and the system is increasing in complexity. A review of the fault management framework is essential to understand if we are doing what we need to do in the most efficient way possible. A highly complex system necessarily requires a holistic approach, where all system components (hardware, firmware, and software) interact with each other to recover a fault condition in the quickest way possible. An interwork means that the different technological layers must know how to talk about faults using the same language and comprehend the same error taxonomy.

RG2 – Explore the fault management framework and show how employing a multi-technologies model can minimize recovery time from faulty conditions within the system.

Preventing is the shortest recovery time possible

Doing the recovery actions at the right level reduce the recovery time, but analyze the system usage, recognize a functional deviation and trying to move back the system in the standard behaviour, means reducing and removing the fault likelihood for the maximum system's resiliency possible. We can make use of AI&ML models and algorithms to identify usage patterns in system resources, environmental parameters, and device error probability. In other words, we are going to design preventive and predictive fault management.

RG3 – Analyze the system data to identify suitable patterns for error prediction, identify fault trend in the time domain for error prevention.

2.2.1 Research Method

In persuasion of an effective and practical research approach, a quantitative engineering study inspired by design science [17] was conducted.

Table 2.1 maps the goals achieved in the corresponding papers.

In this thesis, Paper A proposes a novel fault taxonomy product reliability-oriented and a revised fault management architecture including the fault isolation concept for limiting the fault propagation into the system. The findings in Paper A represents the foundation of the Paper B, that introduces a multi-level

Papers	RG1	RG2	RG3
Paper A		✓	
Paper B		✓	
Paper C	✓		
Paper D	✓	✓	
Paper E			✓

Table 2.1. Mapping of research goals into papers

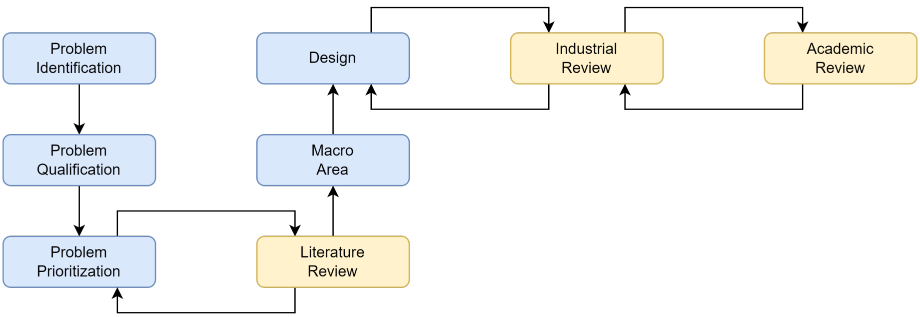

Figure 2.2. Research process

representation of the fault management framework and a multi-technologies fault handling approach. Since Paper B shows the role of the hardware technology in fault management implementation, Paper C focuses in mapping the Reliability requirements in the fault management that simplifies the definition of the fault management hardware requirements. The finding of Paper B and Paper C allow the implementation of efficient fault management solution based on hardware features. Paper D represents a practical application of those findings for a very common case: memory hardware errors. Paper E defines the activities needed in the system data pattern classification for RAN base-band board, specifically defining a model able to predict the environment temperature condition.

2.2.2 Research Approach

We want our results to be valuable and relevant for industry and academia. To achieve this goal, considerations catering to the two communities must be made, concerning our process used, since the goals of the research community and industry differ. In industry, it is important to:

- Maintain the technology leadership, achievable via an always up-to-date fault management competence.
- Reduce maintenance cost, with a special focus on limited return flow to the repair centers.
- interface vendors with a clear and common understanding of components/devices characterization and requirements.
- efficiency and effectiveness of fault management framework in current and next-generation systems

In the research community, there is a much stronger emphasis on that reported findings are general and reproducible. The point of contact between academics and industrial interests is the proof-of-concept implementation of industrial case studies. Figure 2.2 describes the overall research process.

- The starting point of our research method is identifying an actual or potential problem considering the next-generation wireless network baseband board design for which fault management could have a positive impact.
- Once we identify a problem, using the Ericsson fault ranking reports allows a quantification of the identified issues and the definition of a priority list.
- The third step of the research method is the review of existing industrial solutions, studies, and research related to fault management.
- This revision makes it possible to identify sub-areas of interest for fault management and reconsider both the problems and the priority setting assigned in the previous step.

- We design possible solutions for each remaining issue or each macro area of fault management to which it belongs.
- The industrial review will consolidate the findings.
- After deleting possible sensitive data for Ericsson and their customers, we will present the outcomes to the scientific communities for further comments and suggestions.

Chapter 3

Definition & Related Work

3.1 Definition

Slogan	Meanings
5G	5G is the fifth generation of wireless technology, offering faster data speeds, lower latency, and increased connectivity to enable a wide range of innovative applications and devices
6G	6G is the sixth generation of wireless technology, aiming to provide even faster data speeds, ultra-low latency, and advanced capabilities such as holographic communication and seamless integration of artificial intelligence, pushing the boundaries of connectivity
ECC	Error-Correcting Code is a technology used in computer memory to detect and fix errors, ensuring data accuracy and reliability in computing systems
IOT	Internet of Things refers to the interconnected network of physical devices, sensors, and everyday objects embedded with software and connectivity, enabling them to collect, exchange, and analyze data for various applications, enhancing automation and connectivity in diverse environments

Slogan	Meanings
PPR	Post-package repair involves fixing or addressing issues in a product or device after it has been packaged, ensuring that any defects or damages incurred during the packaging process are corrected before the product reaches the end consumer
RAN	Radio Access Network is a crucial component of mobile telecommunications that connects user devices to the core network, facilitating wireless communication by managing radio signals and enabling seamless connectivity for mobile phones and other wireless devices
RAS	Reliability, Availability, and Serviceability focuses on ensuring the dependability, accessibility, and ease of maintenance of a system, emphasizing its overall robustness and performance
SON	Self-Organizing Network refers to a network architecture that autonomously configures, optimizes, and manages itself, reducing manual intervention and enhancing efficiency in wireless communication systems
QoE	Quality of experience is a measure of the delight or annoyance of the user of an application or service.

3.2 Acronyms

Abbreviation	Meanings
5G	the fifth-generation of wireless communication technologies
6G	the sixth-generation of wireless communication technologies
AI & ML	Artificial Intelligence & Machine Learning
AR/VR	Augmented Reality, Virtual Reality
COTS	Commercial Off-The-Shelf
ECC	Error Correction Code
GSM	Global System for Mobile
HPC	High-Performance Computing
IoT	Internet of Things
M2M	Machine to machine communication protocol
OPEX	OPerational EXpenditure
OTT	Over The Top
QoE	Quality of Experience
RAN	Radio Access Network
RAS	Reliability, Availability and Serviceability
SON	Self-Organizing Network
SMS	Short Message Service
x2M	Anything to Machine communication protocol

3.3 Related Work

The thesis start analyzing the existing studies based on macro domains, as described in Figure 3.1. Table 3.1 shows the links to the references.

- **Fault management definitions & terminology**: When facing research, language is the first difficulty. Fault, Error, Failure, and defect in the field of fault management have many definitions, and it is vital to know the meaning of the terminology used to understand the issues and problems proposed in the literature. The studies always addressed and adapted

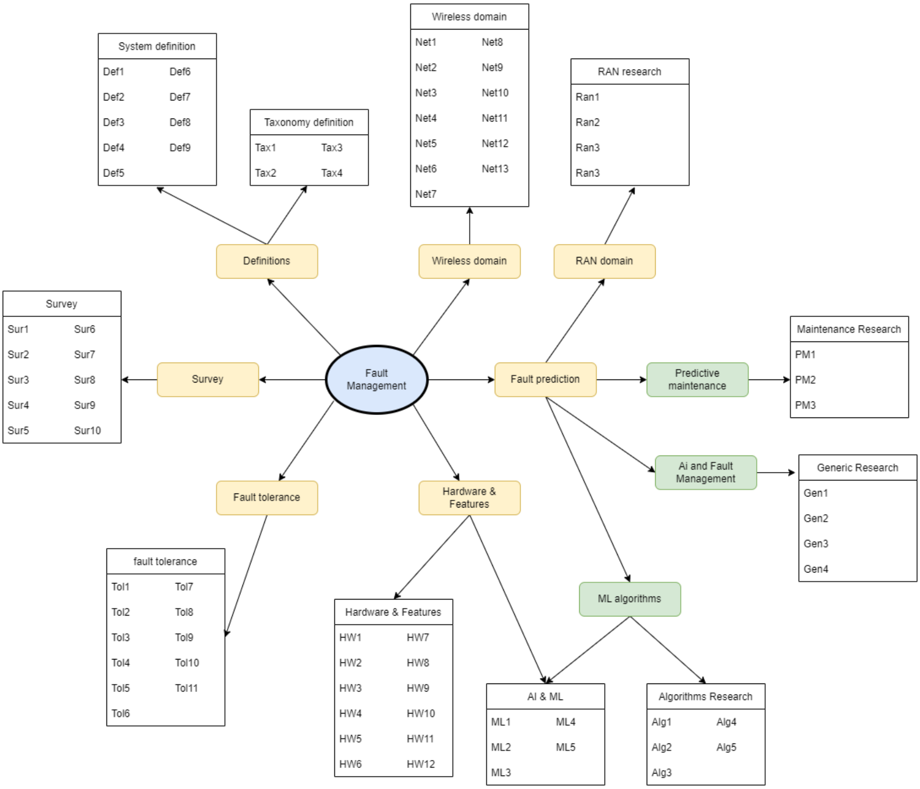

Figure 3.1. Related work listed per macro fault management research domains

fault taxonomy to the technological evolution of systems (for example, from the work of Parhami [26] to the recent adaptation of Bhandari and Ratneshwer [57] for service-oriented architectures). Parallel to the evolution of fault management taxonomy, concepts such as the system's reliability have attracted more and more attention (see, for example, the work of Biroloni [38]). When it comes to the system's reliability, attention shifts to the end user: what we want to achieve is the stability of the offered service. For this purpose, the framework of Reliability, Availability, and Serviceability (RAS [34]) is now widely accepted. It is not a coincidence

Label	reference	label	reference	Label	reference	label	reference
Def1	[18]	Sur8	[19]	Tol5	[20]	ML2	[21]
Def2	[22]	Sur9	[23]	Tol6	[24]	ML3	[25]
Def3	[26]	Sur10	[27]	Tol7	[28]	ML4	[29]
Def4	[30]	Net1	[31]	Tol8	[32]	ML5	[33]
Def5	[34]	Net2	[35]	Tol9	[36]	Alg1	[37]
Def6	[38]	Net3	[39]	Tol10	[40]	Alg2	[41]
Def7	[42]	Net4	[43]	Tol11	[44]	Alg3	[45]
Def8	[46]	Net5	[47]	HW1	[48]	Alg4	[49]
Def9	[50]	Net6	[5]	HW2	[51]	Alg4	[52]
Tax1	[53]	Net7	[54]	HW3	[55]	PM1	[56]
Tax2	[57]	Net8	[58]	HW4	[59]	PM2	[60]
Tax3	[61]	Net9	[62]	HW5	[63]	PM3	[64]
Tax4	[65]	Net10	[66]	HW6	[66]	Gen1	[67]
Sur1	[68]	Net11	[69]	HW7	[70]	Gen2	[71]
Sur2	[72]	Net12	[73]	HW8	[74]	Gen3	[74]
Sur3	[75]	Net13	[76]	HW9	[77]	Gen4	[78]
Sur4	[79]	Tol1	[80]	HW10	[81]	Ran1	[82]
Sur5	[83]	Tol2	[84]	HW11	[85]	Ran2	[86]
Sur6	[87]	Tol3	[88]	HW12	[89]	Ran3	[90]
Sur7	[91]	Tol4	[92]	ML1	[92]	Ran4	[93]

Table 3.1. map of the Figure 3.1 labels in references

that today's networking system characterizations involve concepts such as quality of service (see Mathews et al. [65]) or quality of experience (see Brooks and Hestnes [22]).

However, the studies analyzed by our research seem to have the node as minimum resolution [18], and this leads them to ignore typical concepts of the RAS framework, such as *corrected*, *uncorrected*, and *correctable* error, and the management of the fault of the single hardware component. On the other hand, our research believes that a taxonomy overcoming the existing limitations in the reference literature would be more suitable for fault recovery and improve the quality of experience considered necessary.

- **Survey**: If you want to understand if a particular discipline is suitable for a specific purpose, you must know it well. Our research has identified the fundamental components of fault management by carefully analyzing the available surveys. Since the domain of interest of our study is the radio access network, we considered those surveys that attempted to take stock of the situation for fields related to computing [87], wireless networks [23] and software-defined networks [72]. All the surveys we have analyzed agree with us in seeing fault management as the critical enabler of quality of service. Unfortunately, fault management surveys suffer from a taxonomy with the limitations we have defined in the area of definitions. In our opinion, three knowledge gaps are identifiable:
  - Most surveys are limited to a passive acceptance of the fundamental components of fault management, namely detect, locate and recover. On the other hand, a more detailed exploration of the foundations of these main components would allow us to discover the relationships between fault management in different phases of the product (verification in production, testing in design, and analysis of hardware in repair centers).
  - Although all surveys consider fault recovery as the ultimate goal of fault management, many prefer to focus on fault location [75], on performance monitoring [83], without exploring what fault recovery means in practical.
  - This bare attention to the recovery phase is the knowledge gap most affected by the limitations found in the definition area. The fact that the node is the lowest resolution for fault taxonomy means that alternative routes between different nodes look more than enough rather than understanding how to recover a node to a full or degraded functional mode.
- **Fault tolerance**: The conclusions we arrived at in the survey area show their weight also in the fault tolerance area. Fault tolerance is a necessary design mechanism if you want the optimal reaction to a fault

condition [44]. Knowing the barriers to the propagation of faults and the redundancy techniques is essential from the product design phase to operate the best recovery action. However, the networking systems studies consider fault tolerance essentially at the architectural level [92], as a reaction to the supervision of the path [28] and in dynamic routing policies [32]. If there is total harmony between our research and those from other study groups in recognizing fault management as a critical role for the reliability of the system [24], we have not found as much attention to detail in the hardware design and its role in system reliability.

- **Hardware & features**: The principle underlying our research is that fault management requires a holistic vision for its best implementation: hardware is not only the object of supervision but also the first technological level that must consider the basic principles of fault management, that is, detect, locate, and recovery, directly from the design stage. In this sense, we are particularly interested in analyzing what features exist for the elements of the infrastructure under consideration. Often, the studies focused on memory devices. For example, Liu et al. [55] analyzed the memories to establish a correlation between aging and the probability of error. At the same time, Sridharan et al. [48] studied the weight of main memory errors in modern networking system architectures. It is no coincidence that all memory systems host increasingly sophisticated ECC mechanisms ([94, 89]) and fault isolation mechanisms are available for avoiding data corruption propagation into the system([51]). For devices of different topologies, the studies we have analyzed seem to focus on self-supervision mechanisms, especially with automatic test algorithms ([74, 81]), feature to support the verification of the fault supervision policy ([59]), and information redundancy ([85]). On the other hand, our research would like to analyze the weight of fault management requirements on the hardware design to understand how the hardware can contribute to fault recovery, not only to fault supervision or location. Another area of investigation is how the software can use hardware features in run-time, focusing on the recovery procedure.

- **Fault prediction**: Many research studies are available in the fault prediction area ([78, 95]). In the last decade, the focus has shifted decisively to using AI&ML as a technological step in fault prediction [52]. From this perspective, many research studies have focused on the optimization and validity of AI&ML algorithms [41, 49]. The research confirms the urgency and importance of the so-called preventive maintenance (*predict & prevent*) in systems with widespread distribution, such as IoT, the domain examined by the research. Das et al. [83] present a framework called *Aarohi* with the explicit intention of minimizing the recovery phase. For recovery purposes, it distinguishes the operations of the framework proposed in offline and online analysis. This work confirms our approach to consider the recovery action the fundamental goal of the fault management. It is a work that focuses on the framework, but the domain considered (HPC) does not allow extending the conclusions to other systems. The work of Adamu et al. [56] focuses on the real-time issue but is more interested in validating the considered algorithm (line regression and support vector machine). Boixaders et al. [64]'s study conclusion described the limitation of the studies in the prediction area: the cost-benefit analysis of the solution depends on the system and workload considered. Therefore, in RAN and 5G, study conclusions from the HPC or data center domain are invalid. The most significant knowledge gap concerning the work done is the availability of publications in the domain we are interested in (RAN and 5G). There are limited research papers on fault prediction for 5G and RAN. Most of these attempts implement the so-called Self-Organizing Network (SON), and then they focus more on the node's functionality than on the hardware device fault prediction ([90, 93]). This trend is evident in the works of Vulpe et al. [86], and Zhang et al. [82].

- **Wireless domain**: The studies we have analyzed for fault management in the wireless domain show the same limitations we identified in the fault prediction research. Although the number of investigations available is more significant than those for the RAN domain, they tend to consider the node as the minor granularity, thus ignoring what happens inside it. For this reason, the proposed redundancy mechanisms focused on duplicating the links, the nodes themselves, and alternative routing policies. Still, they need to add more to the discussion on Fault avoidance, i.e., avoiding faults through a device design that considers fault management requirements. The research on automatic fault detection ([39, 43, 58]) is instrumental, especially for the configuration and management of traffic. The correlation between fault management and service, especially for 5G, is confirmed by much of the research we have analyzed ([73, 69, 76]). But only a few studies focus on the characterization of hardware [5], their propagation, and their use in the system [66, 31].

Chapter 4

Research Results

In this section, we discuss the thesis' contributions and the results and how the papers included contribute to the achieved result. The case studies have been performed on industrial partner hardware design for Baseband and radio products. From the point of view of the industrial partner, fault management is a discipline that must evolve in parallel with the new networking solutions [23]. We have identified the areas of interest in the Industrial partner fault management legacy implementation where to introduce changes and improvements. We have verified their validity by comparing them with other solutions proposed in the literature. With this approach, the advantage for the industrial partner is the possibility of designing an adaptive migration of fault management in the next generation of telecommunications systems in respect of the major target of the thesis, *efficiency and effectiveness of fault management framework in current and next-generation Radio Access Network.*

4.1 Thesis Contribution

This section list the contribution of the proposed thesis and the papers realizing the contributions. A mapping relating the contributions to the stated research goals is shown in Table 4.1.

- **C1:** A novel fault taxonomy that considers the product reliability.

	C1	C2	C3	C4	C5	C6	C7
Paper A	X	X					
Paper B			X	X			
Paper C					X	X	
Paper D			X	X	X	X	
Paper E							X
RG1	X	X	X	X			
RG2					X	X	
RG3							X

Table 4.1. Papers mapped to contributions

- **C2:** A revised fault management architecture including the fault isolation concept for limiting the fault propagation into the system.
- **C3:** A multi-level representation of the fault management framework showing significant fault recovery oriented functions.
- **C4:** A multi-technologies fault handling approach where the fault management framework develops as recursive iterations on different technological layers to recover from a fault condition.
- **C5:** A map of the RAS requirements in five area of the fault management.
- **C6:** A set of fault management hardware requirements for an embedded system.
- **C7:** Baseband board fault condition prediction model based on resource usage, environment parameters and fault probability.

4.1.1 C1: A novel fault taxonomy that considers the product reliability

It isn't easy to know a concept if you don't even know the words to express it. Similarly, we need a proper fault taxonomy if we are interested in fault management efficiency. In our attempt to revise the fault management taxonomy, fault recovery is central and dominant. Thus, compared to a classic taxonomy, we have added the reliability and priority info, therefore wanting to propagate the recovery action carried out in the system and the urgency of a further recovery intervention. We also extended the granularity of error information to a single device and the ability to locate a failure in a part of the device itself.

4.1.2 C2: A revised fault management architecture including the fault isolation concept for limiting the fault propagation into the system

Three main functions are the pillars of the standard fault management framework: fault detection, location, and recovery. We proposed a revised framework built on two steps. The first step, to focus more on the system's complexity and the new support technologies for the recovery phase, is to extend the macro areas with two capabilities that will support the fault recovery: fault isolation and prediction. The purpose of fault isolation is to avoid the propagation of an error condition in the system, while fault prediction acts as a preventive maintenance tool. The second step is to explore the functions needed to design the macro areas. The process can continue hierarchically, thus creating a relationship between system functions, hardware characteristics, and fault management macro areas. It is our wanted position. Thanks to the depicted relationships, defining a series of requirements for the devices to implement fault management efficiently will be possible.

4.1.3 C3: A multi-level representation of the fault management framework showing significant fault recovery oriented functions

With Contribution 2, we have seen that efficiency in fault management means recovering from a fault condition as quickly as possible. We explored the different features and saw that hardware can also provide error recovery mechanisms. Therefore, an efficient fault management implementation can only be multi-layered. We must design each layer to manage a fault condition by following the five pillars of fault management. If its recovery action doesn't succeed, then, and only then, the layer propagates fault information to the upper layer using the fault taxonomy defined in Contribution 1. It is worth noting that only the control layer's highest level can mark the system as in failure or function-degraded condition, depending on its recovery procedure.

4.1.4 C4: A multi-technologies fault handling approach where the fault management framework develops as recursive iterations on different technological layers to recover from a fault condition

Memory error handling is an excellent example of the multi-layer approach. The error fault migrates from one layer to another until a recovery action corrects the fault. Memory error handling is also a valid example of multi-technology. We use two RAS features, ECC and PPR, to recover from a memory hard error.

4.1.5 C5: A map of the RAS requirements in five area of the fault management

Reliability, Availability and Serviceability is a computer terminology involving reliability engineering, high availability, and serviceability design. RAS design requires to follow specific requirements and we map RAS compliance statement into the fault management framework. We define hardware requirements based on five area of the fault Management: Fault Avoidance, Fault Coverage, Fault Reporting, Fault Masking, and Fault Tolerance.

4.1.6 C6: A set of fault management hardware requirements for an embedded system

We have identified main fault management hardware design requirements and map them in design features per device and connectivity in the industrial partner baseband boards.

Hardware shall be able to detect errors (fault coverage). General examples of hardware detection feature are the connectivity terminations, that shall supervise the link termination according to the physical link standard specification, and the data flow supervision.

Hardware shall be able to correct errors (fault masking and fault recovery). A typical example is Single Error Correction / Double Error Detection (SECDED) algorithm for memories device.

Hardware shall be able to report errors (fault reporting). Any device shall report detected corrected or uncorrected errors to the software.

Hardware shall be able to isolate the errors (fault isolation and fault recovery).Hardware shall provide features to avoid fault propagation in the system. A typical example is the data poisoning.

Hardware shall be able to provide self-test validation (fault coverage and fault avoidance). Any device shall be able to run a sanity check by command or automatically in case of power-on. Hardware shall provide a fault supervision verification mechanism like, for example, the error injection.

4.1.7 C7: Baseband board fault condition prediction model based on resource usage, environment parameters and fault probability

we use two well-established machine learning algorithms i.e., Random Forest (RF) and XGBoost, to predict ambient temperature for a baseband's boards. Our feature importance assessments reveal that the temperature sensors contribute significantly more towards predicting the ambient temperature compared to the power and voltage readings. Furthermore, the RF model appears less volatile than XGBoost using our training data. As the results demonstrate, our predictive temperature models allow for an accurate error prediction as a function of baseband board sensors.

4.2 Included papers

4.2.1 Paper A

Title: A Reliability-oriented Faults Taxonomy and a Recovery-oriented Methodological Approach for Systems Resilience

Authors: Carlo Vitucci, Daniel Sundmark, Marcus Jägemar, Jakob Danielsson, Alf Larsson, Thomas Nolte
Status: Published in Proceeding IEEE 46th Annual Computers, Software, and Aplications conference (COMPSAC 2022)
Abstract: Fault management is an important function that impacts the design of any digital system, from the simple kiosk in a shop to a complex 6G network. It is common to classify fault conditions into different taxonomies using terms like *fault* or *error*. Fault taxonomies are often suitable for managing fault detection, fault reporting, and fault localization but often neglect to support all different functions required by a fault management process. A correctly implemented fault management process must be able to distinguish between defects and faults, decide upon appropriate actions to recover the system to an ideal state, and avoid an error condition. Fault management is a multi-disciplinary process where recovery actions are deployed promptly by combined hardware, firmware, and software orchestration. The importance of fault management processes significantly increases with modern nanometer technologies, which suffer the risk of so-called soft errors, a corruption of a bit cells that can happen due to spurious disturbance, like cosmic radiation. Modern fault management implementations must support recovery actions for soft errors to ensure a steady system. This paper describes an extended fault classification model that emphasizes fault management and recovery actions. We aim to show how the reliability-based fault taxonomy definition is more suitable for the overall fault management process.

My Contribution: I was the main driver of the work under the supervision of Daniel Sundmark and Thomas Nolte. I produced the proof-of-concept implementation, performed the case-study evaluation and drafted the paper. Co-authors contributed with design discussions, reviews and final paper approval.

4.2.2 Paper B

Title: Fault Management Framework and Multi-layer Recovery Methodology for Resilient System
Authors: Carlo Vitucci, Daniel Sundmark, Marcus Jägemar, Jakob Danielsson,

Alf Larsson and Thomas Nolte
Status: Published in the 6th International Conference on System Reliability and Safety (ICSRS 2022)
Abstract: Fault management is a key function to guarantee the quality of the service. Research has done a lot to improve fault supervision, and investigation is ongoing in fault prediction, thanks to the potentials of artificial intelligence and machine learning. In this study, we propose a fault management framework that puts an emphasis on fault recovery: a framework developed on multi-layer function and a fault recovery methodology distributed over several technological layers. The basic principle of our proposal is that the system's complexity exposes it to a higher probability of temporary error. Newfound attention to the fault recovery phase is the key to keeping the service's quality high and saving maintenance costs by decreasing the return rate.

My Contribution: I was the main driver of the work. I produced the proof-of-concept implementation, performed the case-study evaluation and drafted the paper. Co-authors contributed with design discussions, reviews and final paper approval.

4.2.3 Paper C

Title: The Fault Management Impacts on the Hardware Design for Embedded System
Authors: Carlo Vitucci, Daniel Sundmark, Marcus Jägemar, Jakob Danielsson, Alf Larsson and Thomas Nolte
Status: Published in Proceeding IEEE 49th Annual Conference of the Industrial Electronics Society, IES (IECON 2023)
Abstract: Processing capacity distribution has become widespread in the fog computing era. End-user services have multiplied, from consumer products to industry 5.0. In this scenario, the reliability of the services must be at a very high level. But in a system with such displacement of hardware the reliability of the service necessarily passes through the hardware design. From the high quality of the devices in use, but, above all, in the domain of fault management. Because if it is true that the ultimate goal of fault management is actually to

increase the system's reliability, it is also true that hardware design must take into account all the functions of fault management and participate in the creation of a fault management policy. Efficiently and sustainably, both in the system's performance and in the product's cost. This paper analyzes the hardware design techniques that optimally contribute to the realization of fault management and, consequently, guarantee a high level of reliability and availability for the services offered to the end customer. We describe hardware requirements and how they affect the choice of devices in the hardware embedded system design.

My Contribution: I was the main driver of the work. I produced the proof-of-concept implementation, performed the case-study evaluation and drafted the paper. Co-authors contributed with design discussions, reviews and final paper approval.

4.2.4 Paper D

Title: Run Time Memory Error Recovery Process in Networking System
Authors: Carlo Vitucci, Daniel Sundmark, Jakob Danielsson, Marcus Jägemar, Alf Larsson and Thomas Nolte
Status: Published in the 7th IEEE International Conference on System Reliability and Safety (ICSRS 2023)
Abstract: With the decrease in the size of the transistors, the probability of errors in the system memories due to electrical disturbances, critical operating temperatures, and interference between adjacent memory cells has increased. System memory errors have always been problematic; today, they remain more than forty percent of confirmed hardware errors in repair centers for both data centers and telecommunications network nodes. Therefore, it is in somehow expected that device manufacturers have been concerned with increasing the fault management functions supported by the products in the past years. With the new standard, DDR5, both data redundancy, the so-called Error Correction Code, and physical redundancy, the post-package repair, are mandatory features. Production and repair centers mainly used physical redundancy to replace faulty memory rows. In contrast, field use still needs to be improved, mainly due to a need for integrated system solutions for network nodes. This paper aims

to compensate for this shortcoming and shows a system solution for handling memory errors. It is a multi-technology proposition (mixed use of ECC and PPR) based on multi-layer (hardware, firmware, and software) error information exchange.
My Contribution: I was the main driver of the work. I produced the proof-of-concept implementation, performed the case-study evaluation and drafted the paper. Co-authors contributed with design discussions, reviews and final paper approval.

4.2.5 Paper E

Title: Board Temperature Prediction for Embedded Systems using Machine Learning
Authors: Selma Rahman, Mattias Olausson, Carlo Vitucci and Ioannis Avgouleas
Status: Published in the 8th International Conference on Engineering of Computer-based Systems (ECBS 2023)
Abstract: The fifth-generation telecommunications system, 5G, is the answer to the network operators' request of a sustainable infrastructure as the value of the network has shifted from connectivity to service. The infrastructure requires an increase in the complexity of the network to meet the service-oriented requirements and it is only sustainable if supported by resilient hardware and reduced fault probability. Our research aims to use artificial intelligence and machine learning algorithms to identify relational patterns of fault conditions. This paper will describe the work we have done to allow the prediction of the working temperature for radio access network basebands. We have identified the optimal training and validation dataset to avoid under or overfitting conditions. We have seen how, with the optimal dataset, the Random Forest and XGBoost algorithms allow a temperature prediction with a margin of error lower than one degree Celsius. Our research has also highlighted how the usage of temperature sensors is dominant for defining the predicting working temperature model, while the power and voltage readings are not. Our research also shows that the Random Forest model appears less volatile than the XGBoost model in the case of a suboptimal dataset. Due to the limited scale of variation for the

controlled variables, our research needs to improve its imprecision for very high temperatures, a limitation we would like to eliminate in the next phase of the study. The predictive working temperature model will allow for a more efficient and accurate error prediction as a function of environmental conditions and resource utilization.

My Contribution: The paper is one of the outcomes of an industrial partner's pre-development study. I produced the context, the research objectives and domain definition, the communities' research investigation and I acted as driver for the paper. Selma Rahman and Mattias Olausson designed and implemented the machine learning models under the supervision of Ioannis Avgouleas, I was the reviewer of the model implementation and outcomes description. Co-authors contributed with reviews ad final paper approval.

4.3 Publications not included in the thesis

4.3.1 Paper X

Title: Flexible 5G Edge Server for Multi Industry Service Network.
Authors: Carlo Vitucci and Alf Larsson
Status: Published in International Journal on Advances in Networks and Services, Vol.10, no3&4, 2017
My Contribution: I was the main driver of the work. I produced the proof-of-concept implementation, performed the case-study evaluation and drafted the paper. Co-author contributed with design discussions, reviews and final paper approval.

Chapter 5

Conclusion and Future Work

The main objective of this thesis is to analyze and review the basic principles and implementation of fault management functionality for Radio Access Network embedded systems. Fault management is how the resilience of a complex system can be increased, such as that of 5G and 6G deployment at the edge of the network and close to the end user of the services. Fault management, containing the fault's impact on the system and recovery time, results in better resiliency. This new way of defining fault management has led to a new model for fault management aimed at recovery from a fault situation, for total restoration, or in degraded function mode, of the system functions/services. The fault recovery action maintains centrality in the fault management framework, where, alongside the consolidated fault detection and location actions, the thesis has added the contribution of isolation (for the containment of faults) and prevention (for the containment of recovery times).

The new fault management model allows the implementation of this system functionality with a holistic vision that we have defined as multi-layers and multi-technologies. It is the *translation* of the slogan *do the right thing in the right place in the right time*: proper hardware, firmware, and software design allow the implementation of the fault management framework at different layers. Each layer uses its particular technologies. Therefore, each level of the system can act immediately on a fault condition and propagate the result of its action to the upper layer, where, depending on the outcome, other recovery attempts can follow.

By requiring each system level to carry out fault management actions, the model also translates into a series of requirements for hardware designers. The criticality of a hardware design that meets fault management requirements is the obvious consequence of the need to reduce the maintenance costs of the released product, which, with the increased complexity of system solutions, would be destined to explode if not considered during the hardware design phase.

5.1 Future Work

The thesis emphasized the fault prediction function with the new fault management model. The possibility of recognizing a fault condition pattern and even acting on the system before this happens is undoubtedly valuable for those who have the reduction of the impacts and recovery times of a fault as a guideline.

Fault prediction as a benefit for fault management efficiency is a common understanding. Still, the obstacles to its effective implementation are well-known, especially for an embedded RAN system with severe resource limitations. The available memory, for example, has a direct and often non-negligible impact on the product's final cost and power consumption. Data streaming impacts the availability of backhaul bandwidth for traffic. Processing capacity is limited and sensitive to other processing disturbances, such as cache pollution, task scheduling problems, and missing deadlines for hard or soft real-time functions. The availability and quality of data are the first problems in the implementation of a machine learning algorithm. Still, in the domain where the thesis applies, there is a primordial problem of how data are collected, stored, and treated. A problem that, therefore, has a higher priority.

There are two classes of prediction: the recognition of the error types and the ability to recognize behavior in the system parameters that lead to a fault condition. The work done in this thesis to predict the operating temperature for a baseband is part of the second class. The working temperature of a board has an exponential impact on the occurrence of faults, but it is not sufficient. It is necessary to create a relationship between external parameters, internal parameters, and the use of resources to have a genuinely efficient picture of fault prediction. A synergy with system performance prediction analysis is possible because both analyses use external and internal parameters as datasets.

Intervening in a fault condition in troubleshooting when the product is in the field costs more than any fault management policy implementation during the design phase. Designing a good fault coverage, fault masking, and fault tolerance policy, naming three macro areas of fault management, is much less expensive and certainly does not expose the vendor to a terrible performance in terms of quality of experience. The evaluation cost tends to underestimate the impact of a poor QoE, which directly compromises the business opportunity well beyond the single product. However, the quantification of this cost saving due to investing in the design phase is unavailable. We need to measure the magnitude separating the design and maintenance costs. Without this data, since it is unclear what the economic return is, the only weapon left available for implementing efficient fault management is common sense. More than common sense is needed to justify an increase in design costs.

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