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Security-Driven Design of Real-Time Embedded Systems

by

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献给我的家人

Abstract

REAL-TIME embedded systems (RTESs) have been widely used in modern society. And it is also very common to find them in safety and security critical applications, such as transportation and medical equipment. There are, usually, several constraints imposed on a RTEs, for example, timing, resource, energy, and performance, which must be satisfied simultaneously. This makes the design of such systems a difficult problem.

More recently, the security of RTEs emerges as a major design concern, as more and more attacks have been reported. However, RTEs security, as a parameter to be considered during the design process, has been overlooked in the past. This thesis approaches the design of secure RTEs focusing on aspects that are particularly important in the context of RTEs, such as communication confidentiality and side-channel attack resistance.

Several techniques are presented in this thesis for designing secure RTEs, including hardware/software co-design techniques for communication confidentiality on distributed platforms, a global framework for secure multi-mode real-time systems, and a scheduling policy for thwarting differential power analysis attacks.

All the proposed solutions have been extensively evaluated in a large amount of experiments, including two real-life case studies, which demonstrate the efficiency of the presented techniques.

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Populärvetenskaplig Sammanfattning

INBYGGDA realtidssystem används idag i stor utsträckning i vårt moderna samhälle. Det är mycket vanligt att hitta dem i säkerhetskritiska tillämpningar såsom transport- och medicinsk utrustning. Vanligtvis har inbyggda realtidssystem flera designbegränsningar och krav gällande till exempel timing, resurser, energi och prestanda, som måste vara uppfyllda samtidigt. Detta gör utformningen av sådana system till ett mycket svårt problem.

Under senare tid har säkerheten i inbyggda realtidssystem blivit en viktig konstruktionsaspekt eftersom fler och fler attacker har rapporterats. Tidigare har säkerhetskraven i inbyggda realtidssystem inte betraktats som designparametrar under själva designprocessen. Denna avhandling fokuserar bland annat på utformningen av säkra inbyggda system, huvudsakligen på aspekter som är särskilt viktiga i samband med realtidssystem, till exempel kommunikationssekretess och motstånd mot sidokanalattacker.

I denna avhandling presenteras tre olika tekniker för att utforma säkra inbyggda realtidssystem. Först en teknik för hård- och mjukvaru co-design för kommunikationssekretess för distribuerade plattformar, sedan ett globalt ramverk för säkra multi-mode system och slutligen en schemalägningspolicy för motstånd mot sidokanalattacker.

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List of Abbreviations

AAHE	Average Additional Hardware Expenditure
ACC	Adaptive Cruise Controller
AES	Advanced Encryption Standard
APC	Average Power Consumption
ASIC	Application-Specific Integrated Circuit
CAN	Controller Area Network
CLP	Constraint Logic Programming
CPS	Cyber-Physical Systems
CPU	Central Processing Unit
DPA	Differential Power Analysis
DVFS	Dynamic Voltage and Frequency Scaling
E/D	Encryption/Decryption
EDF	Earliest Deadline First
ES	Embedded System
ET	Execution Time
FPGA	Field Programmable Gate Array
GPU	Graphics Processing Unit
IBC	Iterated Block Cipher
ID	Intrusion Detection
IDA	Intrusion Detection Accuracy
ILP	Integer Linear Programming
LS	List Scheduling
PCP	Partial Critical Path
PDR	Partial Dynamic Reconfiguration
PI	Performance Improvement
QoC	Quality of Confidentiality

QoS	Quality of Service
RDI	Random Delay Insertion
RMS	Rate-Monotonic Scheduling
RTES	Real-Time Embedded System
SA	Simulated Annealing
SCA	Side-Channel Attack
SCADA	Supervisory Control And Data Acquisition
SNR	Signal-to-Noise Ratio
SPARTA	Scheduling Policy for Thwarting Differential Power Analysis Attacks
TT	Transmission Time

List of Symbols

Tasks

τ_i	i^{th} task
c_i	Execution time of τ_i
$\mathcal{P}_i$	Release period of τ_i
$\mathcal{D}_i$	Relative deadline of τ_i
$\mathcal{E}_i^m$	Constant execution time of mandatory part of τ_i
$\mathcal{E}_i^o$	Maximal execution time of optional part of τ_i
c_i^o	Actual execution time of optional part of τ_i
$\mathcal{Q}_i^m$	Constant QoS reward from the mandatory part of τ_i
$\mathcal{F}_i$	QoS reward function from the optional part of τ_i
$\mathcal{L}_i$	Set of messages associated with τ_i
m_{ij}	j^{th} message of τ_i
l_{ij}	Length (in number of blocks) of m_{ij}
w_{ij}	Relative importance of m_{ij}
$\mathcal{T}$	A set of tasks
$\mathcal{HP}(\mathcal{T})$	Hyperperiod of all tasks in $\mathcal{T}$

Dynamic Voltage and Frequency Scaling

Pow	Power consumption
C_{eff_i}	Effective switching capacitance of τ_i
f_i	Applied frequency on τ_i
f^{max}	Maximal frequency of the processor
V_{dd_i}	Supply voltage on τ_i
V_{dd}^{max}	Maximal supply voltage of the processor
$\mathcal{W}_i(f_i)$	Execution time of τ_i under frequency f_i

Security Protections

k_i	An AES subkey
QoC_{ij}^{min}	Minimal required QoC on m_{ij}
C_{ij}	Chosen cipher (or variant) for protecting m_{ij}
x_{ij}	Number of IBC rounds of C_{ij}
ce_i	An encryption task
cd_i	A decryption task
LP_i	A leakage point
$\mathcal{R}$	Robostness of a secret key
$\hat{p}$	Probability of leakage occurrences
$\mathcal{E}_{ID}$	Execution time of the ID task
$\mathcal{P}_{ID}^{min}$	Minimal required release period of the ID task
$\mathcal{P}_{ID}$	Actual release period of the ID task

Multi-Mode Systems

$M^{ij...k}$	A mode in which tasks $\tau_i, \tau_j, \dots$, and τ_k are active
$\mathcal{M}^{func}$	Set of all functional modes
$\mathcal{M}_{\uparrow}^{func}$	Set of top functional modes
$\overline{\mathcal{M}}(M)$	Supermodes of M
$\underline{\mathcal{M}}(M)$	Submodes of M
$\mathcal{M}^{impl}$	Candidates of Pareto spaces to be saved in memory
$\mathcal{M}^{mem}$	Set of Pareto spaces saved in memory
S_M	Pareto space for mode M
$S_M^{M'}$	Derived solution space for mode M from M'
$\mathcal{H}(S_M)$	Hypervolume of Pareto space S_M
$\mathcal{H}_M(\mathcal{M}^{mem})$	Hypervolume of mode M with given pre-stored Pareto spaces $\mathcal{M}^{mem}$
H	Total hypervolume of all functional modes

Applications

G	Acyclic task graph
E	Edges of a task graph
e_{ij}	The edge indicating dependency of τ_j on τ_i
p_i	A computational unit

Chapter 1

Introduction

THE focus of this thesis is on the design and scheduling of secure real-time embedded systems (RTESs). RTESs play a vital role in modern society and, due to their importance, guaranteeing the security of such systems emerges as a critical issue. The main contribution of this thesis is the development of several design techniques for achieving RTES security in the context of performance, energy, and resource constraints typical to such systems. In this chapter, we shall first introduce the fundamental motivations. Then we shall summarize the contributions and present the organization of this thesis.

1.1 Motivation

Real-time embedded systems have been applied in all aspects of our daily lives, from large scale control plants, e.g., the supervisory control and data acquisition (SCADA) systems, to consumer electronics. They usually consist of various processing units and peripherals, e.g., sensors and actuators. There are several design constraints imposed on a RTES, for example, timing, resource, energy, and performance constraints, which must be satisfied simultaneously. These constraints make the design of RTESs a difficult problem, and must be carefully considered together, since treating them separately cannot lead to a globally good solution.

Nowadays, it is common to find RTESs in safety and security

critical areas such as transportation and health-care. The security of such systems is of critical importance, which, however, has been seriously overlooked in the past. This urges the need for providing RTES security, and is the most fundamental motivation for this thesis. For example, in automotive electronics systems [LH02], a typical distributed RTESs, the internal communication and message exchanges are done without any protections [WWP06], and are extremely easy to be eavesdropped and forged. Thus, it is indispensable to revisit the traditional RTES design approaches with security requirements considered as a critical factor. Because of the limited amount of available resources and yet stringent timing constraint, protecting RTES is a difficult problem, and straight-forward techniques cannot achieve satisfactory results. Thus, efficient mechanisms in terms of both solution quality and convergence time are expected. Chapter 4 presents our contributions to the design of secure distributed RTESs.

Many of the proposed techniques in the context of embedded systems security aim at finding lightweight cryptography or efficient implementations of cryptographic algorithms [BMS⁺06, BKL⁺07, HS13]. However, such techniques may not be able to cope with the timing and performance constraints and the increasing complexity of current RTESs. For example, RTESs are not anymore designed for a single dedicated usage but to operate under different modes. Furthermore, there could be multiple critical applications running simultaneously in the system, within each mode. Therefore, how to design such systems to be secure is not anymore a single-objective optimization problem. On the contrary, a design method taking all potential modes and design requirements into consideration is needed in order to achieve the best solution. Chapter 5 presents our contributions to the design of secure multi-mode RTESs.

Even a well designed RTES with sound cryptographic protections, i.e., by applying Advanced Encryption Standard (AES) on all the incoming and outgoing messages, may not be 100% secure. This is because the underlying implementations of the cipher algorithms can disclose sensitive information, e.g., power consumption and electromagnetic radiation, while operating. Such information can leak details about the actual implementation of the chosen cipher, such as the

secret key, and may be exploited by the attacker to break the system (known as side-channel attacks). Such information leakage, rooted from the fundamental physical properties of the hardware platform, must be avoided or hidden in order to deliver the best protections. Chapter 6 introduces a scheduling-based technique to overcome the potential side-channel attacks.

1.2 Summary of Contributions

This thesis presents results towards several design optimization techniques for RTEs in which security is important. The major contributions of this thesis approach three representative design problems of secure RTEs, elaborated in Chapter 4, 5, and 6, respectively.

As revealed by literature [WWP06] the internal communication in many distributed RTEs containing sensitive information lacks even the basic security protection. In Chapter 4, we approach the problem of achieving secure communication within distributed RTEs. We first studied the problem of delivering the best confidentiality protection for the internal communication under the limited amount of available resources. Due to the complexity of this optimization problem, we present a heuristic approach to solve it. Then we look at a configuration in which the computational nodes consist not only of embedded processors but also of reconfigurable hardware, i.e., field-programmable gate arrays (FPGAs). We present two efficient heuristic-based techniques for finding the minimal hardware cost needed to implement the designated cryptographic algorithms for two FPGA technologies. The goal is to reduce the encryption and decryption overhead while satisfy timing constraints. The main challenge is to optimally utilize the available FPGA area.

In Chapter 5, we shall look at multi-mode RTEs. The main difficulty arises from the fact that, during run-time, the system can potentially function in a very large number of modes. Nevertheless, it is impossible to run, at run-time, complex optimizations in order to find an optimal setting from the point of view of timing, energy consumption, and security. We formulate an overall design problem for secure multi-mode RTEs as a two-stage optimization. A set of

solutions are prepared in the off-line stage and are later used in the on-line stage to determine the best option to configure the system for the actual mode. In the off-line phase, the designer can trade-off solution quality with available design time and memory space. We evaluated the techniques in extensive experiments as well as a real-life case study. In addition, the presented techniques are general enough to be applied for different design demands besides the dimensions presented in the chapter.

The contributions mentioned above have focused on efficiently conducting the required computations including the security protection mechanisms, e.g., message encryption and decryption. However, the actual implementation of the chosen cipher algorithm may become the target of attacks. The well-known side-channel attacks (SCAs) aim to retrieve secret information of the underlying cryptographic implementations, for example, by observing the power consumption of the microprocessors. We found that several real-time scheduling policies are able to reinforce the security of cipher implementations, since they generate a certain amount of randomness in the power profile. Then, the question is how well a scheduler could act as a countermeasure against SCAs. In Chapter 6, we first present a metric for measuring the influence of a real-time scheduler on the robustness of AES secret keys under, arguably, the most popular and efficient type of SCAs, the differential power analysis attacks (DPAs). Then, we show that different scheduling policies have different impacts on the robustness of AES secret keys by evaluating two representative scheduling policies, i.e., earliest deadline first (EDF) and rate-monotonic scheduling (RMS). After that, we present a scheduling policy, i.e., SPARTA, for thwarting DPA attacks that shares the same guarantee of schedulability as EDF and, at the same time, counteracts against DPAs. SPARTA is the first real-time scheduler in literature specifically designed as a countermeasure against SCAs.

1.3 List of Publications

Parts of this thesis are presented in the following publications:

- Ke Jiang, Petru Eles, and Zebo Peng. **Optimization of Message Encryption for Distributed Embedded Systems with Real-Time Constraints.** *International Symposium on Design and Diagnostics of Electronic Circuits and Systems (DDECS)*, Cottbus, Germany, April 2011 ([JEP11])
- Ke Jiang, Petru Eles, and Zebo Peng. **Co-Design Techniques for Distributed Real-Time Embedded Systems with Communication Security Constraints.** *Design, Automation Test in Europe (DATE)*, Dresden, Germany, March 2012 ([JEP12])
- Ke Jiang, Petru Eles, and Zebo Peng. **Optimization of Secure Embedded Systems with Dynamic Task Sets.** *Design, Automation Test in Europe (DATE)*, Grenoble, France, March 2013 ([JEP13])
- Ke Jiang, Lejla Batina, Petru Eles, Zebo Peng. **Robustness Analysis of Real-Time Scheduling Against Differential Power Analysis Attacks.** *IEEE Computer Society Annual Symposium on VLSI (ISVLSI)*, Tampa, FL, USA, July 2014 ([JBEP14])
- Ke Jiang, Petru Eles, Zebo Peng. **Power-Aware Design Techniques of Secure Multi-Mode Embedded Systems.** *ACM Transactions on Embedded Computing Systems (TECS)*, 2015 ([JEP15])
- Ke Jiang, Petru Eles, Zebo Peng, Sudipta Chattopadhyay, Lejla Batina. **SPARTA: A Scheduling Policy for Thwarting Differential Power Analysis Attacks,** *Asia and South Pacific Design Automation Conference (ASPDAC)*, Macao SAR, China, January 2016 ([JEP⁺16])

The following publications are not directly covered by this thesis, but are generally related to the design of secure real-time systems:

- Wei Jiang, Ke Jiang, and Yue Ma. **Resource Allocation of Security-Critical Tasks With Statistically Guaranteed Energy Constraint.** *International Conference on Embedded*

and Real-Time Computing Systems and Applications (RTCSA), Seoul, Korea, August 2012 ([JJM12])

- Xia Zhang, Jinyu Zhan, Wei Jiang, Yue Ma, and Ke Jiang. **Design Optimization of Energy- And Security Critical Distributed Real-Time Embedded Systems**. *International Parallel and Distributed Processing Symposium Workshops (IPDPSW)*, Boston, USA, May 2013 ([ZZJ⁺13a])
- Xia Zhang, Jinyu Zhan, Wei Jiang, Yue Ma, and Ke Jiang. **Design Optimization of Security- Sensitive Mixed-Criticality Real-Time Embedded Systems**. *Workshop on Real-Time Mixed Criticality Systems (ReTiMiCS)*, Taipei, Taiwan, August 2013 ([ZZJ⁺13b])
- Ke Jiang, Petru Eles, Zebo Peng, and Wei Jiang. **Power-Aware Design of Secure Multi-Mode Real-Time Embedded Systems with FPGA Co-Processors**. *International Conference on Real-Time Networks and Systems (RTNS)*, Sophia Antipolis, France, October 2013 ([JLE⁺13])
- Wei Jiang, Ke Jiang, and Yue Ma. **Energy Aware Real-Time Scheduling Policy with Guaranteed Security Protection**. *Asia and South Pacific Design Automation Conference (ASPDAC)*, SunTec, Singapore, January 2014 ([JJM14])
- Ke Jiang, Lejla Batina, Petru Eles, and Zebo Peng. **The Influence of Real-Time Scheduling On Differential Power Analysis Attacks**. *TRUDEVICE workshop: (Co-located with DATE15)*, Grenoble, Franch, March 2015 ([JBEP15])
- Wei Jiang, Ke Jiang, Xia Zhang, and Yue Ma. **Energy Optimization of Security-Critical Real-Time Applications With Guaranteed Security Protection**. *Journal of Systems Architecture (JSA)*, 2015 ([JJZM15])
- Liang Wen, Wei Jiang, Ke Jiang, Xia Zhang, Xiong Pan, and Keran Zhou. **Detecting Fault Injection Attacks on Embedded Real-Time Applications: A System-Level Per-**

spective. *IEEE International Conference on High Performance Computing and Communications (HPCC)*, New York, USA, August 2015 ([WJJ⁺15])

- Xiong Pan, Wei Jiang, Ke Jiang, Liang Wen, and Qi Dong. **Energy Optimization of Stochastic Applications with Statistical Guarantees of Deadline and Reliability.** *Asia and South Pacific Design Automation Conference (ASPDAC)*, Macau SAR, China, January 2016 ([PJJ⁺16])

1.4 Thesis Organization

This thesis is organized in seven chapters. In **Chapter 2**, we shall discuss the general background and current status of research related to embedded system design and embedded system security. In **Chapter 3**, we shall present some preliminaries related to the hardware architecture and power models and also the involved security definitions. Our contributions to achieving secure distributed RTEs will be presented in **Chapter 4**. In **Chapter 5**, we shall elaborate on an overall design framework for secure multi-mode RTEs considering four design objectives. In **Chapter 6**, we shall discuss the influence of real-time schedulers on system robustness against SCAs, and present a novel scheduling policy for thwarting SCAs. **Chapter 7** concludes the thesis, and points out possible future research directions in the context of secure RTE designs.

Chapter 2

Background and Related Work

IN this chapter, we shall discuss the background of this thesis, and review the related research contributions from existing literature. Section 2.1 outlines a general embedded system design flow, and highlights the stages that are particularly relevant from the point of view of this thesis. Section 2.2 presents the common requirements typical for embedded system designs, i.e., energy efficiency, timeliness, and multi-mode operation, and the related work along these directions. Section 2.3 discusses existing approaches for designing secure embedded systems.

2.1 Embedded System Design

Embedded systems (ESs) are “information processing systems embedded into enclosing products” [Mar11]. Classical examples of embedded system applications include vehicles, consumer electronics, and airplanes. For example, it is common to find tens of microprocessors (Electronic Control Units or ECUs) in modern vehicles connected by a communication infrastructure, e.g., controller area network (CAN) [CAN91] or Flexray [Fle05]. Common requirements shared among various ESs are real-time guarantees, energy constraints, and cost efficiency. Recently, the concept of *cyber-physical system* (CPS) [Lee08,

Figure 2.1: System design flow

RLSS10] has been introduced, emphasizing the tight interaction between embedded systems and the physical environment. The system-level design of ESs (and CPSs) is usually carried out in several stages as depicted in Figure 2.1.

In the *System Specification* stage, details of the system functionality are described. The designer concretely specifies the jobs the system will handle and the general requirements the system must satisfy. This is the very first step of the design process and provides the foundation for later stages.

In the *Modeling* step, the designer divides the overall system functionality into smaller modules depending on various aspects. For example, the modules can be abstracted based on the associated hardware units for achieving higher parallelism, or depending on different functionalities. In this thesis, the system is modeled as a set of computation tasks, each of which may represent a basic software block or an independent application, depending on the level of abstraction.

At *Constraint Identification*, the set of constraints imposed on the system are identified, e.g., the deadline of executions, energy limitations, and security requirements. These constraints are used to drive the decision makings in later stages.

During *Architecture Selection*, the designer decides on a concrete hardware platform for undertaking the tasks. Several parameters must be considered in the selection, e.g., the organization of the system (distributed or centralized) and cost constraints (more powerful or less powerful processors, or whether to use reconfigurable hardware for accelerations). In the beginning, the architecture is chosen based on estimations and needs to be revisited with feedbacks from later stages to optimize the performance/cost ratio and satisfy the given design constraints.

During *Mapping and Partitioning* [EPKD97, DLJ99], designer allocates the tasks on available processing units, either in software on microprocessors or to hardware modules. The objective is to pursue the best system performance, e.g., minimizing the end-to-end delay or maximizing delivered service quality.

In the *Parameter Selection* stage, the system execution parameters, e.g., extra amount of executions and operation frequencies are tuned for achieving higher performance or efficiency. The selection is driven by one or multiple objective functions reflecting concrete design expectations under given constraints [IPEP05, IPEP08]. Usually, such problems of RTEs are of huge complexities, to which it is impossible to find the optimal solutions. Therefore, good heuristic approaches must be deployed to solve the problem efficiently [DPAM02]. In addition, this stage is often integrated with the next stage, i.e., *Scheduling* to reach globally better solutions. If no satisfying solution is found, then the designer must revisit the decisions from the previous stages, and find potential improvements, e.g., use more powerful processors or derive a more efficient mapping (indicated by the backwards arrows from the *Parameter Selection* stage in Figure 2.1).

In the *Scheduling* stage, the tasks mapped on the computational resources will be scheduled to meet the imposed real-time constraints. A multitude of techniques have been proposed in literature for task scheduling. If the task executions can be interrupted, the schedul-

ing policy is called preemptive scheduling [BMR90]. Otherwise, non-preemptive scheduling is used [GYG⁺08]. Static cyclic scheduling implies the off-line generation of a fixed schedule table that will be followed at run-time to order task executions [XP00, DK08]. Priority based scheduling policies select and execute the task with the highest priority, when there are requests from multiple tasks. Depending on whether the priority of a task is constant or not, priority based scheduling can be further divided into two groups, static priority scheduling and dynamic priority scheduling [LL73, But11]. Quasi-static scheduling tries to combine the advantages of the previous approaches, and prepares a set of possible alternatives off-line that can be used at run-time [CEP04, WMWZ12] for pursuing higher performance. It is also possible that the deadline constraints cannot be satisfied in any solutions under the current setup. Then the designer must revise the previous decisions, e.g., architecture selection (indicated by the arrows from the *Scheduling* stage in Figure 2.1).

In the *Final Synthesis* stage, the solution obtained from the *Scheduling* stage is reviewed. If all the requirements and constraints are met, the design will proceed with the final synthesis of the low level hardware/software implementations. Otherwise, one or several steps have to be revisited.

This thesis mainly focuses on the *Mapping and Partitioning*, *Parameter Selection*, and *Scheduling* stages of the overall design flow.

2.2 Design Requirements

2.2.1 Energy Efficiency

Embedded systems are very often battery-driven or with limited energy budget. Hence, energy efficiency is a must in modern embedded system design. This can be achieved by different methods. A very popular technique for reducing energy consumption is via utilizing the dynamic voltage and frequency scaling technology (DVFS) [BB00, PS01]. The authors of [BAEP09] proposed a thermal aware DVFS approach for reducing system energy consumption which considered the temperature influence on frequency and, consequently, on

energy. The authors of [ML09] proposed a warp processor architecture that leverages DVFS to reduce the power consumption. The authors of [PJPM14] described an integrated power manager that exploited the DVFS capabilities of embedded CPU and GPU together. This is related to the *Parameter Selection* stage in Figure 2.1. The authors of [HCK06] presented an energy-efficient task scheduling approach for heterogeneous architecture with FPGA co-processors, in which the on-board FPGA resources were used both for performance enhancing and energy saving purposes.

2.2.2 Timeliness

Real-time embedded systems (RTEs) are those systems in which not only producing correct results is important, but the timeliness of result delivery is also critical. That is, late delivery of a correct result may cause severe system errors. An example of RTE is the brake-by-wire system. When the driver signals a request of braking, the car must react in due time by adjusting the brakes accordingly. This requires efficient mechanisms to guarantee the timeliness of result deliveries, and is mainly related to the *Scheduling* stage.

The synthesis of RTEs and analysis of real-time properties have been extensively studied by the research community. The authors of [SSL89] presented the Sporadic Server algorithm for scheduling aperiodic independent tasks, and showed the improvement of response times for the tasks with soft-deadlines as well as the guarantees of deadline satisfactions of tasks with hard-deadlines. The authors of [BBMSS10] presented the schedulability tests for global EDF and deadline monotonic policies on multiprocessor platforms. The authors of [AEP15] studied the influence of jitter on stability of real-time control applications, and presented an on-line scheduling policy to limit task response time variations, and thus, to guarantee stability of the control application.

2.2.3 Multi-Mode Operation

Embedded systems today are very often expected to function under a dynamically changing load. This leads to the concept of multi-mode

systems [OH02] which are exposed to dynamic loads with the number and functionality of active tasks changing during run-time. The uncertainty about the execution mode that the system is going to run in at run-time leads to huge design complexity for delivering the best performance in all possible cases. That is, the number of potential combinations of tasks that are to be processed by the system can be very large, which makes designing multi-mode RTEs an extremely complex problem. This problem mainly affects the *Parameter Selection* and the *Scheduling* stages.

Design of multi-mode systems has been well studied. In [MZ05], the energy-efficiency problem of multi-mode distributed RTEs was approached by distributing available slack execution times. The authors of [SAHE05] presented an energy minimization framework for multi-mode distributed RTEs considering the mode execution properties. The authors of [SEPC09] proposed a flexible synthesis approach for multi-mode embedded control systems that can be tuned for better control quality or faster design time. The authors of [SCT10] presented a power-aware task mapping approach for multi-mode multiprocessor SoCs (system on chips). The presented techniques pre-compute and store a set of mapping strategies off-line, and then on-line decide the most power efficient mapping for a newly arriving task using the pre-stored knowledge. The authors of [WAST12] presented an on-line framework for placing multi-mode streaming applications onto partially reconfigurable FPGAs such that the dynamic reconfiguration overhead is minimized. The authors of [LEP15] presented an on-line resource manager for real-time multi-mode applications running on heterogeneous platforms such that the global energy consumption of the system is minimized.

2.3 Secure Embedded Systems Design

As embedded systems are now expected to cope with new applications and challenges, requirements on security characteristics are emerging in the design processes beside the aforementioned aspects. In this section, we shall discuss about the new design requirements related to security. The authors of [RRKH04] outlined the global design chal-

lenges of secure embedded systems. In addition, the adoption of new communication interfaces, e.g., Wi-Fi, that enable tighter interactions between RTEs and the surrounding environment, dramatically increase potential security threats [ZM05, CAS08]. With the trend towards more and more communication demands, sensitive information exchanged among nodes inside a system or with external peers and service centers has been exposed to attackers, which leads to the need for sound cryptographic protections and robust side-channel attack resistance.

2.3.1 Cryptography and Other Security Services

Previous work on ES communication mainly focused on the protocol and application issues from the safety and reliability perspectives [CS07], while the potential security risks have been seriously overlooked. The authors of [WWP06] stated that the internal communication inside modern vehicles is completely unprotected, which is, though, tightly related to safety and privacy. The authors of [KCR⁺10] demonstrated the possibility of hacking into an automotive electronics system remotely and reading out various information of the car, sometimes quite easily. The same research group successfully mounted another set of attacks purely remotely without any physical accesses [CMK⁺11]. Recently, the news that two hackers attacked a vehicle remotely, e.g., turning on/off the fans and even shutting down the engine, caught huge media coverage [Gre15]. All these works urged the need for security protections in automobiles, and more generally, in all critical RTEs.

A RTEs can be of different types and architectures from a component unit of a larger system, e.g., the control system of a unmanned aerial vehicle (UAV) or an end node in a large network, to a system that is distributed over a certain area. However, regardless of the architecture, confidentiality of the communication is arguably the most important component out of the security concepts in the context of RTEs. This is because the messages exchanged via the communication module or infrastructure can contain sensitive information related to the user's privacy or critical system status of the controlled

plant. Such communication needs to be protected against malicious eavesdropping [ILW06, HKD11]. However, the RTES communication protocols usually do not come with any security protections, e.g., for confidentiality or integrity [WWP04]. This makes security protection a mission that the designer must take care of on the application level.

There are works discussing the communication security of distributed embedded systems [GGS04, PP05, RH07] focusing on the vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication. In [WWP06], the authors presented feasible attacks and an overall cryptographic architecture for automotive communication networks. However, the actual resource and timing constraints imposed in the systems were not touched. In [HKD11], the authors described four practically implemented attack scenarios, and brought forward the necessity of applying cryptography to protect the internal bus communication. The authors of [CAYM15] discussed the vulnerabilities and possible attacks to the CAN protocol which is one of the most applied bus protocol in modern vehicles, and also listed several high-level solutions to overcome the security drawbacks. The authors of [MSL⁺15] presented a lightweight authentication framework for automotive communication networks, that allows secure distribution of secret keys without pre-shared secrets.

The authors of [SV03] presented a cryptographic co-processor architecture for efficient message encryptions in embedded systems. A hardware/software co-design technique to protect embedded systems against buffer overflow attacks was presented in [SXZ⁺06]. In [PP08], the authors presented an automatic hardware-software design flow for detecting code injection attacks in multiprocessor SoCs. The authors of [WDL14] presented a model-based design technique considering potential security attacks in the design procedure. However, one of the fundamental design requirements of ESs, namely the real-time aspect, was not present in these works.

There are only a limited number of approaches that try to deliver sound security protection considering the actual timing requirements. In [XQ07], the authors presented an on-line scheduling policy that distributes free time slacks to enhance security services while guaranteeing the real-time constraints. However, the authors solely

considered the security services as the only optimization goal, and ignored the other design requirements that may also be imposed in the system, e.g., energy efficiency and quality of service. Moreover, due to the rather simple slack distribution mechanism, the presented scheduler may struggle to find good solutions purely at run-time. The authors of [LXY⁺09] proposed two off-line techniques to optimize the security protections of the real-time systems running on monoproductors and then rely on EDF to schedule the tasks on-line. However, neither of the techniques is capable to be applied in the systems in which the set or the nature of tasks changes at run-time, because of the high optimization overhead. In addition, neither of these two works touched the problem of protecting RTEs against side-channel attacks. The authors of [YMC⁺13] presented a multicore-based architecture for detecting potential intrusions to RTEs based on inherent timing properties of execution profiles. However, the multi-mode and communication confidentiality aspects were not discussed.

2.3.2 Side-Channel Attacks and Protections

The fundamental step towards security in RTEs is to carry out cryptography and other dedicated protection services. The communication confidentiality particularly requires cryptographic protections, i.e., via message encryption and decryption using cryptographic algorithms. However, the implementations of such algorithms may become the target of attacks. For example, the side-channel attacks (SCAs), which are the most dangerous type of attacks that target the implementations of cryptographic algorithms (including AES), have raised severe alarms regarding embedded system security. In [KJJ99], Paul Kocher et al. presented the so-called differential power analysis attack (DPA), one type of SCA, that has become one of the most efficient attack schemes targeting cipher implementations on embedded platforms. For example, the works of [OGOP04] and [SÖP04] presented the first DPA attack on ASIC (application-specific integrated circuit) and FPGA implementation of AES, respectively. The authors of [MOP07] thoroughly discussed the DPA attacks on software implementations of AES.

There have been numerous works that try to protect the systems against DPA attacks. Random delay insertion (RDI) is a common approach for counteracting DPAs. For example, the authors of [CK09] presented a software approach for generating random delays, which can be used to resist DPAs. The authors of [BVR⁺13] presented an automated hardware design methodology that inserts random jitters for thwarting DPAs. Another popular approach is via randomizing the data being processed on the device, known as masking, to make the power consumption independent of the processed data [Geb06, CB08]. Architectural modification that alters the power trace is also a widely used technique for preventing DPAs on cipher implementations [MD11, MD12]. However, none of these works can be easily applied in RTEs, since the timing constraints and energy limitations may be violated in the resource limited environments, or changes to the underlying hardware are expected.

Chapter 3

Preliminaries

IN this chapter, we shall present the preliminaries related to the architectures and power models we assume throughout the thesis. We shall also define the security metrics we use in this thesis. Section 3.1 presents the overall hardware architecture and power model we consider. Section 3.2 elaborates on the involved security metrics used in this thesis.

3.1 Hardware Architecture and Power Model

3.1.1 Hardware Architecture

Figure 3.1 illustrates an overall hardware structure of a RTES, that is composed of several subsystems, i.e., a subsystem running on a distributed platform, e.g., Figure 3.1 (a), and two subsystems on two independent computational units, e.g., Figure 3.1 (b). The subsystems are connected via a central gateway, which handles the communication among different subsystems, and also takes charge of external communication with the outside world.

The subsystem illustrated in Figure 3.1 (a) is referred to as a distributed RTES, of which the hardware architecture consists of a set of computational units, i.e., embedded processors, electronic control units, and FPGA (field-programmable gate arrays) devices, connected by a communication bus, e.g., CAN [CAN91]. The computational units take care of all processing requests, e.g., processing raw sen-

Figure 3.1: An overall hardware architecture

sor data and control signals. While, the message exchanges between different computational units are accomplished by transmitting messages over the underlying bus infrastructure.

For pursuing higher efficiency and performance, reconfigurable hardware devices, especially FPGAs, have been extensively utilized in embedded system designs [HV08, ZSJ09, ZSJ10]. In this thesis, we consider that the FPGA co-processors (if present in the system) support static reconfiguration and possibly also partial dynamic reconfiguration (PDR). If PDR is supported, part of the FPGA area can be dynamically reconfigured while the rest of the FPGA continues to process. In fact, modern FPGA families, like the Xilinx Virtex or Altera Stratix, provide efficient partial dynamic reconfiguration support. This offers great flexibility, allowing customization of the hardware platform according to different system requirements. One scenario often employed for current reconfigurable platforms is that the FPGA is partitioned into a static and a PDR region. The static region hosts a microprocessor, a reconfiguration controller (which takes

care of reconfiguring the PDR region), and, potentially, other peripheral modules that need not change at run-time. The PDR region is organized as reconfigurable slots (composed of heterogeneous configurable tiles), where hardware modules can be reconfigured at run-time [KLH⁺11].

The other type of subsystems shown in Figure 3.1 can be an independent system or an end component of a bigger system. Such a unit consists of a DVFS-enabled microprocessor connected with a set of peripherals, e.g., sensors and actuators, and communication modules, via which the unit interacts with other peers or service centers (over wire or wirelessly). The supply voltage (and implicitly the frequency) of the processor can be selected from a discrete set, depending on actual operational requirements.

3.1.2 Power Model

In this section, we present the models we use for estimating the power consumption of the processors. The power consumption of a processor (designed with CMOS technology) consists of several parts: dynamic power (Pow^{Dyn}), static power (Pow^{Stat}), inherent power (Pow^{On}) [MFMB02], and short circuit power. *Short circuit power* consumption occurs only during signal transitions, and is negligible [Vee84]. Pow^{On} represents the *inherent power* consumption incurred by keeping the processor on, and has a constant value. The *dynamic power* consumed by the processor can be calculated as

$$Pow^{Dyn} = C_{eff} V_{dd}^2 f, \quad (3.1)$$

where C_{eff} , V_{dd} and f denote the effective switching capacitance due to computations, the supply voltage, and clock frequency of the processor, respectively. The dependency of the operating frequency on supply voltage [MFMB02] is given by

$$f = \frac{((K_4 + 1)V_{dd} + K_5 V_{bs} - v_{th1})^\alpha}{K_6 L_d}, \quad (3.2)$$

where K_4, K_5, K_6 and v_{th1} are technology dependent coefficients, L_d is the logic depth, and α is a measure of velocity saturation. In this

thesis, we assume that the processor can run at discrete designated voltages, and, consequently, at the corresponding discrete frequencies. Dynamic power is consumed only when the processor is active, i.e., executing tasks. *Static power* does not depend on switching activity, and is consumed due to leakage current, which is mainly a combination of sub-threshold conduction (I_{sub}) and reverse bias junction current (I_{ju}) [MFMB02]. The static power (consumed both when the processor is active and idle), is given by

$$Pow^{Stat} = L_g(V_{dd}I_{sub} + |V_{bs}|I_{ju}), \quad (3.3)$$

where, L_g is the amount of logic gates in the circuit, and V_{bs} is the voltage applied between the body and the source of a transistor. As shown in [MFMB02], the sub-threshold leakage current can be approximated with the following expression

$$I_{sub} \approx K_1 e^{K_2 V_{dd}} e^{K_3 V_{bs}},$$

where K_1, K_2 and K_3 are constant fitting technology dependent parameters.

3.2 Security in Embedded Systems

In this thesis, we focus on two representative security design objectives that are particularly important in the context of embedded systems, namely, confidentiality and intrusion detection. In order to achieve these two goals, we must implement corresponding protection mechanisms, that are cryptography for delivering confidentiality and intrusion detection applications for detecting potential intrusions. Note that, the confidentiality protection strength of cryptographic algorithms lies in two aspects with respect to two different attack methods. We shall elaborate on this in more details in the next section.

3.2.1 Confidentiality

Confidentiality is usually of central importance among the key components of embedded system security. In this thesis, we shall focus

on achieving confidentiality for the communication. While, the confidentiality aspects of the data storage, e.g., how to securely save and keep critical data in memory, is not in the scope of this thesis.

The fundamental step towards communication confidentiality is to apply cryptography. In order to protect the confidentiality of the communication, we must carry out encryption/decryption (E/D) on the exchanged messages. However, this comes with extra computational overhead, which is a problem for the designers, since embedded systems very often have limited computational capacity and have to function under stringent timing constraints. There are three main approaches in cryptography: public-key cryptography, symmetric-key cryptography, and cryptographic hash functions. In public-key cryptosystems, different but related keys are used, including a public key and a private key. They have mainly been developed based on the computational complexity of certain hard mathematical problems, e.g., integer factorization, and are relatively costly in computational demand, compared to most symmetric key algorithms with equivalent security level. This has limited their use in resource constrained environments like embedded systems for encryption purposes.

In symmetric-key cryptography, the same key (or trivially related keys) is used for both encryption and decryption. The key represents a shared secret between two or multiple parties that have access to the confidential information. Such crypto-algorithms, e.g., AES [DR02] and RC6 [RRSY98], have been designed to be highly efficient, even on embedded microprocessors. In resource constrained systems, public-key algorithms can be used for occasionally exchanging secret keys for symmetric-key algorithms which will perform the actual message encryption and decryption. Cryptographic hash functions are used for verifying the integrity of a message or the identity of the sender. By this, the convenience and efficiency of the three different cryptosystems are combined. In this thesis, we shall concentrate on maintaining confidentiality of the communication by utilizing arguably the most widely used branch of symmetric cryptography, the iterated block ciphers.

3.2.1.1 Iterated Block Ciphers

Iterated block ciphers (IBCs) are one type of symmetric-key cryptography and are widely adopted for protecting information confidentiality. IBCs are constructed by applying a function repeatedly in order to provide better information confusion and diffusion as the number of rounds increases. They are particularly suitable for embedded systems [PP10] because of their properties of high throughput, implementation simplicity, and sound protection strength. In this thesis, we focus on using two representative IBCs, i.e., the Advanced Encryption Standard (AES or Rijndael) [DR02] and the very flexible RC6 block cipher [RRSY98], for encrypting and decrypting messages under different design requirements. However, the techniques presented in this thesis are general enough to be also applied on other IBCs.

The execution time (ET) (nominal time with respect to a given execution setup, i.e., platform and frequency) of an E/D task of an IBC on a message m_i is growing linearly with the number of rounds. In other words, the more rounds are used for encryption and decryption, the longer execution time the procedure will take, but the closer the output is to a random bitstream, making it more secure. For correct message transmission, the same number of rounds must be used by an E/D process pair. Since the E/D procedures of a chosen IBC on message m_i are similar but inverse to each other, they have roughly the same nominal ET calculated as follows,

$$\mathcal{E}_{ED} = w_{ED} + r_{ED} * x_i \quad (3.4)$$

where, w_{ED} represents the constant nominal ET of the chosen IBC for doing the pre-/post-whitening on the encryption and decryption tasks, representing the initialization and finalization operations of the algorithm. The coefficient r_{ED} represents the nominal ET for doing one round of E/D. Variable x_i is the number of rounds used by the chosen cipher variant C_i for m_i . However, the actual ETs for the E/D tasks depend on the computational resources they are mapped to and the frequencies they are executed at. We shall come back to this in later chapters.

3.2.1.2 Protection Strength of IBC

If the only information the attacker has access to is the transmitted data (for example, she does not have physical access to the computational units, or the whole computational system including the power supply is protected with tamper-resistance technology [RRC04]), then she can mount attacks only based on the captured messages. In addition, we assume a strong attacker who also can feed the cryptosystems with arbitrary plaintexts. Under such a scenario, the attacker can do cryptanalysis attacks on the IBC algorithm, trying to recover secret information based on the theoretical weaknesses of the algorithm.

A large number of plaintexts and their corresponding encrypted versions (the cipher texts) generated from the target system are required in order to do a successful attack [BS91]. The efforts needed to gather such required information grow exponentially as more rounds are used, because, as mentioned in the previous section, closer-to-random cipher texts are produced. From now on, we shall refer to a chosen implementation of an IBC with x rounds as one of its variant. Due to the actual timing and resource constraints, as well as considering the current security threats present in the RTESSs, we may have to sacrifice certain protection strength, i.e., using variants with less rounds of the chosen IBC for faster encryption or decryption¹. Then the question is how good protection an IBC variant delivers with respect to the chosen number of rounds.

In order to quantify the protection strength of an IBC and compare the strengths of different IBCs or IBC variants, we capture the IBC strength as the logarithm of the number of plaintext-cipher pairs needed to break the algorithm by the *best known cryptanalysis attack*. We have conducted extensive studies on cryptanalysis attacks on four representative IBCs, i.e. RC5 [BK98], RC6 [KM01, HKHF11], AES [ZWF07, LDKK08] and Blowfish [Vau96]. In the end, we have chosen seven variants of the RC6 algorithm which enjoy the highest rate of protection strength to encryption speed ratio, among all investigated IBCs. RC6 is simple and flexible while providing sound security

¹Remember that the encryption and decryption time is linear to the number of rounds.

Table 3.1: Protection strength and encryption time of different RC6 variants

Variant	RC6-4	RC6-6	RC6-8	RC6-10	RC6-12	RC6-14	RC6-16
Strength	29	45	61	78	94	110	118
Time	23	31	38	46	54	62	70

protection [NBB⁺00], if the design parameters are carefully decided.

The results of our study on the seven chosen RC6 variants are listed in Table 3.1, in which RC6- x means x rounds are carried out for this variant of RC6. Half of the data is encrypted in one round in RC6, so two rounds are considered as the smallest unit for doing encryption and decryption using RC6 in the rest of this thesis. The first row in Table 3.1 presents the referred RC6 variants indexed by the number of applied E/D rounds (4, 6, 8, etc). The second and third rows list the corresponding protection strength (logarithm based) and execution time (μs) per block (16 bytes)², respectively. The encryption and decryption times of a RC6 variant are very similar, so we assume them equal for simplicity of the presentation (as shown in Eq 3.4). The variants of RC6 with more than 16 rounds of E/Ds are omitted, since they are considered to be fully secure against cryptanalyses [NBB⁺00]. It is worth mentioning that our proposed design framework is general enough to be applied to other quantification methods and cryptographic algorithms or variants too, if similar strength/time trade-offs can be derived.

3.2.1.3 Side-Channel Attacks on IBC

If the attacker has physical access to the hardware, then she can do more powerful attacks to the target device. We assume that the actual computational units, e.g., the processor and memory, are tamper-resistant [RRC04]. That is, the attacker cannot directly read the sensitive information from the memory or registers, or control the

²Estimated from ANSI C implementation of RC6 on a processor running at the frequency of 7.2MHz [RRSY98].

processor operations. As in the previous section, we also assume a strong attacker who can feed the system with arbitrary plaintext, e.g., by changing the data from the sensors. In addition, we also assume that she can accurately measure the power consumption of the microprocessor. As the microprocessor is tamper-resistant, she cannot change the task schedule, or directly read out the secret key(s), but instead, she can mount attacks based on the side-channel information that she can measure (e.g., the power consumption) aiming to find secret information of the system.

As mentioned in Section 2.3.2, DPA attacks are arguably the most efficient attack scheme on IBC implementations. Therefore, we focus on DPA attacks on AES in this thesis. The DPA attacks try to reveal the secret key K used by AES at the granularity of subkey³. The procedure is, in brief, as follows. The attacker first identifies a fraction in an AES round that is a function of a given text and an 8-bit subkey k . This fraction is referred to as a leakage point LP_k . Of all the AES encryption (or decryption) operations with the same AES secret key K , the same subkey k is used to operate on different input texts using the same function at LP_k . Therefore, there exists a certain relation among all the measured power consumptions at occurrences of LP_k . After identifying LP_k , the attacker feeds the AES process with chosen plaintexts, and measures the power of the processor. Then, based on a timespan TS that the attacker defines, she divides the whole obtained power trace (of G time units) into $S = G/TS$ samples. In fact, based on our observations from a large number of experimental evaluations, choosing $TS = \mathcal{P}$ ($\mathcal{P}$ is the period of the AES task ce/cd , which depends on the period of its parent task associated with the corresponding message.) gives the best alignment among all the possible values of TS . This is to the most advantage of the attacker, and also the worst case from the designer's perspective. So we assume that the attacker knows $\mathcal{P}$ to reserve sufficient security margin. Then the attacker organizes the samples into a 2D matrix $P = [i - j](i = 1, \dots, S; j = 1, \dots, V)$ with size $S * V$, in which $V = \mathcal{P} \times F$. F is the sampling frequency of the attack equipment.

³The definition and how to obtain the AES subkeys can be found in [DR02].

Figure 3.2: Calculate correlations between power measurements and hypotheses

Thus, V is the number of obtained power values within $\mathcal{P}$. Each $P_{x,y}$ denotes an actual measured power value of sample x at relative time point y (with respect to F).

The next step is to produce the hypotheses regarding the processor power at leakage point LP_k . Since there are only $2^8 = 256$ different possibilities of subkey k , the attacker can enumerate all the possible 256 values on all the plaintexts she used, and derive another 2D matrix $H = [i - j](i = 1, \dots, S; j = 1, \dots, 256)$, each of which is a hypothetical power value of the corresponding plaintext-subkey pair, and is calculated depending on her knowledge about the underlying hardware.

The last step is to find correlations between the actual measured power of the processor and the attacker's hypothetical power on each column P_i of P and H_j of H by calculating, for example, the Pearson correlation coefficient ρ_{ij} (as shown in Figure 3.2). Column P_i and H_j has high correlation if ρ_{ij} is high. And the highest value $\rho_{max} = \rho_{xy}$ reveals that k_y was the real subkey used at relative time t_x . Then, the attacker tries to recover the whole secret key K by going through all the subkeys, or until it is trivial to mount a brute-force attack on

the rest of the key bits.

Then the question is how difficult it is to retrieve the secret key K from the attacker's perspective, or how robust K is from the designer's point of view. Assuming that the highest correlation between two columns of P and H is ρ_{max} , the attacker aims to get a value of ρ_{max} which stands out among all the values ρ_{ij} . Due to various reasons, e.g., clock drifting, the occurrences of leakage point LP_k with respect to subkey k may happen at different times in different samples, thus, leading to lower values of ρ_{max} . If $\forall \rho : \rho \approx 0$, then there is no dominating ρ_{max} , that is, there is no clear correlation between any column of P and H . This is the optimal case in terms of robustness against DPA of the AES implementation, meaning that the attacker needs infinite amount of samples to observe a high ρ_{max} . Let us denote the moment of time when LP_k happens with the highest probability among all the samples as $\hat{t}$. The corresponding column of $P_{\hat{t}}$ will have the highest correlation with the column $H_{sk_{ij}}$ of H which is the actual subkey used in the leakage point. The probability that the leakage point occurs at $\hat{t}$ is captured as $\hat{p}$.

We assume that the processor execution is noise-free, that is the signal-to-noise ratio (SNR) is 0, to reserve sufficient security margin. The number of samples defining the strength of the secret key against DPAs can be calculated with Equation 4.44 from [MOP07] as follows,

$$\mathcal{N} = 3 + 8 \cdot \frac{z_{1-\alpha}^2}{\ln^2\left(\frac{1+\rho_{max}}{1-\rho_{max}}\right)}, \quad (3.5)$$

where α and $1 - \alpha$ are known as the error probability and confidence interval of detecting a significant ρ_{max} from all the correlation values between the columns (see Figure 3.2). $z_{1-\alpha}$ is the quantile of standard normal distribution that determines the distance between the distribution of $\rho = 0$ and $\rho = \rho_{max}$, and is calculated as follows

$$z_{1-\alpha} = \sqrt{2} \cdot \text{erf}^{-1}(1 - 2 \cdot \alpha). \quad (3.6)$$

As shown in [MOP07], ρ_{max} can be expressed as

$$\rho_{max} = \rho(H_{S,k_c}, \check{P}_{S,\hat{t}}) * \hat{p} * \sqrt{\frac{\text{Var}(\check{P}_{S,\hat{t}})}{\text{Var}(P_{S,\hat{t}})}}, \quad (3.7)$$

where, $P_{S,\hat{t}}$ and $\check{P}_{S,\hat{t}}$ are all power consumption points and the points related to leakage points at time $\hat{t}$ in the samples, respectively. Coefficient $\rho(H_{S,k_c}, \check{P}_{S,\hat{t}})$ solely depends on the accuracy of the attacker's simulation or power model about the targeted device, and is set to the most conservative value 1. The variances $Var(P_{S,\hat{t}})$ and $Var(\check{P}_{S,\hat{t}})$ are from the device characteristics, and are assumed to be equal to make our analysis independent of devices. Thereby, we have

$$\rho_{max} = \hat{p}. \quad (3.8)$$

Now if we combine Equation 3.5 and Equation 3.8, and set $\alpha = 0.1$ (that gives $z_{1-\alpha} = 1.282$), then we can calculate the lower bound of the number of samples $\mathcal{N}$ to observe a noticeable ρ_{max} as follows,

$$\mathcal{N} = 3 + \frac{13.148}{\ln^2(\frac{1+\hat{p}}{1-\hat{p}})}. \quad (3.9)$$

Now, we define the robustness $\mathcal{R}$ of the secret key K against DPA attacks as the total amount of time needed to gather $\mathcal{N}$ samples:

$$\mathcal{R} = \mathcal{N} * \mathcal{P}, \quad (3.10)$$

where $\mathcal{P}$ is the occurrence period of AES having the secret key K .

3.2.2 Intrusion Detection

Besides communication confidentiality and side-channel resistance, detecting potential intrusions to the system is another important security aspect in the context of embedded systems. Intrusions [LJ97] are the malicious activities that try to access secret information or violate predefined security policies of a target system. An intrusion detection (ID) application actively monitors network and/or system activities and status changes, e.g. critical variables and log records, for possible intrusion evidences. We consider a host-based intrusion detection technique [YD03] that runs as an independent task in the system. To ensure detection effectiveness, it is recommended to employ both signature-based and anomaly-based intrusion detection techniques [SM07]. The signature-based technique tries to recognize

known threats from patterns of existing attacks, while the anomaly-based technique tries to find possible malicious activities with suspicious behaviors that deviate from normal system executions.

There exist various techniques for building ID models, either via manual knowledge engineering or automatic model abstractions, and detecting intrusions. For example, the automatic approaches presented in [HFS98, LSM99] are prominent techniques for developing ID applications in embedded systems. Both can be used for signature-based and anomaly-based IDs. In this thesis, we assume a hybrid ID task, in which both techniques cooperate for achieving the best detection accuracy, co-existing with application tasks. Considering the limited memory size on embedded platforms, we assume that the models of normal behaviors stored in memory are obtained using the approach presented in [HFS98], which finds unique system call sequences of length 10, and exhibits low memory footprint. The technique in [LSM99] is only used for finding the models of known malicious attacks to be stored in memory. At run-time, the ID task checks the system execution traces for potential intrusions by comparing with both the pre-stored rules of normal behaviors and signatures of attacks.

The ID application task can be adjusted according to the desired trade-off between detection accuracy and consumed processor bandwidth. The only assumption is that higher detection accuracy will consume more processor bandwidth. In principle, we do not restrict to any particular forms in which the accuracy/overhead trade-off is captured. For the sake of simplicity, we shall assume that the ID task has a given nominal execution time $\mathcal{E}_{ID}$ (with respect to the highest supply voltage of the processor), and, at each release, it examines all necessary information for possible intrusion evidences. Meanwhile, the ID task may be activated with different periods $\mathcal{P}_{ID}$, depending on the available resources and also on the estimated level of threats. The longer the interval between two successive ID task releases, the easier the intrusion evidence can be hidden or even erased. Thus, the accuracy and promptness of the intrusion detection is directly influenced by the release period $\mathcal{P}_{ID}$. We define the intrusion detection

accuracy (IDA) as follows,

$$IDA = \frac{\mathcal{P}_{ID}^{min}}{\mathcal{P}_{ID}}, \quad (3.11)$$

where $\mathcal{P}_{ID}^{min}$ is the shortest period that the ID task needs to be released in order to achieve the best detection performance. Note that our proposed techniques are not tied to any particular ID technique and accuracy quantification. Other variants of ID implementations and quantifications can be adapted as long as an accuracy vs. resource overhead trade-off relation can be provided.

Chapter 4

Design of Secure Distributed Embedded Systems

WE shall present our design techniques for achieving confidential internal communication in distributed real-time embedded systems. We present two approaches to efficiently implement protection schemes depending on the architecture of the computational units in the system. In the first approach, we focus on achieving the highest affordable confidentiality protection on the architecture in which computational nodes are resource-limited microprocessors. In the second approach, we consider nodes that also contain reconfigurable FPGA areas that can be used for accelerations. The real-time properties are guaranteed in both approaches. The problem to be solved, which builds upon static scheduling of a set of dependent tasks on multiple processing resources, is known to be NP-hard [Ull75]. To solve the design problems, we first produce constraint logic programming (CLP) formulations, and solving a CLP formulation exactly will return the optimal solution for the corresponding problem. However, this is computationally expensive and, hence, efficient heuristics are proposed as alternatives. Note that the presented techniques can be applied both in the early system design phase and on the off-the-shelf systems.

The rest of this chapter is organized as follows. Section 4.1 introduces the common application model shared in the two design problems. Section 4.2 and 4.3 detail the respective hardware architectures, and formulate the two problems, as well as present the proposed techniques and experimental evaluations. The chapter is summarized in Section 4.4.

4.1 System Model

4.1.1 Architecture Model

The hardware architecture is a distributed hardware platform as discussed in Section 3.1.1, and composed of two parts, a set of computational nodes and a communication bus which handles message communications. Each computational node has an embedded processor. All the tasks are executed in software on the processors. This is the architecture we consider for our first design problem (Section 4.2). In the second case (Section 4.3), we assume that a computational node consists of both a processor and an FPGA accelerator, which can be used to offload certain computations to enhance system performance. The processors in both cases can be of different types and processing capabilities.

4.1.2 Application Model

In this chapter, we capture an application as a directed acyclic task graph $G(\mathcal{T}, E)$ that is mapped to a distributed hardware platform as described in the previous section. $\mathcal{T}$ represents a set of non-preemptive tasks that need to be executed in the system. The mapping from tasks to computational nodes is given by a function $\mathcal{F} : \mathcal{T} \rightarrow P$, where $P = \{p_1, p_2, \dots, p_n\}$ is the set of available computational nodes. $\mathcal{F}(\tau)$ is the node that task τ is mapped to for execution. The bus is considered as a special resource that only handles the message transmissions. The execution time (ET) of a task τ is given as a constant value c .

The edges E of graph G capture the data dependencies between tasks. An edge $e \in E$ from τ_s to τ_t indicates that there exists a data

Figure 4.1: A simple application with 5 tasks

dependency between τ_t and τ_s (τ_t depends on τ_s). If τ_s and τ_t are mapped to the same processing node, i.e., $\mathcal{F}(\tau_s) = \mathcal{F}(\tau_t)$, then the data transfer is achieved by memory copies, and no message will be transmitted over the bus. Otherwise, a message m will be transferred from $\mathcal{F}(\tau_s)$ to $\mathcal{F}(\tau_t)$ over the bus, after τ_s finishes. The message transmission times of messages are also given.

The task mapping is defined by the designer, so the set of messages is known. Figure 4.1 depicts an illustrative application containing 5 tasks and 5 edges. Tasks $\{\tau_1, \tau_4\}$ and $\{\tau_2, \tau_3, \tau_5\}$ are mapped to processor p_1 and p_2 , respectively. As the consequence of this mapping, there is no message transmission on edge e_5 in Figure 4.1, as $\mathcal{F}(\tau_3) = \mathcal{F}(\tau_5)$. On the other hand, the edge e_3 , for example, will lead to a message communication m_3 sent from $\mathcal{F}(\tau_2)$ to $\mathcal{F}(\tau_4)$. A task can only start execution after all of its preceding tasks have finished and its input data have been successfully received. The whole application must complete its execution before an end-to-end delay $\mathcal{D}$, known as its global deadline.

4.2 Confidentiality Optimization

Now, let us first look at the case of hardware nodes without FPGA acceleration. In order to achieve good overall security protection in the context of tight resource limits and stringent timing constraints, we need to find the best system-affordable cryptographic protections to the internal communication, during the early stages of system design and optimization.

Figure 4.2: A processor-based platform

4.2.1 Motivational Example

Let us consider the case that the application shown in Figure 4.1 is mapped to the hardware architecture depicted in Figure 4.2. The task to processor mappings follow the example mentioned in Section 4.1.2, and are captured in the figure. The communication messages $\{m_1, m_2, m_3, m_4\}$ are transferred over the bus, denoted as p_3 . The ETs of the tasks are set as $c_1 = 110, c_2 = 90, c_3 = 170, c_4 = 110$, and $c_5 = 150$, respectively, and the payload transmission times of all the messages are set as 15. The global deadline is 700 time units.

In order to protect the communication against malicious snooping, encryption and decryption should be deployed on the messages. If no E/D task is performed, the shortest end-to-end delay of this application is 535 time units. The corresponding schedule is shown in Figure 4.3. As can be observed, the system currently has time slacks that potentially can be utilized to perform encryption and decryption operations within the global deadline of 700 time units.

Let us assume that the designer wants to apply RC6 [RRSY98] on the messages, of which the pre/post-whitening and one E/D round both take 2 time units to finish on both processors. A simple approach to protect the communication of the application would be to maximize the protections on all the messages. Assuming the designer wants to use RC6 variant of 20 rounds, then he will get a schedule as shown in Figure 4.4. However, the end-to-end delay of the application is now

Figure 4.3: Schedule without cryptographic protections

Figure 4.4: Schedule with RC6-20 on all messages

Figure 4.5: Schedule after balanced maximization on all messages

Figure 4.6: Schedule after distribution of the slacks from Figure 4.5

Table 4.1: Results of different solutions in Figure 4.3-4.6

Solution	m_1	m_2	m_3	m_4	Schedule
No E/D	0	0	0	0	Figure 4.3
Fixed high-protection for all messages	20	20	20	20	Figure 4.4 (Not schedulable)
Even slack distribution	14	14	14	14	Figure 4.5
Further rounds increment	14	18	14	16	Figure 4.6

757, which violates the deadline constraint of 700 time units. So this solution is not feasible.

Another alternative solution would be to distribute the number of E/D rounds evenly to all messages. The best possible solution without violating the global deadline in this case is to assign 14 E/D rounds to each message transmitted over the bus, and the corresponding schedule is illustrated in Figure 4.5. Assigning 16 or more rounds to all messages at the same time would violate the imposed deadline of 700. Nevertheless, the schedule in Figure 4.5 still contains small time slacks, which means that the number of E/D rounds for certain individual messages can still be increased.

Figure 4.6 illustrates a solution in which the available slacks have been further utilized to increase the security level of selected messages. Now the applied numbers of E/D rounds for the messages become 14, 18, 14 and 16, in which two messages are further encrypted by 4 and 2 more rounds, respectively. This is the optimal solution we can achieve. The number of rounds used by the messages in the aforementioned solutions are presented in Table 4.1.

4.2.2 Problem Formulation

Now we shall formulate the design optimization problem. As already mentioned, the goal is to find the best affordable confidentiality protections for the internal communication. That is, we want to optimize the protection for messages transmitted over the bus using IBCs, under the available processing power and the imposed timing

constraints. The optimization problem is decomposed into two sub-problems that are performed in two steps.

4.2.2.1 Step I

In the first step, we want to find the maximal number of rounds N that all E/D tasks can perform. In other words, we aim at finding a schedulable solution of the system within the deadline, in which N rounds of the chosen IBC are used by all E/Ds. This step maximizes the smallest number of rounds globally (see Figure 4.5 and the fourth row in Table 4.1).

4.2.2.2 Step II

In the second step, the system may still have extra time slack due to unbalanced workload and the diverse processing power of different processors. Hence, we can further increase the security strength of the internal communication by utilizing the available processor bandwidth. Thereby, the E/D modules running on the smallest number of rounds and generating the plaintext-cipher pairs (refer to Section 3.2.1.2) are reduced. As a result, the potential vulnerability of the system is further dwindled. This is particularly effective if different E/D pairs use distinct secret keys to encrypt their messages.

In this step, we want to increase the number of E/D rounds as much as possible until the designer specified threshold, e.g., RC6-20, is reached, while also trying to provide a certain balance between the individual security degrees of the messages. These two aspects are captured by the following cost function that drives the optimization:

$$Cost = \alpha * Avg(X) - \beta * StandDev(X) \quad (4.1)$$

in which

$$Avg(X) = \frac{1}{n} * \sum_{i=1}^n x_i$$

$$StandDev(X) = \sqrt{\frac{1}{n} * \sum_{i=1}^n (x_i - Avg(X))^2}$$

Figure 4.7: Reconstructed task graph of Figure 4.1

α and β are the designer-provided weights depending on how balanced the security levels of different messages are desired.

For the sake of illustration purposes, we consider that all messages on the network share the same security requirement. However, the proposed approach can be generalized in a straightforward way if messages have different security requirements. For example, in Step II, the numbers of E/D rounds of different messages can be weighted with different coefficients to capture their actual security demands.

4.2.3 Proposed Techniques

Let us consider again the application in Figure 4.1 with mapping in 4.2. In order to keep the messages confidential, we have to perform message E/Ds. Each message will be encrypted before being sent over the bus by the source processor, and decrypted when received by the destination processor. To capture these operations in our representation, we shall make the procedure of the two cryptographic operations explicit. The newly added tasks for encryption and decryption are mapped to the same processors as the corresponding sending and receiving tasks. For example, encryption task ce_1 is mapped to processor p_1 , while the corresponding decryption task cd_1 to processor p_2 . The reconstructed application and updated task mappings are illustrated in Figure 4.7 and Figure 4.8, respectively.

Figure 4.8: New task mapping from Figure 4.2

4.2.3.1 CLP Formulation

We first formulate the optimization problem using constraint logic programming (CLP) in which the problem is represented as a process of constraint satisfaction using a set of clauses capturing the constraints. Then the program is passed to a CLP solver that tries to find the optimal solution using various acceleration methods, such as branch and bound search. However, the complexity of finding the optimal solution by CLP still grows exponentially as the problem size grows. The reason of formulating the problem in CLP is to compare the later presented techniques with the optimums returned by the CLP solver.

Now let us present the CLP constraints grouped in two sets. The first set captures the dependencies of the original task graph, e.g., the encryption task ce_1 needs to be executed after task τ_1 in Figure 4.7. The second set represents the schedulability constraints, e.g., the very last task τ_5 in Figure 4.7 must successfully finish its execution before 700 time units. The CLP constraints we used are as follows.

Dependency constraints This set of constraints reflects the structure of the task graph. Each task is allowed to execute only after all

its parent tasks have finished, i.e.,

$$\begin{aligned} \forall \tau_i \in \mathcal{T} \text{ and } \forall \tau_j \in \text{Parent}(\tau_i), \\ \text{StartTime}(\tau_i) \geq \text{StartTime}(\tau_j) + ET(\tau_j) \end{aligned} \quad (4.2)$$

Schedulability constraints There are three types of constraints in this set, which together guarantee that the obtained result is schedulable within the global time constraint, and, in addition, the final schedule is correct.

- Execution time constraints:

The non-E/D tasks have constant ETs, while the E/D tasks have variable ETs that are related to the optimization variable x_i as stated in Equation 3.4. So, in order to capture this behavior, we assign fixed values as the ETs for non-E/D tasks, and restrict the ETs of E/D tasks to a domain containing all the possible values that they can take with respect to all the designated number of rounds.

- Parallelization and sequence constraints:

The target application is mapped to a distributed platform. Therefore, the tasks on different processors can run in parallel, while the executions of different tasks on the same processor must not overlap with each other.

- Deadline constraint:

As all dependencies have been defined, we formulate the deadline constraint as follows: the last task of the application must finish its execution before the deadline D , i.e.,

$$\text{StartTime}(\tau_{last}) + ET(\tau_{last}) \leq D. \quad (4.3)$$

If multiple tasks can be the last one in execution, meaning that none of them has a succeeding task, then a “virtual” last task with 0 execution time is added into the task graph that depends on all the potential last tasks. Then the deadline constraint is checked on this virtual task instead.

Optimization objectives The two steps of the optimization have different objectives. In Step I, the objective is to find the maximal number of rounds N that all the E/D pairs can perform without violating any constraint, including the final deadline constraint. While in Step II, the objective is to maximize the cost presented in Equation (4.1) based on the number N obtained from Step I.

4.2.3.2 Heuristic Approach

Although the CLP formulation outlined above returns the optimal solutions, it cannot scale to large systems due to its computational complexity. In this section, we describe our heuristic alternative for solving the optimization problem which can handle large designs efficiently. The heuristic approach is based on two well-known algorithms, list scheduling (LS) [EPPD00] and simulated annealing (SA) [KJV83]. The former handles the schedulability test, and the latter optimizes the system with respect to the cost function.

Step I is achieved by gradually adding two rounds to all E/D tasks, whose ETs are also increased by the ETs of doing two rounds of RC6 on corresponding processors, until the system cannot be scheduled within the deadline limit. LS must be applied on the system for schedulability check after each increment of the rounds. This is because that, after each increment, ET of the E/D tasks changes. Consequently, the critical path determining the new end-to-end delay of the system may be different from the one before. Therefore, we cannot simply derive the end-to-end delay by adding the extra ETs to the length of the original critical path. The final obtained value of N is the largest number of rounds that all the E/D tasks can perform without breaking the system schedulability, and will be used as the initial value for Step II. The pseudocode for this step is shown in Algorithm 1.

After the first step, there may exist time slacks that some E/D task pairs can use to undertake extra encryption and decryption rounds. So distributing these slacks in a smart way is crucial for getting closer result of $Cost$ (Equation 4.1) to the optimum. We have used a SA-based heuristic driven by the second objective to approach good so-

Algorithm 1 Heuristic approach: Step I

```

1: init ETs of all E/Ds with corresponding  $w_E$ 
2: for  $i = 2, 4, \dots, Bound$  do
3:   increase ETs of all E/Ds with corresponding  $r_E * 2$ 
4:   if  $ListScheduling(G) > D$  then
5:     return  $N = i - 2$ 
6: return  $N = Bound$ 

```

lutions. At the beginning, $Cost$ and all $x_i (i \in \{1, 2, \dots, n_M\})$ are initialized with $currentcost$ and N , and the ETs of the E/Ds are also initialized correspondingly. Then SA randomly selects one E/D pair, e.g., ce_i and cd_i , to manipulate each time. Both increment and decrement manipulations are allowed and randomly decided to be performed on x_i , but decrement moves leading to $x_i < N$ are prohibited. If the updated system can be scheduled by the list scheduling algorithm, then the program proceeds to check whether $currentcost$ is higher than $Cost$. Otherwise, this pair of ce_i and cd_i are restored to the previous state. Now if $currentcost$ is higher than $Cost$, then $Cost$ is updated as $currentcost$. If not, a random number $rn \in (0, 1)$ is generated and compared with $\exp(-\delta/tp)$, where tp is the current temperature (control parameter for the SA algorithm), and δ is the cost decrement caused by this move. The current state and $currentcost$ are kept only in case $rn < \exp(-\delta/tp)$. This helps the search procedure to escape from a local optimum.

The above optimization procedure will terminate when no improvement is found in a certain number of consecutive steps. The set of decision variables $x_i (i \in \{1, 2, \dots, n_M\})$ hold the numbers of rounds for all E/D pairs. And the system schedule is retrievable from the LS schedule table. The pseudocode for the second step is given in Algorithm 2. The SA parameters, including initial temperature, temperature reduction scheme and stopping condition, are set accordingly on different problem sizes from our observations in extensive experiments.

Algorithm 2 Heuristic approach: Step II

```

1: init all  $x_i$  with  $N$  and  $Cost$  with  $currentcost$ 
2: init ETs of E/Ds with  $w_E + r_E * N$  of corresponding processors
3: while stopping condition is not reached do
4:   while executions on temperature level is not reached do
5:     randomly select  $i$  and the move  $MV$  to be performed
6:     if  $MV$  will lead to  $x_i < N$  then
7:       continue
8:     update  $x_i$ ,  $c_{ce_i}$  and  $c_{cd_i}$  according to  $MV$ 
9:     if  $ListScheduling(G) > D$  then
10:      restore  $x_i$ ,  $c_{ce_i}$  and  $c_{cd_i}$  to the previous state
11:   else
12:     if  $currentcost > Cost$  then
13:        $Cost = currentcost$ 
14:   else
15:     randomly generate  $rn \in (0, 1)$ 
16:     if  $rn < \exp(-\delta/tp)$  then
17:        $cost = currentcost$ 
18:   else
19:     restore  $x_i$ ,  $c_{ce_i}$  and  $c_{cd_i}$  to the previous state
20:    $t = \alpha * t$ 

```

4.2.4 Experimental Results

We have performed experiments on randomly generated task graphs with 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 application tasks (excluding the later added E/D tasks) that were mapped on 2, 3, 3, 4, 4, 5, 5, 6, 6, 7 processors respectively. On each problem size, 50 different applications have been randomly produced. All experiments were performed on a Linux machine having a four-core Intel Xeon CPU with 2.66GHz frequency and 8GB RAM.

The experiments with the CLP formulations were implemented in *ECLiPSe* constraint programming system [AW06], and were conducted with a timeout setup. If the *ECLiPSe* engine can find the optimal solution of an experiment before the timeout restriction, it returns the optimum for this application. Otherwise, it stops execu-

tion without producing any result. This setup is used to restrict the overall optimization time of the extensive CLP experiments; otherwise, the CLP engine may run for extremely long time for some cases, and even may not terminate. The computational complexity of the CLP executions is therefore characterized by two parameters. One is the average execution time of those experiments that terminate and return optimal solutions. The other is the percentage of cases that fail to retrieve the optimums within the timeout restriction. In contrast, the proposed heuristic-based techniques will always terminate, and produce good solutions. Note that CLP formulation is problem specific, that is, each test application and task to processor mapping gives a different set of constraints. It is impossible to manually formulate CLP problems for all the test applications. So we developed an automatic CLP code generator that takes a task graph and given mapping, and returns a complete CLP formulation.

We set the timeout bounds of Step I and Step II as 300 and 1800 seconds, respectively, in all CLP experiments. The comparison of the average execution time (of both steps) of the finished CLP instances and corresponding heuristic executions is illustrated in Figure 4.9. The CLP experiments successfully found the optimal solutions for all the 50 test applications only on the smallest size with 10 tasks in the application. For graph size 15 and 20, there were 35 and 22 cases, respectively, out of 50 in which the optimums were retrieved before the timeout. While, starting from size 30, the CLP engine cannot anymore find the optimal solution for any of the CLP formulations, so their execution times are dismissed in Figure 4.9.

As we can see, the execution time of the CLP experiments grows exponentially as the graph size increases. Therefore, finding the optimal solution using the CLP formulation, is only feasible for very small applications. Figure 4.9 shows that the execution time of the proposed heuristics is much smaller than that of the CLP solutions. Of course, the execution time grows also aggressively due to the nature of the simulated annealing algorithm, but the average execution time of the heuristic is only around 900 seconds even for the biggest task graphs (with 90 non-E/D tasks).

The result comparison of the two approaches is presented in Fig-

Figure 4.9: Average execution time of finished CLP experiments and heuristic approach

Figure 4.10: Result comparison of step I

Figure 4.11: Result comparison of step II

ure 4.10 and 4.11 for Step I and II, respectively. When comparing the results, the experiments that CLP failed to find the optimal solutions before timeout are eliminated. So we only analyze the CLP-obtained optimums and their correspondences returned by the proposed heuristics. For example, only 22 experiments of graph size 20 are used to generate the data in Figure 4.11. In both Figure 4.10 and 4.11, the dark gray bars without hatchings (left ones for size 10 and 15 in Figure 4.10, and for size 10 in Figure 4.11) indicate that all the CLP experiments found the optimal solutions, while the rest with hatchings present the results of only the finished CLP executions. The light gray bars are the results obtained by our heuristic approach. Figure 4.10 illustrates the comparison of N for Step I. Averagely, the results produced by the heuristic is 93.83% of the optimums. In Step II, the costs were obtained by setting the weights as $\alpha = 0.7$ and $\beta = 0.3$. As shown in Figure 4.11, the final *Cost* returned by our heuristic approach and the optimal solutions retrieved by CLP are presented, and 94.5% of the optimal result can be achieved by the presented heuristic. From graph size 30, the results of CLP formulations are missing since none of the experiments found the optimal solution within our timeout bound.

4.2.5 A Real-Life Case Study

We also evaluated the proposed techniques on a real-life application, i.e., an adaptive cruise controller (ACC), similar to the one described in [Pop03]. The ACC application automatically maintains a safe following distance from the preceding vehicle. It also has the possibility of autonomous changes of the maximum speed depending on the speed-limit regulations, and assists the driver to brake in case of emergency.

The ACC application is composed of 22 tasks and 15 message communications. The application is constrained by a global deadline of 500 time units. The tasks are distributed to three microprocessors connected by a bus. The original task graph and the ETs of the tasks are shown in Figure 4.12, and the task-to-processor allocation is illustrated in Figure 4.13.

Figure 4.12: An adaptive cruise controller

Figure 4.13: Hardware architecture of ACC

Table 4.2: Result comparison of the ACC application

	N	$Cost$	Time I	Time II
CLP	12	-	9	-
Heuristic	12	10.59	0.03	2.315

The results returned by CLP and our heuristics are presented in Table 4.2, in which N is the maximal number of rounds that all E/D tasks can handle, and $Cost$ is the final optimization result obtained with $\alpha = 0.7$ and $\beta = 0.3$. Time I and Time II indicate the execution time (in seconds) for solving the first and second step, respectively. The CLP formulation for the Step II cannot find the optimal solution using any of the available search acceleration methods within our timeout setup of 1800 seconds. So no result is given in the "Cost" and "Time II" columns of CLP formulation. As can be observed, our heuristic found identical N as the optimum in the first step, and returns the result within a very short period.

4.3 Implementation Optimization

Now let us look at another type of hardware architecture of the end computational node, in which each node is formed of a microprocessor and some attached FPGA area. The microprocessors in the system can be of different types and architecture as in the previous section. The FPGA co-processor shares the same memory with the processor, and is used to offload certain task executions. Since tasks mapped to FPGA can run in parallel with the tasks on processor of the same node (if no data dependency), and many tasks can be executed more efficiently in hardware than software, the system performance can be highly accelerated.

The characteristics of FPGAs match well with the core operations of IBCs, i.e. bit-substitution, XOR, and lookup table operations. In fact, the IBCs usually have good suitability, high performance, and small area consumption on FPGAs [EYCP01, DPR00]. In addition,

VHSIC Hardware Description Language (VHDL) and Verilog implementations of IBC algorithms are also easily accessible¹. Therefore, we only consider offloading the E/D tasks in the following discussions to simplify the designer's role in using the presented techniques. By offloading and parallelizing the E/D tasks, the global performance will then be enhanced. Moreover, due to the fact that the life cycle of cryptographic algorithms is significantly lower than the life time of most RTEs (which may be used for tens of years), we can flash the FPGAs with up-to-date algorithms when needed without replacing the hardware, which is much more convenient comparing with having application-specific integrated circuit (ASIC) hardware implementations of given cipher algorithms.

Additionally, as already mentioned in Section 3.1.1, modern FPGA devices also allow modification of only a part of the gate array (called partial dynamic reconfiguration capability, abbr. as PDR). This capability offers even more flexibilities to the system designers, since such PDR enabled FPGAs can have part of the device reconfigured at run-time, while the rest keeps operational. Meanwhile, the FPGAs without PDR capability can only be reconfigured off-line. We will consider both kinds of FPGAs in this section. Such platforms with FPGA co-processors usually are designated to be more powerful in order to accommodate more challenging distributed applications. For such systems, we want to find the minimal total FPGA area that can help the system to implement the desired IBC protections on all message exchanges as well as to meet the deadline constraint.

4.3.1 Motivational Example

Let us consider the application $G(\mathcal{T}, E)$ of Figure 4.14 with task to computational node mapping given as Figure 4.15. The on-board FPGA co-processors beside the microprocessors are depicted by the hatched areas. The application consists of tasks $\mathcal{T} = \{\tau_1, \tau_2, \tau_3, \tau_4, \tau_5\}$ and data dependencies $E = \{e_1, e_2, e_3, e_4, e_5\}$. There are four message transmissions, i.e., $\{m_1, m_2, m_3, m_4\}$, based on the given map-

¹Otherwise, the designer has to develop FPGA modules for all the application tasks.

Figure 4.14: Another illustrative application

Figure 4.15: An FPGA-accelerated architecture

ping. Task $\{\tau_1, \tau_5\}$, $\{\tau_2, \tau_4\}$ and $\{\tau_3\}$ are mapped to the computational nodes p_1 , p_2 and p_3 , respectively. The communication messages $\{m_1, m_2, m_3, m_4\}$ are transferred over the bus (denoted as p_4). The ETs of the tasks are $\{60, 180, 50, 140, 150\}$, respectively, and the transmission times (TTs) of all the messages are assumed to be 20 time units. The system is constrained by a global deadline D of 600 time units.

As mentioned in the previous section, we need to encrypt the messages before sending, and decrypt them after receiving on another node to make the internal communication confidential using software only implementations of RC6. In this section, we consider that the E/D tasks can be implemented either in hardware or software. However, implementing all cryptographic operations in software very likely cannot provide a schedulable solution due to the imposed security and

real-time constraints. But we can make use of the onboard FPGAs to accelerate the E/D processes. Let us consider the scenario that the designer choose to implement the AES standard of the 128-bits version on all messages. Since the AES decryption performs similar operations as the encryption, but in reverse order, (and replaces several inner operations, e.g., *SHIFTRROWS*, with their inverse operations), the required amount of FPGA area and the execution times of AES E/D tasks are roughly the same. Therefore, we assume that the area overhead of implementing one E/D task in FPGA is 1 unit. Consequently, the extra hardware overhead to system is the total FPGA units used.

Let us illustrate the schedules corresponding to different solutions. Assuming that all the messages are in plaintext manner (i.e., no E/D operations were performed), the corresponding schedule is shown in Figure 4.16. The end to end delay of the application is 490 units, and, as can be observed, we have some time slacks that can be used to perform E/D operations on the messages. The ETs of E/D tasks are determined by the function in Equation 3.4. In this system, the designated AES variant to be implemented is AES-128bit version with rounds $x_i = 10$ on all messages. The values of (w_{ED_i}, r_{ED_i}) of software and FPGA implemented E/D tasks are set to be (4, 10) and (2, 4), respectively.

If we do not introduce FPGA units into the system (for new designs) or utilize the existing FPGAs (for off-the-shelf systems), we have to carry out all E/D tasks in software on the microprocessors, as discussed in the previous section. In this case, in order to satisfy the deadline of 600, we can only encrypt the messages with 3 rounds, which is not a satisfactory solution. The schedule can be found in Figure 4.17. A simple approach that tries to reach the required number of 10 rounds, while respecting all constraints, is to accommodate all E/D tasks in FPGA. This leads to an end-to-end delay of 594 and hardware overhead of 8 as shown in Figure 4.18.

If we look closer at the schedule in Figure 4.18, we can find that the encryption operations of m_2 and m_4 may share the same FPGA unit without violating the deadline constraint. The same goes for decryption operations of m_1 and m_2 . In addition, we can save one

Figure 4.16: Schedule without cryptographic protections

Figure 4.17: Schedule of software only solution

Figure 4.18: Schedule of assigning FPGA to all E/Ds

Figure 4.19: Schedule of the optimal solution for static FPGA

Figure 4.20: Schedule of the optimal solution for PDR-enable FPGA

Table 4.3: Results of different solutions in Figure 4.16-4.20

Solution	Rounds	HW overhead	Schedule
No E/D	0	0	Figure4.16
Software	3	0	Figure4.17
Straight-forward	10	8	Figure4.18
Static configuration	10	5	Figure4.19
PDR enabled	10	4	Figure4.20

extra FPGA unit by implementing the encryption operation of m_1 in software. By this, we save three FPGA units without sacrificing the protection level, as can be observed in Figure 4.19. By this, the system is able to encrypt all messages with the required 10 rounds of AES, assisted by 5 FPGA units. In fact, this is the optimal solution, if FPGAs with static configuration are used.

Furthermore, if the FPGA supports PDR², we can also achieve the same level of security using even less hardware area. If the re-configuration time is assumed to be 60 units, the schedule of the optimal solution is illustrated in Figure 4.20. The FPGAs on p_1 and p_2 only undertake E/D tasks of the same kind (all are encryptions, or all are decryptions), so they do not need to be reconfigured at run-time. While, the FPGA unit on p_3 must be reconfigured dynamically (depicted as orange rectangles), since it is shared by both kinds of cryptographic operations. The numbers of achieved rounds and hardware overheads of all the above solutions are listed in Table 4.3.

4.3.2 Problem Formulation

The application is modeled as a task graph $G(\mathcal{T}, E)$ that is mapped to a distributed hardware platform. The ETs and TTs of ordinary tasks and messages are known. The values of software and FPGA implemented w_{ED_i} and r_{ED_i} are given. The hardware cost implied by an E/D task is considered to be 1 unit as already mentioned. The application is constrained by a given end-to-end delay D , and

²Remind that PDR stands for partial dynamic reconfiguration

is required to meet a specific confidentiality protection level, that is given by the set $X = \{x_1, x_2, \dots, x_n\}$. The variable x_i indicates an IBC variant with x_i rounds that need to be applied on message m_i . Different messages can have different security demands reflecting their importance or specific design requirement.

We are interested in finding the minimal overall number of FPGA units FN that need to be added into the system, such that the system reaches the designated confidentiality protection, and, at the same time, the real-time constraints are satisfied. Therefore, the objective is to find the appropriate implementation for all E/D tasks and the corresponding system schedule that lead to the minimal hardware overhead. In the following sections, we shall present our proposed techniques and corresponding experimental evaluations on two different FPGA technologies, which are, FPGA with static configuration and with PDR capability.

4.3.3 Proposed Techniques

We first formulate the design optimization problem using CLP, and then present our heuristic approaches that can be employed even on large designs. In order to make the system more flexible to be scheduled and analyzed, we explicitly represent the message E/D operations as independent tasks using the same method as in Section 4.2.3. Remind that now each computational node has both a microprocessor and an FPGA co-processor to use, where the message E/D tasks can both be allocated to. Figure 4.21 represents the updated application corresponding to the one in Figure 4.14. For example, the encryption operation of message m_1 is explicitly captured as ce_1 , and can be mapped to the microprocessor or an FPGA unit on computational node p_1 .

4.3.3.1 FPGAs with Static Configuration

CLP formulation The CLP formulation for the statically configured FPGAs shares two sets of constraints with the ones presented in Section 4.2.3.1, which are the dependency constraints and the schedulability constraint. So we only focus on the new sets of constraints

Figure 4.21: Reconstructed task graph of Figure 4.14

in this section. We denote an encryption or decryption task as ed_i to simplify the following discussions.

- Implementation constraints

The first set of constraints restricts that an E/D task can only be implemented once, either in software or in FPGA, i.e.,

$$sw_{ed_i} + \sum_{j=1}^U hw_{ed_i}^j = 1. \quad (4.4)$$

where, $sw_{ed_i}, hw_{ed_i}^j \in \{0, 1\}$. ed_i is implemented in software if $sw_{ed_i} = 1$, or on the j th FPGA unit of $\mathcal{F}(ed_i)$ if $hw_{ed_i}^j = 1$. U is a constant that indicates the size of available areas on the FPGA co-processor. For existing off-the-shelf platforms, U represents the actual available areas on a co-processor. For the design from scratch of a new system, U is set to a large number only for CLP implementation purposes.

- Execution time constraints

Similar to the execution time constraints presented in Section 4.2.3.1, the non-E/D tasks and messages have fixed ETs and TTs. While, the ETs of E/D tasks depend on their actual implementations, i.e., in software or FPGA, as follows:

$$ET(ed_i) = \begin{cases} w_{ED}^{\mu P} + r_{ED}^{\mu P} * x_i, & \text{if } sw_{ed_i} = 1, \\ w_{ED}^{FPGA} + r_{ED}^{FPGA} * x_i, & \text{otherwise.} \end{cases} \quad (4.5)$$

The values of $(w_{ED}^{\mu P}, r_{ED}^{\mu P})$ and $(w_{ED}^{FPGA}, r_{ED}^{FPGA})$ (refer to Equation 3.4) are the ET parameters of E/D tasks executed on processor and FPGA, respectively.

- Resource sharing constraints

The E/D tasks on the same computational node cannot share the same FPGA unit, if they are not of the same type. For example, if the j -th FPGA unit is occupied by the implementation of an encryption task with a certain IBC variant, then this unit may only be reused by the encryption tasks of the same IBC variant. This is formulated as

$$\forall p_i \in P \text{ and } \forall j \in \{1, \dots, U\},$$

$$\sum_{ce_s \in \{\text{All E on } p_i\}} hw_{ce_s}^j * \sum_{cd_t \in \{\text{All D on } p_i\}} hw_{cd_t}^j = 0. \quad (4.6)$$

However, this does not restrict that all the IBC variant of the same type should always share the same unit, since multiple FPGA implementations can be necessary when the deadline constraint is tight.

Optimization objective If a potential FPGA unit on p_i is assigned with at least one E/D task, the corresponding FPGA areas have to be added into the system or occupied on the existing FPGA areas. Therefore, the optimization objective is to find the minimal number FN of FPGA units that are needed, such that all constraints are satisfied. This can be represented as follows,

$$FN = \sum_{\forall p_i \in P} \sum_{j=1}^U N'_j, \quad (4.7)$$

where,

$$N'_j = \begin{cases} 0, & \text{if } \sum_{\forall ed_k \text{ on } p_i} hw_{ed_k}^j = 0 \\ 1, & \text{otherwise.} \end{cases}$$

Algorithm 3 Heuristic for FPGA with static configuration

```

1: while ( $sl = \text{ListScheduling}(S) > D$ ) do
2:   detect the tasks on the critical path of  $S$ 
3:    $best = \text{FindBestProc}(S)$ 
4:   if  $best \neq \text{null}$  then
5:     for each  $ed$  on  $best$  do
6:        $\text{MoveToFPGA}(ed)$ 
7:   else
8:     save the critical E/D tasks on FPGA into  $edList$ 
9:     if  $edList$  is empty then
10:      return  $S$  cannot satisfy the deadline
11:     sort  $edList$  in descending order of PCP length
12:     for each  $ed$  in  $edList$  do
13:       move  $ed$  back to the original  $\mu P$ 
14:       if ( $\text{ListScheduling}(S) \leq sl$ ) then
15:         break
16:       else
17:          $\text{MoveToFPGA}(ed)$  in SKIP mode
18:         if  $\text{ListScheduling}(S) < sl$  then
19:           break
20:         else
21:           move  $ed$  back to the previous FPGA
22:           release the FPGA if one was added in line 17

```

Heuristic Given the CLP formulation of a certain problem, a CLP solver will return the optimal solution that satisfies the constraints outlined above, if such a solution exists. Due to the complexity of solving CLP problems, we propose a heuristic alternative for handling large system designs that is divided into two parts, resource allocation and list scheduling [EPPD00]. The former controls the outer co-design problem of FPGA allocation and resource sharing. The latter tries to find a feasible system schedule. The pseudocode is shown in Algorithm 3.

We first detect the tasks on the critical path of the given system, S , i.e., a task graph with given mapping decisions, (line 2 of Algorithm

Figure 4.22: An example with 3 consecutive messages

3). Then $\text{FindBestProc}(S)$ returns the microprocessor carrying the most number of critical (on the critical path) software implemented encryption tasks (or decryption tasks) (line 3). If two microprocessors have the same number of critical encryption or decryption tasks, the one with the longest total partial critical path (PCP) length [EPPD00] of the critical tasks is chosen. After that, all encryption or decryption tasks on microprocessor *best* are moved to a new FPGA unit (line 5-6). As, in this case, an FPGA unit can only be configured for encryption or decryption tasks, the function $\text{MoveToFPGA}(ed)$ checks whether *ed* and each FPGA unit belong to the same computational node, and whether the unit is for the same type of IBC variant.

If there is no software implemented critical E/D task, the algorithm tries to find the critical E/Ds on FPGAs, and save them into a list *edList* (line 8). If *edList* is empty, it means that no E/D task is left on the critical path. Hence, the application cannot be further accelerated by hardware implementation of E/D tasks, and, thus, the heuristic is terminated. Otherwise, we sort *edList* in descending order of their PCP lengths, and try to allocate each E/D task $ed \in edList$ in an appropriate implementation (line 11-22). Figure 4.22 is an illustrative example for this.

Assuming that the task graph in Figure 4.22 (a) is part of a bigger system. The ET of τ_t is 100 time units, and TT of the messages is 10

time units. The (w_{ED_i}, r_{ED_i}) values of software and FPGA implemented E/D tasks are assumed to be (4, 10) and (2, 4), respectively. The messages m_i, m_j and m_k are received at time 490, 500 and 510, respectively. Let us consider the following scenario. In order for the system to meet the global deadline, τ_t must finish its execution before 700 time units. Currently, all the three decryption tasks cd_i , cd_j and cd_k are on the PCP, and are allocated on the same FPGA unit leading to the schedule in Figure 4.22 (b). As can be noticed, τ_t finishes at time 716, which means that the global deadline will be violated. The algorithm tries to move cd_i back to the μP that it originally belongs to. This will lead to an end-to-end delay shorter than the previous case, so the algorithm keeps the current system setting, and breaks from the inner loop (line 13-15). The schedule can be found in Figure 4.22 (c).

In another case, if τ_t must finish before 680 time units, reallocating cd_i back to the original microprocessor will not give a schedulable solution, so the algorithm tries to allocate the next task cd_j in *edList* on an FPGA unit that it was not be mapped to before (line 17), e.g., a new FPGA unit possibly or another existing FPGA unit on the same computational node that is free for cd_j . This leads to the schedule in Figure 4.22 (d). Then, the algorithm breaks from the inner loop (line 19). Otherwise, it moves cd_j back to the FPGA unit which it was mapped to previously, and release the FPGA unit if a new one was occupied or added into the system (line 21-22). The algorithm continues until the system can be scheduled within the global deadline, and returns the final solution. Or, it terminates when *edList* is empty, which means that the system cannot satisfy the deadline constraint while achieving the designated confidentiality protection.

We have two settings that help avoid deadlocks. Each E/D task has a history list keeping track of the FPGAs that it had been implemented on. If it needs to be moved to FPGA in *SKIP* mode (line 17), it avoids being moved to an FPGA unit in its history list. And we ignore the E/D tasks that have been moved too many times, and keep them in the microprocessor or FPGA unit where it appears the most times. The length of the history list and value of maximal moves can

be tuned for each problem size to reach the best optimization results.

4.3.3.2 Partial Dynamic Reconfiguration

PDR enabled FPGAs allow reconfiguring a portion of the FPGA areas, while the other parts remain functional. In this case, different types of operations, i.e. encryption and decryption tasks, can share the same FPGA unit, if there is enough time for reconfiguration in between. The PDR capability increases the flexibility of resource sharing, thereby reducing the hardware overhead.

CLP formulation The CLP formulation for the PDR enabled FPGAs is similar with the previous case, so we only focus on the ones that differ, namely, the resource sharing and reconfiguration constraints. The E/D tasks can be implemented on the same FPGA unit, which needs to be reconfigured if a task is of different kind with the previous one. We define a new kind of tasks, called the PDR tasks, to capture the reconfiguration procedures of the FPGAs. The ET of the PDR tasks can be 0 or $\mathcal{E}^{PDR}$. That is, a PDR task is a virtual task if its ET is 0, or a valid task otherwise with a constant execution time $\mathcal{E}^{PDR}$ given by the designer that reflects the partial dynamic reconfiguration overhead for an E/D module.

- Partial dynamic reconfiguration:

The FPGA units must be reconfigured on the fly to support resource sharing between encryption and decryption operations. These constraints can be formulated as follows.

$$\begin{aligned}
& \forall p_i \in P \text{ and } \forall fp_j \in \{\text{all potential FPGA units on } p_i\}, \\
& \forall ed_s \in \{\text{all E/D tasks on } p_i\}, \\
& ed_t \text{ is the previous task of } ed_s \text{ and } hw_{ed_t}^{fp_j} = 1, \\
& ET(\tau_{ed_s}^{fp_j}) = \begin{cases} 0, & \text{if } \begin{cases} hw_{ed_s}^{fp_j} = 0 \\ hw_{ed_s}^{fp_j} = 1 \text{ and } E(ed_s) = E(ed_t) \end{cases} \\ \mathcal{E}^{PDR}, & \text{if } hw_{ed_s}^{fp_j} = 1 \text{ and } E(ed_s) \neq E(ed_t) \end{cases}
\end{aligned} \tag{4.8}$$

where, $\tau_{ed_s}^{fp_j}$ is the PDR task for ed_s on potential FPGA unit fp_j , and

$$E(ed_s) = \begin{cases} 0, & \text{if } ed_s \text{ is an encryption task} \\ 1, & \text{if } ed_s \text{ is a decryption task.} \end{cases}$$

- PDR dependencies:

The executions of E/D tasks and PDR tasks on the same FPGA unit cannot overlap with each other. An E/D task can only start its execution after the module has been successfully reconfigured for its use, which is already captured by dependency constraints.

Optimization objective The objective is to minimize the total number of FPGA units that need be added into the system for new designs or to be occupied on existing systems, as mentioned in the previous static configuration approach (refer to Equation 4.7).

Heuristic The structure of our proposed heuristic for PDR enabled FPGAs is similar to that of Algorithm 3. We also guide the resource distribution by analyzing the E/D tasks on the critical path. But when looking for the microprocessor *best* (line 3), the algorithm counts the number of critical E/D tasks of both encryption and decryption, since they can share the same FPGA unit via dynamic re-configurations. If an E/D task ed needs to be moved to FPGA (the $\text{MoveToFPGA}(ed)$ function), the algorithm only checks whether ed

and each FPGA unit belong to the same computational node. In addition, we insert a set of new tasks capturing the reconfiguration operations when we schedule the application. In order to avoid deadlocks, the ideas of maximal moves and history lists are adopted from Section 4.3.3.1. To avoid repetitions, we shall skip the details of the algorithm.

4.3.4 Experimental Results

We have performed experiments on six sets of applications having 10, 15, 20, 40, 80 and 120 tasks (excluding E/D tasks) that are mapped to 2, 3, 4, 7, 10 and 15 processors respectively. All experiments were performed on a Linux machine having a quad-core Intel Xeon CPU with 2.66GHz frequency and 8GB RAM. In the experiments, we set the (w_{ED}, r_{ED}) values for software and FPGA as (4, 10) and (2, 4), respectively. The messages are assumed to have the same confidentiality requirement, that is AES-128 version with 10 rounds. We modified the automatic CLP code generator mentioned in Section 4.2.4 to obtain correct CLP formulations with the new properties specified in the previous sections. The formulated CLP problems were solved by the *ECLiPSe* constraint programming system [AW06], and were carried out with a timeout setup of 1800 seconds.

4.3.4.1 FPGA with Static Configuration

Due to the fact that solving the CLP problems does not scale even for middle-sized systems, we also compare our heuristic with a greedy straight-forward approach. This approach repeatedly assigns a new FPGA unit to take over the E/D tasks from the microprocessor that currently has the most number of E/D tasks. It terminates when the system can be scheduled within the deadline, and returns the solution. Otherwise, it terminates when there is no software implemented E/D task left, which means that the system cannot be protected with the designated requirements, while satisfying the timing constraints, using this greedy approach.

For each set of applications, we have performed experiments on 20 individual applications that have the same number of application

Figure 4.23: Optimization time with statically configured FPGA

Figure 4.24: Results with statically configured FPGA (1)

Figure 4.25: Results with statically configured FPGA (2)

tasks and similar amount of bus communications. The average optimization times of CLP, our heuristic and the greedy approach are presented in Figure 4.23, in which the y -axis is in logarithmic scale. For the times of CLP, we only considered those experiments which terminated before the timeout (for example, in the case of application size 20, only 5 out of 20 CLP runs finished before the timeout). Starting from size 40, no CLP experiment could find the optimal solution within the timeout restriction.

When comparing the results obtained by two different approaches, we calculate the average additional hardware expenditure (AAHE) of one approach over the other. This is formulated as

$$AAHE = \frac{1}{n} \left(\sum_{\forall i \in n} \frac{FN'_i - FN_i}{FN_i} \right) * 100\% \quad (4.9)$$

where, FN_i and FN'_i are the obtained results (refer to Equation 4.7) with the two approaches for the same application, and n is the number of valid experiments, i.e., in which both approaches found solutions. Figure 4.24 presents the AAHE of our proposed heuristic over CLP and of the greedy approach over CLP for problem sizes of 10, 15, and 20, in which at least some of the CLP formulations were solved. As can be observed, our heuristic approach provides very close results to the optimums. For example, on the largest application size, 20, where *ECLiPSe* managed to solve some experiments, our heuristic only requires about 11% extra FPGA units compared to the optimal solutions. Figure 4.25 depicts the AAHE of the greedy approach over our proposed heuristic on all application sizes. We can notice that our heuristic approach saves significant amount of FPGA units compared with the greedy method.

4.3.4.2 Partial Dynamic Reconfiguration

We have conducted the same set of experiments as those in static configuration considering FPGAs with PDR capability. The optimization comparison of the CLP and heuristic approach can be found in Figure 4.26. Starting from application size 40, no execution time is presented for the CLP formulation, since none of the experiments finished within the timeout limit.

Figure 4.26: Optimization time with PDR enabled FPGA

Figure 4.27: Results with PDR enabled FPGA (1)

Figure 4.28: Results with PDR enabled FPGA (2)

We use the same analytical method (Equation 4.9) as before to compare the quality of results. In Figure 4.27, we compare the optimal solutions obtained by CLP with the results returned by our heuristic approaches for both FPGA techniques. The experiments that CLP failed to find the optimum within the timeout setup are ignored. The hardware savings using PDR enabled FPGA over static configured FPGA for all application sizes are illustrated in Figure 4.28. It can be observed that our heuristic performs well comparing with the optimal results obtained from CLP, and achieves large FPGA unit savings (33% on average over all problem sizes) if PDR-enabled FPGAs are used in the system.

4.4 Summary

In this chapter, we have presented our optimization techniques for protecting the confidentiality of internal communication using iterated block ciphers for distributed real-time embedded systems. We investigated two design problems with respect to two different architecture configurations, one with microprocessor only and the other with also FPGA co-processors. We first formulated the problems in CLP, and then proposed heuristic alternatives for solving the problems more efficiently both in terms of time and result quality.

The presented techniques can be either applied as a security patch on the off-the-shelf distributed RTEs, or employed in the early design phase of any new systems where the internal communication confidentiality is required.

Chapter 5

Design of Secure Multi-Mode Embedded Systems

THIS chapter addresses the design challenges of secure multi-mode embedded systems. While considering real-time and quality of service requirements, we also study the emerging security and power efficiency demands. Modern RTEs very often are not developed for a fixed single purpose, but instead designed for undertaking various processing requests. This leads to the concept of multi-mode RTEs, in which the number and nature of active tasks change during run-time. Under dynamic situations, providing high performance along with various design concerns becomes a really difficult problem. We present our design optimization techniques that enhance *quality of service* under *timing*, *security*, and *energy* constraints. Due to the complexity of exactly solving this problem, we propose an efficient heuristic-based technique that generates near optimal solutions.

The rest of this chapter is organized as follows. Section 5.1 highlights the hardware and application model used in this chapter. Section 5.2 outlines the design objectives we face in each mode. Section 5.3 presents an illustrative example as a motivation. Section 5.4 formulates the overall design optimization problem. The proposed techniques are elaborated in Section 5.5. The experimental evalua-

Figure 5.1: An illustrative multi-mode system

tions and a real-life case study are presented in Section 5.6 and 5.7, respectively. Section 5.8 summarizes the whole chapter.

5.1 System Model

5.1.1 Hardware Model

We consider a uniprocessor platform based on a DVFS-enabled embedded processor which handles all computations (Figure 5.1). As discussed in Section 3.1.2, the supply voltage (and implicitly the frequency) of the processor can be selected at run-time from a discrete set, depending on concrete operational requirements. If the real-time constraints are tight, the voltage (and frequency) could be increased in order to finish task executions earlier. If, on the contrary, the available energy in the system is limited, the voltage (and frequency) could be reduced in order to lower the power consumption.

The system has a communication module, via which it interacts, by wire or wirelessly, with other peers or service centers, and an on-board memory, that can be used to store pre-defined system configurations. In this chapter, a system configuration contains the resource allocation decisions, cipher variant selections for message E/Ds, period assignment for the intrusion detection (ID) task, and voltage/frequency decisions for all tasks for a certain mode. We shall detail these aspects in the following sections.

5.1.2 Application Model

5.1.2.1 Task Model

At any moment in time on the system, there is a set of active tasks representing the current mode M of the system. In this chapter, we consider the imprecise computation model for tasks [LSL⁺94]. That is, the tasks must deliver timely results and provide a minimal given quality of service. If longer execution time is available, better quality results can be produced. For example, an image processing task can deliver more accurate output if longer execution time is affordable. The tasks are preemptive and periodic. We assume that task executions are independent (i.e., without any precedence constraints or data dependencies).

Formally, a task $\tau_i \in \mathcal{T}$ is composed of a mandatory and an optional execution, and is associated with a set of design attributes denoted as $(\mathcal{E}_i^m, \mathcal{E}_i^o, \mathcal{P}_i, \mathcal{D}_i, \mathcal{L}_i, C_{eff_i}, \mathcal{Q}_i^m, \mathcal{F}_i)$. $\mathcal{E}_i^m$ is the execution time (ET) of the mandatory part. $\mathcal{E}_i^o$ is the maximal amount of time for the optional execution, i.e., the actual additional execution time $c_i^o \in [0, \mathcal{E}_i^o]$. Both $\mathcal{E}_i^m$ and $\mathcal{E}_i^o$ are nominal ETs, that is, they are obtained with respect to the highest available processor frequency f^{max} . Thus, the actual ET of τ_i at frequency f_i can be calculated as

$$c_i(f_i) = \frac{(\mathcal{E}_i^m + c_i^o) \cdot f^{max}}{f_i}. \quad (5.1)$$

$\mathcal{P}_i$ is the release period of τ_i , and $\mathcal{D}_i$ is its relative deadline ($\mathcal{D}_i \leq \mathcal{P}_i$). The attribute $\mathcal{L}_i$ is the set of messages associated with task τ_i . Each message $m_{ij} \in \mathcal{L}_i$ is associated with a length l_{ij} (in number of blocks of the chosen IBC), i.e.,

$$l_{ij} = \lceil \frac{m_{ij} \text{ length in bits}}{\text{block length in bits}} \rceil,$$

a weight w_{ij} representing its relative importance, and a minimal quality of confidentiality (QoC) requirement, QoC_{ij}^{min} . C_{eff_i} is the effective switching capacitance of task τ_i reflecting its power hungriness (refer to Equation 3.1). $\mathcal{Q}_i^m$ is the constant quality of service (QoS) value produced by the mandatory execution of τ_i . $\mathcal{F}_i$ is the

Figure 5.2: The Hasse diagram of modes for Figure 5.1

reward function that will be introduced in Section 5.2.1, expressing the amount of additional QoS produced by the extra execution c_i^o of the optional part.

5.1.2.2 Execution Modes

All the tasks that might occur in the system are given as a set $\mathcal{T} = \{\tau_1, \tau_2, \dots, \tau_n\}$. At different points of time, the set of active tasks can be different and is dynamically changing at run-time. The currently active set of tasks defines the current *mode* $M \subseteq \mathcal{T}$. When new tasks come or existing tasks terminate, the system switches to a new mode. The complete set of modes for a given system is the power set of $\mathcal{T}$, denoted with $\mathcal{M}$, having cardinality $|\mathcal{M}| = 2^{|\mathcal{T}|}$. However, certain modes can be excluded due to functionality constraints. In the rest of the chapter, we are interested only in the modes that can occur at run-time, and we shall refer to them as the *functional* modes $\mathcal{M}^{func} \subseteq \mathcal{M}$.

Mode $M \in \mathcal{M}$ is called a *supermode* of $M' \in \mathcal{M}$, if $M' \subset M$. Similarly, M' is called a *submode* of M . The sets of all supermodes

and submodes of M are denoted with $\overline{\mathcal{M}}(M)$ and $\underline{\mathcal{M}}(M)$, respectively. The mode containing all the tasks in $\mathcal{T}$ is referred to as the *root* mode. Functional modes that do not have any functional supermodes are called *top functional* modes, denoted by $\mathcal{M}_\uparrow^{func}$. Let us consider the example system in Figure 5.1. Four application tasks may occur in the system, i.e., τ_1, τ_2, τ_3 , and τ_4 . The corresponding partial order capturing the relations of all potential modes is depicted in Figure 5.2 as a Hasse diagram. The functionally excluded modes, e.g., $M^{124} = \{\tau_1, \tau_2, \tau_4\}$, $M^{14} = \{\tau_1, \tau_4\}$, $M^{24} = \{\tau_2, \tau_4\}$, and $M^3 = \{\tau_3\}$, are marked out with a cross. The only top functional mode is $\mathcal{M}_\uparrow^{func} = \{\tau_1, \tau_2, \tau_3, \tau_4\}$, which is also the root mode.

5.1.3 Scheduling Model

We assume that the system is scheduled according to the earliest deadline first policy (EDF). Thus, whether the system is schedulable can be verified by a processor utilization test with task deadlines. First, the load caused by the execution of τ_i , together with the potential E/D tasks on its communication messages, with respect to its deadline, is

$$U_i(f_i) = \frac{c_i(f_i)}{\mathcal{D}_i} + \sum_{m_{ij} \in \mathcal{L}_i} \frac{c_{ij}^{ED}(f_i)}{\mathcal{D}_i}, \quad (5.2)$$

where $c_{ij}^{ED}(f_i)$ is the E/D time (at the given processor frequency f_i) for message m_{ij} using the chosen cipher variant C_{ij} , i.e.,

$$c_{ij}^{ED}(f_i) = \frac{l_{ij} \cdot c_{C_{ij}} \cdot f^{max}}{f_i}.$$

The variable $c_{C_{ij}}$ is the corresponding ET (measured at the highest processor frequency f^{max}) of the selected IBC variant C_{ij} for encrypting/decrypting one block of message m_{ij} , and l_{ij} is the length of message m_{ij} in number of blocks.

Now we can test the system schedulability: a set of tasks is schedulable by EDF if and only if the total processor utilization with respect to deadlines is not more than 100%. The utilization $U_i(f_i)$ of a task τ_i at a certain processor frequency f_i was defined in Equation 5.2.

Thereby, the schedulability of a certain configuration for mode M can be examined by the following condition:

$$U_M = \sum_{\tau_i \in M} U_i(f_i) + U_{ID} \leq 1. \quad (5.3)$$

The variable U_{ID} is the utilization of the intrusion detection task, which we shall elaborate in Section 5.2.3.

5.2 Design Objectives

In this section, we shall introduce the design objectives of this chapter. Our ultimate design goal is that, no matter which mode and what constraints the system is running under, an efficient operation solution will be produced with respect to the four aspects described in the following subsections.

5.2.1 Quality of Service

The demands of delivering high quality of service (QoS) are increasing in RTES designs. QoS is usually associated with the pleasantness of user experience, e.g., the quality of cell phone conversation, or accuracy of control performance, e.g., fuel injection decision to the car engine. Throughout this thesis, the computational requests are modeled as tasks. There exists different QoS models of task executions. In this chapter, we consider the imprecise computation model [LSL⁺94] where the delivered QoS of a task is given as a function of its actual execution time, which can be composed of two parts. The first part is mandatory to be executed, if τ_i is released. This part has a fixed execution efforts $\mathcal{E}_i^m$ from which the actual execution time can be calculated based on concrete processor frequencies. The second part is optional with a variable execution efforts c_i^o that is in the range $[0, \mathcal{E}_i^o]$. The upper bound of execution $\mathcal{E}_i^o$ can be 0, indicating that there is no additional execution associated with τ_i . Similarly, the actual execution time of the optional part at a given frequency can also be derived correspondingly from c_i^o .

The mandatory part delivers a constant QoS value, Q_i^m , that task τ_i delivers minimally. The optional part leads to additional QoS depending on the actual extra execution time, c_i^o , allocated. We would like to emphasize that only the first, mandatory, part is obligatory for each task. Thus, some tasks may not have any optional part, which means that the quality of service produced by these tasks, at each activation, will be Q_i^m . For the other tasks with optional parts, the more execution is performed, the higher QoS the task produces. Then the QoS value produced by τ_i as a whole is as follows,

$$QoS_i = Q_i^m + \mathcal{F}_i(c_i^o), \quad (5.4)$$

where $\mathcal{F}_i$ is the non-decreasing reward function of task τ_i . Thereby, the total QoS delivered by the system in mode M is calculated as

$$QoS_M = \sum_{\tau_i \in M} QoS_i. \quad (5.5)$$

5.2.2 Quality of Confidentiality

Let us denote the j -th message generated by task τ_i as m_{ij} . In this chapter, we shall assume the use of RC6 (refer to Section 3.2.1.1) due to its wide range of strength/overhead trade-off. Assuming that the RC6 variant applied on m_{ij} is C_{ij} , then the quality of confidentiality (QoC) protection for m_{ij} is quantified as

$$QoC_{ij} = \frac{e^{\text{Strength}(C_{ij})/MAX} - 1}{e - 1}, \quad (5.6)$$

where, MAX is the highest protection strength value required in the system, e.g. 118 delivered by RC6-16 in Table 3.1. The set of all messages over which task τ_i interacts with the environment is captured in $\mathcal{L}_i$. The weight representing the relative importance of message m_{ij} is denoted as w_{ij} . Now we can define the QoC delivered by the system in a mode M as follows,

$$QoC_M = \frac{\sum_{\tau_i \in M} \sum_{m_{ij} \in \mathcal{L}_i} QoC_{ij} \cdot w_{ij}}{\sum_{\tau_i \in M} \sum_{m_{ij} \in \mathcal{L}_i} w_{ij}}. \quad (5.7)$$

When the system is switching into another mode and the IBC selection for a message is to be changed, the system will send out an

encrypted notification message to the corresponding communication peer to notify the update. This is carried out only when the requirement changes and the IBC selection is also changed. The extra time overhead of generating and transmitting the notification messages is very small compared to the overall computation and communication load due to normal functionality. Therefore, we did not explicitly model this process.

5.2.3 Intrusion Detection Accuracy

Another design objective is to maximize the intrusion detection accuracy. As described in Section 3.2.2, we quantify the accuracy as $IDA = \frac{\mathcal{P}_{ID}^{min}}{\mathcal{P}_{ID}}$ (Equation 3.11). The ID task has two associated parameters, i.e., a constant ET, $\mathcal{E}_{ID}$, and the minimal required release interval $\mathcal{P}_{ID}^{min}$, namely the minimal period, that ID task executes with, in order to achieve the highest detection accuracy. The actual execution time of the ID task is then

$$c_{ID}(f_{ID}) = \frac{\mathcal{E}_{ID} \cdot f_{ID}^{max}}{f_{ID}}, \quad (5.8)$$

where f_{ID} is the assigned frequency to the ID task. We assume $\mathcal{D}_{ID} = \mathcal{P}_{ID}$ (the deadline is equal with its current period). Then, we can calculate the processor utilization of the ID task as follows,

$$U_{ID} = \frac{c_{ID}(f_{ID})}{\mathcal{P}_{ID}}. \quad (5.9)$$

5.2.4 Average Power Consumption

The last design goal is to reduce the overall average power consumption (APC) of the system for the mode. Knowing all the components of microprocessor power consumption (see Section 3.1.2), we can calculate its average power consumption by considering the utilization of all the tasks, since the dynamic power is consumed only when a task is actively running on the processor. The dynamic power consumption caused by execution of task τ_i is as follows,

$$Pow_i^{Dyn} = C_{eff_i} V_{ddi}^2 f_i. \quad (5.10)$$

Correspondingly, we have the dynamic power consumption of the ID task as follows,

$$Pow_{ID}^{Dyn} = C_{effID} V_{ddID}^2 f_{ID}. \quad (5.11)$$

The power consumed by the E/D operations on τ_i related communication messages is then

$$Pow_{\mathcal{L}_i}^{Dyn} = C_{effED} V_{ddi}^2 f_i. \quad (5.12)$$

C_{effED} is the switching capacitance of the chosen IBC algorithm on the target processor. The E/D operations share the same voltage and frequency with τ_i . All the three power consumptions above only occur when the corresponding tasks are actively running on the processor. Now we can calculate the contribution of task τ_i to the APC in mode M as

$$\begin{aligned} Pow_i &= Pow_i^{Dyn} \cdot \frac{c_i(f_i)}{\mathcal{P}_i} + Pow_{\mathcal{L}_i}^{Dyn} \cdot \sum_{m_{ij} \in \mathcal{L}_i} \frac{c_{ij}^{ED}(f_i)}{\mathcal{P}_i} \\ &= V_{ddi}^2 \cdot (C_{effi} \cdot \frac{(\mathcal{E}_i^m + c_i^o) \cdot f_i^{max}}{\mathcal{P}_i} + \sum_{m_{ij} \in \mathcal{L}_i} C_{effED} \cdot \frac{l_{ij} \cdot c_{C_{ij}} \cdot f_i^{max}}{\mathcal{P}_i}). \end{aligned} \quad (5.13)$$

Similarly, we have the contribution of the ID task as follows,

$$\begin{aligned} Pow_{ID} &= C_{effID} V_{ddID}^2 f_{ID} \cdot \frac{c_{ID}(f_{ID})}{\mathcal{P}_{ID}} \\ &= V_{ddID}^2 \cdot C_{effID} \cdot \frac{\mathcal{E}_{ID} \cdot f_{ID}^{max}}{\mathcal{P}_{ID}}. \end{aligned} \quad (5.14)$$

Now we can calculate the APC of the processor in a certain mode M as follows,

$$\begin{aligned} Pow_M &= Pow^{Stat} + Pow^{On} + Pow^{Dyn} \\ &= Pow^{Stat} + Pow^{On} + Pow_{ID} + \sum_{\tau_i \in M} Pow_i. \end{aligned} \quad (5.15)$$

As can be observed from Equation 5.13, Equation 5.14, and Equation 5.15, for a given resource allocation decision (task additional execution times, cipher selection decisions, and ID task period assignment), an effective way to reduce the system average power consumption is to reduce the supply voltages V_{dd} during execution of the

Table 5.1: Task attributes for Figure 5.1

Task	$\mathcal{E}^m$	$\mathcal{E}^o$	$\mathcal{P} = \mathcal{D}$	$\mathcal{L}$	C_{eff}	$\mathcal{Q}^m$	α	β	γ
τ_1	300	400	1500	$\{m_{11}\}$	8	4	0.008	0.1	0.08
τ_2	400	600	2300	$\emptyset$	5	5	0.016	0.13	0.09
τ_3	600	300	2500	$\{m_{31}\}$	9	7	0.009	0.9	0.17
τ_4	500	700	2000	$\{m_{41}\}$	6	4	0.011	0.08	0.12

tasks, using the dynamic voltage and frequency scaling (DVFS) technique. Recent works [PPS⁺13, HMGM13, LPD⁺14] have shown that, for modern microprocessors, the switching between voltages (and frequencies) is performed very efficiently with overheads at the scale of μs (time) and μJ (energy). Such overheads are negligible compared with the duration and energy consumption of the actual applications. Therefore, we ignore the overhead due to switching between voltages, and focus on the overall power consumption of the application.

5.3 Motivational Example

Now let us consider the system illustrated in Figure 5.1 with given task parameters in Table 5.1. The reward functions of all tasks are set to have the form $QoS_i = \mathcal{Q}_i^m + \alpha \cdot c_i^o + \beta \cdot \sqrt{c_i^o} + \gamma \cdot \sqrt[3]{c_i^o}$. Each task is associated with at most one message for illustration purposes. The length and importance weights (l, w) of messages m_{11} , m_{31} , and m_{41} are $(2, 0.7)$, $(3, 0.3)$, and $(1, 0.4)$, respectively. The processor supports 7 discrete supply voltage levels that are 1.2V, 1.3V, ..., 1.8V. Note that the value of the nominal task execution times are given according to the highest supply voltage $Vdd^{max} = 1.8V$, i.e., the highest frequency $f^{max} = 777$ MHz, thus, are the shortest time values. We assume that the ID task takes 400 time units to finish a detection procedure at f^{max} , and delivers the best protection with period $\mathcal{P}_{ID}^{min} = 1500$ time units (refer to Section 5.2.3).

Let us look at the case when the system is going to switch to mode $M^{134} = \{\tau_1, \tau_3, \tau_4\}$, in which task τ_2 is not active. With the

given attributes in Table 5.1, we can calculate the smallest processor utilization, that is, when the system only carries out the mandatory parts of τ_1, τ_3, τ_4 , and does not pursue any security protections or extra QoS. We can find that, if the processor runs at the highest frequency, the utilization is $U = \mathcal{E}_1^m / \mathcal{P}_1 + \mathcal{E}_3^m / \mathcal{P}_3 + \mathcal{E}_4^m / \mathcal{P}_4 = 0.69$. This indicates that the processor is underutilized if all the tasks are executed at $Vdd = 1.8V$. Therefore, in order to improve the power efficiency of the system, we can lower the processor supply voltage until the system schedulability cannot be guaranteed any longer. If all tasks share the same voltage level, then the lowest voltage that the system can operate at correctly with executing only the mandatory parts of the tasks is $Vdd = 1.4V$ ($f = 554$ MHz). However, this is not the most power efficient solution ($Pow_{M^{134}} = 0.93W$). If we assign $1.4V$, $1.3V$, and $1.5V$ to τ_1 , τ_3 , and τ_4 , respectively, then we can reach the lowest power consumption of $Pow'_{M^{134}} = 0.92W$, which is the optimal power for mode M^{134} under the current setting. Note that the system provides minimal QoS, and does not carry out any security protections with this configuration.

If we want to maximize the delivered QoS, we would like to provide the maximal execution time to the optional parts, i.e., $c_1^o = 400$, $c_3^o = 300$, and $c_4^o = 700$. However, this cannot lead to a feasible solution even if we set the supply voltage to the maximal value $Vdd = 1.8V$ for all the three tasks. In fact, the highest achievable QoS ($QoS_M = 41.51$) can be obtained by having $c_1^o = 30.15$, $c_3^o = 300$, and $c_4^o = 339.46$. And the supply voltages are all set to $Vdd = 1.8V$ to ensure system schedulability. Consequently, the system power consumption is $Pow_{M^{134}} = 2.06W$. However, there is absolutely no security protection in this case, since the extra computation efforts are all dedicated to improve the QoS performance, and no message E/D or ID operation is performed.

Alternatively, we can protect the system communication, namely the messages m_{11} , m_{31} , and m_{41} , with the highest confidentiality protection ($QoS_M = 1$), that is to encrypt them with the strongest cipher variant available, e.g., as RC6-16 from Table 3.1. Thereby, we need to devote 140, 210, and 70 time units (at $Vdd = 1.8V$) on encrypting m_{11} , m_{31} , and m_{41} , respectively. Consequently, we have

the power consumption of $Pow_{M^{134}} = 2.07W$. In fact, the condition $QoC_M = 1$ can be reached with the optimal power efficiency by setting $Vdd_1 = 1.7V$, $Vdd_3 = 1.8V$, and $Vdd_4 = 1.6V$ that lead to $Pow_{M^{134}} = 1.89W$. In the same way, the highest ID level ($IDA = 1$) can also be independently optimized, i.e., to carry out the ID task with period $\mathcal{P}_{ID} = \mathcal{P}_{ID}^{min} = 1500$. To this end, the most power efficient solution can be reached by assigning $Vdd_1 = 1.8V$, $Vdd_3 = 1.6V$, $Vdd_4 = 1.8V$, and $Vdd_{ID} = 1.8V$, which give $Pow_{M^{134}} = 1.84W$.

The four design scenarios outlined above (to independently minimize system power consumption, or maximize QoS, QoC, or IDA) represent cases in which the system either only undertakes the mandatory computations or ignores extra QoS or other security demands. In practice, none of these extreme corner cases may be attractive. Instead, the designer may prefer to achieve a reasonable balance among the four objectives, which makes the underlying design problem for each mode M a multi-objective optimization problem along these four dimensions. The solutions to this problem can be captured in a 4D space having infinite amount of points. However, due to the time and memory limitations, we cannot afford to find and store all the optimal points. Thereby, in the rest of this chapter, we refer to a subset of finite near-optimal points from the solution space as the *Pareto Space* S_M of mode M . In other words, S_M represents the set of solutions that we find and store in memory. The points on S_M cannot dominate each other, that is, be better in all design dimensions, and are considered to be equally good but with different emphasizes.

A solution $s \in S_M$ consists of the resource allocation decisions (processor bandwidth and voltage selections) for the four objectives, i.e., a certain delivered QoS (as result of the allocated optional execution time to application tasks), QoC (as result of the cipher variant assignments), IDA (as result of the chosen period of the ID task), and APC (as result of the allocated processor bandwidth and voltages to the tasks). For example, the Pareto space for mode M^{134} is depicted in Figure 5.3. For illustration purposes, we try to plot the 4D Pareto space within a 3D dimension. Thereby, we denote the fourth design objective, i.e., the average power consumption, using the color-map shown on the right side of the plot. If a point is more towards the

Figure 5.3: Pareto space of mode M^{134}

red (or blue), then it implies higher (or lower) power consumption. The solutions to the four aforementioned corner cases are highlighted with squares.

Let us assume that, during run-time, the points shown in the Pareto space in Figure 5.3 are stored in memory, and the system switches to mode M^{134} . The question at this moment is how to distribute the processor bandwidth among execution demands, e.g., how much to provide to security services and at which voltage level to run the tasks. Based on the actual system status and external threat level, the security monitor or remote control center determines the security requirement levels as QoC^R and IDA^R for confidentiality and intrusion detection, respectively. The system power manager retrieves the current battery information, and sets the maximal power budget Pow^R . With the constraints QoC^R , IDA^R , and Pow^R , the run-time manager can look for an operation point from the Pareto space that satisfies all constraints, and produces the highest QoS. This procedure is performed every time the system is entering a new mode, or any of

Figure 5.4: Derived solution space for mode M^{13} from M^{123}

Figure 5.5: Derived solution space for mode M^{13} from M^{134}

Figure 5.6: Derived solution space for mode M^{13} from M^{1234}

the system states (e.g., security threats and battery status) change. For example, if the current constraints are $QoC^R = 0.7$, $IDA^R = 0.5$, and $Pow^R = 2.2W$, the run-time manager can choose the resource allocation decision specified by the point (18.8, 0.71, 0.52, 2.19) (marked with a triangle in Figure 5.3). In fact, $QoS = 18.8$ is the highest value that can be achieved under the given constraints (security, power, and schedulability). The system configurations for this operation point are as follows, $c_1^o = 3$, $c_3^o = 8.15$, $c_4^o = 6.67$, $C_{11} = \text{RC6-12}$, $C_{31} = \text{RC6-12}$, $C_{41} = \text{RC6-12}$, $\mathcal{P}_{ID} = 2881.28$, $Vdd_1 = 1.8$, $Vdd_3 = 1.8$, $Vdd_4 = 1.8$, and $Vdd_{ID} = 1.8$.

If all functional modes have their corresponding Pareto spaces stored in memory, then the above procedure can be repeated when new modes are entered or system states are changed, and allows determining the best operation points based on the current situation, on-the-fly. However, this is only the ideal case, and there are several reasons why this is not possible:

- The number of functional modes to be processed grows exponentially with the increasing number of tasks $|\mathcal{T}|$. Thus, it can be impossible, even at design-time, to explore all functional modes and generate the Pareto spaces accordingly for large systems.
- Solving the multi-objective optimization problem identified earlier in this chapter is of exponential complexity.
- The size of available memory on the target system is limited, thus restricting the number of Pareto spaces that can be stored.

Thus, we can only afford to explore and save a limited amount of Pareto spaces for selected modes. Hence, the next question is, when the system enters a mode which has no Pareto space pre-stored, how a good operation point can be quickly identified. In this chapter, we propose an efficient on-line method that extrapolates an operation point from the available pre-stored spaces.

Let us consider the scenario that the system currently runs in mode M^{134} , and must switch to mode M^{13} for which no Pareto space is pre-stored. In this case, the system tries to make use of the available Pareto spaces of its supermodes in order to find a good operation

point for M^{13} . In this example, we assume that the Pareto spaces of modes M^{123} , M^{134} , and M^{1234} are available in memory. What is needed is to derive an approximation of the Pareto space for the mode M^{13} as a starting point, from the available Pareto spaces of its supermodes. Since all supermodes in $\overline{\mathcal{M}}(M^{13})$ contain task τ_1 and τ_3 together with other tasks, the system can derive a solution space from the Pareto spaces of $\overline{\mathcal{M}}(M^{13})$ by ignoring the utilization due to the non-existing tasks $M^{123} \setminus M^{13} = \{\tau_2\}$, $M^{134} \setminus M^{13} = \{\tau_4\}$, and $M^{1234} \setminus M^{13} = \{\tau_2, \tau_4\}$.

Figure 5.4, 5.5, and 5.6 depict the derived spaces for M^{13} from its supermodes M^{123} , M^{134} , and M^{1234} , that are denoted as S_{13}^{123} , S_{13}^{134} , and S_{13}^{1234} , respectively. The next step is to look for a good operation point from the derived spaces for M^{13} based on concrete operational requirements. Assuming that the current constraints are $QoC^R = 0.5$, $IDA^R = 0.4$, and $Pow^R = 2$, then we can look for the most promising operation point, i.e., that meets all the constraints and delivers the highest QoS value, directly from the derived spaces. In this case, we come to an operation point $s = (25.64, 0.52, 0.41, 1.57)$ on the derived spaces S_{13}^{123} (as marked in Figure 5.4 with a triangle). The corresponding system parameters are set as $c_1^o = 0.48$, $c_3^o = 176.74$, $C_{11} = \text{RC6-8}$, $C_{31} = \text{RC6-12}$, $\mathcal{P}_{ID} = 3682.63$, $Vdd_1 = 1.7$, $Vdd_3 = 1.7$, and $Vdd_{ID} = 1.7$. Let us remind that, this point s is obtained by ignoring the computational resources allocated for task $\tau_2 \in M^{123}$ that does not exist in mode M^{13} . Therefore, this solution may be sub-optimal, since a portion of the processor bandwidth is left unused. The current processor utilization with respect to this selected point is only $U = 0.79$, and the power consumption is $Pow = 1.57$. Therefore, we can further improve the QoS by extending, in the next step, the optional execution time of τ_1 and τ_3 to $c_1^o = 225.75$ and $c_3^o = 300$, respectively. By this, the system QoS is increased to $QoS = 34.22$ accordingly, and all operational constraints are still met. More details regarding the above procedure will be discussed in Section 5.5.

5.4 Problem Formulation

We formulate the design problem into a two-stage optimization. At *design-time*, we prepare Pareto spaces for the system to use at run-time. This is captured as a multi-objective optimization problem on all functional modes. There are potentially $|\mathcal{M}| = O(2^{|\mathcal{T}|})$ instances of optimization problems to be solved, which becomes infeasible to go through as $|\mathcal{T}|$ grows. Thus, we can only afford to explore a subset of $\mathcal{M}$ limited by the available off-line design optimization time. Then, depending on the size of available memory of the target platform, we select the Pareto spaces of the most rewarding modes to be stored in the memory. At *run-time*, the system chooses the best operation solution whenever needed, e.g., when the system is switching to another mode or the current security demands or available power budget is changed.

5.4.1 Design-Time Optimization

For each functional mode, we would like to find system designs considering four objectives, i.e. QoS (Equation 5.5), QoC (Equation 5.7), IDA (Equation 3.11), and APC (Equation 5.15). As already mentioned, the solutions to this problem can be represented by a 4D Pareto space. Theoretically, there are infinite number of operation points in this space, but we only can explore and store a finite number of them due to time and space limitations. Before going further, let us first introduce the method that we used to compare two solution spaces S_i and S_j . We say that space S_i outperforms S_j if and only if the hypervolume [ZT98] $\mathcal{H}$ of S_i is strictly larger than that of S_j ; $\mathcal{H}(S_i) > \mathcal{H}(S_j)$. The hypervolume is the volume of the objective space under the surface defined by the dominating points that represents the quality of a solution space. The calculation of hypervolume is performed according to the algorithm introduced in [Zit01]. Thereafter, we also define the hypervolume of a mode M . If S_M is stored in memory, i.e., $M \in \mathcal{M}^{mem}$ ($\mathcal{M}^{mem}$ is the set of modes which have their Pareto spaces stored in memory), then $\mathcal{H}_M$ is the hypervolume $\mathcal{H}(S_M)$. Otherwise, $\mathcal{H}_M$ is defined as the hypervolume of the best derived space from its supermodes. Then the hypervolume of mode

M given the pre-stored Pareto spaces $\mathcal{M}^{mem}$ is calculated as

$$\mathcal{H}_M(\mathcal{M}^{mem}) = \begin{cases} \mathcal{H}(S_M), & \text{if } M \in \mathcal{M}^{mem} \\ \max_{M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem})} (\mathcal{H}(S_M^{M'})), & \text{otherwise.} \end{cases} \quad (5.16)$$

$S_M^{M'}$ is derived for M from its supermode M' by removing the resources occupied by tasks $M' \setminus M$. That is, $S_M^{M'}$ collects a set of solutions for mode M which are obtained from the Pareto space of its supermode $S_{M'}$ by ignoring the non-existing tasks. This means that $S_M^{M'}$ is not the real Pareto space for M , but a space derived from its supermode, for example, the derived space S_{13}^{123} in Figure 5.4.

We decouple the design-time optimization into three subproblems. The first subproblem is the multi-objective optimization for a given mode M . The second subproblem is the global design exploration of the Hasse diagram to obtain the subset $\mathcal{M}^{impl} \subseteq \mathcal{M}$ containing the candidate modes possibly to be stored in memory. The third subproblem is to select the most rewarding subset $\mathcal{M}^{mem} \subseteq \mathcal{M}^{impl}$ to be stored in memory depending on available memory space on the target system.

5.4.1.1 Multi-Objective Optimization for A Given Mode

The inputs to this subproblem are:

- the active tasks in mode M ;
- the task attributes $(\mathcal{E}_i^m, \mathcal{E}_i^o, \mathcal{P}_i, \mathcal{D}_i, \mathcal{L}_i, C_{eff_i}, \mathcal{Q}_i^m, \mathcal{F}_i)$ for all $\tau_i \in M$, as well as l_{ij} , w_{ij} , and $Q_{m_{ij}}^{min}$ corresponding to all messages $m_{ij} \in \mathcal{L}_i$;
- execution time $\mathcal{E}_{ID}$ and the optimal period $\mathcal{P}_{ID}^{min}$ (for achieving full accuracy) for the ID task;
- a strength/time trade-off table of selected cryptographic algorithms and variants (as Table 3.1).

The optimization constraint is the schedulability requirement as described in Equation 5.3, and must be satisfied in all solutions $s \in S_M$.

The optimization objectives are

$$\begin{aligned} & \max QoS_M \\ & \max QoC_M \\ & \max IDA_M \\ & \min Pow_M \end{aligned}$$

And the final output is a Pareto space S_M with non-dominated solutions optimized for the four aforementioned objectives.

5.4.1.2 Hasse Diagram Exploration

In this subproblem, the Hasse diagram (see Section 5.1.2.2) capturing the whole set of modes is explored in order to find a subset of candidate modes $\mathcal{M}^{impl} \subseteq \mathcal{M}$ to be stored in memory. The inputs to this subproblem are

- the whole set of modes $\mathcal{M}$ modeled as a Hasse diagram;
- the set of functional modes $\mathcal{M}^{func}$ that may occur at run-time;
- the top functional modes $\mathcal{M}_\uparrow^{func} \subseteq \mathcal{M}^{func}$ with no functional supermode.

The output for this subproblem is the implementations¹ of selected modes $\{S_M, \forall M \in \mathcal{M}^{impl} : \mathcal{M}^{impl} \subseteq \mathcal{M}^{func}\}$. The constraints are

- each functional mode $M \in \mathcal{M}^{func}$ must have its own implementation or an implementation of at least one of its supermodes to ensure functionality correctness, i.e.

$$\forall M \in \mathcal{M}^{func}, (\{M\} \cup \overline{\mathcal{M}}(M)) \cap \mathcal{M}^{impl} \neq \emptyset. \quad (5.17)$$

This implies the requirement that the top functional modes must be implemented, i.e.,

$$\forall M \in \mathcal{M}_\uparrow^{func}, M \in \mathcal{M}^{impl};$$

¹We refer to the Pareto space of a mode as its implementation.

- the available optimization time.

The design objective for this problem is to select a set of candidate modes $\mathcal{M}^{impl}$ such that the total hypervolume H of all functional modes is maximized, i.e.

$$\max H = \sum_{M \in \mathcal{M}^{func}} \mathcal{H}_M(\mathcal{M}^{impl}), \quad (5.18)$$

where, $\mathcal{H}_M$ can be calculated according to Equation 5.16 depending on whether $M \in \mathcal{M}^{impl}$ or not. Note that, in order to be consistent among the objectives and to correctly calculate the hypervolumes, we transfer the fourth objective of minimize Pow_M to maximize the power saving Pow_M^{saving} with respect to a given power budget.

5.4.1.3 Selection of Candidate Modes

In this subproblem, a subset of $\mathcal{M}^{impl}$ is identified such that the corresponding set of Pareto spaces is the most rewarding to be stored, at run-time, in memory. The inputs to this subproblem are

- the top functional modes $\mathcal{M}_{\uparrow}^{func}$ that must have their Pareto spaces in memory;
- the candidate modes $\mathcal{M}^{impl}$ and corresponding hypervolumes returned from subproblem 5.4.1.2;
- required memory size for storing each mode $M \in \mathcal{M}^{impl}$;
- the available memory space, Mem , on the target system.

The output is the set of chosen modes $\mathcal{M}^{mem}$, for which the corresponding Pareto spaces are stored in memory, which are later used at run-time. The constraint is that the total memory size of storing $\{S_M : M \in \mathcal{M}^{mem}\}$ cannot exceed the total size of available memory space Mem on the target system.

5.4.2 Run-Time Optimization

At run-time, the system is expected to function with the best configuration, regardless of which mode the system is running on or what

concrete constraints, e.g., security and power, the system has. This is achieved by realizing a solution selection mechanism which, whenever the system changes behavior (mode or/and constraints), finds an efficient operation point based on the pre-stored Pareto spaces. This problem takes the following as input,

- available Pareto spaces $\{S_M : M \in \mathcal{M}^{mem}\}$ that are stored in memory;
- the mode M that the system will run in;
- the security constraints, i.e, QoC^R and IDA^R , received from the run-time security monitor or external control center;
- the maximal power budget Pow^R .

The constraints are that all the security and real-time requirements must be met, i.e.,

$$\begin{aligned} QoC_s &\geq QoC^R \\ IDA_s &\geq IDA^R \\ Pow_s &\leq Pow^R \\ U_s &\leq 1. \end{aligned}$$

The goal is to find an efficient operation point s based on the pre-stored Pareto spaces, that delivers as high QoS as possible. If $M \in \mathcal{M}^{mem}$, then s is directly selected from the stored Pareto space S_M . Otherwise, s is chosen from one of the derived spaces of the super-modes $M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem})$. Moreover, the free resource released due to non-existing tasks (tasks in $\mathcal{M}' \setminus \mathcal{M}$) should be further distributed to maximize QoS.

5.5 Proposed Techniques

In this section, we shall elaborate on our proposed framework for solving the design optimization problem formulated in the previous section. We present the overall flow diagram of our design framework in Figure 5.7, which, as can be observed, is divided into two phases, an off-line (Section 5.5.1) and an on-line phase (Section 5.5.2).

Figure 5.7: Overall flow diagram of our proposed design framework

5.5.1 Design-Time (Off-line Phase)

5.5.1.1 Multi-Objective Optimization for A Given Mode

As described in Section 5.4.1.1, the system is expected to be optimized along four independent dimensions. However, it is impossible to find the optimal Pareto space even for one given mode, due to the huge computational complexity. Hence, we use a heuristic for generating a near-optimal Pareto space. We chose the genetic algorithm based multi-objective optimization framework NSGA-II [DPAM02] to solve the problem. NSGA-II mimics the process of natural selection via inheritance, mutation, selection, and crossover operations. We packed the following optimization variables as the gene of each individual:

- the additional execution time of each active task;
- the selected cipher or cipher variant on each communication message;
- the period of the ID task $\mathcal{P}_{ID}$;
- the assigned voltage V_{dd} to each task.

Note that, we consider a discrete set of possible periods of the ID task and discrete supply voltages (and frequencies) to the processor.

After a user specified stopping condition is reached, NSGA-II returns a set of solutions that cannot dominate each other on all objectives, and represent the generated Pareto space S_M for mode M . The parameters used in NSGA-II, e.g. number of generations, population size, and mutation rates, are fine-tuned for different problem sizes.

5.5.1.2 Hasse Diagram Exploration

The main challenge of solving the second subproblem is to efficiently explore the set of functional modes $\mathcal{M}^{func}$ within the given time and space budget, especially when the total number of tasks $|\mathcal{T}|$ and, thus, number of modes are large. Our proposed technique for approaching the problem is based on a breadth-first search of the Hasse diagram. The modes are explored in a top-down fashion and from the levels of modes with more tasks to the ones with less tasks. Exploration on

a branch is stopped when there is no significant improvement from saving the Pareto space of a mode over using the derived spaces from its supermodes. This depth of exploration is determined by a user given variable λ , referred to as the improvement factor, that can be tuned by the designer to trade-off design-time against result quality. Therefore, instead of giving a design-time constraint explicitly, the user provides λ as an input to the optimization problem to guide the trade-off. Before going further, let us introduce the definition of immediate submodes of M as

$$\mathcal{M}^-(M) = \{M' \in \underline{\mathcal{M}}(M) : |M'| = |M| - 1\}. \quad (5.19)$$

More precisely, mode M' is an immediate submode of mode M , if M' is a submode of M , and has strictly one less task than M . For example, $M^1 = \{\tau_1\}$ is an immediate submode of $M^{12} = \{\tau_1, \tau_2\}$, but not of $M^{123} = \{\tau_1, \tau_2, \tau_3\}$; thus, $M^1 \in \mathcal{M}^-(M^{12})$ and $M^1 \notin \mathcal{M}^-(M^{123})$.

The main optimization procedure is presented in Algorithm 4. We first define three sets of modes, $\mathcal{M}^{wait}$, $\mathcal{M}^{impl}$, and $\mathcal{M}^{skip}$, to keep track of the modes that are to be processed, have been implemented, and have been ignored, respectively (Line 1). As already mentioned, the top functional modes $\mathcal{M}_{\uparrow}^{func}$ must be implemented. Therefore, we first apply NSGA-II on each $M \in \mathcal{M}_{\uparrow}^{func}$ in order to obtain the corresponding Pareto spaces that must be later stored in memory to guarantee functional correctness. After that, they are included in the implemented mode list $\mathcal{M}^{impl}$, and their intermediate submodes are added into the waiting list $\mathcal{M}^{wait}$ (Line 2-5).

After having produced the Pareto spaces for all $M \in \mathcal{M}_{\uparrow}^{func}$, we have a set of modes in $\mathcal{M}^{wait}$ that are to be processed. As long as there still exist modes in $\mathcal{M}^{wait}$, i.e., $\mathcal{M}^{wait} \neq \emptyset$, we take out the element from the set that has the most number of tasks $M = \text{most_tasks}(\mathcal{M}^{wait})$ as shown in Line 6-7. If M demands to be processed, that is, M is a functional mode, and has not been implemented or skipped, then we derive solution spaces $S_M^{M'}$ (see Section 5.4.1) for M from all its implemented supermodes $M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{impl})$, and record the derived space that gives the highest hypervolume $\mathcal{H}_D$ (Line

Algorithm 4 Heuristic for Hasse Diagram Exploration

```

1: Initialize set  $\mathcal{M}^{wait} \leftarrow \emptyset$ ,  $\mathcal{M}^{impl} \leftarrow \emptyset$ , and  $\mathcal{M}^{skip} \leftarrow \emptyset$ 
2: for each  $M \in \mathcal{M}_{\uparrow}^{func}$  do
3:   Apply NSGA-II on mode  $M$ , and obtain the Pareto space  $S_M$ 
4:   Set  $\mathcal{M}^{impl} \leftarrow \mathcal{M}^{impl} \cup \{M\}$ 
5:   Set  $\mathcal{M}^{wait} \leftarrow \mathcal{M}^{wait} \cup \mathcal{M}^-(M)$ 
6: while  $\mathcal{M}^{wait} \neq nil$  do
7:   Take out the element with the most tasks  $M = most\_tasks(\mathcal{M}^{wait})$ 
8:   if  $M \in \mathcal{M}^{func} \setminus (\mathcal{M}^{impl} \cup \mathcal{M}^{skip})$  then
9:     for each  $M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{impl})$  do
10:      Derive a solution space  $S_M^{M'}$  from  $S_{M'}$  for  $M$ 
11:      Calculate  $\mathcal{H}(S_M^{M'})$ , and set  $\mathcal{H}_D = MAX(\mathcal{H}(S_M^{M'}), \mathcal{H}_D)$ 
12:      Apply NSGA-II on  $M$ , and obtain Pareto space  $S_M$ 
13:      if  $\mathcal{H}(S_M) \geq \mathcal{H}_D * (1 + \lambda)$  then
14:         $\mathcal{M}^{impl} \leftarrow \mathcal{M}^{impl} \cup \{M\}$ 
15:         $\mathcal{M}^{wait} \leftarrow \mathcal{M}^{wait} \cup \mathcal{M}^-(M) \setminus (\mathcal{M}^{impl} \cup \mathcal{M}^{skip})$ 
16:      else
17:         $\mathcal{M}^{skip} \leftarrow \mathcal{M}^{skip} \cup \{M\} \cup \underline{\mathcal{M}}(M)$ 
18:         $\mathcal{M}^{wait} \leftarrow \mathcal{M}^{wait} \setminus \underline{\mathcal{M}}(M)$ 

```

8-11). Thereafter, we apply NSGA-II on M to get the actual space S_M as shown in Line 12.

Now we check whether S_M deserves to be implemented and, potentially, stored by comparing the hypervolumes $\mathcal{H}(S_M)$ and $\mathcal{H}_D$, that captures how much we gain by having an actual implementation S_M as opposed to using the derived spaces at run-time when mode M occurs. We consider that implementing M is sufficiently rewarding, if $\mathcal{H}(S_M) \geq \mathcal{H}_D * (1 + \lambda)$. If the condition is satisfied, the immediate submodes of M , i.e., $\mathcal{M}^-(M)$, are added into $\mathcal{M}^{wait}$ (Line 13-15). Otherwise, the Pareto space of M is discarded, and succeeding searches along its submodes are skipped (Line 16-18). The reason why we decide not to go through the submodes $\underline{\mathcal{M}}(M)$ is that, if $\mathcal{H}_D * (1 + \lambda) > \mathcal{H}(S_M)$, the derived space is close to the Pareto space (with respect to the improvement factor λ). In other words, all tasks

in M have already enjoyed adequate resources in the solutions of the supermode S_{M_b} , in which they have to compete for resources with additional tasks $M_b \setminus M$. Moreover, the tasks in the submodes $\underline{M}(M)$ are subsets of M . So they will also receive sufficient resources in the solutions of S_{M_b} . Therefore, we heuristically skip the submodes $\underline{M}(M)$ to achieve faster optimization convergence. When the Hasse diagram exploration terminates, that is, $\mathcal{M}^{wait} = \emptyset$, we have a set of mode implementations $\mathcal{M}^{impl}$.

The improvement factor $\lambda(\lambda \geq 0)$ in Line 13 is a parameter that the designer can tune for changing the exploration depth, and thereby, trading-off solution quality with optimization time and maximal needed memory. The smaller λ is, the more modes on the Hasse diagram are traversed. The most extensive exploration happens when $\lambda = 0$, in which case all functional modes are analyzed.

5.5.1.3 Selection of Candidate Modes

After the previous stages, the designer has a set of modes $\mathcal{M}^{impl}$ with their generated Pareto spaces that are candidates to be stored in the target platform at run-time. However, the memory space of the system may not be sufficient to accommodate all of them. Thus, the last step of the design-time optimization is to further select the best modes to be stored in memory, depending on the actual memory constraint. We formulate this problem as an integer linear programming (ILP) problem. The expected output is the set of chosen modes $\mathcal{M}^{mem}$ that have their Pareto spaces stored in memory.

We assign each Pareto space $S_{M:M \in \mathcal{M}^{impl}}$ with a binary variable ϕ_M . If $\phi_M = 1$, mode M will have its Pareto space stored in memory. Otherwise, S_M is ignored. For all top functional modes, ϕ_M is set to 1, i.e., $\forall M \in \mathcal{M}_\uparrow^{func}, \phi_M = 1$. The required memory size of each Pareto space is determined by the total number of points in the Pareto space obtained from NSGA-II times the number of active tasks in the mode. For example, the Pareto space for mode M^{134} contains 100 operation points (see Section 5.3). Then the required memory space for saving $S_{M^{134}}$ is calculated as $100 \times 3 \times \alpha$. The coefficient α is the size of memory needed for saving all the corresponding system parameters,

e.g., execution times of optional task executions, cipher selections, and voltage levels, of a task. The optimization goal of this ILP problem is to maximize the total hypervolume of the stored Pareto spaces under the memory constraint, similar to the classic Knapsack problem. We used the IBM ILOG CPLEX Optimization Studio to efficiently solve this ILP problem. As our experiments show (Section 5.6.1), solving this ILP problem takes negligible time compared with the first two subproblems.

5.5.2 Run-Time (On-line Phase)

At run-time, the system has a set of Pareto spaces $\{S_M : M \in \mathcal{M}^{mem}\}$ stored in memory. Thus, the system can react to mode, security requirements, and power budget changes dynamically by switching to an operation point that delivers the highest QoS under the current constraints. There exist two potential scenarios when the system is expected to do an operation switch to mode M , namely the Pareto space of M is stored in memory ($M \in \mathcal{M}^{mem}$) or not ($M \notin \mathcal{M}^{mem}$). We shall discuss these two scenarios separately in this section. The overall run-time optimization procedure is presented in Algorithm 5.

5.5.2.1 $M \in \mathcal{M}^{mem}$

In this case, the Pareto space (a set of solutions) for mode M is available in memory. Thereafter, the system can directly select the best operation point $s \in S_M$ that delivers the highest QoS with respect to given security and power constraints QoC^R , $IDAR$, and Pow^R (Line 1-4). It can be possible that there exists no solution from the space S_M satisfying all the constraints, even if the processor is set to the highest supply voltage and no optional task execution is undertaken. If such situation occurs, the run-time monitor will be notified, and emergency measures must be taken, e.g., to carry out only the mandatory executions of the tasks and turn off the communication, or shut down the system (Line 5-6).

Algorithm 5 Heuristic for Run-time Operation Point Adaptation

- 1: Get the current constraints QoC^R , IDA^R , and Pow^R
 - 2: **if** $M \in \mathcal{M}^{mem}$ **then**
 - 3: Retrieve the Pareto space S_M from memory
 - 4: Find $s \in S_M$, s.t. $QoS_s \geq QoS_{s', \forall s' \in S_M}$, and $QoC_s \geq QoC^R$,
 $IDA_s \geq IDA^R$, $Pow_s \leq Pow^R$
 - 5: **if** $s = null$ **then**
 - 6: Notify the run-time monitor
 - 7: **else**
 - 8: **for** all $M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem})$ **do**
 - 9: Retrieve the Pareto space $S_{M'}$ from memory
 - 10: Derive solution space $S_M^{M'}$ by removing the resources occu-
 pied by $\tau \in M' \setminus M$
 - 11: Find $s \in S_M^{M'} (\forall M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem}))$, s.t. $QoS_s \geq$
 $QoS_{s', \forall s' \in S_M^{M'}}$ and $\forall M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem})$,
 $QoC_s \geq QoC^R$, $IDA_s \geq IDA^R$, and $Pow_s \leq Pow^R$
 - 12: **if** $s \neq null$ **then**
 - 13: Increase the optional parts of $\tau_i \in M$ in the order of $f_i'(c_i^o)$
 - 14: **else**
 - 15: Find $s \in S_M^{M'} (\forall M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem}))$ having the short-
 est Euclidean distance between (QoC_s, IDA_s, Pow_s) and
 (QoC^R, IDA^R, Pow^R)
 - 16: Try to satisfy the security constraints from s using available
 resources
 - 17: **if** $QoC_s \geq QoC^R$, $IDA_s \geq IDA^R$, and $Pow_s \leq Pow^R$ **then**
 - 18: Increase the optional parts of $\tau_i \in M$ in the order of $f_i'(c_i^o)$
 - 19: **else**
 - 20: Notify the run-time monitor
-

5.5.2.2 $M \notin \mathcal{M}^{mem}$

In this case, we do not have the Pareto space for M stored in memory. Then, the first step is to derive solution spaces from the Pareto spaces of those supermodes of M that are available in the memory, i.e., $M' \in (\overline{\mathcal{M}}(M) \cap \mathcal{M}^{mem})$, as shown in Line 8-10. After that, we can look for an appropriate operation point $s \in S_M^{M'}$ from all the derived spaces

(Line 11) in which the constraints are satisfied, and the delivered QoS is the highest among all the points. Remember that the solution s is obtained in the way that the resources assigned to tasks $M' \setminus M$ are left unused. Therefore, starting from s , we can further redistribute the unused resources that were previously occupied by the tasks $M' \setminus M$ to enhance system performance. There are two different situations that we must consider depending on whether the constraints can be satisfied with s or not.

If QoC^R , IDA^R , and Pow^R can be satisfied in $S_M^{M'}$ ($s \neq null$), we shall get an operation point s from the previous step, and then leave the security protections unchanged. Until now, we have not utilized the free resources that were previously occupied by the non-existing tasks in $M' \setminus M$. Thereby, we can further improve the system QoS by increasing the optional task executions among the tasks $\tau_i \in M$ in the priority order of the derivative $f_i'(c_i^o)$ of the reward function (refer to Equation 5.4) until the real-time constraint or/and power budget is violated (Line 12-13). By this, resources are provided with priority to those tasks whose QoS deliveries are more sensitive to extra assigned processor bandwidth.

Otherwise ($s = null$), we start from the solution $s \in S_M^{M'}$ that has the shortest Euclidean distance from (QoC_s, IDA_s, Pow_s) to (QoC^R, IDA^R, Pow^R) (Line 15). We first check whether $IDA_s \geq IDA^R$ or not. If not, then we allocate unused processor bandwidth to achieve the required period of the ID task $\mathcal{P}_{ID_s} = \mathcal{P}_{ID}^{min} / IDA^R$. If the processor utilization bound and power budget are not violated, we continue with a similar procedure regarding the requirement QoC^R . If QoC^R is not met, we distribute the currently available resources to improve the confidentiality level to the communication messages with priority to the messages with higher importance w_{ij} (Line 16). In the end, if Pow^R as well as QoC^R and IDA^R are all satisfied, the same QoS improvement method is carried out as stated in the previous case (Line 17-18). In case any of the requirements QoC^R , IDA^R , and Pow^R cannot be achieved, the run-time monitor will be signaled (Line 19-20), and emergency measures are carried out.

5.6 Experimental Results

We have conducted experiments on a Linux machine having a four-core Intel Xeon CPU with 2.66GHz frequency and 8GB RAM. We have studied four different problem sizes having task numbers $|\mathcal{T}| = 4, 6, 8$, and 10. On each problem size, 20 test applications were randomly generated, in which 80% of the modes are functional modes. The ID task execution time $\mathcal{E}_{ID}$ and minimal period $\mathcal{P}_{ID}^{min}$ were set as 400 and 1500 time units. The mandatory execution time $\mathcal{E}_i^m$ and maximal optional execution time $\mathcal{E}_i^o$ of task τ_i were randomly chosen from the intervals $[500, 1400]$ and $[100, 800]$, respectively. Each task was associated with a set of messages, each of which had a length of $l_{ij} \in \{1, 2, \dots, 8\}$ blocks and a random weight $w_{ij} \in [0, 1]$. The reward functions were assumed to be of the form $f_i(c_i^o) = \alpha_i \cdot c_i^o + \phi_i \cdot \sqrt{c_i^o} + \gamma_i \cdot \sqrt[3]{c_i^o}$.

5.6.1 Design-Time

We first evaluated our *design-time* optimization technique. Five different improvement factors λ were studied in the experiments, i.e. 0, 0.2, 0.4, 0.8, and 1.6, to evaluate the trade-off between optimization time and performance. The larger λ was, the less modes were explored on the Hasse diagram. Thus, less optimization time was required, but with a potential sacrifice in result quality. The situation with $\lambda = 0$ provided the most extensive exploration, in which the algorithm exhaustively visited the Hasse diagram, and generated Pareto spaces for all functional modes. We assumed that the available memory in the system was 70% of the total required memory² of storing $\mathcal{M}^{impl}$, i.e., $Mem = Mem(\mathcal{M}^{impl}) * 0.7$.

We have run the off-line step on problem sizes with 4, 6, 8, and 10 tasks. As mentioned earlier, for each of the four levels, we generated 20 instances resulting in a total 80 test sets. The experiments have been run with the five different values of λ yielding a total of 400 cases. For each of these cases, a set of Pareto spaces has been obtained to be stored, at run-time, in the memory of the target system.

Let us remind that each functional mode $M \in \mathcal{M}^{func}$ must have

²We did not restrict the memory size under $\lambda = 0$ for comparison purposes.

its own implementation or an implementation of at least one of its supermodes stored in memory to ensure functional correctness. Therefore, the scenario when the system has only the Pareto spaces of the top functional modes, i.e. $\mathcal{M}^{mem} = \mathcal{M}_{\uparrow}^{func}$, is the minimal set of feasible solutions. Under this case, the total hypervolume $H_{\mathcal{M}_{\uparrow}^{func}}$ is actually the minimum that could be obtained satisfying all functional requirements. Thereby, we chose this case as the baseline for comparison in our experiments. For each λ on a given test application, we computed the achieved performance improvement (PI) ratio as follows,

$$PI = \frac{H_{\mathcal{M}^{mem}} - H_{\mathcal{M}_{\uparrow}^{func}}}{H_{\mathcal{M}_{\uparrow}^{func}}} * 100\%, \quad (5.20)$$

where $H_{\mathcal{M}^{mem}}$ is the total hypervolume of all functional modes under the situation when the Pareto spaces of modes in $\mathcal{M}^{mem}$ were stored in memory (refer to the cost function in Equation 5.18).

Figure 5.8 shows the obtained results comparing with the baseline solution $\mathcal{M}^{mem} = \mathcal{M}_{\uparrow}^{func}$. The horizontal and vertical axes indicate the number of tasks $|\mathcal{T}|$ and the average PI in each experimental setup, respectively. It can be observed that, on the same problem size, bigger improvements can be achieved with smaller λ , since more modes are explored and stored. For example, with the problem size of 8 tasks, the obtained PI values using $\lambda = 0.2$ and $\lambda = 1.6$ were 121% and 38%, respectively. Of course, the general trend shows that, with a smaller λ , the performance improvements PI are larger, since the number of explored modes increases. However, it is also visible that with a λ of, e.g., 0.4, already significant levels of PI can be achieved.

The average optimization time (in seconds) for each λ and problem size is depicted in Figure 5.9. As can be noticed, no result was shown for the largest problem size with the smallest improvement factor, i.e., $|\mathcal{T}| = 10$ and $\lambda = 0$, in Figure 5.8 and 5.9. The reason is that the experiments took extremely long run-times that are beyond our timeout restriction. This reflects the fact that the Hasse diagram exploration with small λ (or, in the extreme case, $\lambda = 0$) induces huge computational cost. It becomes impractical to explore a big portion of the Hasse diagram using a small λ for large system designs. However,

Figure 5.8: Performance improvement of off-line phase

Figure 5.9: Optimization time of off-line phase

Figure 5.10: Average time of solving ILP

as shown in the results, good result quality and fast optimization convergence can still be achieved using a larger λ .

The average time (in milliseconds) of solving the ILP problem formulated in Section 5.5.1.3 is illustrated in Figure 5.10. Note that the case of $\lambda = 0$ is not presented, since all functional modes have their Pareto spaces stored in memory under this scenario. As can be seen, the overall average time that the CPLEX solver took is less than $15ms$ among all the experimental settings, which is negligible comparing with the efforts of solving the first two steps in the off-line design phase.

5.6.2 Run-Time

The ultimate goal of the whole design optimization procedure is to make sure that, whenever the system changes modes or states, it always adapts to the situation with an efficient operation point. The design-time phase is our first step for achieving the goal. Our second set of experiments took a close look at the run-time system. To this end, we have considered the 400 cases discussed above, and we have executed the run-time system for each of them. For each of these 400 experiments, the run-time system has been exposed to a randomly generated sequence of 20 external requests. Each request is of the form (M, QoC^R, IDA^R, Pow^R) representing the mode and the constraints to be considered when choosing a new operation point. At least one of these four components of the new request differed from the previous request in the same sequence. For each case handled by the run-time system, we registered the QoS delivered with the selected operation point. Based on these experiments, we have answered the following three questions.

1) *How is the QoS provided by our run-time algorithm compared to the situation when all Pareto spaces are stored in memory?* This “ideal” situation means that, for all requests, the Pareto space corresponding to the requested mode is available (see Section 5.5.2.1) as opposed to having to extrapolate operation points from derived solution spaces in certain situations (see Section 5.5.2.2). In Figure 5.11, we show the average degradation of QoS provided by the run-

Figure 5.11: Average distance (%) from solutions on Pareto spaces

Figure 5.12: Average performance improvement over greedy method

Figure 5.13: Average time of on-line operation point adaptation

time system compared to the hypothetical case that Pareto spaces corresponding to all functional modes are available in memory. Not surprisingly, the degradations increase with the increase of λ , since the number of stored Pareto spaces decreases. For $\lambda = 0.2$, the probability is high that, for the mode to be entered, the Pareto space is already stored in memory, or, at least, the space corresponding to a very close supermode is available. This probability is decreasing with larger values of λ . Thus, in all cases, a larger number of Pareto spaces are stored if a smaller λ is chosen. It is, however, important to note that even for $\lambda = 0.8$ this deviation is about 3% or less. This proves the capacity of our run-time heuristic to find efficient operation points even in the absence of the Pareto space corresponding to the entered mode.

2) *Does it, at all, make sense to store Pareto spaces?* If one carefully follows the run-time heuristic in Algorithm 5 and the discussion in Section 5.5.2.2, one can observe the sequence in Line 16-18 in which available resources are redistributed to satisfy constraints and improve QoS. In Algorithm 5, this redistribution is performed on the resources originally occupied by tasks $\mathcal{M}' \setminus \mathcal{M}$. In fact, one can imagine a run-time heuristic that uses a similar technique to find an operation point. Instead of relying on pre-stored Pareto spaces, this technique would consider the whole processor bandwidth available, and use the above “redistribution” method to assign resources upon solving a new request. Such a scenario corresponds to the extreme case of our run-time system in Algorithm 5, in which $\mathcal{M}^{mem} = \emptyset$ (no Pareto space stored), and only Line 16-20 are executed. We have implemented such a simple run-time system, and compared the obtained QoS with that returned by our Pareto-space-based approach with $\lambda = 0.4$. Figure 5.12 depicts the average QoS gains produced by our proposed technique, which lie between 40% and 80%. This proves that using pre-calculated Pareto spaces is considerably increasing performance compared to a simple greedy resource distribution method.

3) *What is the time overhead of adapting to an operation point on-the-fly?* Since our proposed run-time system will be used on-line, the induced time overhead is another critical aspect to look at. Therefore, we also measured the execution times of the aforementioned run-time

technique. Two situations need to be analyzed separately, that are when the Pareto space of the corresponding mode is available in memory, i.e., $M \in \mathcal{M}^{mem}$ and when it is not, i.e., $M \notin \mathcal{M}^{mem}$. The time overheads (in milliseconds) are illustrated in Figure 5.13. We can see that our run-time manager, on average, took roughly the same effort ($\approx 0.1ms$) to find an operation point on all problem sizes under the case $M \in \mathcal{M}^{mem}$. This can be correlated with the fact that, in the experiments, the number of operation points in the Pareto spaces returned by NSGA-II were set to be the same on all levels. Thus, the run-time system dealt with the same amount of information for selecting a point regardless of problem sizes. When the Pareto space for the corresponding mode is not available, i.e., $M \notin \mathcal{M}^{mem}$, the average overheads for larger problem sizes were bigger than that for smaller sizes. This is due to that, for larger problem sizes, our run-time system operated on distributing resources to more tasks. However, as reflected by the upper line in Figure 5.13, the overhead grew linearly with problem sizes, since the computational load of the run-time manager in this case is proportional to the number of tasks.

5.7 A Real-Life Case Study

In order to further validate our proposed techniques, we applied the presented approach to a real-life benchmark that is a smartphone example. The system contains five applications, namely, a GSM codec [DB92], an MP3 decoder [Hag97], a JPEG codec [IJG98], an H.264 decoder [Cis14], and an NMEA 0183 parser [Moc14]. Each application is modeled as a task, and there is no data dependency among the tasks. They provide five different services to the user, i.e., phone calls/standby, online music playing, digital camera, video streaming, and navigation, respectively. The applications have been software profiled to retrieve the execution characteristics of the corresponding five tasks and task parameters. The hardware architecture was a DVFS-enabled SAMSUNG S3C2440 (ARM9) processor [SAM04].

We give a coexistence table as in Table 5.2, instead of presenting a full Hasse diagram to illustrate the functional modes. A "Y" (or "N") in Table 5.2 means that the two tasks can (or cannot) coexist at the

Table 5.2: Task coexistence relations

	GSM	MP3	JPEG	H.264	NMEA
GSM	-	Y	Y	Y	Y
MP3	Y	-	Y	N	Y
JPEG	Y	Y	-	Y	Y
H.264	Y	N	Y	-	Y
NMEA	Y	Y	Y	Y	-

same time in the system. For example, the MP3 task and the H.264 task cannot coexist, due to competition for the audio playback hardware. Therefore, the modes that contain both tasks are functionally excluded. The task parameters of the five applications are given in Table 5.3. Note that, the GSM task has no optional execution part, and delivers constant QoS value at every activation. The other four tasks may carry out additional executions for achieving extra performance enhancement, e.g., better sound or image quality, with respect to the given reward functions shown in the last column of Table 5.3. The weights of m_{11} , m_{21} , m_{41} , and m_{51} are considered equal, and their sizes are 64, 512, 2048, and 32 bytes, respectively.

We have conducted the off-line optimization steps with five different improvement factors, i.e., $\lambda = 0, 0.2, 0.4, 0.8, 1.6$. The memory limitation is set as 70% of total required memory size of the candidate Pareto spaces obtained from the Hasse diagram exploration³ with λ . The system has been exposed to a run-time test sequence consisting of 10 representative evaluation scenarios (first two columns of Table 5.4), each of which is of form (M, QoS^R, IDA^R, Pow^R) as seen in the previous section. The system runs under each scenario for a certain period between 5 seconds to 10 minutes which represents the most common use case of mobile phones. The ten consecutive scenarios are used to simulate different on-line requirements that the system may face. For example, the mode that the system is going to switch

³As an exception for $\lambda = 0$, we remove the memory limitation to make sure that all modes have their Pareto spaces stored in memory for comparison purposes as in Section 5.6.2

Table 5.3: Task parameters of the smartphone benchmark

	$\mathcal{E}^m(\mu s)$	$\mathcal{E}^o(\mu s)$	$\mathcal{P} = \mathcal{D}(\mu s)$	$\mathcal{L}$	C_{eff}	QoS reward function
GSM	770	0	5000	$\{m_{11}\}$	5.6	$QoS_{GSM} = 3.7$
MP3	830	900	4000	$\{m_{21}\}$	8.1	$QoS_{MP3} = 4.9 + 2.13 * \ln(c^o)$
JPEG	2020	1200	10000	$\emptyset$	5.8	$QoS_{JPEG} = 6.5 + 0.019 * c^o + 0.0024 * (c^o)^{\frac{4}{3}}$
H.264	560	880	3000	$\{m_{41}\}$	11.2	$QoS_{H.264} = 3.8 + 0.32 * \sqrt{c^o} + 0.6 * \sqrt[3]{c^o}$
NMEA	410	260	8000	$\{m_{51}\}$	3.3	$QoS_{NMEA} = 3.5 + 0.047 * c^o$

Table 5.4: Experimental results of the smartphone benchmark

Test Case		Obtained QoS						
$Mode$	(QoS^R, IDA^R, Pow^R)	$\lambda = 0$	$\lambda = 0.2$	$\lambda = 0.4$	$\lambda = 0.8$	$\lambda = 1.6$	Greedy Method	
M_{135}	(0.34, 0.34, 1.05)	70.6	✓	67	67	67	45.2	
M_{123}	(0.52, 0.47, 1.61)	62.7	✓	✓	50.9	49	16	
M_{1345}	(0.44, 0.37, 1.85)	40.8	✓	✓	✓	✓	26.2	
M_{14}	(0.54, 0.24, 2.44)	21.8	21.7	19.5	18.8	18.8	15.5	
M_{125}	(0.34, 0.51, 2.00)	44.4	✓	✓	44.1	44.1	36.5	
M_{1235}	(0.14, 0.97, 2.25)	32.8	✓	✓	✓	✓	21.1	
M_{134}	(0.24, 0.68, 1.88)	59.1	✓	51.5	51.5	51.5	×	
M_{12}	(0.77, 0.84, 1.75)	22.7	21.9	18.3	12.7	12.7	12.2	
M_{15}	(0.94, 0.55, 2.81)	20.2	20.2	20.2	20.2	20.2	20.2	
M_{125}	(0.74, 0.55, 2.56)	37.1	✓	✓	32.2	32.2	31.2	

to can contain many tasks, e.g., M^{1235} and M^{1345} , or only two tasks, e.g., M^{12} and M^{15} . Additionally, some modes may appear more often than the others, e.g., M^{125} , for various reasons. At the same time, the concrete security and power constraints may vary, for example, one or both security requirements are high, e.g., (0.94, 0.55, 2.81); the power budget is very limited, e.g., (0.34, 0.34, 1.05); or all the constraints are tight, e.g., (0.77, 0.84, 1.75).

The QoS values that the system delivered under the experimental setups are presented in Table 5.4. The first two columns indicate the corresponding test case. The 3rd column depicts the results as if the Pareto space was stored in memory for that mode, and, thus, represents the best results. The 4th to 7th columns show the QoS values obtained using different λ values in the off-line phase. For comparison purpose, we also conducted the greedy method described in Section 5.6.2 (in which the run-time optimization is directly applied with no Pareto space stored in memory) on the test sequence. The results from the greedy method are shown in the last column.

The check marks mean that the Pareto space for the mode is saved in memory. Therefore, the same result is retrieved as that in the third column (for $\lambda = 0$, all Pareto spaces are stored in memory - see footnote 3). The cross mark shows that the greedy method cannot find a solution for mode M^{134} meeting all constraints (0.24, 0.68, 1.88) simultaneously. As can be noticed in Table 5.4, for $\lambda = 0.2$, Pareto spaces are available in 7 cases (in which case, the best results can be obtained); and high QoS values (very close to those in Column 3 of Table 5.4) can be reached in the other three cases. When choosing $\lambda = 1.6$, the system can still produce much higher QoS than the greedy method. On average (discarding the 7th case in which the greedy method failed to find a satisfiable solution), our approach with $\lambda = 1.6$ achieved 46.2% higher QoS than the greedy method.

The off-line optimization time and the on-line mode switching time are presented in Figure 5.14. The x-axis shows the five different settings of improvement factor λ . The optimization time of our off-line design phase for different λ is represented by the continuous line, and is aligned to the y-axis on the left (in seconds). The time for finding an operation point at run-time using the proposed on-line techniques

Figure 5.14: The off-line and on-line optimization overheads

is captured by the dashed line, and is aligned to the secondary y-axis on the right (in milliseconds). As can be noticed, the off-line optimization took longer time to finish for smaller λ , since more modes on the Hasse diagram got visited. Meanwhile, as λ becomes smaller, the time overhead of the on-line phase is reduced. This is because that, with smaller λ , more Pareto spaces were stored in memory (since the memory limitation is set as 70% of the total required memory of $\mathcal{M}^{impl}$), and, consequently, more solutions could be directly obtained without deriving solution spaces and further processing the solutions. However, our proposed on-line heuristic is very efficient, and used only $0.24ms$ to retrieve a solution on average ($0.72ms$ in the longest case). Also worth mentioning, the time overhead of the on-line phase optimization was, in the worst case, $0.72/5000 = 0.014\%$ of the duration of the next mode that is to be switched into. Therefore, the time overhead of our on-line heuristic is negligible.

5.8 Summary

In this chapter, we have presented a set of design optimization techniques for secure multi-mode embedded systems with dynamic task sets. We first analyzed a design problem for a single mode with four dimensions, namely, confidentiality protection, intrusion detection, power optimization, and QoS optimization. And then we discussed how to cope with the potentially large number of functional modes.

After that, we studied the problem of on-line choosing the best operational point. However, the problems that we face impose huge computational complexity for solving exactly. Therefore, in order to master the complexity issues, we proposed a heuristic based two stage scheme as an alternative. The efficiency of the proposed techniques has been demonstrated by extensive experiments including a real-life case study. Note that the presented techniques are general enough to be also applied with other design requirements of multi-mode RTEs.

So far, we have discussed protecting the security aspects of RTEs by deploying extra security protection mechanisms, e.g., cryptography and intrusion detection. However, the actual implementations of such protection mechanisms may be under attacks, which weaken the overall protection strength. In the next chapter, we shall elaborate on preserving security of the underlying IBC implementations.

Chapter 6

Design of A Secure Scheduler Against Differential Power Analysis Attacks

CHAPTER 4 and 5 have detailed our design techniques for secure RTESs. The goal was to efficiently carry out implementations of security protection mechanisms. However, as shown in Section 3.2.1.3, implementations of the security protection mechanisms on embedded platforms may be under severe threats. In this chapter, we shall present our solutions to resist such threats.

In order to achieve confidential communications, cryptographic algorithms, e.g., IBCs, need to be applied. However, the underlying cryptographic implementations leak side-channel information, e.g., power and sound, to the surrounding environment, which can be exploited by the attacker to retrieve secret information of the system. One of the most powerful and representative side-channel attacks is the differential power analysis attacks (DPAs). In this chapter, we shall discuss our solution against the DPAs. Theoretical guarantees and preliminary experimental results are presented to demonstrate the efficiency of the presented solution.

This chapter is organized as follows. Section 6.1 introduces the re-

Figure 6.1: An illustrative system

lated hardware and application model. Section 6.2 and 6.3 present the fundamental motivations and an illustrative example, respectively. The presented concept is evaluated on two representative scheduling policies in Section 6.4. Section 6.5 elaborates our proposed scheduling policy that both guarantees the real-time properties of the system and resists DPA attacks. The results of the experimental evaluations on the proposed scheduler are presented in Section 6.6. Finally, Section 6.7 summarizes the chapter.

6.1 System Model

6.1.1 Hardware Model

The system we consider is a mono-processor RTES as shown in Figure 6.1. It is connected with various peripherals, e.g., sensors, actuators, and communication modules, via which it interacts with the environment or other peers. The microprocessor μP and memory architecture are implemented with tamper-proof technology [SCG⁺03], making the computational operations and memory hierarchy not accessible. However, the power supply to the microprocessor may be approached.

6.1.2 Application Model

There is a set of preemptive and periodic computation tasks $\mathcal{T}$ running on the microprocessor. The execution time and period (also the deadline) of task $\tau_i \in \mathcal{T}$ is denoted as c_i and $\mathcal{P}_i$, respectively. Task τ_i may generate or/and receive a set of messages $\mathcal{L}_i$ to interact with other systems ($\mathcal{L}_i = \emptyset$ if no message is associated). The length of message $m_{ij} \in \mathcal{L}_i$ is l_{ij} . The tasks are scheduled based on earliest deadline first (EDF), or rate-monotonic scheduling (RMS), or the proposed policy that will be elaborated in Section 6.5.

To make sure that the communication from/to the system is confidential, AES encryption and decryption operations [DR02] are required to be performed on all outgoing/incoming messages. The AES E/D procedure τ_{ij}^{AES} on message m_{ij} is considered to be part of the execution of task τ_i to simplify further discussions on scheduling. In other words, task τ_i (and execution time c_i) includes the normal computations of the task and the corresponding AES operations (and respective time overhead c_{ij}^{AES}) on all associated messages $m_{ij} \in \mathcal{L}_i$.

6.2 Time Dimension Shuffling Based Countermeasures

As mentioned in Section 3.2.1.3, the measurement samples need to be noise-free and well aligned for DPA to be the most efficient. Having noise-free samples means that the power of the processor solely depends on the preformed operations and processed data. Thus, the attacker can make relatively accurate hypotheses on power consumptions, and the highest correlation ρ_{max} is obvious enough (see Section 3.2.1.3). This leads to the first type of countermeasures aiming at reducing the signal-to-noise-ratio (SNR) [TAV02], which is referred to as *hiding in amplitude dimension*. In this thesis, we shall focus on the second limitation of DPAs, that is, the less measured power values of the samples in column P_i are due to executing the same leakage, the less efficient DPAs become.

As already discussed in this thesis, RTEs are demanded to provide strict guarantees on the timeliness of delivered results. Assigning

Figure 6.2: Power traces of AES on two messages with the same key

random delays into the execution as discussed in [CK09], to counteract against DPAs does not work in the context of RTES, since it may break the deadline constraints. However, dynamic scheduling algorithms [But11] serve, to a certain extent, the purpose of *hiding in time dimension* by their nature. Because of dynamic preemptions, the leakage fingerprints may occur at different times in different samples, which reduces the correlations between columns of the matrices P and H (see Section 3.2.1.3). The impact of real-time schedulers on DPA attacks has not been studied in the past. In this chapter, we propose an analytical framework to quantitatively capture the impact of task scheduling on the robustness of cipher implementations against DPA attacks, and also a scheduling policy that resists DPA attacks while guaranteeing real-time properties.

Figure 6.2 depicts two aligned power traces of AES on two different messages with the same key K . The leakage point of the first subkey k_1 occurs at 1.2ms (highlighted in the rectangle). Assuming that two samples are sufficient to observe a high correlation with the hypothetical powers, then the attacker can already retrieve k_1 , if the power traces like in Figure 6.2 are obtained. However, if the two leakages happened at different time, then she needs more samples to observe a dominating correlation for obtaining k_1 . As just mentioned, DPA attacks work better if the operations at the same relative time point of all samples are the same. That is, in all the samples, the leakage points occur at the same relative time with respect to the starting time of the sample. Now the question is how to quantify the strength of an AES key under DPA attacks.

Table 6.1: Task parameters for Figure 6.1

Task	c	$\mathcal{P}$	$\mathcal{L}$
τ_1	3	10	$\emptyset$
τ_2	8	20	$\{m_2\}$
τ_3	9	30	$\emptyset$

6.3 Motivational Example

As mentioned in Section 3.2.1.3, the highest probability $\hat{p}$ that the leakage point occurs at the same relative time point $\hat{t}$ determines the robustness of the key under analysis. One way to get $\hat{p}$ is through simulation of system execution, that is, to simulate and record the system execution and then to apply statistical methods on the recorded schedule. Thereafter, the robustness of the key can be calculated using Equation 3.10. Let us consider a simple example with three tasks as given in Table. 6.1. Task τ_1 and τ_3 do not have message communication, while, task τ_2 generates one 128-bits long message m_2 , and encrypts it with AES before sending it out over the communication module. In this example, we assume that the 8-th time unit of τ_2 is the leakage point.

If the system is scheduled by the EDF policy, we shall get the schedule as shown in Figure 6.3 (a) for one hyperperiod $\mathcal{HP}$ of the task set $\mathcal{T}$. The hyperperiod of $\mathcal{T}$ is the least common multiplier of all task periods, i.e., $\mathcal{HP} = 60$ in this case, and is the minimal time interval that the task execution pattern repeats. In other words, the system schedule is identically repeating after one hyperperiod. The gray rectangles represent the normal task executions including the non-leakage parts of AES, and the rectangles with hatching depict the leakage points. Assuming that the attacker measures the μP power at each time unit, she will then obtain 60 discrete power values, each of which corresponds to a specific operation, e.g., task execution or AES, retrievable from the simulated schedule in Figure 6.3 (a). After that, she divides the whole obtained power trace into 3 individual samples based on $\mathcal{P}_2 = 20$ to align the samples (as depicted in Figure

Figure 6.3: (a) The system schedule under EDF; (b) The aligned samples of (a)

Figure 6.4: (a) Another system schedule; (b) The aligned samples of (a)

Figure 6.5: (a) Random schedule of $\mathcal{HLP}$; (b) Random schedule for $\mathcal{HLP}'$; (c) The aligned samples of (a) and (b)

6.3 (b)). To highlight the leakage points, we do not show the non-leakage executions (the gray rectangles), which are independent from the leakages. After the hyperperiod, the same schedule will repeat. Therefore, we can find that the leakage occurs at relative time $\hat{t} = 13$ with the highest probability $\hat{p} = \frac{2}{3} = 0.67$. By now, we can calculate the robustness of the key K_2 using Equation 3.10, i.e., $\mathcal{R}_2 = 180$.

However, this does not seem to be a satisfying solution. An obvious alternative of scheduling the tasks is, for instance, to exchange the execution order of the first leakage point at $t = 13$ with the first fraction of τ_3 from $t = 14$ to $t = 19$ as shown in Figure 6.4 (a). If we align the samples as explained just now, we would get the result as in Figure 6.4 (b). We can observe that, now, the three leakage points occur at three different times, i.e., $t = 20$, $t = 16$, and $t = 13$. However, this schedule repeats after one hyperperiod, making $\hat{p} = \frac{1}{3} = 0.33$. Then the robustness of K_2 is $\mathcal{R}'_2 = 620$.

An even better solution will be an enhanced random scheduler that can both guarantee the deadlines and reduce the value of $\hat{p}$. Figure 6.5 (a) illustrates the simulation of the system with such a scheduler under the first hyperperiod $[0, \mathcal{HP})$. As can be noticed, the leakage points occur at three different times, respectively. Furthermore, due to the randomness introduced by the scheduler, the simulation of the next hyperperiod (shown in Figure 6.5 (b)) gives a different schedule than Figure 6.5 (a). Thereby, if we align the two hyperperiods, we can get the samples as in Figure 6.5 (c). Now in this new scenario, in order to get the actual $\hat{p}$, we need to simulate the system execution for an extended timespan instead of just on hyperperiod, and, consequently, we would get $\hat{p} = 0.11$ and $\mathcal{R}''_2 = 5460$.

6.4 Proof of Concept on Existing Schedulers

We have evaluated the impacts of scheduling policies against DPA attacks on two representative real-time schedulers, namely EDF and RMS [LL73]. We have conducted experimental analyses on a Linux machine with a quad-core Intel Xeon 2.66GHz CPU. The test applications were randomly generated under the requirements of different evaluation scenarios. Each task is associated with at most one mes-

sage having length (in AES blocks) randomly selected from the set $\{0, 1, 2, 3, 4\}$ with probability $\{50\%, 12.5\%, 12.5\%, 12.5\%, 12.5\%\}$, respectively. If $l_{ij} = 0$, then τ_i does not have any communication demand, i.e., $\mathcal{L}_i = \emptyset$. The number of AES leakage fingerprints depends on the number of blocks of the message. We carried out experiments on EDF and RMS under three different scenarios to study the influence of the scheduler against DPA attacks from different perspectives.

6.4.1 Evaluation under Different Processor Utilizations

Now let us first have a look at how processor utilization influences the robustness of the system against DPA attacks under EDF and RMS. In order to judge which scheduler outperformed the other in an experiment, we have the following definition that focuses on which scheduler gives higher robustness for a key k :

$$f(\mathcal{R}^{EDF}(k), \mathcal{R}^{RMS}(k)) = \begin{cases} 1 & , \text{ if } \mathcal{R}^{EDF}(k) > \mathcal{R}^{RMS}(k) \\ 0 & , \text{ if } \mathcal{R}^{EDF}(k) = \mathcal{R}^{RMS}(k) \\ -1 & , \text{ if } \mathcal{R}^{EDF}(k) < \mathcal{R}^{RMS}(k). \end{cases} \quad (6.1)$$

Then, the overall performance indicator $\mathcal{F}$ for a set of experiments, i.e., the robustness of the secret key $Key(\tau_{ij}^{AES})$ from all experiments under the same evaluation criteria, is defined as follows,

$$\mathcal{F}(Key(\tau_{ij}^{AES})) = \frac{1}{n} \sum_{\gamma=1}^n f(\mathcal{R}_{\gamma}^{EDF}(Key(\tau_{ij}^{AES})), \mathcal{R}_{\gamma}^{RMS}(Key(\tau_{ij}^{AES}))), \quad (6.2)$$

where, n is the total number of valid experiments where $\mathcal{L}_i \neq \emptyset$. The result $\mathcal{F}(Key(\tau_{ij}^{AES}))$ captures the average overall superiority of the EDF scheduler over RMS. If EDF delivers higher robustness for $Key(\tau_{ij}^{AES})$ in more cases, $\mathcal{F} > 0$. Similarly, if RMS outperforms EDF on average, $\mathcal{F} < 0$. EDF delivers better results in all the experiments, if $\mathcal{F} = 1$. While, $\mathcal{F} = -1$ would indicate that RMS gives higher robustnesses in all cases.

The results presented in Figure 6.6 were obtained under 9 different utilization levels U from 0.5 to 0.9. On each level, 200 test applications with 5 tasks were randomly generated. The results demonstrate

Figure 6.6: Results of 5 tasks under different processor utilizations

Figure 6.7: Results of different problem sizes

that, on average, EDF outperformed RMS in all situations. However, when the processor utilization was low, both policies provided similar protections on average, e.g., $\mathcal{F} = 0.043$ at utilization $U = 0.5$. This is because when the utilization is low, task executions are very sparsely spread over time. Therefore, the executions have little preemptions and, thus, occur more regularly at fixed time points for both EDF and RMS. As the utilization became higher, EDF delivered better and better robustness on average than RMS, e.g., $\mathcal{F} = 0.307$ at utilization $U = 0.9$. This can be explained by the fact that task priorities are dynamically changing based on their timelinesses in EDF, that introduces more randomness into the occurrences of tasks executions.

6.4.2 Evaluation on Different Problem Sizes

We also conducted experiments on seven different problem sizes having $|\mathcal{T}| = 4, 5, \dots, 10$ tasks. On each problem size, we randomly generated 200 test applications with utilization $0.7 \leq U \leq 1$, and used the average performance indicator $\overline{\mathcal{F}}_e = \frac{1}{|\mathcal{T}|} \sum_{i=1}^{|\mathcal{T}|} \mathcal{F}(\text{Key}(\tau_{ij}^{AES}))$ of all messages as the final indication for each problem size. The results are presented in Figure 6.7. From the results, we can notice that

Figure 6.8: Robustness $R(Key(\tau_{41}^{AES}))$ of 30 experiments under EDF and RMS

on average EDF outperformed RMS on all problem sizes under the utilization bound $0.7 \leq U \leq 1$.

6.4.3 Evaluation on the Same Problem Size

Figure 6.8 presents the actual robustness values of secret key $Key(\tau_{41}^{AES})$ from 30 randomly selected valid experiments from the previous experiments, with number of tasks $|\mathcal{T}| = 5$. As can be noticed, EDF provided better protection for $Key(\tau_{41}^{AES})$ in 15 experiments, while RMS outperformed EDF in 4 tests (Experiment 19, 21, 25, and 28). In the rest of the cases, EDF and RMS gave the same robustness values. The experiments showed that, in the majority of cases, EDF produced higher robustness to $Key(\tau_{41}^{AES})$. Also worth-mentioning, EDF delivered 4.83 times higher robustness on average in the experiments, and satisfied all deadline requirements. While, deadline misses were suffered in 2 cases when the system was scheduled with RMS. However, we cannot conclude that EDF was always preferable, since, in several cases, RMS delivered excellent results while also satisfying deadline constraints for all tasks, e.g., Experiment 19 and 28.

6.5 A New Scheduling Policy for Thwarting DPA Attacks

As demonstrated in the previous section, different scheduling policies have different influences on system robustness. However, neither EDF nor RMS was particularly designed to thwart DPA attacks. There-

fore, in this section, we propose a new scheduling policy that aims to improve system robustness while satisfying all deadline constraints. For illustration purposes, we make the following simplification in the rest of this section: each task is associated with at most one message encryption occurring at the end of its execution, and the leakage point happens at the last δ time units of the task execution time. However, all the presented techniques and analyses can be easily extended to more practical cases in which a task may be associated with multiple messages, and the leakage point can occur anywhere within the task execution time.

6.5.1 Proposed Scheduler: SPARTA

What we propose in this section aims at the reduction of the alignment probability of leakage points in the columns of matrix P (see Section 3.2.1.3). Such an approach of implementing countermeasures is often referred to as *hiding in time dimension* [MOP07]. Note that this type of countermeasure techniques are compatible with those implementing the *hiding in amplitude dimension* concept. It is recommended to implement multiple countermeasures to achieve the best protection.

In this section, we present our EDF-based scheduler named SPARTA and related theoretical guarantees. We use the following notations for describing the scheduler:

- L_s : An ordered list of active tasks within time-interval $[T_s, T_{s+1})$.
- L'_s : A list of tasks picked by SPARTA to be executed within $[T_s, T_{s+1})$. Note that $L'_s \subseteq L_s$.
- rt_i : The execution time of a task τ_i to be carried out within a given time-interval.
- et_i : The execution time of a task τ_i , ignoring the execution time of its leakage point, to be carried out within a given time-interval; $et_i = rt_i - \delta$
- t'_i : The time instant where the leakage of task τ_i starts.
- $\mathcal{X}_i$: The leakage time-interval of task τ_i , i.e., $\mathcal{X}_i = [t'_i, t'_i + \delta)$.

- Z_s : An ordered list of leakage points within $[T_s, T_{s+1})$.

In the following, we describe the workflow of SPARTA:

1. The scheduler is activated at each *task arrival*. The time of the s -th activation of SPARTA is denoted as T_s . At time T_s , the scheduler considers the set of tasks to be executed within time-interval $[T_s, T_{s+1})$, where T_{s+1} is the time of the next task arrival. Then SPARTA decides a concrete schedule of these tasks to help thwart DPA attacks.
2. Unlike the EDF policy, which, at each *task finish*, executes the task that is closest to its deadline, SPARTA determines the schedule for the whole set of tasks that will be executed within $[T_s, T_{s+1})$. It first sorts the tasks that are ready for execution at time T_s based on the proximity to their respective deadlines. The resulting sorted list is captured by L_s and the first entry of L_s contains the task closest to its deadline.
3. The scheduler walks through L_s , starting from its first entry, and continues picking a task from L_s , until processor bandwidth within $[T_s, T_{s+1})$ is fully utilized, or L_s becomes *empty*. The list of tasks picked by the scheduler is kept in the list L'_s and rt_i captures the execution time of τ_i to be carried out within $[T_s, T_{s+1})$. Therefore, once the scheduler finishes walking through L_s , the following relationship must hold:

$$\left(\sum_{\tau_i \in L'_s} rt_i = T_{s+1} - T_s \right) \vee (L_s = \phi). \quad (6.3)$$

4. In this step, SPARTA decides a concrete schedule of tasks by first assigning leakage points at different time instants. Note that et_i captures the execution time of task τ_i to be carried out within $[T_s, T_{s+1})$, ignoring the execution time of its leakage point. Therefore, $et_i = rt_i - \delta$ (recall that δ is the execution time of a leakage point), for tasks with leakage points, and $et_i = rt_i$, otherwise. SPARTA randomly picks a task τ_{x_1} , which has leakage point, from L'_s and randomly allocates the leakage point

at time t'_{x_1} . In order to preserve the timing constraints, t'_{x_1} must be within the time interval $[T_s + et_{x_1}, T_{s+1})$. Once t'_{x_1} is assigned, SPARTA randomly selects another task τ_{x_2} having leakage point and randomly assigns its leakage point at time t'_{x_2} , where t'_{x_2} satisfies the following condition:

$$t'_{x_2} \in \begin{cases} [T_s + rt_{x_1} + et_{x_2}, T_{s+1}), & \text{if } t'_{x_1} \leq T_s + et_{x_1} + rt_{x_2} \\ [T_s + et_{x_2}, T_{s+1}) \setminus \mathcal{X}_{z_1}, & \text{otherwise.} \end{cases} \quad (6.4)$$

In general, SPARTA keeps an ordered list Z_s for the allocated leakage points. Z_s is ordered based on the time of occurrence of a leakage point and the first entry of Z_s holds the leakage point occurring the *earliest* in time. Let us assume n leakage points have been assigned (*i.e.* $|Z_s| = n$) and these leakage points are ordered in Z_s as follows: $t'_{z_1} < t'_{z_2} < \dots < t'_{z_{n-1}} < t'_{z_n}$. To assign the leakage point of a task $\tau_{x_{n+1}}$ (from L'_s), we choose $t'_{x_{n+1}}$, satisfying the following criteria:

$$t'_{x_{n+1}} \in \begin{cases} [T_s + \sum_{i=1}^n rt_{z_i} + et_{x_{n+1}}, T_{s+1}), \\ \quad \text{if } t'_{z_n} \leq T_s + \sum_{i=1}^{n-1} rt_{z_i} + et_{z_n} + rt_{x_{n+1}} \\ [T_s + \sum_{i=1}^{n-1} rt_{z_i} + et_{x_{n+1}}, T_{s+1}) \setminus \mathcal{X}_{z_n}, \\ \quad \text{if } t'_{z_n} > T_s + \sum_{i=1}^{n-1} rt_{z_i} + et_{z_n} + rt_{x_{n+1}} \\ \quad \quad \quad \wedge t'_{z_{n-1}} \leq \sum_{i=1}^{n-2} rt_{z_i} + et_{z_{n-1}} + rt_{x_{n+1}} \\ \dots \\ [T_s + et_{x_{n+1}}, T_{s+1}) \setminus \bigcup_{i \in [1, n]} \mathcal{X}_{z_i}, \\ \quad \text{otherwise.} \end{cases} \quad (6.5)$$

This step ends when all the leakage points are allocated.

5. Once all the leakage points are assigned, we try to glue the

task executions as tight as possible to reduce the number of preemptions. Let us assume that the list Z_s is ordered as follows: $t'_{z_1} < t'_{z_2} < \dots < t'_{z_{l-1}} < t'_{z_l}$, where $|Z_s| = l$. Our scheduler picks τ_{z_1} and assigns the remaining execution time et_{z_1} directly before t'_{z_1} . Similarly, the remaining execution time of τ_{z_2} (i.e. et_{z_2}) is allotted before t'_{z_2} . Once the remaining execution time of all the tasks in Z_s has been allocated, the tasks in $L'_s \setminus Z_s$ (tasks without leakage points), are considered. In particular, each such task is allocated by greedily occupying the first available slots.

As can be noticed, we consider each task to be associated with at most one message, and the leakage point always occurs at the end of the task execution. However, it is worthwhile to mention that the scheduler can be extended to support the situations where a task is associated with multiple messages, and the leakage point occurs at an arbitrary position in the execution. Both aspects can be solved by dividing the task into subtasks based on occurrences of leakage points. Subsequently, the assignments of leakage points can be carried out on these subtasks similar to Equation 6.5.

6.5.2 Properties of SPARTA

Now let us present the important theoretical properties of SPARTA that are related to schedulability and complexity.

6.5.2.1 Schedulability Guarantee

SPARTA satisfies the following crucial property.

Property 6.5.1. *Let us assume that Z_s holds l entries after all leakage points have been assigned and the list Z_s is ordered as follows: $t'_{z_1} < t'_{z_2} < \dots < t'_{z_{l-1}} < t'_{z_l}$, where $|Z_s| = l$. Our scheduler guarantees that for all $i \in [1, l]$, the remaining execution time et_{z_i} of task τ_{z_i} is assigned before t'_{z_i} .*

Proof. To prove for the general case, we consider an arbitrary leakage point t'_{z_n} . Let us distinguish between the following scenarios to show that the assignment of t'_{z_n} is *safe*, i.e., τ_{z_n} is able to finish its execution before t'_{z_n} .

- **Case I:** All the tasks $\tau_{z_i}, \forall i \in \{1, 2, \dots, n-1\}$ have been processed from list L'_s before task τ_{z_n} (cf. step 4 of SPARTA).
 - **Subcase A:** $t'_{z_n} > t'_{z_{n-1}}$, because t'_{z_n} cannot be placed before any t'_{z_i} , where $i \in [1, n-1]$. From Equation 6.5, we can observe that this scenario must happen for the first case, i.e., when the lower bound of t'_{z_n} is at least $T_s + \sum_{i=1}^{n-1} rt_{z_i} + et_{z_n}$. This directly implies the fact that the non-leakage part of τ_{z_n} can finish before t'_{z_n} . This is because of the assignment via Equation 6.5, as $t'_{z_n} \geq T_s + \sum_{i=1}^{n-1} rt_{z_i} + et_{z_n}$.
 - **Subcase B:** $t'_{z_n} > t'_{z_{n-1}}$, but t'_{z_n} could have been placed before some t'_{z_i} , where $i \in [1, n-1]$, according to Equation 6.5. This means t'_{z_n} might, at least, be assigned before $t'_{z_{n-1}}$, according to Equation 6.5. Based on the constraints starting from the second condition in Equation 6.5, we can observe that $t'_{z_{n-1}} > T_s + \sum_{i=1}^{n-2} rt_{z_i} + et_{z_{n-1}} + rt_{z_n} = T_s + \sum_{i=1}^n rt_{z_i} - \delta$. From our hypothesis, we have $t'_{z_n} > t'_{z_{n-1}}$. Therefore, $t'_{z_n} > t'_{z_{n-1}} > T_s + \sum_{i=1}^n rt_{z_i} - \delta$. This also implies directly that the assignment of t'_{z_n} is safe.
- **Case II:** There is at least one task τ_{z_i} ($i \in [1, n-1]$) that was processed from list L'_s after task τ_{z_n} (cf. step 4 of SPARTA). Consider the last task, say τ_{z_y} ($y \in [1, n-1]$), with leakage point assigned within $[T_s, t'_{z_n})$. The reason why t'_{z_y} can be assigned before t'_{z_n} is that there is sufficient processor bandwidth left for τ_{z_y} before t'_{z_n} . From the constraints of Equation 6.5, we know this is possible only if $t'_{z_n} > T_s + \sum_{i \in \{1, 2, \dots, n-1\} \setminus \{y\}} rt_{z_i} + et_{z_n} + rt_{z_y}$. Therefore, $t'_{z_n} > T_s + \sum_i^n rt_{z_i} - \delta$. This proves that the assignment of t'_{z_n} is safe.

□

Schedulability test From Property 6.5.1, we can state that SPARTA guarantees the assignments of leakage points to be *safe*. This means that, for the tasks with leakage points Z_s , the demanded executions will be finished upon the respectively allocated leakage points, which

are before the corresponding tasks' deadlines. This is due to the fact that, within the interval $[T_s, T_{s+1})$, there is no task release or deadline constraint under the assumption of task deadline equal to task period. For the tasks with no leakage $L'_s \setminus Z_s$, the corresponding executions will be greedily allocated to the first available slots (see Section 6.5.1). This ensures that no slack will be left between task executions. Since the task set L'_s is determined based on EDF policy, the free processor bandwidth after assigning the tasks in Z_s is sufficient to accommodate the tasks in $L'_s \setminus Z_s$ using SPARTA.

Therefore, SPARTA guarantees to schedule all tasks from the list L'_s , which is the same set of tasks (along with their respective execution time to be carried out within the time-interval $[T_s, T_{s+1})$) picked by a classic EDF scheduler. Since the proof is not restricted to a particular choice of $[T_s, T_{s+1})$, i.e., s is arbitrary, we can conclude that the schedulability test for SPARTA is exactly the same as of EDF, that is,

$$\sum_{\tau_i \in \mathcal{T}} \frac{c_i}{p_i} \leq 1. \quad (6.6)$$

6.5.2.2 Upper-bound of Context Switches

Lemma 6.5.2. *Let us use l_s to denote the length of Z_s , which is the ordered list of leakage points assigned within $[T_s, T_{s+1})$ as in Property 6.5.1. Then the number of context switches¹ CS_s introduced by allocating the tasks with leakage points satisfies $l_s \leq CS_s < 2l_s$.*

Proof. The proof below goes through the tasks in Z_s in the same order as SPARTA allocates their non-leakage executions. Remind that, SPARTA allocates the non-leakage part of a task $\tau_{z_i} \in Z_s$ into the closest available slacks prior to t'_{z_i} (see Section 6.5.1). It is obvious that no slack is left between the starting and finishing time of τ_{z_i} , which may also contain other task executions (implying context switches). Execution of τ_{z_i} introduces at least one context switch when it starts execution. Extra context switches from τ_{z_i} happen

¹We refer to the start of a task execution or continuation of a task after being interrupted for some time as a context switch.

Figure 6.9: An example schedule of $CS_s^{i=k} = k$

Figure 6.10: An example schedule of $CS_s^{i=k} = k + 1$

Figure 6.11: An example schedule of $CS_s^{i=k} = k + 2$

only when the execution of τ_{z_i} cannot fit within the first available slack, and has to be expanded over multiple slacks. Now let us prove Lemma 6.5.2 by induction.

- **Base case:** Let us look at the first task $\tau_{z_1} \in Z_s$, which is the first task to be allocated in the fifth step of SPARTA. The non-leakage part is allocated directly before the leakage, leading to $CS_s^{i=1} = 1$. Thereby, Lemma 6.5.2 holds for $i = 1$, as $1 \leq CS_s^{i=1} < 2$.
- **Inductive step:** Let us assume that, for $i = k$, Lemma 6.5.2 holds, that is, $k \leq CS_s^{i=k} < 2k$. The minimal number of context switches after allocating τ_{z_k} is k . Now we shall look at task $\tau_{z_{k+1}}$. The minimal number of context switches it may introduce is 1 as mentioned. Thereby, the left hand side of Lemma 6.5.2 holds ($k + 1 \leq CS_s^{i=k+1}$) for $i = k + 1$. Then we focus on proving the right hand side of Lemma 6.5.2, i.e., $CS_s^{i=k+1} < 2(k + 1)$. From the assumption $k \leq CS_s^{i=k} < 2k$, we can find that the actual number of context switches until τ_{z_k} can only be one of the following cases:
 - $CS_s^{i=k} = k$: Since executing a task will at least introduce 1 context switch, no execution of $\tau_{z_j} : j \in [1, k]$ is spread over multiple slacks as shown in Figure 6.9 (the arrows indicate the context switches). In this case, the execution of $\tau_{z_{k+1}}$ can maximally expand over all the $k + 1$ slacks. So the number of context switches introduced by $\tau_{z_{k+1}}$ is at most $k + 1$. Therefore, $CS_s^{i=k+1} \leq k + k + 1 < 2(k + 1)$.
 - $CS_s^{i=k} = k + 1$: In this case, there is only one task τ_{z_j} having its execution expanded over its previous task $\tau_{z_{j-1}}$ as shown in Figure 6.10, and there is no slack left between the two execution fractions of τ_{z_j} . So the total number of available slacks is k . Consequently, the maximal number of context switches $\tau_{z_{k+1}}$ may introduce is also k . Therefore, $CS_s^{i=k+1} \leq k + 1 + k < 2(k + 1)$.
 - $CS_s^{i=k} = k + 2$: In this case, there can be one task τ_{z_j} with execution expanded over two of its previous tasks as shown

in Figure 6.11(a) or two tasks τ_{z_h} and τ_{z_j} with executions expanded over one of their respectively previous task as in Figure 6.11(b). Under both scenarios, the number of slacks left is $k - 1$. So the maximal number of context switches that $\tau_{z_{k+1}}$ may introduce is also $k - 1$. Therefore, $CS_s^{i=k+1} \leq k + 2 + k - 1 < 2(k + 1)$.

– ...

- $CS_s^{i=k} = 2k - 1$: This case can be caused by various scenarios, e.g., τ_{z_k} has its execution expanded over all the previous tasks or each task execution is split into two parts. However, under all possibilities, the total number of available slacks left is 2, that are before the starting of τ_{z_1} and after the end of τ_{z_k} , respectively. So the maximal number of context switches that $\tau_{z_{k+1}}$ may introduce is 2. Therefore, $CS_s^{i=k+1} \leq 2k - 1 + 2 < 2(k + 1)$.

Thereby, we can conclude that Lemma 6.5.2 holds. □

Property 6.5.3. *The total number of system context switches introduced by SPARTA is at most 2 times of that implied by EDF.*

Proof. Assuming that the number of tasks to be executed within $[T_s, T_{s+1})$ is n_s , then the system has n_s context switches if scheduled by EDF.

- $l_s = n_s$: In this case, all tasks in L'_s have leakage points. As shown by Lemma 6.5.2 ($CS_s < 2n_s$), Property 6.5.3 holds within $[T_s, T_{s+1})$.
- $l_s < n_s$: In this case, some tasks in L'_s have no leakage point. After allocating all tasks in Z_s , the actual number of context switches $CS_s^{i=l}$ is in the range $[l_s, 2l_s)$. Similar to the proof of Lemma 6.5.2, we can prove the property by enumerating all the possible scenarios of $CS_s^{i=l}$. For the sake of conciseness, we only show the proof for the last case, i.e., $CS_s^{i=l} = 2l_s - 1$, as follows.

In this case, the number of available slacks is 2 (as the case $CS_s^{i=k} = 2k - 1$ in the proof of Lemma 6.5.2), and no slack exists

within the allocated executions. SPARTA greedily assigns the tasks in $\tau \in L'_s \setminus Z_s$ into the first available slacks starting from T_s . Note that there can be maximally only 1 task τ_x introducing 2 context switches, because the execution of τ_x needs to continue in the second slack only when the first slack is full. All the other tasks in $L'_s \setminus Z_s$ can finish within either slack, yielding 1 context switch. Therefore, the maximal number of context switches from the tasks without leakage is $n_s - l_s + 1$. So we have $CS_s = 2l_s - 1 + n_s - l_s + 1 = n_s + l_s < 2n_s$. So Property 6.5.3 holds within $[T_s, T_{s+1})$.

Since the selection of s is arbitrary, we can conclude that Property 6.5.3 holds in general. □

6.5.2.3 Complexity of SPARTA

Property 6.5.4. *The complexity of each SPARTA activation is $O(n^2)$, where n is the total number of tasks in the system.*

Proof. Let us focus on the SPARTA activation at T_s , and study the individual overhead of each step. In step 1, it calculates T_{s+1} by going through all n tasks, thus, the complexity of step 1 is $n = O(n)$. In step 2, SPARTA sorts the n_a ($n_a \leq n$) ready tasks into a list L_s , leading to complexity $n_a \lg(n_a) = O(n \lg(n))$. In step 3, SPARTA selects the executions to be allocated from the sorted list L_s until the interval $[T_s, T_{s+1})$ is full, therefore, the complexity of step 3 is $n_s = O(n)$, where n_s is the length of L'_s . In step 4, SPARTA assigns leakage points one by one for all tasks with leakages. Before allocating a leakage point, SPARTA examines all the allocated leakages to decide a proper range. If the number of tasks with leakage is l_s ($l_s \leq n$), then we can find that the complexity of step 4 is $0 + 1 + 2 + \dots + l - 1 = \frac{1}{2}(l_s^2 - l_s) = O(n^2)$. In the last step, SPARTA allocates the non-leakage executions greedily to the first possible slacks, yielding complexity of $n_s = O(n)$. Finally, we can find that the overall complexity of SPARTA is $O(n^2)$. □

6.6 Experimental Evaluation

In order to evaluate the achieved protection strength against DPA attacks enhanced by SPARTA, we have performed experimental evaluations under two representative criteria, i.e., different processor utilization levels and different problem sizes (different amount of tasks). Each task τ_i is associated with at most one message m_i with length $l_i = 1$. The task periods are chosen uniformly at random from $\{200, 400, \dots, 2000\}$ to avoid simulation of long hyperperiods. On each problem size, the task execution times were randomly generated under the current utilization level.

We have implemented SPARTA in C, and conducted experiments under a simulation environment on a Linux machine with a quad-core Intel Xeon processor and 8GB of memory. For illustration purposes, we compared the protection strength delivered by SPARTA with protection provided by EDF. We define the robustness of a set of experiments as the average achieved robustness over all keys, i.e.,

$$\overline{\mathcal{R}} = \frac{1}{n} \sum_{i=1}^n \frac{1}{|\mathcal{L}_i|} \sum_{m_j \in \mathcal{L}_i} \mathcal{R}_j, \quad (6.7)$$

where n is the number of experiments, and $\mathcal{L}_i$ is the set of messages in the i -th experiment. $\mathcal{R}_j$ is calculated according to Equation 3.10. The improvement achieved by SPARTA over EDF is defined by:

$$\overline{\mathcal{I}} = \frac{1}{n} \sum_{i=1}^n \frac{1}{|\mathcal{L}_i|} \sum_{m_j \in \mathcal{L}_i} \frac{\mathcal{R}_j^{SPARTA} - \mathcal{R}_j^{EDF}}{\mathcal{R}_j^{EDF}}. \quad (6.8)$$

The two evaluation scenarios are presented as follows.

6.6.1 Different Processor Utilizations

In this set of experiments, we would like to study the influence of different processor utilizations on achieved protection strength. We conducted experiments with different processor utilization levels on the same problem size. That is, all experiments are with 6 tasks. The studied processor utilization levels are $U \in \{1, \dots, 0.5, 0.4\}$, and

Figure 6.12: Results of SPARTA on different processor utilizations

on each level, 200 random test applications were generated with different task periods and execution times. The results are presented in Figure 6.12. The light gray and dark gray bars show the average robustness $\overline{R}$ of EDF and SPARTA, respectively, with the corresponding setups, and are aligned to the primary (logarithmic) y-axis on the left. The curve indicates the improvement $\overline{I}$ of each set of experiments, and is aligned to the secondary y-axis on the right. We can observe that the achieved improvements are gradually increasing as processor utilization drops (indicated by the line). We can also notice that SPARTA dominates EDF on all utilization levels, and it works better, when the processor is less loaded, due to the larger amount of free time slacks that it can make use of. Therefore, SPARTA has more flexibility in allocating leakage points when U is low.

6.6.2 Different Problem Sizes

We now evaluate the performance of SPARTA on different problem sizes, i.e., systems with different amount of tasks. There are in total five sizes studied, namely, $|\mathcal{T}| \in \{4, 6, \dots, 12\}$. On each size, we randomly generated 200 test applications (having different task periods and execution times) with utilization $U = 0.7$. The obtained results are shown in Figure 6.13, and the same representations are shared with those of Figure 6.12. We can find that SPARTA delivers nearly a constant improvement level (indicated by the line) compared with EDF, and the absolute delivered protection is higher on larger problem sizes. It is also worth mentioning that, for individual cases,

Figure 6.13: Results of SPARTA on different problem sizes

SPARTA delivered better protections for the AES secret keys in all the instances of experiments, and the average relative improvements is $\bar{\mathcal{I}} = 441$.

6.7 Summary

Cryptographic algorithms, e.g., AES, have been deployed for protecting sensitive information. However, AES implementations in embedded platforms are known to be vulnerable towards side-channel attacks, e.g., DPA attacks. Therefore, the problem of how to design secure RTEs with robust AES must be carefully studied.

In this chapter, we evaluated the impact of the scheduling policy on the robustness of secret keys against DPA attacks using EDF and RMS, and showed that different scheduling policies do have different impacts on key robustness. Therefore, the designer must carefully choose the most suitable scheduler for the given application considering both deadlines and robustnesses.

After that, we have presented a new real-time scheduling policy SPARTA that thwarts DPA attacks. SPARTA shares the same schedulability test with EDF, and, at the same time, enhances security of the underlying AES implementations. We have conducted experiments to demonstrate that the protection strength of SPARTA is much better than that of EDF under different evaluation criteria. Finally, it is worth mentioning that, while in this chapter, we considered DPA attacks, similar analyses can be done for other side-channel

attacks based on the observations of other parameters, such as temperature and sound.

Chapter 7

Conclusions and Future Work

IN this chapter, we shall summarize the main contributions of this thesis (Section 7.1), and outline the potential directions of future work (Section 7.2).

7.1 Conclusions

In recent years, real-time embedded systems have been extensively used in critical application areas and also been unprecedentedly exposed to dynamic and open environments. Hence, the potential threats, as well as successful attacks, aiming at system security violations have drastically increased lately. Therefore, how to protect such systems is rapidly emerging to a critical problem. Meanwhile, RTEs are becoming much more complex and demanded to undertake multiple functionalities. How to achieve the existing requirements of a RTE design and, at the same time, guarantee the system security under potential threats has become a really difficult problem.

This thesis approaches the aforementioned design problems under three concrete design scenarios of RTEs, that are: 1. design and optimization techniques for communication confidentiality on distributed platforms (Chapter 4); 2. a global framework for secure multi-mode RTEs (Chapter 5); 3. a scheduling policy for resisting side-channel

attacks (Chapter 6).

7.1.1 Confidentiality-Aware Design Techniques

In Chapter 4, we presented two confidentiality-aware design and optimization techniques for distributed RTEs, in which applications are modeled as task graphs. In the first case, we aim at achieving the best system affordable confidentiality protection for the message transmissions over the internal communication infrastructure under strict real-time requirements. In the second case, we consider more powerful platforms with FPGA accelerations, and focus on finding the minimal overall hardware overhead needed for implementing the designated cryptographic operations on the internal communication while achieving imposed constraints. We have carried out large amounts of experiments on both techniques, and also compared the obtained solutions with the optimums returned by solving corresponding CLP formulations.

7.1.2 Secure Multi-Mode RTE Design Framework

In Chapter 5, we addressed the design optimization problem of secure multi-mode RTEs. We considered different combinations of functionalities as modes, represented by the set of active tasks. Due to the potentially large number of tasks that may appear in the system, the amount of possible modes that can occur during system execution can be infeasible to explore. Moreover, even designing for one single mode is not a simple job, since the designer may want to obtain good performance along several conflicting objectives. Therefore, we presented a two stage heuristic approach to solve the problem efficiently. In the off-line stage, a set of Pareto-optimal solutions are developed and stored in memory. In the on-line stage, the system quickly adapts to concrete execution requirements making use of the solutions pre-stored in the off-line stage. The efficiency of the presented framework has been evaluated in extensive experiments, including a case study of a smartphone application.

7.1.3 Scheduling Against Side-Channel Attacks

In Chapter 6, we outlined a scheduling policy, SPARTA, that actively thwarts side-channel attacks, more specifically, the differential power analysis attacks (DPAs). We observed that the power measurements corresponding to the leakage points need to be relatively noise-free and well aligned for DPA to be more efficient, and realized that dynamic schedulers introduce randomness into task schedules, thus, reducing the predictability of the executions. Consequently, the system is more robust towards potential DPAs. We verified the concept by evaluating the influence of EDF and RMS on difficulties of mounting DPAs under different scenarios. After that, we presented the SPARTA scheduler and its fundamental properties. Two different sets of experiments have been conducted on SPARTA to demonstrate its improved protection strength.

7.2 Future Work

This thesis has motivated the needs and addressed several concrete problems of designing secure RTESSs. However, potential threats to modern RTESSs exist in various aspects, and cannot be all covered by this thesis. Therefore, we would like to point out several possible directions for future research.

Among the important concepts of security, we have been focusing on techniques for delivering confidentiality to the internal communication of distributed RTESSs. However, other aspects, e.g., integrity, can also be important in certain distributed RTESSs. So an overall design framework that guarantees both confidentiality and integrity of system communication, while achieving timeliness, is needed.

For the multi-mode systems, we have depicted a holistic design approach that both considers the modes the system may run in and the constraints the system must satisfy simultaneously. However, we did not consider the probability of mode occurrences in the off-line phase. That is, all functional modes are assumed to occur in the system with the same probability, which may not capture the reality well. Thus, a framework that takes the variation of mode appearances

into consideration can be an interesting extension to Chapter 5.

Side-channel attacks are posing serious threats to the underlying implementations of cryptographic algorithms. So side-channel attack resistance is an indispensable aspect that must be ensured in the design of RTESSs. Due to the actual timing and resource constraints of RTESSs, countermeasures against side-channel attacks must be carefully studied. An interesting extension to SPARTA is to enhance system robustness for the RTESSs in which task execution times expose random behaviors. Further, one could combine SPARTA with other techniques, such as the ones aimed at reducing the signal-to-noise-ratio, for achieving even better protections.

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