Application Deployment Strategies for Spatial Isolation on Many-Core Accelerators

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Current cache side-channel attacks (SCAs) countermeasures have not been designed for many-core architectures and need to be revisited in order to be practical for these new technologies. Spatial isolation of resources for sensitive applications has been proposed taking advantage of the large number of resources offered by these architectures. This solution avoids cache sharing with sensitive processes. Consequently, their cache activity cannot be monitored and cache SCA cannot be performed. This work focuses on the implementation of this technique in order to minimize the induced performance overhead. Different strategies for the management of isolated secure zones are implemented and compared.

CCS Concepts: •**Security and privacy** → **Domain-specific security and privacy architectures;**

1. INTRODUCTION

Side-Channel Attacks (SCAs) [Ge et al. 2016] allow an attacker, which has no direct access to critical data, to analyze indirect or side channel information during or after the execution of a sensitive application (e.g., a cryptographic algorithm) in order to deduce the sensitive application behavior or critical information such as a cryptographic key. Depending on the side channel information to exploit, the attacker may or may not require physical access to the system. We focus on logical cache-based SCAs which do not require any physical access and which see the memory cache as the source of leakage. The cache is indeed a resource that several concurrent processes, sensitive and potentially malicious, compete for. When shared with an adversary, this latter can extract some information about the victim's activity that can be used to perform cryptanalysis. ***These attacks can be performed at different granularities; within a single core when the victim and attacker processes execute on the same core and share the level 1 (L1) cache [Percival 2005] as well as across cores, when the victim and attacker applications execute on different cores but share the Last Level Cache (LLC). These attacks have been proved practical as well in a cloud environment when the victim and the attacker applications execute on different Virtual Machines (VMs) logically isolated, since applications across VMs are still sharing the LLC [Yarom and Falkner 2014][Liu et al. 2015][Irazoqui et al. 2015]. These attacks can steal sensitive information from systems implementing logically isolated execution environments [Evtyushkin et al. 2016]. Recently, these attacks have been extended to multiprocessor and Network-on-Chip (NoC)-based systems [Irazoqui et al. 2016] [Reinbrecht et al. 2016b].*** We focus on clustered NoC-based multi and many-core architectures (Figure 1). In fact, these latter architectures have recently emerged as they provide massive parallelism and high performance allowing a wide number of applications, from different sources and with different levels of trust, to be executed in parallel sharing physical resources (computation, memory and communication infrastructure). ***One example is the automotive field, in which the vehicle computer is indeed responsible for handling multimedia applications (user interface, car navigation, entertainment such as radio, Internet, etc.), safety-critical vehicle applications (airbag and braking system for instance), vehicle communication applications (in a connected car context), as well as vehicle and engine management applications. In this context, multi and many-core systems could cope with the performance requirements [Trung-Dung et al. 2016][Burgio et al. 2016]. However, the cohabitation of these different applications sharing physical resources, makes mandatory the integration of security mechanisms.*** In particular, sensitive processes sharing caches with potentially malicious applications are vulnerable to logical cache-based SCAs and can be attacked. A large amount of works aiming at countering logical cache-based SCAs have been proposed (Section 2.2). However, most of them have not been designed for recently emerged many-core architectures. These solutions require to be evaluated and, or revisited in order to be practical and efficient on multi and many-core architectures.

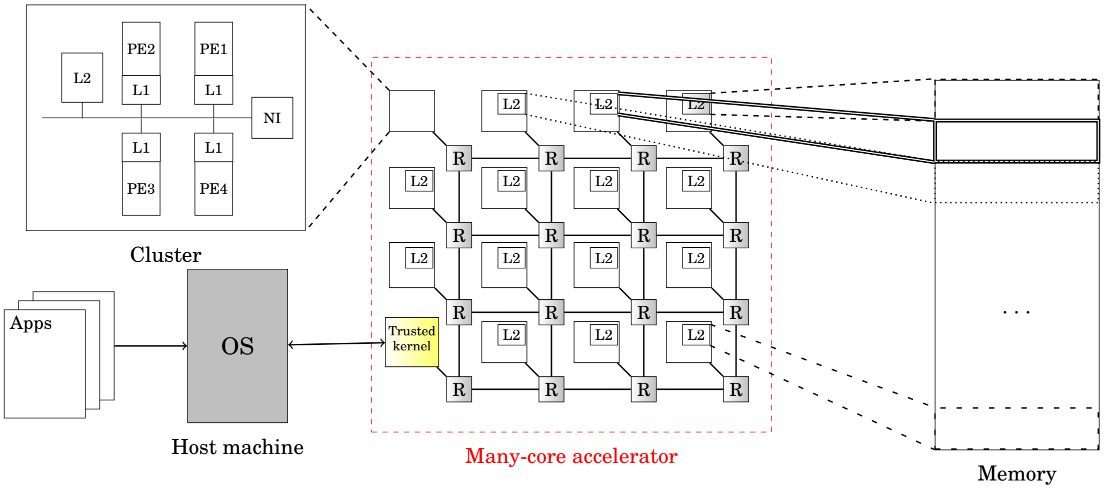


Fig. 1: Overview of the considered system

A countermeasure taking advantage of the large number of resources in many-core architectures has been proposed in [Méndez Real et al. 2016a]. The aim is to prevent cache sharing with a sensitive application by temporarily dedicating part of the physical resources in order to execute it within an isolated environment (*secure zone*). All the resources within the secure zone are dedicated to this single isolated application preventing it from cache sharing. Consequently, its cache activity cannot longer be monitored and cache-based SCAs cannot longer be performed. In the meanwhile, non-isolated applications execute normally and still share resources.

This paper is an extension of [Méndez Real et al. 2016a]. It particularly focuses on its implementation in order to study and reduce the induced performance overhead. In this work we extend [Méndez Real et al. 2016a] with different deployment strategies for the dynamic creation, management of the secure zones. These strategies are evaluated on a TSAR-like architecture [TSAR 2014] and are compared in terms of induced performance overhead according to several performance metrics. Results show that hybrid strategies between completely static and dynamic secure zone size approaches offer more flexibility and reduce the induced performance overhead on the total execution time compared to fully dynamic approaches.

The new contributions presented in this paper are:

— The implementation of a set of services on a manager kernel based on the ALMOS Operating System (OS) kernel [Almaless 2014] in order to dynamically control the deployment of applications.
— The extension of the manager kernel in order to integrate the secure-enable mechanisms proposed in [Méndez Real et al. 2016a] guaranteeing the physically isolated execution of each sensitive application.
— The proposal of different secure zones deployment strategies including a static and dynamic secure zone size, as well as hybrid deployment strategies targeting a minimum guaranteed performance and resources reservation.
— The implementation and evaluation of the proposed strategies on a TSAR like many-core architecture through virtual prototyping.
— The comparison of the gathered results regarding performance metrics including the total performance overhead, the performance overhead on the execution of both, spatially isolated and non-isolated applications, the resources utilization rate, the waiting time for each application to be mapped, the time spent on the Trusted Manager kernel services including the deployment strategies algorithms and resource allocation decisions.
— Finally, the comparison of the different deployment strategies according to the performance metric to be optimized and to the considered execution scenario.

The remainder of this paper is organized as follows: Section 2 presents some background on cache-based side-channel attacks and current countermeasures. Section 3 presents the targeted architecture and associated threat model, and further explains the spatial isolation countermeasure that we consider in our work. In Section 4, different secure zone deployment and management strategies are explained and discussed. Then, Section 5 presents the baseline strategy as well as the implementation of the proposed deployment strategies. Section 6 presents the evaluation environment and the evaluation setup for the validation of the proposed approaches. In Section 7, results for each proposed strategy are analyzed and compared regarding a set of performance metrics. ***Section 8 discusses the presented work in terms of security, previous and future work. Finally, Section 9 draws some conclusions and presents some future work.***

2. BACKGROUND

SCAs correspond to an important class of attacks on multitasks systems [Ge et al. 2016]. These attacks exploit the leakage of information during or after the execution of the sensitive process from different physical measurements in order to deduce important information about a critical process (e.g., a cryptographic algorithm) [Blömer and Krummel 2007]. When the attacker has no physical access to the platform, analyzing neither the electromagnetic radiation nor the power consumption of the system is possible. However, when physical resources are shared between sensitive and malicious applications, logical SCAs based on the analysis of the execution time of certain operations or memory accesses, are still possible. Especially, cache-based SCAs represent a main threat when caches are shared. This section first introduces logical cache-based SCAs. Then, literature related work is presented.

2.1. Cache-based SCAs

Cache-based attacks may be sophisticated, but their underlying idea is relatively simple: an attacker observes cache-based side-channel information such as the victim's execution time or memory accesses in order to gain information about the victim process sensitive data. Additionally, if the attacker can run code on the victim's machine, as well as manipulate the state of the cache, he/she is able to gain extra information. By exploiting this knowledge, the attacker can retrieve confidential data of the critical program [Blömer and Krummel 2007]. Among cache-based SCAs, one distinguishes time-driven (or timing) from access-driven attacks.

2.1.1. Time-driven attacks. These attacks exploit the vulnerability that, for some algorithms, the execution time is directly related to sensitive data. Moreover, attackers can exploit the fact that the execution time of an application is influenced by the current state of the cache leading to potential leakage of information. There are two categories of time-driven attacks; passive and active. The main difference is the location of the attacker. A passive adversary does not have access to the victim's machine and thus, cannot manipulate the state of the cache directly. Here, the attacker process triggers the sensitive application (e.g., an encryption algorithm) a certain number of times and measures the execution time. This latter is influenced by the state of the cache, which is itself influenced by each sensitive application execution. These attacks need more samples than active ones and often require statistical methods in order to successfully retrieve the sensitive information. In [Bernstein 2005], a passive time-driven attack is remotely performed on AES algorithm. On the other hand, an active attacker has access and is able to run code on the victim's machine. This allows him to directly manipulate and probe the state of the cache by filling it with its own data or by evicting some specific cache lines. Here, the attacker can trigger the sensitive application, manipulate the state of the cache and measure the execution time. This gives to the attacker additional cache information, compared to passive attacks, and leads to more efficient attacks. A well known technique is the EVICT+TIME [Osvik et al. 2006]. Authors perform an active timing attack on AES showing its efficiency compared to the passive attacks presented in [Bernstein 2005]. ***Finally, in [Bonneau and Mironov 2006], authors improve this type of attacks by almost four orders of magnitude compared to [Bernstein 2005] by specifically focusing on individual cache collisions during encryption and by attacking the final round of AES encryption instead of the first one in previous work.***

2.1.2. Access-driven attacks. Access-driven attacks rely on the fact the attacker has access to the victim's machine and that there is a shared cache between the attacker and the victim processes. These attacks exploit the vulnerability that, for some systems, some instructions are related to sensitive data. The principle is to deduce which cache lines the victim has accessed by directly manipulating and probing the shared cache and observing the memory access time. This additional information about the victim's cache accesses makes these attacks more efficient than time-driven ones. PRIME+PROBE is a well known technique [Percival 2005]. Assume that an attacker manipulates the state of the shared cache by accessing some specific memory addresses by filling the cache with its own data (PRIME). Then, the victim runs for a certain time and potentially changes the state of the cache. Finally, the attacker measures the time to access the same memory addresses again (PROBE). A short access time would indicate that the attacker's data is still in the cache (a cache hit) and thus that the victim has not accessed this cache memory line. On the contrary, a large access time would indicate a cache miss which indicates that the victim has accessed the same cache memory line. By exploiting this technique, the attacker infers information about the memory locations accessed by the victim, and thus the instructions and data that have been accessed. These attacks are possible both, among the same execution core and across-cores.

Among the same execution core: Initially, cache-based attacks were performed through L1 caches in multithreaded system when two processes, an attacker and a victim one, are concurrently running on the same core and thus share the same L1 cache. In [Gullasch et al. 2011], authors implemented this technique against a 128-bit AES implementation of OpenSSL 0.9.8n on Linux.

Across-cores: The focus of cache-based attacks has shifted from first-level to shared Last-Level Caches (LLC) [Liu et al. 2015] [Irazoqui et al. 2016] [Kayaalp et al. 2016], enabling to perform these attacks across cores. The FLUSH+RELOAD technique [Yarom and Falkner 2014] for instance, targets the LLC. Consequently, to launch this attack, the victim and the attacker programs do not need to execute on the same core. This attack extends the technique presented above [Gullasch et al. 2011] with adaptations for multi-core environments. Furthermore, the FLUSH+RELOAD attack is a variant of the PRIME+PROBE technique [Percival 2005] but relies on shared memory pages between the victim and the attacker. Here, the attacker exploits the inclusiveness property of Intel LLC; every data on lower caches is cached as well in the LLC. Consequently, the attacker can evict a specific cache line (e.g., through a specific assembly instruction such as *cflush*) from the LLC wich will in turn evict the line from all the lower level caches. A round of attack of the FLUSH+RELOAD [Yarom and Falkner 2014] technique consists of three phases: In the first phase, a monitored shared memory line is flushed from the cache hierarchy. During the second phase the attacker waits letting some time to the victim to execute and to potentially access the monitored cache line. Finally, in the third phase, the attacker reloads the monitored cache line measuring the time necessary to load it. If the victim accessed the cache line during the waiting phase, then the line will be accessible in the cache and the load time measured by the attacker will be short. On the other hand, if the victim did not access the line, when reloaded, the line will be fetched from the main memory and the measured access time will be significantly longer. In [Yarom and Falkner 2014], Yarom et al., present some implementations of this technique. However, attackers might request a significant number of reloads which can be detectable. A variant in order to prevent attackers from reloading, resulting in a faster attack, is to replace the reload phase by a second flush phase (FLUSH+FLUSH) [Gruss et al. 2016]. Across-cores access-driven attacks have been proven practical across VMs [Irazoqui et al. 2015]. Furthermore, in [Reinbrecht et al. 2016b], a PRIME+PROBE-based attack has been implemented on a NoC-based Multiprocessor System-on-Chip (MPSoC). While cache-based SCAs are often performed against cryptographic algorithms, techniques presented above are generic and can be used to eavesdrop other non-cryptographic applications in order to recover sensitive (e.g., personal) information. In [Gruss et al. 2016] for instance, authors use the FLUSH+RELOAD technique in on eavesdropping keystroke timings.

In this work we focus on active time-driven and access-driven SCAs. In the next subsection, existing countermeasures are presented.

2.2. Cache-based SCAs countermeasures

We distinguish three different categories according to their main goal.

2.2.1. Modifying the implementation or traces of critical processes. Application-specific countermeasures have been proposed in order to make sure that the leaked information by the critical applications implementation is independent of secret data. Crane et al. [Crane et al. 2015], propose a technique to transform each program in order to make its trace unique offering probabilistic protection against cache-based SCAs. A countermeasure against access-driven attacks, is to modify the implementation of sensitive applications (i.e., cryptographic algorithms) in order to avoid any cache access preventing cache leakage useful for access-based SCAs. Different implementations of some classic cryptographic algorithms have been proposed. In [Blömer and Krummel 2007], authors focus on AES algorithm [Daemen and Rijmen 2002] and propose several implementations. Results show that this approach leads to less efficient implementations in terms of execution time. Against time and access-driven SCAs, some works propose to modify the critical applications implementation in order to make them *constant-time*, i.e. which do not branch on secrets and do not perform memory accesses that depend on secrets [Campo 2016]. In [Barthe et al. 2014], authors give a proof that constant-time programs do not leak confidential information through the cache. However, these solutions are application specific. Alternative approaches are presented below.

2.2.2. Disrupt the adversary measurements. A more flexible approach is to allow non constant-time implementations but to introduce some disruptions on the possible attacker measurements in order to prevent the extraction of sufficient useful information from caches. One approach is to completely flush all the caches at each context switch [Tromer and Osvik 2010]. In this way, cache line monitoring would be ineffective since the attacker will always observe that all lines are evicted from the cache. In [Guanciale et al. 2016], this approach is implemented in AES examples on one core execution. However, this approach introduces a significant performance overhead on the execution of all processes (untrusted but also trusted processes) due to the increased cache miss rate (up to one order of magnitude delay overhead). This overhead is added to the cost of the flushing itself.

At the cache-level, in [Wang and Lee 2007], authors propose to introduce some uncertainty on the behavior of the cache by randomly permuting cache lines or by randomizing the memory-to-cache mapping. At the NoC level, in [Sepulveda et al. 2015], authors introduce random delay on each memory and cache access.

However these solutions offer probabilistic protection only. Other solutions, providing strict isolation in order to avoid any interference between the attacker and victim processes, are presented below.

2.2.3. Avoiding cache sharing. Disabling caches seems a naive solution in order to counter cache-based SCAs. Indeed, blocking attackers to use the caches concurrently with sensitive processes would make caches invisible to them and consequently, cache-based attacks would be impossible. However, this countermeasure may entail great performance costs for applications not using the cache.

Another approach is to partition the physical resources, especially the cache. One solution is to exploit a partitioned cache against cache-based SCAs guaranteeing that a sensitive application does not share partitions in cache. This solution avoids cache interference. Partitions are mostly static [Page 2005] [Kim et al. 2012]. A variant of this approach introducing dynamism on a cloud environment is page coloring [Shi et al. 2011] [Raj et al. 2009] which aims at isolating VMs cache dependencies. In this manner, physical memory pages are partitioned among VMs in such a way that no VM shares cache lines with any other VM. Same than page coloring, specific memory lines can be locked in the cache in order to ensure that only a given sensitive application can evict these lines from the cache [Wang and Lee 2007].

Previous approaches have not been originally designed for emergent architectures such as many-core systems. These solutions need to be evaluated and, or revisited in order to be practical and efficient for these new technologies. In contrast, in [Méndez Real et al. 2016a], the spatial isolation has been proposed in order to thwart cache-based SCAs on multi and many-core systems. This solution takes advantage of the large number of resources available in these systems. The main idea is to temporary dedicate part of the physical resources (called *secure zone*) to a single sensitive application providing an isolated environment for its execution. This solution avoids any cache sharing with the critical application and ensure the non interference with any other applications. Consequently, the sensitive application's cache activity cannot longer be monitored and cache-based SCAs cannot longer be performed. This countermeasure will be further explained in Section 3.4. In this work we focus on this last solution and especially on its implementation in order to minimize its performance degradation.

3. CONSIDERED SYSTEM

We consider a many-core accelerator and we focus on the evaluation of different application strategies for the implementation of the spatial isolation solution against cache-based SCAs proposed in [Méndez Real et al. 2016a]. In this section, the system and associated threat model are explained.

3.1. Many-core accelerator

The system considered in this work (Figure 1) is composed of a host machine and a clustered NoC-based many-core accelerator. The host machine runs an OS and executes a great number of applications in parallel. The host machine and the accelerator are connected via a local interface (e.g., a Peripheral Component Interconnect (PCI)). TSAR [TSAR 2014] architecture, Kalray's Massively Parallel Proces-

Application (App)	**Number of clusters used by this App**	**Percentage of the App exec. time where clusters have been shared**	**Applications sharing the cluster with**
Application 1	5 clusters	1 cluster shared for 99.4% of the exec. time	Application 2
Application 2	5 clusters	1 cluster shared for 74.6% of the exec. time	Application 1
		1 cluster shared for 99.9% of the exec. time	Application 3
Application 3	5 clusters	1 cluster shared for 83.0% of the exec. time	Application 2
		1 cluster shared for 16.9% of the exec. time	Application 4
		1 cluster shared for 99.9% of the exec. time	Application 5
Application 4	6 clusters	1 cluster shared for 75.6% of the exec. time	Application 3
		1 cluster shared for 37.1% of the exec. time	Application 5
Application 5	8 clusters	1 cluster shared for 15.7% of the exec. time	Application 3
		1 cluster shared for 45.6% of the exec. time	Application 4

Table I: Cache attacks vulnerability in baseline strategy with 77% average resources utilization rate

sor Array (MPPA) [Kalray's 2016], Mellanox' TILE-Gx36 [TILE-Gx36 2017] and TILE-Gx72 [TILE-Gx72 2017] processors, are some examples of many-core architectures.This work relies on the TSAR architecture [TSAR 2014] used as an accelerator. This latter is composed of clusters interconnected with a 2D-Mesh NoC. Each cluster is composed of 4 processing elements (PEs), a network interface and a L2 memory bank (here the L2 cache is the LLC). While L1 cache is private to each PE, L2 cache is shared among all clusters of the platform. Moreover, the physical address space of the main memory is statically partitioned into a fixed number of segments (equal to the number of clusters in the architecture). Each segment is statically mapped on a L2 memory bank as shown in Figure 1. Consequently, each cluster L2 memory bank is in charge of one memory segment. ***The memory is then logically shared among all the PEs but physically distributed. Indeed, L2 caches are instantiated close to the cluster's cores.*** This particularity of the architecture that was initially designed in order to allow a locality aware deployment is suitable as well for the implementation of the spatial isolation. For this work we consider a monotask PE. This prevents to share L1 caches. However processes executing on different processors still share the LLC. When launching an application through the host machine OS, the user specifies whether the application needs to be executed spatially isolated within a secure zone. The host machine is responsible for the launch and execution of applications. However, it can delegate part of the execution workload to the many-core accelerator. Moreover, depending on the user applications requirements, the host machine can request the accelerator manager to create a secure zone on the accelerator. On the accelerator side, a dedicated cluster allows the execution of the manager responsible for the dynamic deployment and execution of applications.

3.2. Case study cache-based attacks vulnerability

A study was conducted in order to evaluate the vulnerability to cache-based SCA of applications in a normal execution scenario on a many-core architecture. For this, a TSAR-like (Figure 1) [TSAR 2014] architecture and ALMOS OS [Almaless 2014] are considered. In this scenario, there is no security mechanism implemented. The architecture encompasses a 4×4 2D-mesh NoC connecting 16 clusters: 15 regular clusters encompassing 4 processors, and one manager dedicated cluster encompassing only one processor (61 processors in total). Table II summarizes the parameters of the architecture used for these experimentations. ***5 concurrent matrix multiplication applications are considered. Each executing a 256×256 matrix computations. Each application is composed of 17 parallel tasks. A master task creates the matrices, splits the computation load, creates 16 child tasks and sends to each the required data. Each child task makes its own computation and sends the results to the master task (see further details in Section 6.2.2)***. Tasks of each application may be spread across several clusters and thus may use and share several cluster memory banks (one LLC memory bank per cluster) with other applications. Experiment results, summarized in Table I, present, for each application, the percentage of its execution time where the application shared LLC memory banks, as well as the number of different applications the banks have been shared with. These results highlight the time that each application is vulnerable to cache-based attacks as well as the potential attacker processes (applications sharing LLC memory banks with). It can be concluded that, in this scenario, where the average resources (computing and memory) utilization rate is 77%, resource sharing introduces an important vulnerability for each application (from 15.7% up to 99.9% of their execution time) that needs to be addressed.

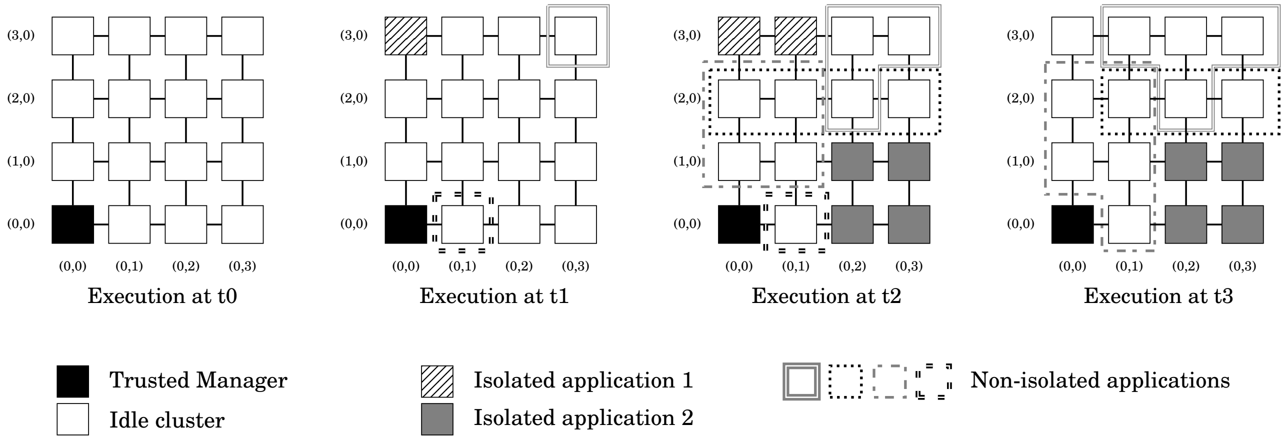


Fig. 2: Principle of spatial isolation

3.3. Threat model

For this work, the physical platform is considered trusted and not physically accessible. ***Furthermore, we consider that the attacker is able to know the code of sensitive applications running on the accelerator (e.g., cryptographic algorithm which code is public) and to trigger its execution, but cannot access it during runtime nor modify it.*** Finally, this work focuses on cache-based SCAs which do not require any physical access to the system. The manager on the accelerator executes the minimum services required to control the deployment and execution of the applications (Section 5). It is also responsible for the isolation mechanisms and secure zones deployment strategies. Hence, the software code running on the manager must be trusted (Trusted Manager). This work focuses on the dynamic application deployment, execution and resource management on the accelerator. Thus, we assume that:

— the manager on the accelerator is trusted (Trusted Manager) and the boot step is protected,
— the communication between the host machine OS and the Trusted Manager is protected,
— the off-chip accesses to external memory and peripherals as well as the NoC communications are secured.

Moreover, in this work, application migration is not considered due to the induced complexity and cost. Indeed, migration would imply the secure remapping of the application and processor context switch as well as the memory remapping of the application data and instructions in order to leverage data locality. However, migration might be considered in the future in order to cope with problematics such as dark silicon, component aging, faulty components, etc. Finally, sensitive and potentially malicious applications may run concurrently on the accelerator.

3.4. Spatial isolation of sensitive applications

In order to thwart cache-based SCAs, we consider the physical isolation of sensitive applications proposed in [Méndez Real et al. 2016a]. The aim is to prevent cache sharing for every critical application by temporarily dedicating physical resources (*secure zone*) for its execution. A secure zone, is composed of a number of clusters that are completely dedicated to a single sensitive application during its entire execution time. ***Secure zone clusters might be spatially contiguous in order to minimize the NoC latency on the communication between tasks within an isolated application.*** Secure zones are dynamically deployed, managed and released. In this way, cache sharing with an isolated application is avoided, and cache-based attacks are no longer possible against isolated applications. Moreover, several isolated applications can run simultaneously (Figure 2), each one within a separate secure zone. Finally, when an isolated application has been executed, memory within its secure zone is cleared in order to avoid any leakage of information. Figure 2 illustrates the principle of this technique for dynamic size secure zones. Different consecutive execution times are shown ($t0 < t1 < t2$). At *t0*, there is no load on the platform. Then, at *t1*, three different applications, including *Isolated application 1* requiring to be spatially isolated, are deployed and start their execution. At that time, there are enough available resources. Consequently, applications do not share resources and do not interfere with each other. Later, at *t2*, previous applications have extended on several clusters, secure zone 1 encompasses now two clusters which are dedicated and are not shared with any other application. Further, *Isolated application 2* has been deployed and executes within a 4 clusters secure zone. Other non-isolated applications have been deployed as well. Due to the increasing load on the platform, non-isolated applications are obliged to share their resources with each other. Before deploying a sensitive application, a secure zone is created dedicating a certain number of clusters, depending on the chosen deployment strategy (see Section 4). The sensitive application executes within the secure zone. Every task created by an isolated task is mapped and executed within the secure zone. Depending on the deployment strategy, secure zone resources can be dynamically released. Once the isolated application finishes, its remaining secure zone resources are released and memory within the secure zone is cleared in order to avoid any leakage of information. At this stage, released resources are declared available again and can be used by other applications. In order to integrate the new services required to dynamically manage the secure zones, the kernel services are extended. Notice that in this approach, the non-isolated applications still use and share caches with other untrusted applications.On the other hand, the dedication of secure zone clusters resources might introduce an under utilization of resources and thus a performance degradation. In this work, we focus on the implementation of this technique in order to minimize and handle the induced performance overhead.

4. DIFFERENT APPROACHES FOR THE DEPLOYMENT OF SECURE ZONES

To implement spatial isolation, the kernel executed by the Trusted Manager requires to be extended with new services responsible for the dynamic management of applications and secure zones.

4.1. Static approach

A naive approach is to create a secure zone of a static size in terms of clusters. It can be composed of all the needed resources in order to achieve the isolated application maximum parallelism. Or it can be restrained to a limited size. The secure zone size is assumed to be known (e.g., previously determined, specified by the user, or through application profiling). The secure zone is created and all the resources within it are dedicated before the first task of the application can start executing. The secure zone size being fixed, each new task within the application will need to be mapped on the secure zone resources. If the zone includes all the resources the isolated application needs, each time there is a new isolated application task, resources within its secure zone will be available and the task will be mapped without waiting for resources. Once all tasks of the isolated application are finished, all the secure zone resources are released and are declared available again. If there are not enough available resources to create a secure zone, another attempt will be made when a resource is released. Consequently, the application will wait for available resources. Figure 3 shows the flow of the secure zone creation for every deployment strategy, the dashed block corresponds to a secure zone creation algorithm (see Algorithms 1 and 2). Algorithm 1 is responsible for the creation of a fixed size secure zone. This algorithm is the base for every strategy presented below. Algorithm 1 explains the fixed size secure zone algorithm with the following notations (lists are spelled in upper-case letters while single elements and variables in lower-case letters):

- — A: architecture,
- — P: list of idle clusters in A,
- — l: required size in terms of number of clusters for the secure zone,
- — E: list of secure zone clusters,
- — c: an initial cluster from which the secure zone is created (white cluster in Figure 4),
- — d: current depth of explored clusters starting from c. ***Depth d is ranged from 1 to l. Figure 4 shows the cluster exploration space according to d, for l=3. Indeed, when d=1, only the initial cluster c is explored (white cluster in Figure 4). When d=2, the initial cluster c has been explored and its 4 direct neighbor clusters are explored (light gray clusters in Figure 4). Finally, when d=3, thus, d=l, (c and its 4 direct neighbor clusters have been explored) the neighbor clusters of the neighbor clusters of c are explored (dark gray clusters in Figure 4). In Figure 4, it can be seen that the solution, a zone of l contiguous clusters starting from c, can exist only within the represented zone (when d is less or equal to l, see Algorithm 1, line 33),***
- — Vc: list of explored clusters from c at current depth d (light gray clusters in Figure 4),

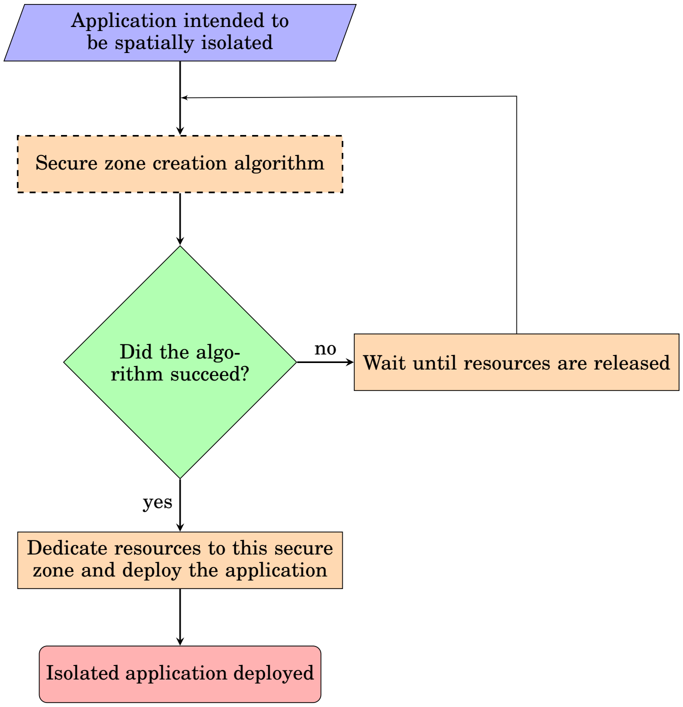

Application intended to be spatially isolated
Secure zone creation algorithm
Did the algorithm succeed?
no
Wait until resources are released
yes
Dedicate resources to this secure zone and deploy the application
Isolated application deployed

Fig. 3: Creating a Secure Zone

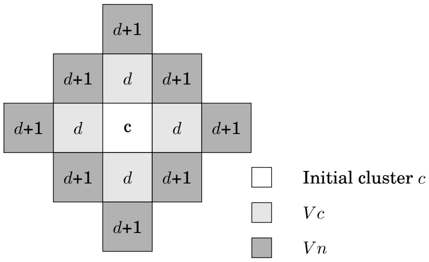


Fig. 4: Exploration of clusters

- c': the first cluster in Vc,
- $sort$(list): sort of clusters in a list by the distance between each cluster and the initial cluster c (in ascending order) and
- Vn: list of clusters to explore at depth d+1 (dark gray clusters in Figure 4).

For performance reasons, deployment strategies are based on greedy algorithms aiming at finding a solution, in this case l idle contiguous clusters, as fast as possible and not necessarily at finding the global best solution. ***The algorithm receives as input the architecture state as well as the required size of the secure zone (*** A***, and*** l ***respectively in notations above). It gives as output, a list of*** l ***contiguous clusters starting from a given cluster*** **initial cluster,** c ***in Algorithm 1 if success (here*** E***). On the contrary, if the algorithm does not succeed, then the output is a failure notification.***

Considering that idle clusters are in list P***, the algorithm considers each idle cluster as the initial cluster*** c ***(Algorithm 1, line 14), but stops as soon as it finds a solution. Starting from*** c***, it tries to find enough idle contiguous clusters by selecting for each cluster in the secure zone, the idle neighbor cluster the closest one to the original cluster*** c***. This, in order to minimize the communication cost between the*** **father task**, ***that will be mapped on the original cluster*** c***, and the children tasks created by the father task and mapped on the remaining clusters within the secure zone.***

First, the algorithm considers the first element in P ***list (Algorithm line 18), adds it to a list of currently considered clusters*** Vn ***(line 19), and removes it from*** P ***(line 20) in order to prevent from considering the same cluster again. Clusters in*** Vn ***are sorted in*** Vc ***by their Manhattan distance to the original cluster*** c ***in an ascending order (line 22). The variable*** d***, indicating the current clusters exploration depth, is increased. The closest idle cluster to*** c ***found (first element in*** Vc***),*** c'***, is added to the list of secure zone clusters*** E ***(line 27) and removed from*** Vc ***(line 28). If the required size of*** E ***is reached, then the algorithm is finished and*** E ***is returned. Otherwise, if the clusters exploration depth has not reached*** l***, then the idle direct neighbor clusters of*** c' ***in*** P ***are added to the currently considered clusters in*** Vn ***list and removed from*** P ***(lines 34, 35). This procedure is repeated until the list*** Vn ***is empty. Indeed, an empty*** Vn ***list indicates that there is no zone of*** l ***idle contiguous clusters starting***

ALGORITHM 1: Creating a fixed size Secure Zone

```
Input:
$l$: size of $E$ in terms of number of clusters
$A$: architecture
Output:
$E$: list of clusters in the Secure Zone if success,
FAILED: if failure
Let be:
$P$: list of idle clusters in $A$
$Vc$: list of clusters from $P$ to explore at depth $d$
$Vn$: list of clusters from $P$ to explore at depth $d$ + 1
$d$: current depth
$c$, $c$': clusters in $P$

while $P \neq []$ do
    $d$ := 0
    $Vc$ := []
    $E$ := []
    let $c$ being the first cluster in $P$
    $Vn$ := [$c$]
    remove $c$ from $P$
    while $Vn \neq []$ do
        $Vc$ := sort($Vn$), Vn is sorted by the distance from $c$ in ascending order
        $Vn$ = []
        $d$ = $d$ + 1
        while $Vc \neq []$ do
            let $c$' be the first cluster of $Vc$
            add $c$' to $E$
            remove $c$' from $Vc$
            if size($E$) = $l$ then
                return $E$
            end if
            for all $v$ a neighbor cluster of $c$' in $P$ do
                if $d$<$l$ then
                    remove $v$ from $P$
                    add $v$ to $Vn$
                end if
            end for
        end while
    end while
end while
return FAILED
```

from c in the architecture A. In this case, a different initial cluster c is selected in P. If every cluster in P has been considered as initial cluster, then, there is no secure zone of l idle contiguous clusters. In this case the algorithm returns a failure notification.

— **Advantages:** ***In this approach, the size of the secure zone, in terms of clusters, is determined before its deployment. The amount of resources that the secure zone will include, will determine the parallelism that the isolated application will be able to achieve. Therefore, the performance of the isolated application can be favored by selecting a suitable secure zone size. The application will indeed be able to achieve its maximum parallelism if the secure zone is composed of all the resources needed by the isolated application.***

— **Drawbacks:** ***On the other hand, before the isolated application can be deployed, it will wait until the necessary contiguous clusters are available in order to create its secure zone.*** Thus, we can expect an extra waiting time before the execution of isolated applications that will depend on the load of the accelerator and size of its secure zones. Moreover, since the resources within the secure zone are dedicated to a single sensitive application during the application entire execution time, an under-utilization of resources within the secure zone is expected. ***In the same way, the untrusted applications are prevented to use the dedicated resources, which will impact their performance as well as the global performance (i.e., execution time of the set of applications running on the accelerator) due to the potential under-utilization of resources within the secure zones.***

4.2. Dynamic approach

In order to cope with the under-utilization of resources within secure zones, three approaches involving a dynamic secure zone size have been considered.

ALGORITHM 2: Creating a dynamic size Secure Zone

```
Input:
$A$: architecture
Output:
$E$: list of clusters in the Secure Zone if success,
FAILED: if failure
Let be:
$c$: cluster in $A$

$E$ := []
for all $c \in A$ do
    add $c$ to $E$ if $c$ is idle
    return $E$
end for
return FAILED
```

ALGORITHM 3: Extending a dynamic size Secure Zone

```
Input:
$E$: list of clusters in the Secure Zone,
$A$: architecture
$c$: original cluster on which the father task is mapped
Output:
$E$: list of clusters in the Secure Zone if success,
FAILED: if failure
Let be:
$P$: list of idle clusters in $A$
$Vc$: list of clusters from $P$
$Vn$: list of clusters from $Vc$
$c'$: a cluster in $E$
$c''$ a cluster in $Vc$

for all $c' \in E$ do
    $Vc$ := []
    $Vn$ := []
    for all $v$ a non explored neighbor cluster of $c'$ in $P$ do
        add $v$ to $Vn$
    end for
    if $Vn \neq$ [] then
        $Vc$ := sort($Vn$), $Vn$ is sorted by the distance from $c$ in ascending order
        let $c''$ be the first cluster of $Vc$
        add $c''$ to $E$
        return $E$
    end if
end for
return FAILED
```

4.2.1. Fully dynamic approach. In this fully dynamic approach, the size of the secure zone is dynamically adapted to the needs of the isolated application according to the load of the platform. For this, the isolated application requires only one single idle cluster to form its initial secure zone (see Algorithm 2), and physical clusters are dynamically added (Algorithm 3) and released from the secure zone. When a new task belonging to an isolated application requires to be mapped, the dynamic approach algorithm first searches for an idle processor within the secure zone. If there is no idle processor within the secure zone, then it searches for an idle cluster contiguous to clusters within the secure zone. If no contiguous cluster is available, then, there are two possibilities, either the new task waits until a resource within the isolated application secure zone is released, or the task waits until a resource on the architecture is released and the secure kernel adds it to its secure zone.

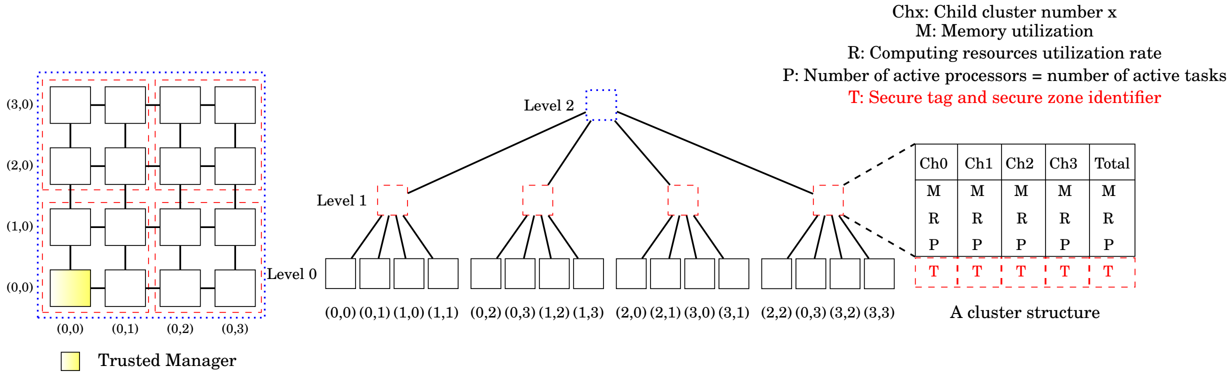
- **Advantages:** Isolated applications might wait a shorter time than in a static size approach since an isolated application only needs one single cluster to start executing. Moreover, since the size of a secure zone is dynamically adapted, a better utilization of resources is expected. Consequently, the performance of untrusted applications may be less penalized.
- **Drawbacks:** While this approach might entail better resources utilization and less impact on the untrusted applications performance, isolated applications performance will no longer be a priority. Consequently, we can expect that increasing the secure zones size will be more difficult.

4.2.2. Hybrid approach. A variant of the fully dynamic approach explained above, is to dedicate a non-optimized number of clusters (specified by the user, parameter l in Algorithm 1) to an isolated application before executing it, but to dynamically add resources to the secure while needed (following the approach presented in Algorithm 3). In this approach the isolated application needs to wait until the secure kernel finds the minimum number of clusters required to form a secure zone before starting its execution. Once the secure zone is created and the secure kernel launches the execution of the isolated application, clusters can be dynamically added and released, but the minimum specified secure zone size is always guaranteed.

- **Advantages:** This solution guarantees a minimum size of the secure zone, and by consequence, a minimum performance of the isolated application. On the other hand, it also takes into account the current load of the accelerator when trying to dedicate more resources to the secure zone. Resources utilization rate is thus expected to be better than in a static approach thanks to dynamism. Moreover, untrusted applications are expected to be less penalized than in the static secure zone size scenario since less resources are expected to be dedicated.
- **Drawbacks:** However, this solution may penalize the isolated applications performance since achieving their maximum parallelism is not guaranteed. Finally, this solution requires fixing a minimum secure zone size for each isolated application.

4.2.3. Resource reservation. ***An approach in order to favor the dynamic extension of secure zones when there are not enough available resources to create a secure zone of a suitable size (e.g., encompassing all the resources the isolated application needs), is to reserve currently non-available resources, in order to prevent other applications from using them once they are declared completely available again. Indeed, when an application intended to be isolated is ready to be mapped and there are not enough available resources to create an optimal size secure zone (referred to as l), the largest available zone is chosen (of size l') and dedicated to the isolated application which immediately starts its execution. Further, the number of missing clusters on the secure zone (l-l') are selected among contiguous clusters to be*** **reserved.** ***These latter need to be contiguous to clusters within the secure zone or if necessary, to the reserved clusters. Reserved clusters are tagged and when a resource within them is available, it will not be allocated to any other (trusted or untrusted) application. Once all the resources within a reserved cluster are declared available, the kernel adds it to the secure zone if the isolated application still needs it. Moreover, the secure kernel will constantly update the number of required clusters by the isolated application. In the meanwhile, if there are not sufficient clusters within the secure zone, isolated application tasks will need to wait for computing resources in its secure zone to be released. In this case, less reserved clusters would be necessary. Consequently, the secure kernel may dynamically release reserved clusters. As in this work application migration is not considered (see Section 3.3), once an isolated application starts to be executed, it cannot be migrated when a larger zone than its current secure zone is released.*** More sophisticated parameters can be used in order to decide which clusters are worthy to reserve. Indeed, the execution time left for processors in each cluster or the number of pending tasks could also be taken into account when selecting clusters to reserve. While this would entail higher and more complex activity on the secure kernel, it would certainly increase the chances of extending the secure zones.

- **Advantages:** In case of a *good* bet, this solution can be very interesting as isolated applications only need one single cluster to start to be executed and reserved clusters allow achieving a good performance of isolated applications. Furthermore, the dynamism of the approach entails *good* resources utilization rates.
- **Drawbacks:** On the other hand, if the bet turns out to be *bad*, this approach can be very penalizing for isolated applications. In fact, if the reserved resources are not released during the execution of the isolated application, then, the secure zone will not be extended and new tasks within this application will wait for other tasks within the secure zone to finish in order to start its execution. Consequently, the isolated application may not achieve its maximum performance depending on the load of the accelerator and on the quality of the bet. Moreover, this approach requires a high activity on the trusted kernel compared with a static approach.



Physical architecture (Level 0 clusters)

Associated monitoring structure

Fig. 5: Overview of the monitoring structure

5. IMPLEMENTATION: BASELINE STRATEGY AND ITS EXTENSION

The services responsible for the dynamic allocation and management of resources on the accelerator (*kernel services*) are executed on a dedicated processor called *manager*. In their original state, they do not encompass any security mechanism and have been designed to favor performance based on the implementation of the ALMOS OS [Almaless 2014] (baseline strategy). These services have been extended in order to integrate the spatial isolation mechanisms proposed in this work. In this section, key kernel services are explained in their original and extended versions.

5.1. Monitoring

The state of the accelerator needs to be constantly monitored in order to dynamically make decisions on the resource allocation. For performance purposes, as in [Almaless 2014], a tree structure showing the state of each cluster has been implemented. Figure 5 shows an overview of the monitoring structure for a 16 clusters architecture, each cluster encompassing 4 processors. In this tree structure, physical clusters (level 0 clusters) are grouped by 4 forming a logical cluster (level 1). In the same way, logical clusters are grouped by 4 forming an upper level logical cluster (level 2). Each physical or logical cluster is associated with a data structure (*A cluster structure* in Figure 5) containing some parameters describing the state of the resources (the processors and memory utilization rates as well as the number of active processors and tasks). For a physical cluster, the first 4 columns in its corresponding cluster structure concern the state of the memory and the computing resources within the physical cluster. The fifth column is the sum of the 4 first columns. On the other hand, for a logical cluster the first 4 columns concern the states of the 4 child clusters (lower level clusters). The fifth column concerns the sum of the first 4 columns. This organization has been designed for performance purposes as it allows, when visiting the structure from top to bottom, to bypass clusters that do not provide enough resources for the current request. Moreover, it allows a bottom-up approach as well, in order to locally find available resources from a given physical cluster. While the shape and size of the monitoring structure are static, the parameters within the cluster structures describing the state of the accelerator are regularly updated. Two monitoring updates are implemented. First, a systematic one is made when a task is mapped on a processor or when a processor is released. For this update, it is necessary to visit and update values of the concerned physical cluster(s) but also of each upper level parent (logical) cluster. Second, resources utilization rates are periodically updated. The monitoring structure is consulted each time a decision on resource allocation needs to be made.

Extension: The monitoring structure has been extended in order to associate to each cluster a secure tag indicating if the cluster is dedicated to a secure zone as well as the secure zone identifier (*T* in Figure 5). In fifth column, this active tag would indicate that all child clusters are already dedicated to a secure zone. Secure tags and secure zone identifiers are taken into account when taking a resource allocation decision, since these clusters are not available to other applications while tagged secure.

5.2. Mapping new applications or new tasks

The new application and new task mapping services are described in this subsection. First, the algorithm responsible to map new applications aims at finding a **good** ***processor to map the new task. At most, this algorithm visits the entire monitoring structure. The structure browse starts from the highest level cluster (i.e., the root of the tree structure, level 2 in Figure 5). The aim is to find an idle processor. For this, if according to the fifth column values there is at least one idle processor, the first 4 columns are visited until one idle processor is found. When it is the case, the child cluster containing the found idle processor is visited. The process is repeated until an idle processor is found on a physical cluster. If there is no idle processor on the entire platform, the task is added to the pending tasks list and it will wait for a processor to be released. Second, a task may ask for the mapping of*** **child** ***tasks. Parent and child tasks are expected to communicate together. In order to favor performance, the mapping algorithm aims at minimizing the communication costs. For this purpose, a child task must be mapped the closest possible to its parent task. Indeed, the task mapping algorithm searches for an idle processor starting from the physical cluster of the parent task (level 0 cluster). If no idle processor is found in this cluster, the algorithm goes up and searches on the logical cluster containing the parent physical cluster (level 1 cluster). The algorithm consults then the fifth column of the logical cluster structure and if there is at least one idle processor in one of the child clusters (level 0), it goes down to the found cluster. On the other hand, if there is no idle cluster, the algorithm goes up to the parent cluster (level 2 logical cluster). This process is repeated until either one idle processor is found, or the entire structure has been visited and no idle processor is found. In this last case, the task is added to the pending tasks list and it will wait for a processor to be released.***

Extension: ***These two services have been extended considering that, when deploying a new application or task, the Trusted Manager knows whether it is intended to be isolated. If the new application or task to be mapped does not require to be isolated, then the*** **original** ***mapping algorithm is used. However, resources within clusters tagged secure in the monitoring structure are considered temporarily not available for non-isolated applications. Consequently, the original service algorithm exploration zone might be reduced since clusters tagged secure are not visited. On the other hand, if the application or task requires to be isolated, then the Trusted Manager uses one of the new algorithms for the creation and management of a secure zone proposed in this work according to the considered strategy presented in Section 4.***

5.3. Releasing secure clusters

When an isolated application is finished, all the clusters remaining within its secure zone are released. Additionally, in dynamic secure zone size approaches, clusters are dynamically released. When a cluster from a secure zone is released, different steps are taken. First, memory within the cluster as well as remanent information (buffers, registers, state of the caches) need to be cleared in order to avoid any leakage of information. Second, the cluster is declared available again. This latter step requires to modify the secure tag T ***in the monitoring structure (Figure 5), for the corresponding cluster structure. Finally, the monitoring structure is updated in order to propagate the new information.***

The extension of the kernel services including the different strategies presented in Section 4 have been implemented and compared via a virtual prototyping environment.

6. EVALUATION ENVIRONMENT AND EXPERIMENTAL SETUP

In this section, the virtual prototyping tool used for these evaluations and the experimental setup are presented.

6.1. Evaluation environment

The extension of the kernel manager services including the proposed deployment strategies have been evaluated and compared through the MPSoCSim tool [Wehner et al. 2015]. MPSoCSim is based on the Open Virtual Platforms (OVP) technology [OVP 2017], coupled with SystemC models [SystemC 2017]. It allows the evaluation of clustered NoC-based multi- and many-core architectures [Méndez Real et al.

Processor parameters	**Chosen value**
Cortex A9 ARM Frequency	667MHz
MicroBlaze (MB) Frequency	100MHz
Nominal MIPS	100
Real flit time (ARM)	850ns
Real flit time (MB)	40ns
System memory parameters	**Chosen value**
L1 cache size	64 KBytes
LLC Size	3 MBytes
NoC parameters	**Chosen value**
Network frequency	100MHz
2D Mesh network size	4×4 clusters
Number of processors per regular cluster	4
Number of processors in total	60 MBs + 1 ARM
Router clock delay pass through	1 cycle

Table II: System parameters used for the Sevaluations

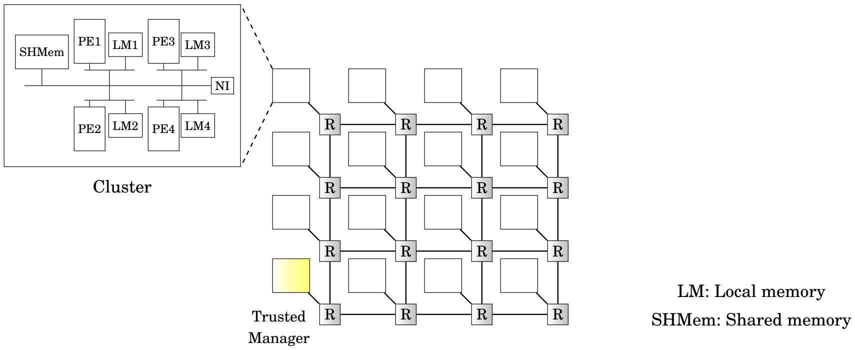


Fig. 6: Overview of the prototyped system

2016b]. MPSoCSim relies on a system level modeling SystemC NoC where each router is connected to a SystemC Transaction Level Modeling standard (TLM-2.0) Network Interface (NI) connected to a local group called cluster. Each cluster can encompass up to 4 OVP processor models, each one connected to its local memory and shared resources within the cluster such as shared memory and a NI.

6.2. Experimental setup

6.2.1. MPSoCSim setup. For the evaluation of the experimentations presented in this work, a 2D mesh 4×4 NoC-based system has been prototyped (Figure 6). The NoC is composed of 15 *regular clusters* of 4 processors each, and one cluster encompassing one single processor dedicated to the execution of the kernel manager services. The system encompasses 60 processors and 1 processor dedicated to the kernel manager services. Each processor is connected to a private and shared memory that emulate L1 and L2 memory banks respectively. Table II summarizes the system parameters used for the experimentations. Notice that the chosen NoC parameters are identical to those used for the validation of the MPSoCSim tool [Wehner et al. 2015] providing reliable results.

6.2.2. Execution scenario. In this subsection, the Trusted Manager, the evaluated applications and execution scenarios are presented.

— Many-core accelerator Trusted Manager:
For these experimentations, one processor is dedicated and acts as the Trusted Manager of the accelerator. It computes the decision algorithms for the dynamic deployment of the applications (see Section 5), as well as the services needed for creating and handling secure zones (Section 4).
— Applications:

We consider that, when launching an application, the user specifies whether it requires to be isolated within a secure zone. Synthetic applications with a high degree of parallelism such as matrix multiplications are used. Each application corresponds to 256×256 matrix computations. A first task (*master* task), generates the matrices, splits the computation and dynamically sends the data to each mapped *slave task*. Slave tasks can be mapped on the cluster executing the master task or on distant clusters according to the load of the platform. Slave tasks access to the memory within their cluster, perform the corresponding computation and send back to the master task the generated results.When a task is finished, its PE is released and the Trusted Manager flushes the corresponding memory partition. A 17 parallel tasks application allows the study of an unfavorable scenario for the considered system. Indeed, when the size of the secure zone is fixed to achieve the application maximum parallelism, or when there are sufficient available resources, the secure zone will be composed of 5 clusters out of 16 in this considered case. However, only 17 processors out of 20 will be used. In consequence, 3 out of 4 processors on the 5th cluster will not be used, which represents an unfavorable case for the considered architecture. Applications are duplicated in order to increase the workload on the accelerator. All the applications are supposed to be ready to execute from the beginning of the execution scenario. However, a priority level is associated to each application (master task) to determine in which order the ready tasks are served. For these experimentations, 5 applications, each one composed of 17 parallel tasks, are concurrently executing. This is 85 concurrent tasks in total and an average resources utilization rate of 77% when there is no isolated application.

— Evaluated secure zone deployment and management strategies:
The deployment strategies explained in Section 4 have been evaluated and compared:
  — **baseline strategy** This scenario corresponds to the minimum services presented in Section 5. It does not include any security mechanism and no application is isolated.
  — **Strategy A.1.** Secure zones with a fixed size encompassing all the resources needed by the spatially isolated application in order to achieve its maximum parallelism. In the case considered in this work, the application parallelism is 17 tasks running in parallel and clusters are composed of 4 PEs. Consequently, the secure zone size in this case encompasses 5 clusters (20 dedicated PEs in total).
  — **Strategy A.2.** Secure zones with a fixed restrained size limited to 4 clusters.
  — **Strategy B.1.** Fully dynamic approach.
  — **Strategy B.2.** Hybrid approach. In this case we fixed the guaranteed minimum secure zone size to 2 clusters.
  — **Strategy B.3.** Resource reservation.

— Evaluated execution scenarios:
For the evaluation of the performance overhead induced by each proposed strategy, different execution scenarios have been considered.
  — **Single zone, priority 1 scenario.** One single application (out of 5) requires to be spatially isolated within a secure zone. In this first scenario, this application has the highest priority (1 out of 5, 1 being the highest and 5 the lowest priority). ***Consequently, when mapped, there is no load on the platform. This is the best scenario for an isolated application since it will be mapped the first one, then when there is no load on the accelerator.***
  — **Single zone priority 4 scenario.** One single application needs to be isolated. However, unlike the previous scenario, this application has a medium priority (4 out of 5). This allows to take into account the load of the accelerator when trying to create the secure zone.
  — **Multiple zones, multiple priorities scenario.** In this last scenario, the load of the accelerator, as well as the number of applications requiring to be isolated, are considered. In fact, 3 out of 5 applications, with priority levels of 1, 3 and 5 respectively, require to be spatially isolated.

7. RESULTS

In this section, results of each pair of deployment strategy and each execution scenario are presented. Then, results are summarized and strategies are compared according to several performance metrics.

7.1. Results organization

Applications introduced in Section 6.2.2 are first run concurrently without any secure-enable mechanism (*baseline strategy*). Then, applications are concurrently run according to each pair of secure zone deployment strategy, and execution scenario. Finally, since approaches are deterministic, experiments are run once. The main objective is to compare the different deployment strategies for the implementation of the spatial isolation in terms of induced performance overhead and to analyze them according to different performance metrics:

— total execution time for the set of applications,
— average execution time of spatially isolated applications,
— average execution time of non-isolated applications,
— average computing resources utilization rate,
— execution time spent on the kernel services impacted by the spatial isolation mechanisms,
— average time the isolated applications wait before been mapped.

Apart from resources utilization rates in Table III, overhead results are presented in terms of percentage compared to the baseline strategy. Results in Figures 7 to 11 and Table III allow the comparison of each performance metric for each pair of secure zone deployment strategy, and execution scenario (Section 7.2). Then, Figures 12 to 14 gather results of every performance metric classified by execution scenario.

7.2. Comparison according to each performance metric

First, notice that, execution scenario Single zone, priority 1 is particular. In fact, in this scenario, the application intended to be spatially isolated is served the first one since it has the highest priority. Consequently, when the manager deploys it there is no load on the accelerator. As a result, strategies with a guaranteed minimum secure zone size (B.2.) and with resource reservation (B.3) give similar results than 5 cluster static secure zone size strategy A.1. Indeed, in B.2 strategy, only the kernel services execution time and total performance overhead are slightly different. Regarding B.3, it turns out to be identical than A.1 since the algorithm finds a secure zone encompassing all the resources needed by the application (5 clusters secure zone) directly without requiring to reserve any cluster. In this subsection, results for each performance metric are presented.

The **total execution time** overhead for each pair of secure zone deployment strategy, and execution scenario, is presented in Figure 7. While the dynamism in the considered scenarios makes it difficult to explain every aspect of the results, several observations can be made. First, according to these results, the static 5 clusters Secure Zone (SZ) (**A.1.** strategy) turns out to be the best solution in the evaluated scenarios providing the lowest overhead on the total execution time, almost negligible when there is no load on the accelerator (0.04%). While limiting the size of the SZ to 4 clusters (**A.2.**) entails a higher overhead than a 5 clusters SZ, the rest of the strategies does not seem to follow any trend but depend on the execution scenario. In order to better understand and compare these results, it is important to take into account that the total execution time is mostly impacted by both, the applications (isolated and non-isolated) execution time as well as the time spent on the Trusted Manager services for the execution of the deployment mechanisms. Finally, notice that applications and the Trusted Manager run in parallel. In order to compare the impact of different deployment strategies, **the execution time of both, isolated and non-isolated applications** are highlighted in Figures 8 and 9 respectively. ***First, in Figure 8, it can be seen that in scenario Single zone, priority 1, results are negative. As these results represent an overhead, negative ones indicate a better performance (reduced execution time) for isolated application(s) compared to the baseline strategy when the considered application was not isolated. This is explained by the exclusiveness of cluster resources and by the fact that, since the isolated application has the highest priority in this scenario, it is deployed the first one when there is no load on the platform. Indeed, contrary to the baseline strategy, isolated applications do not share cluster resources which avoids resource concurrency. Moreover, due to the highest priority of the isolated application, all the strategies, except for A.2., achieve the optimal size for the secure zone (5 clusters in this case), statically (i.e., A.1. strategy), or dynamically (B strategies). Consequently, the isolated application achieves its maximum parallelism which entails achieving better performance. In the A.2. strategy on the contrary, the size of the secure zone is fixed to a non-optimal size (4 clusters in this case), regardless of the fact that at the deployment time, all the resources are available on the accelerator.*** Furthermore, the static 5 cluster SZ strategy (**A.1.**) always achieves a very good performance of isolated applications, but penalizes non-isolated applications. Moreover,

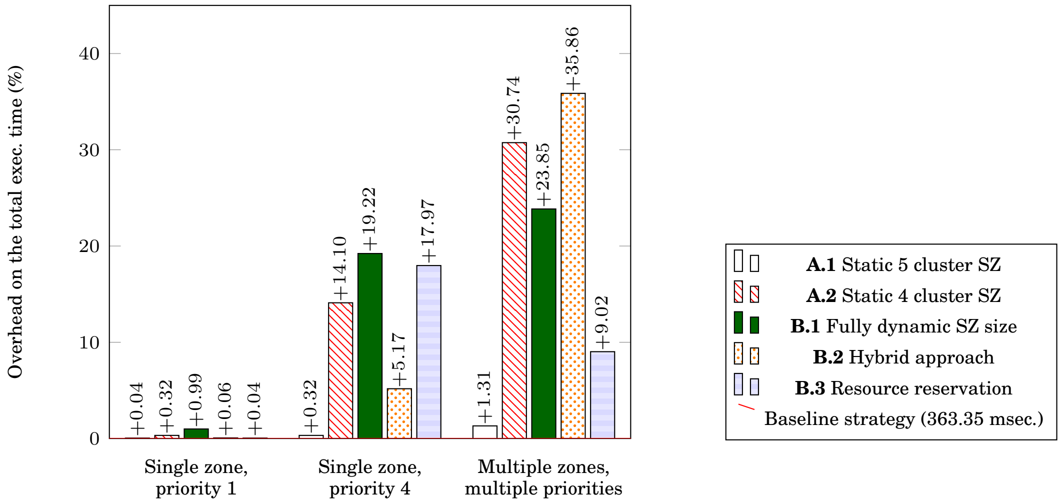


Fig. 7: Total exe. time overhead (in %) compared to the baseline strategy

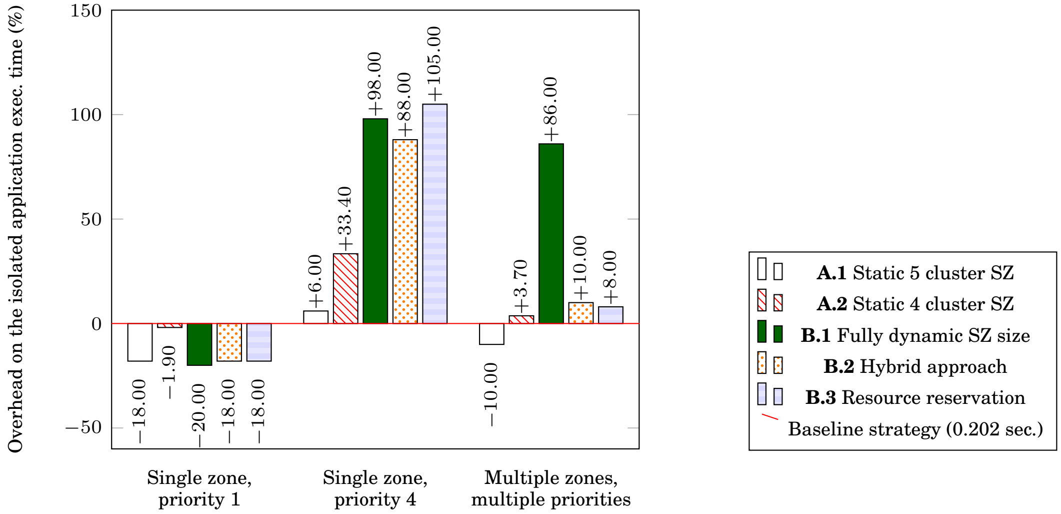


Fig. 8: Overhead on the average exec. time of **isolated** applications, in % compared to the average application exec. time in the baseline strategy

when limiting the resources within the secure zone (**A.2.**) the performance of isolated applications is lower than in the first strategy for every scenario. However, limiting the secure zone size to 4 clusters (**A.2.**) instead of 5, further penalizes non-isolated applications execution time. This is because less resources are dedicated (only 4 clusters) and thus not available for non-isolated applications, but for a longer time. Indeed, in this case, isolated tasks need to wait for available resources within the secure zone, entailing longer execution time and thus longer resources dedication time. Furthermore, the fully dynamic strategy (**B.1**) and hybrid approach (**B.2.**) tend to penalize isolated over non-isolated applications. However, the hybrid approach guarantees a minimum number of resources for isolated applications so they can achieve better performance.

On the other hand, the **time spent by the Trusted Manager** kernel on the services impacted by the isolation mechanisms proposed in this work are presented in Figure 10. ***These services are: mapping of each application and task (both, isolated and non-isolated), dynamic allocating and releasing resources, as well as creating, managing and releasing secure zones. Results are presented in terms of induced overhead in percentage of the time spent on the baseline***

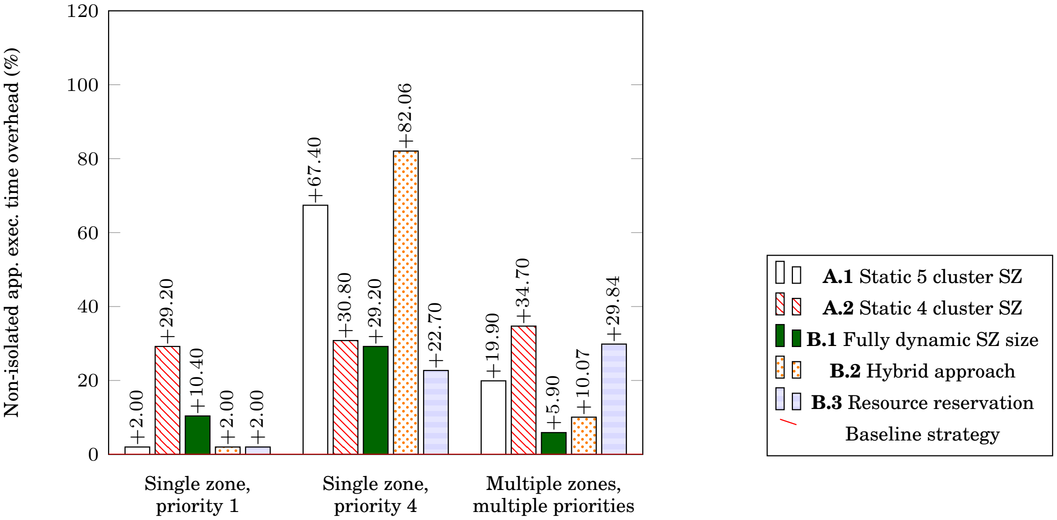


Fig. 9: Overhead on the average exec. time of **non-isolated** applications, in % compared to the average application exec. time in the baseline strategy

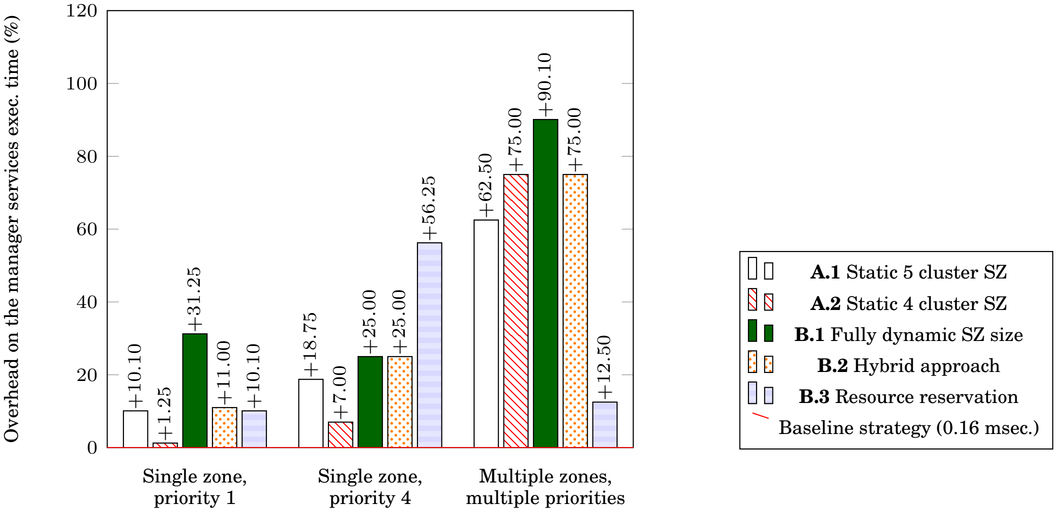


Fig. 10: Time spent on the Trusted Manager kernel services impacted by the secure-enable mechanisms in % compared to the baseline strategy

strategy. Dynamic strategies require a higher activity on the Trusted Manager compared to static secure zone size strategies. ***Moreover, resource reservation results greatly vary according to each scenario. This is because its performance totally depends on the quality of the bet when selecting the resources to reserve. Smarter selection metrics would improve results and would make them more steady (see Section 7.3)***. Furthermore, according to the secure zone deployment strategy and to the load of the accelerator, isolated applications require to **wait before they can be deployed**. In fact, in a static secure zone scenario, the Trusted Manager will wait until there are enough available resources before it can create a secure zone. Figure 11 shows the average time that isolated applications wait before being deployed for each deployment strategy and execution scenario. It can be noticed that strategies able to guarantee a number of dedicated resources to the secure zone introduce an extra delay depending on the accelerator load. ***Finally, although overheads in Figure 11 seem significantly penalizing compared to the baseline scenario, these are negligible compared to the application execution time (up to 2.5%) and are already included in the to-***

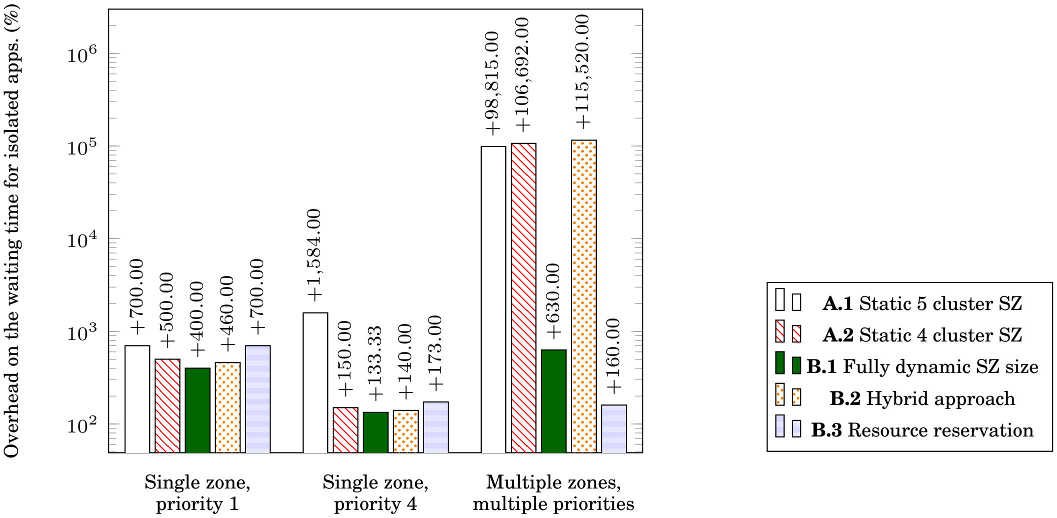


Fig. 11: Overhead on the average waiting time before the deployment of **isolated** applications, in % compared to the baseline strategy

	Single zone, pr. 1		**Single zone, pr. 4**		**Mult. zones, mult. priorities**	
	SZ	**Total**	**SZ**	**Total**	**SZ**	**Total**
Static approach, optimal size (5 clusters)	85%	68,5%	85%	71%	85%	61,6%
Static approach, limited size (4 clusters)	65%	64%	65%	69%	65%	55%
Fully dynamic	85%	72%	89%	69%	92%	67%
Hybrid approach	85	68.5%	81%	60%	85%	55,6%
Resource reservation	85%	68.5%	85,4%	67%	86,2%	65%

Table III: Computing resources utilization rate within secure zone(s) (*SZ*) as well as in total (*Total*). The resources utilization rate in the baseline strategy is 77%

tal execution time for the set of applications running on the accelerator in Figure 7 as well as in the execution time of the isolated applications in Figure 8.

In Table III the **computing resources utilization rate** is compared in total as well as within dedicated clusters to secure zones for each deployment strategy and execution scenario. While the resources utilization rate within secure zones allows the comparison between different deployment strategies with each other, the resources utilization rate in total shows the overhead of each deployment strategy compared to the baseline strategy (with a resources utilization of 77%). In this table, for each column the best and worst rate are highlighted in light and dark gray respectively. It can be noticed that since the fully dynamic strategy (**B.1.** strategy) adapts the resources the best to the needs of applications and load of the accelerator, it achieves the best resources utilization rates.

7.3. Strategies comparison according to each execution scenario

Figures 12, 13 and 14, gather the results presented above in order to allow the comparison of the strategies according to each different performance metric for each execution scenario. The values of each performance metric of Section 7.1 are presented in terms of induced overhead in percentage compared to the baseline strategy (dashed line at 0% on the chart). Moreover, the scale is arranged in order to present results in such a way that, for each parameter (each axis), the closer a value is to the chart border, the better. Finally, for readability reasons, results concerning the *waiting time* are presented in their *log* value.

— Static approach: When the size of the secure zone is well chosen, this approach is the best solution for the performance of isolated applications. However, when the secure zone size is not well chosen,

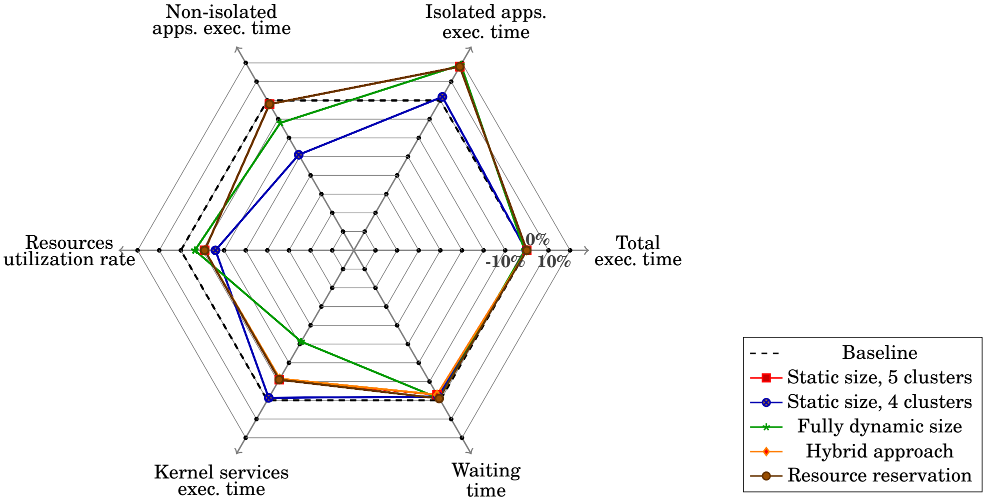


Fig. 12: Single zone, priority 1 scenario. Values presented in terms of induced overhead in % compared to the baseline value. **Arranged scale**: the closest to the chart, the better. Scale: 1 division : 10%

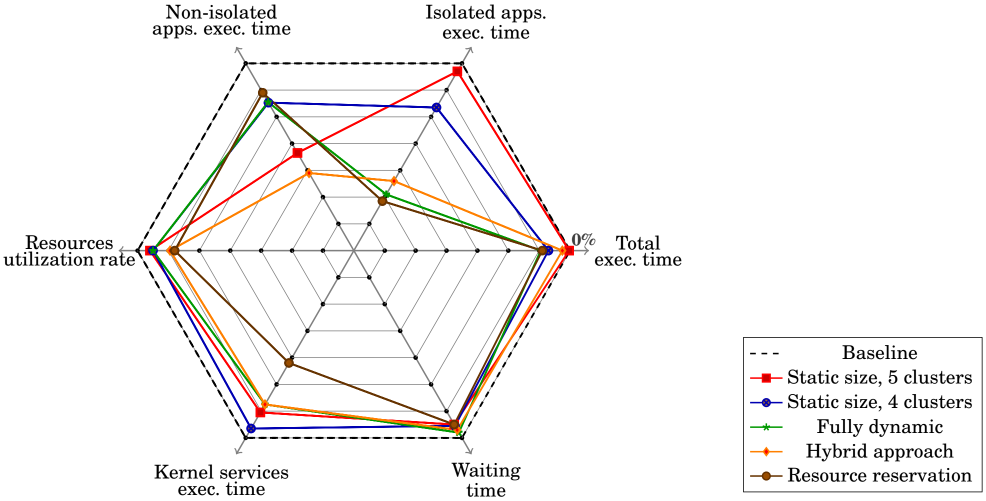


Fig. 13: Single zone, priority 4 scenario. Values presented in terms of induced overhead in % compared to the baseline value. **Arranged scale**: the closest to the chart, the better. Scale: 1 division : 20%

for example in the **A.2.** strategy, applications performance (both isolated and non-isolated) may be very penalized. In fact, in **A.2.** strategy, only 4 clusters instead of 5 are dedicated to the sensitive application. Unlike what could be expected, this solution further penalizes non-isolated applications than in **A.1.** because the resources are dedicated much longer since some isolated application tasks require to wait for other tasks within the same secure zone to release their resources. Consequently, the isolated application execution time is much longer. On the other hand, in static secure zone size approaches, isolated applications require to wait longer to start their execution depending on the availability of resources. However, once they are mapped, they may achieve very good performance. In conclusion, this approach is suitable when the performance of isolated applications is a priority, however it requires a very good knowledge of the isolated applications in order to choose a good size of the secure zone.

— Fully dynamic approach: This approach is the best one when it is required to maximize the resources utilization rates within the secure zones and in total, and when the performance of isolated applications is not a priority. Indeed, it does not entail a significant performance overhead on the

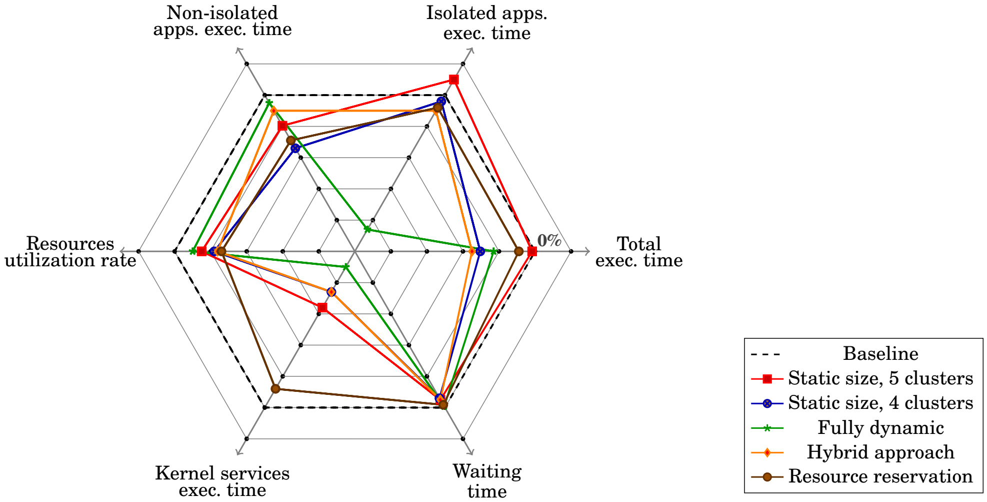


Fig. 14: Multiple zones, multiple priorities scenario. Values presented in terms of induced overhead in % compared to the baseline value. **Arranged scale**: the closest to the chart, the better. Scale: 1 division : 20%

total execution time (total execution time overhead from 0.99% in scenario **Single zone, priority 1**, up to 23.85% in scenario **Multiple zones, multiple priorities**). However, it tends to penalize the performance of isolated applications and entails a high activity on the Trusted Manager.

— Hybrid approach: This approach is a good trade-off between fully dynamic and completely static approaches. It guarantees a minimum number of dedicated resources to the isolated application, thus a minimum performance. Also, this approach takes into account the load of the accelerator when trying to extend the secure zones. As a result, non-isolated applications are less penalized than in **A.1.** strategy. Moreover, due to its dynamic side, this approach achieves a good resources utilization rate, but entails more activity on the Trusted Manager compared to a static approach.

— Resource reservation: This approach is interesting but requires more sophisticated metrics when selecting resources to reserve. Indeed, the size of the secure zone as well as the performance of the isolated application depend on the load of the accelerator when creating a secure zone, and on the bet. In this approach, no performance is guaranteed. More complex reservation metrics are necessary in order to increase the chances of extending a secure zone and achieving good performance of isolated applications. However, it would lead to higher complexity of the kernel algorithms.

7.4. Further experimentations with different applications

In this subsection, two different applications were considered in order to study the impact of the spatial isolation mechanisms on a second execution scenario. For these experimentations, an AES encryption and decryption based on axTLS implementation [axTLS 2016] [axTLS implementation 2017] is used in addition to matrix multiplications. As for previous experiments, 5 concurrent applications with different priorities are considered. First, one task-application is performing an AES encryption and decryption of a 64 bytes message following the Cypher Block Chaining (CBC) mode with a 256 bits key (test vectors were taken from [test vectors 2001]). Additionally, matrix multiplications are used (see description in Section 6.2.2). Three different scenarios are evaluated, in every scenario, only the AES application is isolated. In Single zone, priority 1 and Single zone, priority 4 scenarios, an AES application, additionally to 4 matrix multiplications are executed. Moreover, the AES application is isolated on a 1 cluster-secure zone and has priorities 1st and 4th respectively. Finally, in the third scenario (Multiple zones, multiple priorities) 3 AES and 2 matrix multiplications are executed. AES applications have priorities 1st, 3rd and 5th respectively. Finally, each scenario was compared to their baseline scenario in which no application is isolated. Figure 15 shows the performance overhead of the isolation mechanisms in scenarios Single zone, priority 1 and Single zone, priority 4 on both, the total execution time for

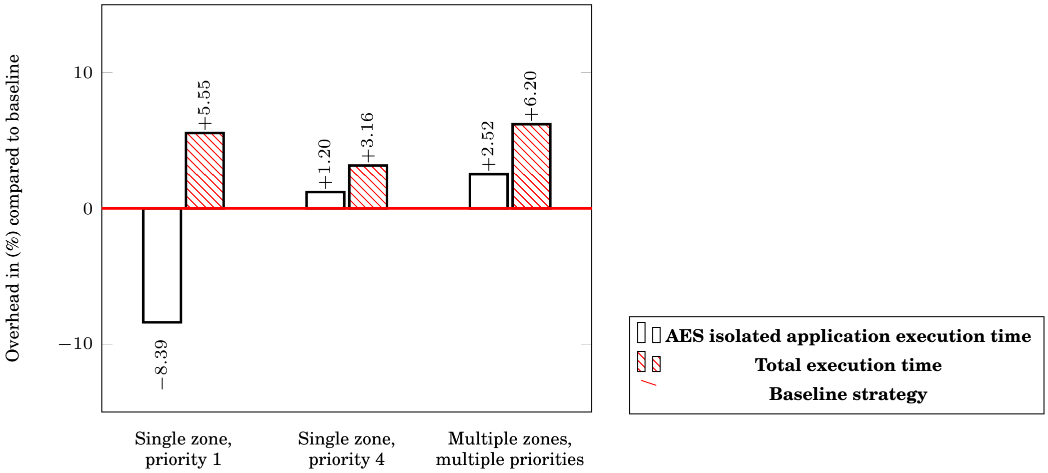


Fig. 15: Overhead of the spatial isolation mechanisms in % compared to the baseline strategy

performing the set of considered applications, as well as on the execution of the isolated application. Results are presented in terms of percentage compared to the baseline scenario. These results show little overhead on the total execution time, up to 5.55% in Single zone, priority 1 scenario, that increases with the number of secure zones (up to 6.2% in multiple zones, multiple priorities). However, similarly to results in Section 7.2, the performance of the isolated application is less impacted (up to 1.2% in Single zone, priority 4 scenario) and can even be improved according to the load on the platform due to the dedication of resources to its execution (down to -8.39% in Single zone, priority 1 scenario).

8. DISCUSSION

This section first discusses results regarding the threat model (see Section 3.3). Then, further attacks not considered in this work are discussed. Finally, the positioning of this work regarding our previous work and some possible leads for future work are presented.

8.1. Back to the threat model:

Physical resources isolation is achieved through secure zones. Unlike results presented in Table I, each sensitive application executes within its secure zone preventing any cluster resource sharing with other applications. In this way, caches used by an isolated application are no longer shared (0% of caches sharing). Consequently, considered cache-based SCAs in this work are no longer possible since secure zone cache activity cannot longer be monitored by potential attacker processes. Notice that this solution requires the kernel to be trusted since this latter is responsible for the handling of secure zones. Finally, inter application communication and of-chip accesses are considered trusted as well.

8.2. Further attacks:

8.2.1. Spatial isolation properties. In this work, we study the spatial isolation on many-core architectures against cache-based SCAs. However, the proposed spatial isolation introduces further security properties. Indeed, besides cache-based SCAs, the spatial isolation of applications running in secure zones prevents as well Denial of Services (DoS) attacks on the resources within the secure zones. In fact, the Trusted Manager, is responsible for dedicating some resources to a secure zone for one single sensitive application and to allocate non-dedicated resources only to other applications. Thus, the Trusted Manager guarantees that attacker processes are no longer able to use the dedicated cluster resources and as a consequence, DoS attacks on these resources are no longer possible. However, other resources such as the NoC are not DoS free and further mechanisms in order to protect these resources are necessary. ***On the other hand, isolated applications themselves could perform DoS attacks by requesting a huge number of resources to be dedicated as well as by not releasing the dedicated resources. In this work we have not considered any mechanism preventing the isolated applications from performing DoS attacks. Monitoring the activity of isolated applications***

and/or forcing them to release the resources after a given time, for example, could be considered in order to detect and/or prevent this kind of attacks.

8.2.2. Further confidentiality and integrity attacks. Spatial isolation counters cache-based SCAs in which the access to data is indirect by monitoring the cache activity and inferring sensitive information. However, attacks through illegal direct access to the memory (reading or writing) are still possible. State-of-the-art countermeasures such as Memory Management Unit (MMU) and/or Memory Protected Unit (MPU) are compatible with our work.

8.2.3. NoC attacks. ***According to the threat model (Section 3.3), the communication through the NoC is considered secured. In fact, despite of resource dedication within secure zones clusters, the NoC resources are still shared between all the applications. Some literature works consider the problem of information leaked through NoC communication [Wang and Edward 2014][Reinbrecht et al. 2016a][Sepulveda et al. 2015]. However, little work can be found on practical attack implementations. In [Reinbrecht et al. 2016b], authors propose a timing attack on NoC on a shared LLC MPSoC platform. However, this attack relies on a single LLC shared between all the processors on the platform which is not the case in many-core for scalability reasons (e.g., memory bottleneck). Indeed, in the system considered in this work, the LLC is distributed among the clusters which makes very difficult to analyze NoC traffic. To our best knowledge, there is no attack proving their practicality on distributed LLCs many-core architectures. However, some literature countermeasures addressing NoC attacks are compatible with our work. For instance, using semi-adaptive routing such as west-first logic instead of the traditional deterministic XY logic, proposed in [Sepulveda et al. 2015], in order to disturb the attacker observations on the NoC traffic can be used in the context of our work. This solution has been implemented and has been used together with the spatial isolation mechanisms (for the deployment strategy A.1 and execution scenario Single zone, priority 1), showing an overhead on the total execution time of 2%. Another solution in order to isolate the NoC communication within secure zones, would be to use adaptive routing in order to avoid any non-isolated application from using the NoC resources within secure zones. These techniques have been used mostly as fault-tolerance mechanisms in NoC-based architectures. In [Fuguet Tolero 2016] for instance, reconfiguration-based recovery mechanisms have been studied on the TSAR architecture [TSAR 2014] in order to allow the system to work in spite of faulty NoC elements such as routers and links. A similar approach could be used in our context, in order to isolate secure zones NoC communications by seeing dedicated resources as temporary faulty components for non-isolated applications.***

8.3. Contributions compared to our previous work:

In this work we have focused on the implementation of the spatial isolation proposed in [Méndez Real et al. 2016a]. We have extended the secure zone deployment and management strategies initially proposed with new strategies offering a trade-off between completely static and dynamic approaches. These new strategies offer flexibility compared to previous solutions, and are able to achieve better performance on the total execution than a completely dynamic approach (resource reservation strategy induces around 1.5% and 15% less performance overhead than fully dynamic strategy in execution scenarios **Single zone, priority 4** and **Multiple zones, multiple priorities**, and to less penalize isolated applications performance on execution scenario **Multiple zones, multiple priorities** (resource reservation strategy induces 78% less overhead on the isolated applications performance than fully dynamic approach). Finally, each strategy has been further studied according to the considered execution scenario and to the performance metric to optimize.

8.4. Future work

In this work we have considered contiguous secure zones in order to favor isolated application NoC communications. As a consequence, this tends to favor the isolated application performance, which in turn tends to minimize the time that secure zone's resources are dedicated and thus the time that non-isolated applications are prevented from using them. Moreover, this approach would make easier the isolation of the secure zone application NoC communication if required (see Section 8.2.3). However, considering non-contiguous secure zones would give more flexibility when creating and extending secure zones. On the other hand,

isolated applications being spread onto distant clusters, their communication cost would increase, which will in turn impact their execution time and the resources dedication time. The interest of this approach compared to contiguous secure zones would be interesting to study in terms of induced overhead on both, isolated and non-isolated applications and is certainly worthy to consider. Moreover, considering migration of secure zones and/or non-isolated applications would as well give more flexibility to our approach since it would be possible to dynamically rearrange allocated resources both, dedicated to a secure zone and non dedicated ones. Finally, the protection of off-chip accesses to memory and peripherals is another possible lead for future work.

9. CONCLUSION

This work focuses on the spatial isolation of sensitive applications on a many-core accelerator in order to thwart cache-based SCAs proposed in [Méndez Real et al. 2016a]. Particularly we focus on its implementation in order to provide a flexible solution minimizing the induced performance overhead. A dedicated processor runs the Trusted Manager of the accelerator and is responsible for the dynamic deployment of applications and secure zones. Sensitive applications are executed within a secure zone spatially isolated from other applications preventing any resource sharing within the dedicated clusters. As a consequence, their caches activity cannot longer be monitored and cache-based SCAs cannot longer be performed against them. The Trusted Manager kernel services have been enhanced in order to integrate the proposed mechanisms. Several new secure zone deployment strategies have been proposed in order to minimize the induced performance overhead. The proposed strategies have been evaluated according to several performance metrics. Results show that these new strategies offer a trade-off between completely static and dynamic secure zone size approaches. ***Non-contiguous secure zones, secure zones migration as well as the protection of off-chip accesses are some possible leads worthy to considered in future work.***

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REFERENCES

Ghassan Almaless. 2014. *Operating System Design and Implementation for Single-Chip cc-NUMA Many-Core*. Ph.D. Dissertation. Université Pierre Marie Currie (PMC), FRANCE.

axTLS. 2016. http://axtls.sourceforge.net/. (2016).

axTLS implementation. 2017. https://ccodeblog.wordpress.com/2012/05/25/aes-implementation-in-300-lines-of-code/. (2017).

Gilles Barthe, Gustavo Betarte, Juan D. Campo, Carlos Luna, and David Pichardie. 2014. System-level non-interference for constant-time cryptography. In *Proc. of the Conference on Computer and Communications Security*. ACM, 1267–1279.

Daniel J. Bernstein. 2005. *Cache-timing attacks on AES*. Technical Report https://cr.yp.to/antiforgery/cachetiming-20050414.pdf.

Johannes Blömer and Volker Krummel. 2007. Analysis of Countermeasures Against Access Driven Cache Attacks on AES. *Selected Areas in Cryptography* 4876 (2007), 96–109.

Joseph Bonneau and Ilya Mironov. 2006. Cache-Collision Timing Attacks Against AES. In *Proc. of the International Workshop on Cryptographic Hardware and Embedded Systems (CHES)*. Springer, 201–215.

Paolo Burgio, Marko Bertogna, Ignacio Sanudo Olmedo, Paolo Gai, Andrea Marongiu, and Michal Sojka. 2016. A Software Stack for Next-Generation Automotive Systels on Many-Core Heterogeneous Platforms. In *Proc. of the Euromicro Conference on Digital System Design (DSD)*. IEEE.

Juan Campo. 2016. *Formally verified countermeasures against cache based attacks in virtualization platforms*. Ph.D. Dissertation. Montevideo : UR.FI.INCO.

Stephen Crane, Andrei Homescu, Stephan Brunthaler, Per Larsen, and Michael Franz. 2015. Thwarting Cache Side-Channel Attacks Through Dynamic Software Diversity. In *Proc. of the Annual Network and Distributed System Security Symposium, (NDSS)*. IEEE, 142–151.

Joan Daemen and Vincent Rijmen. 2002. *The Design of Rijndael: AES-The Advanced Encryption Standard* (1st ed.). Springer-Verlag Berlin Heidelberg.

Dmitry Evtyushkin, Jesse Elwell, Meltem Ozsoy, Dmitry Ponomarev, Nael Abu-Ghazaleh, and Ryan Riley. 2016. Flexible Hardware-Managed Isolated Execution: Architecture, Software Support and Applications. *IEEE Transactions on Dependable and Secure Computing (TDSC)* PP (2016), 1.

César Fuguet Tolero. 2016. *Introduction of Fault-Tolerance Mechanisms for Permanent Failures in Coherent Shared-Memory Many-Core Architectures*. Ph.D. Dissertation. Université Pierre Marie Currie (PMC), FRANCE.

Quian Ge, Yuval Yarom, David Cock, and Gernot Heiser. 2016. A Survey of Microarchitectural Timing Attacks and Countermeasures on Contemporary Hardware. *Journal of Cryptographic Engineering (Cryptogr Eng)* 1–27 (2016), 1.

Daniel Gruss, Clémentine Maurice, Klaus Wagner, and Stefan Mangard. 2016. FLUSH+FLUSH: A Fast and Stealthy Cache Attack. In *Proc. of the Conference on Detection of Intrusions and Malware & Vulnerability Assesment (DIMVA)*. Springer.

Roberto Guanciale, Hamed Nemati, Christoph. Baumann, and Mads Dam. 2016. Cache Storage Channels: Alias-Driven Attacks and Verified Countermeasures. In *Proc. of the Symposium on Security and Privacy (SP)*. IEEE.

David Gullasch, Endre Bangerter, and Stephan Krenn. 2011. Cache Games-Bringing Access-Based Cache Attacks on AES to Practice. In *Proc. of the Symposium on Security and Privacy (SP)*. IEEE, 490–595.

Gorka Irazoqui, Thomas Eisenbarth, and Berk Sunar. 2015. S$A: A Shared Cache Attack that Works Across Cores and Defies VM Sandboxing and its Application to AES. In *Proc. of the Symposium on Security and Privacy (SP)*. IEEE.

Gorka Irazoqui, Thomas Eisenbarth, and Berk Sunar. 2016. Cross Processor Cache Attacks. In *Proc. of the 11th Asia Conference on Computer and Communications Security (ASIA CCS)*. ACM, 353–364.

Kalray's. 2016. MPPA. http://www.kalrayinc.com/kalray/products/. (2016).

Mehmet Kayaalp, Nael Abu-Ghazaleh, Dmitry Ponomarev, and Aamer Jaleel. 2016. A High-Resolution Side-Channel Attack on Last-Level Cache. In *Proc. of the 53rd Annual Design Automation Conference (DAC)*. ACM, 72.

Taesoo Kim, Marcus Peinado, and Gloria Mainar-Ruiz. 2012. STEALTHMEM: System-Level Protection Against Cache-Based Side Channel Attacks in the Cloud. In *Proc. of the 21st Security Symposium*, USENIX (Ed.).

Fangfei Liu, Yuval Yarom, Quian Ge, Gernot Heiser, and Ruby B. Lee. 2015. Last-Level Cache Side-Channel Attacks are Practical. In *Proc. of the Symposium on Security and Privacy (SP)*. IEEE, 605–622.

Maria Méndez Real, Philipp Wehner, Vincent Migliore, Vianney Lapotre, Diana Goehringer, and Guy Gogniat. 2016a. Dynamic Spatially Isolated Secure Zones for NoC-based Many-core Accelerators. In *Proc. of the International Symposium on Reconfigurable Communication-centric Systems-on-Chip (ReCoSoC)*, IEEE (Ed.).

Maria Méndez Real, Philipp Wehner, Jens Rettkowski, Vincent Migliore, Vianney Lapotre, Diana Goehringer, and Guy Gogniat. 2016b. MPSoCSim extension: An OVP Simulator for the Evaluation of Cluster-based Multicore and Many-core architectures. In *Proc. of the International Conference on Embedded Computer Systems: Architectures, Modeling, and Simulation (SAMOS)*. IEEE.

Dag A. Osvik, Adi Shamir, and Eran Tromer. 2006. Cache attacks and countermeasures: the case of AES. In *Proc. of the RSA Conference Cryptographers Track (CT-RSA)*.

OVP. 2017. Open Virtual Platforms. https://www.ovpworld.org/. (2017).

Dan Page. 2005. *Partitioned Cache Architecture as a Side-Channel Defense Mechanism*. Cryptology eprint archive, report 280.

Colin Percival. 2005. Cache missing for fun and profit. In *BSDCan 2005*.

Himanshu Raj, Ripal Nathuji, Abhishek Singh, and Paul England. 2009. Resource management for isolation enhanced cloud services. In *Proc. of the 2009 ACM workshop on Cloud computing security (CCSW)*. ACM, 77–84.

Cezar Reinbrecht, Altimiro Susin, Lilian Bossuet, and Johana Sepulveda. 2016a. Gossip NoC – Avoiding Timing Side-Channel Attacks through Traffic Management. In *Proc. of the Computer Society Annual Symposium on VLSI (ISVLSI)*. IEEE.

Cezar Reinbrecht, Altamiro Susin, Lilian Bossuet, Georg Sigl, and Johanna Sepulveda. 2016b. Side channel attack on NoC-based MPSoCs are practical: NoC Prime+Probe attack. In *Proc. of the 29th Symposium on Integrated Circuits and Systems Design (SBCCI)*. IEEE.

Martha J. Sepulveda, Jean-Philippe Diguet, Marius Strum, and Guy Gogniat. 2015. NoC-Based Protection for SoC Time-Driven Attacks. *Embedded Systems Letters, IEEE* 7, 1st (2015), 7–10.

Jicheng Shi, Xiang Song, Haibo Chen, and Binyu Zang. 2011. Limiting Cache-based Side-Channel in Multi-tenant Cloud using Dynamic Page Coloring. In *Proc. of the 41st International Conference on Dependable Systems and Networks Workshops (DSN-W)*. IEEE, 194–199.

OVP & SystemC. 2017. Open Virtual Platforms Imperas Software Limited. http://www.ovpworld.org/technology_systemc. (2017).

Nist AES test vectors. 2001. http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-38a.pdf. (2001).

TILE-Gx36. 2017. http://www.mellanox.com/page/products_dyn?product_family=237&mtag=tile_gx36. (2017).

TILE-Gx72. 2017. http://www.mellanox.com/page/products_dyn?product_family=238&mtag=tile_gx72. (2017).

Eran Tromer and Dag A. Osvik. 2010. Analysis of Countermeasures Against Access Driven Cache Attacks on AES. *Journal of Cryptology* 23, 1st (2010), 37–71.

Pham Trung-Dung, Nguyen Van-Tien, and Nguyen Truong-Son. 2016. Development of a Many-core Architecture for Automotive Embedded Systems. *Journal of Automation and Control Engineering* 4, 2 (2016), 147–152.

TSAR. 2014. https://www-soc.lip6.fr/trac/tsar. (2014).

TSUNAMY. 2016. The TSUNAMY project. https://www.tsunamy.fr. (2016).

Yao Wang and Suh G. Edward. 2014. Cache Games-Bringing Access-Based Cache Attacks on AES to Practice. In *Proc. of the 6th International Symposium on Networks on Chip (NoCS)*. IEEE/ACM.

Zhenghong Wang and Ruby B. Lee. 2007. New Cache Designs for Thwarting Software Cache-based Side Channel Attacks. In *Proc. of the Symposium on Computer Architecture (ISCA)*. IEEE, 494–505.

Philipp Wehner, Jens Rettowski, and Diana Goehringer. 2015. MPSoCSim: An extended OVP Simulator for Modeling and Evaluation of Network-on-Chip based heterogeneous MPSoCs. In *Proc. of the International Conference on Embedded Computer Systems: Architectures, Modeling, and Simulation (SAMOS)*. IEEE.

Yuval Yarom and Katrina Falkner. 2014. FLUSH+RELOAD: A High Resolution, Low Noise, L3 Cache Side-Channel Attack. In *Proc. of the Security Symposium*, USENIX (Ed.). 719–732.