

AKER: A Design and Verification Framework for Safe and Secure SoC Access Control

Francesco Restuccia*[†], Andres Meza*, and Ryan Kastner*

*University of California San Diego

[†] Scuola Superiore Sant’Anna Pisa

{frestuccia, anmeza, kastner}@ucsd.edu

Abstract—Modern systems on a chip (SoCs) utilize heterogeneous architectures where multiple IP cores have concurrent access to on-chip shared resources. In security-critical applications, IP cores have different privilege levels for accessing shared resources, which must be regulated by an access control system. AKER is a design and verification framework for SoC access control. AKER builds upon the Access Control Wrapper (ACW) – a high performance and easy-to-integrate hardware module that dynamically manages access to shared resources. To build an SoC access control system, AKER distributes the ACWs throughout the SoC, wrapping controller IP cores, and configuring the ACWs to perform local access control. To ensure the access control system is functioning correctly and securely, AKER provides a property-driven security verification using MITRE common weakness enumerations. AKER verifies the SoC access control at the *IP level* to ensure the absence of bugs in the functionalities of the ACW module, at the *firmware level* to confirm the secure operation of the ACW when integrated with a hardware root-of-trust (HRoT), and at the *system level* to evaluate security threats due to the interactions among shared resources. The performance, resource usage, and security of access control systems implemented through AKER is experimentally evaluated on a Xilinx UltraScale+ programmable SoC, it is integrated with the OpenTitan hardware root-of-trust, and it is used to design an access control system for the OpenPULP multicore architecture.

I. INTRODUCTION

Modern System on a Chip (SoC) have heterogeneous architectures comprised of microprocessors, hardware accelerators, on-chip memory hierarchies, and I/O. They utilize complex on-chip communication networks where the processors and accelerators transfer information between themselves and other shared resources, often with tight constraints on throughput, latency, and resource usage [1], [2].

In security-critical applications, on-chip resources have different levels of trustworthiness and criticality that are often dynamic in nature. Examples include: 1) a shared memory may be (temporally) isolated from an untrusted IP core, 2) certain resources are only accessible during debug mode, and 3) only the hardware root of trust can access security critical control and status registers.

In order to operate in a safe and secure manner, SoCs use an *access control system* that enforces an *access control policy*. The access control policy defines the ability of the SoC controllers to access the different peripherals. The access control policy changes over the SoC life-cycle – design, manufacturing, testing, passing through several OEMs, and on to the final user. Access control policies are dynamic, e.g., policies differ when in boot mode, secure operating modes, reset, and normal operating scenarios. Thus, SoC access control policies require an efficient and flexible access control system.

The access control system plays a critical role for ensuring safe and secure operation. Thus, an access control system must undergo a rigorous verification process. Verification includes functional correctness. Additionally, and equally as important, it must undergo a security verification process that addresses potential security weaknesses and vulnerabilities. An exploit in the access control system endangers the confidentiality, integrity, and availability of the SoC.

Unfortunately, it is challenging to correctly implement SoC access control systems. The MITRE common weakness enumeration (CWE)

database reports a substantial and growing number of hardware weaknesses [3]. Our security verification process identified 30 of these CWEs related to access control systems (see Section III). Access control flaws are extremely dangerous as they provide the opportunity for low-level system access. Furthermore, they are challenging to patch. At best they require a firmware rewrite; at worst, they require disabling features or re-manufacturing the chip.

This work proposes AKER – a framework for the development of safe and secure on-chip access control systems targeting the requirements of modern safety- and security-critical applications. These requirements include:

Security Verification: AKER provides a property-driven security verification procedure [4] to ensure that the SoC access control policy is devoid of any CWEs. This provides high assurance on the secure operation of AKER-based access control systems. The security verification is done at three levels: the *IP level*, the *firmware level*, and the *system level*. AKER can be easily extended to handle next-generation SoCs and address different CWEs.

Interoperability: AKER is AXI-compliant and fully transparent to controllers and interconnect. No knowledge or modifications on the internals of the controllers, peripherals, and interconnect are required to integrate an AKER access control system.

Immediate Filtering of Illegal Requests: AKER filters transactions at the source, before entering the interconnect – no illegal transactions are allowed to enter the network. This avoids any identification issues and prevents system-level interference generated by illegal transactions (e.g., DoS attacks, see Section IV-A).

Secure Configuration: AKER access control systems easily integrate with a Hardware Root of Trust (HRoT) for runtime monitoring and management of the controllers. Section III-C describes the integration and verification of the OpenTitan [5] HRoT with AKER.

Flexibility: AKER-based access control systems allows static or dynamic configuration of the access control policy by the HRoT. This provides the required flexibility to cope with the complex life-cycle of modern SoCs.

Diagnostic Information: AKER access control systems log diagnostic information regarding illegal attempts. This provides flexibility to the HRoT on how to perform modules readmission.

Efficient Performance and Resource Usage: AKER access control systems incur only 1 clock cycle delay per AXI transaction independent on the number considered memory regions (see Section IV-A). This corresponds to an impact of < 1% in the tested scenarios. The resource usage of an AKER-based access control system is minimal and is configurable to be tailored to the SoC and use case.

Open-Source: The design and the security properties developed within AKER are openly released. This allows further verification and provides a solid base for design and security verification extension, facilitating broader use. Our repo contains all of the designs, security properties, and security property templates proposed in AKER [6].

Ease of Integration: AKER access control systems are experimentally validated via their integration into SoCs implemented on a FPGA SoC architecture and on the OpenPULP [7].

II. SoC ACCESS CONTROL

An SoC architecture consists of a set of controller devices accessing a set of peripheral devices.¹ Different processors, accelerators, and other IP cores can be assigned as a controller. This allows them to autonomously and concurrently communicate with shared peripheral resources available on the SoC, e.g., a DRAM memory controller, on-chip memories, ROM, IP core control and status registers (CSRs), and GPIOs. On-chip data transfers use a communication protocols like the AMBA AXI [8] or TileLink [9], which employ a flexible, asymmetric, synchronous interface targeting high performance and low latency communications. A key aspect of any SoC access control system is arbitrating accesses to on-chip resources. High-speed on-chip communications protocols use memory mapped addressing to allow controllers to specify the resources they wish to access. An access control policy specifies whether a data request is allowable at that given time. It is important that the access control system exactly implements the access control policy while having a minimal impact on performance and area.

A. SoC Interconnect Architectures

Figure 1 shows an SoC interconnect architecture with N controllers C (C_1, \dots, C_N) each with a manager (M) interface, L peripherals P (P_1, \dots, P_L) with a subordinate (S) interface, and an interconnect I_{AXI} connecting them. We adopt AMBA AXI standard due to its widespread usage. Our techniques are applicable to other on-chip communication protocols with minimal modifications. AXI defines an asymmetric communication interface comprised of five independent channels: address read (AR), address write (AW), data read (R), data write (W), and write response (B). I_{AXI} arbitrates the access of C modules to the shared P modules.

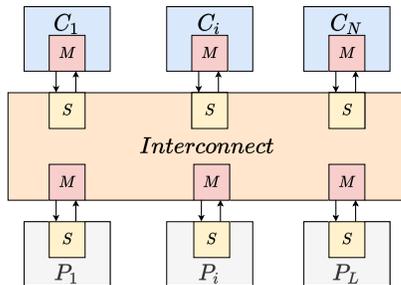


Fig. 1: An SoC on-chip interconnect architecture composed of N controller modules (C) connected to L peripheral modules (P).

A controller C_i can initiate a transaction to a shared peripheral P_j issuing an *address request* through its AXI M interface. The address requests is routed to the peripheral P_j by the AXI interconnect. P_j is accessible by C_i through a unique set of contiguous addresses, also called *peripheral address region*. P_j serves the received requests providing the required data (read request) or accepting the write data and replying with a write response (write request).

B. Threat Model

The threat model consists of one or more controllers that are malicious or misprogrammed and attempt to perform transactions that violate the SoC access control policy. Security threats are related to integrity (e.g., untrusted controller modifies a peripheral's control and status register), confidentiality (e.g., secret key leakage), and

¹We adopt the terminology controller/peripheral to describe system-level interactions between IP cores. We use M (manager) and S (subordinate) when specifically referring to the AXI protocol.

availability (e.g., a denial-of-service attack). Many of the MITRE hardware CWEs [3] relate to access control. We assume the attacker has full knowledge of these types of weaknesses. Often, weaknesses are not caught due to a superficial *security verification* of the access control system. We articulate specific vulnerabilities that we consider as formal properties as part of the AKER Security Verification process (see Section III). These properties are then verified using a property-driven hardware security methodology [4].

We assume that an access control policy specifies allowable transactions between on-chip controller resources and shared peripheral resources. The policy describes the allowable read and write requests between resources using a set of address ranges. A range is a contiguous address space encoded as the base address and the range size. Additionally, we assume the functionalities of P , the routing functionalities of I_{AXI} , and the Trusted Entity functionalities are trustworthy and implemented correctly.

C. On-chip Access Control Systems

This section discusses options for the implementing on-chip access control system. The primary options include access control monitoring in the interconnect, at the peripherals, in a centralized location, or at the controller (AKER's solution).

1) *Access Control using AXI Interconnect*: The access control policy is enforced within the crossbar interconnect by implementing only the selected physical connections between controllers and peripherals according to the privacy and integrity requirements [10]. The AXI interconnect is statically configured only with physical connections between a controller and peripheral that are allowed by the policy.

Limitations: Hard-coding the access control system does not allow for dynamic updates to the access control policy. Therefore, this approach is not a viable option for modern SoCs having complex lifecycles. Moreover, the definition of the access control policy can be limited to simplified and unrealistic scenarios for several applications (see Section IV-A).

2) *Access Control in Peripherals*: Each peripheral P includes additional logic that analyzes each request and decides whether to serve it depending on the access control policy [11], [12]. This methodology implicitly assumes that each request is somehow securely marked with the information regarding the identity of the issuing controller. Typically, access control policies enforced in peripherals are configurable, providing some flexibility to handle dynamic policies.

Limitations: The AXI standard does not define any information about the source controller. A common workaround uses the AXI ID signals for identification [13]. However, the AXI IDs are intended to denote parallel execution of threads. An AXI controller is allowed to issue address requests using multiple ID values. Thus, IDs are not suitable for access control. Additionally, AXI does not address the integrity of the ID(s), which allows ID manipulation during request propagation and adds uncertainty about the provenance of the request [8]. Another consideration is that any illegal requests received by a peripheral must be terminated with an AXI-compliant error to avoid network locks. This causes unwanted interference with the execution of legal transactions (see Section IV-A). Such solutions can also pose strong limitations in the definition of realistic access control policies (see Section IV-A).

3) *Centralized Policy Engine*: Another option is a centralized security policy engine [14], [15]. The central security policy engine is responsible for authenticating any memory transaction.

Limitations: All decisions are made by the central security engine, which requires communication between the wrapper and the security engine on each transaction. This communication can impact the performance of the system and create bottleneck at the central security

engine. Thus, such solutions are not suitable for high-performance or latency-critical systems.

III. AKER

AKER is a design and verification framework for developing SoC access control systems, aimed at meeting the performance, security, and flexibility requirements of modern safety- and security-critical applications. AKER builds upon the Access Control Wrapper (ACW) – a high-performance, programmable module that supervises the behaviour of memory transactions from a controller. AKER includes property-driven security verification [4] at the IP level, firmware level, and system level. AKER uses CWEs to identify potential weaknesses, develop property templates to aid in the property generation process, and use information flow tracking hardware verification tools to validate complex behaviors related to confidentiality and integrity of the SoC access control system.

A. The Access Control Wrapper

The Access Control Wrapper (ACW) is a configurable access control module designed to monitor an AXI-compliant controller. The ACW exports an AXI M interface, an AXI-lite S configuration interface, and an output interrupt line. An ACW can be used on any SoC controller resource whose memory accesses require arbitration for safety or security reasons; each untrusted controller C_i is wrapped by an ACW module ACW_i . Figure 2 provides an example of an AKER-based access control system. The M interface of ACW_i is connected to the AXI interconnect (in place of the M interface of C_i), while the S interface and the interrupt line are connected to a Trusted Entity (TE) (i.e., a HRoT, see Section III-B).

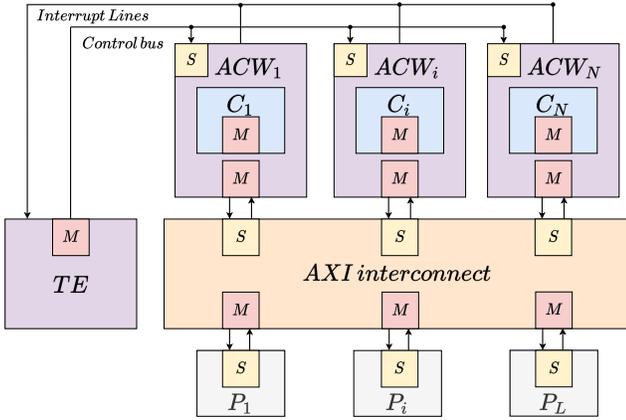


Fig. 2: Extended AXI multi-controller, multi-peripheral architecture incorporating an AKER-based access control system. The Trusted Entity TE manages the ACW modules. Only legal requests are transmitted to the AXI interconnect, i.e., the peripherals receive only legal AXI transactions.

ACW_i holds a local access control policy $LACP_i$, configured and maintained by TE . $LACP_i$ describes the address regions legally accessible by C_i , defining n_r regions for read operations and n_w regions for write operation. Each memory request issued by C_i is checked against the configuration of $LACP_i$; if the request is fully contained in at least one of the $LACP_i$'s address regions, the request is considered *legal* by ACW_i and allowed to propagate to the AXI interconnect. n_r and n_w impact the resource consumption of the ACW module – the ACW design allows to easily customize such values according to the SoC requirements. To minimize the latency, the address regions are checked in parallel. Thus, the latency introduced by the ACW is constant and independent of n_r and n_w .

The ACW_i has three operating modes:

1) *Reset Mode*: the initial state of ACW_i . It is awaiting configuration with a valid $LACP_i$. Any request issued by C_i is blocked and does not propagate to the interconnect. Once $LACP_i$ is configured, ACW_i moves to *Supervising Mode*.

2) *Supervising Mode*: the normal operating mode of the ACW_i . Each address request issued by C_i is compared against the stored $LACP_i$. Legal requests are propagated to the AXI interconnect; illegal requests are denied and never reach the AXI interconnect. An illegal request moves ACW_i into *Decouple Mode*.

3) *Decouple Mode*: an illegal request has occurred. ACW_i saves diagnostic information about the illegal request into its internal anomalies registers. ACW_i raises an interrupt to notify the TE of the illegal access attempt. Any further request from C_i is blocked and the ACW_i waits on the TE for readmission. Decoupling C_i after an illegal attempt ensures that TE can take appropriate actions on C_i before the safe readmission of the module in the system.

Readmission Policy: The TE can analyze the diagnostic information internal to ACW_i and perform recovery operations on C_i before switching back to *Supervising Mode* and thereby readmitting C_i to communicate to the SoC. Examples of recovery operations are resetting, reconfiguring, or even reprogramming C_i . In the most extreme scenario, if the TE decides that the illegal request is the result of a permanent fault, it can keep the ACW_i in *Decouple Mode*, thus permanently disconnecting C_i from the system.

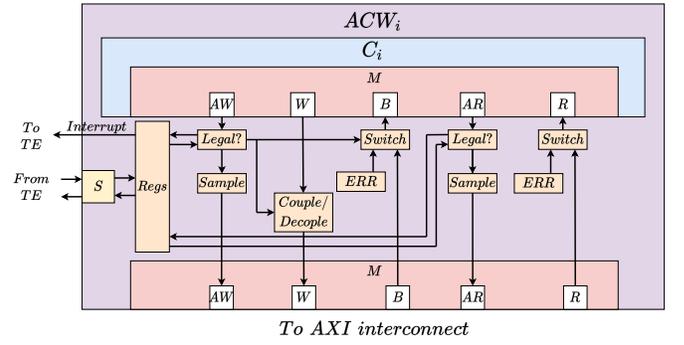


Fig. 3: ACW_i architecture: C_i is the controller module using an AXI M interface. $Regs$ are the configuration registers holding $LACP_i$. The AXI S interface is connected to the HRoT.

Figure 3 shows a representation of the internals of the ACW_i . The following discusses how ACW_i behaves on read and write transactions. ACW is compatible with any AXI-compliant request. When C_i issues a read request AR through its M interface, ACW_i has the following behaviors:

- **Address Check**: Check AR against $LACP_i$ by comparing the address of AR against each of the allowable read regions.
- **Legal Request**: If AR is fully included in at least one of the allowed read regions of $LACP_i$, propagate AR to the AXI interconnect.
- **Illegal Request**: If AR is not fully included in any of the read regions described in $LACP_i$, AR is not propagated to the AXI interconnect. ACW_i saves internally information regarding the illegal request AR . ACW_i sends an AXI-compliant error to C_i , notifies TE , and switches into *Decouple Mode*.
- **Outstanding Transactions**: Any legal outstanding transaction initiated before an illegal transaction is completed normally.

When C_i issues a write request AW , ACW_i behaves in a similar manner as a read request using AW instead of AR and comparing

the address request with the write regions of $LACP_i$, instead of the read regions. Additionally, since AXI transactions cannot be aborted, C_i expects to provide the write data after it issues the illegal request. ACW_i waits to sample all the data words corresponding to AW provided by C_i , discards them, and replies C_i with an AXI-compliant error.

B. IP-level Security Verification

Security verification is crucial in scenarios where the design serves a security-critical role such as implementing an access control system. AKER uses a six-step security verification process following a property-driven hardware security methodology [4]. The security verification process describes the threat model, identifies security assets, articulates potential weaknesses, defines security requirements, specifies security properties, and verifies the security properties.

To drive our discussion, we first consider the IP-level verification of the ACW, which consists of three entities: a single controller C , a single ACW which wraps C , and a single peripheral P . We assume that the ACW's local access control policy $LACP$ is statically configured in RTL. In later sections, we apply the same verification process to implement different SoC access control systems. Section III-C performs firmware-level security verification adding a hardware root-of-trust to configure the ACW. Section III-D describes system-level security verification that ensures that multiple ACWs adhere to a global access control policy.

1) *Create Threat Model*: The first step in the security verification process develops the threat model. It is crucial to articulate the relevant security concerns. Hardware threats are vast and must be assessed based upon the usage of the hardware under design. We consider an integrity scenario where C is untrusted and the ACW and P are trusted. Therefore, the threat model considers C 's ability to communicate with P via the ACW in a manner which does not adhere to the statically-configured $LACP$. Threats related to confidentiality are similarly possible given that confidentiality is a dual to integrity [16].

2) *Identify Assets*: The second step identifies the assets (i.e., design signals) that will be secured via the remainder of the verification process. Each asset will eventually have at least one associated security requirement/property that will be used to verify its security.

Given our design and threat model, the assets we identify are the design signals that make up the five AXI channels which connect the ACW to C and P , and the design signals that make up the configuration and anomaly registers. In later sections, we will refer to these assets as the M AXI group and config/control group, respectively, due to the similarity in their security requirements.

3) *Identify Potential Weaknesses*: The third step determines potential weaknesses, which are defined as any mechanism that could introduce a security vulnerability relevant to the threat model and identified assets. Identifying these weaknesses is often challenging and time-consuming since it requires designers to understand the design's specification, the design's implementation, the subtleties in the correlation between these two, and which parts of the design are most relevant to the threat model. In an effort to increase the chance of identifying security critical weaknesses, we use the threat model and design to find relevant CWEs from MITRE's extensive database following to the CWE-IFT methodology [17].

We identified 17 CWEs relevant to the IP-level verification that are divided into two groups. The first group relates to M AXI and includes the read and write access points available to C , i.e., the five M AXI channels. The second group includes the configuration registers which store the ACW's $LACP$, the anomaly registers which store illegal request metadata, and the control logic which checks the legality of and samples or blocks C 's transactions.

Relevant CWEs: 1220, 1221, 1244, 1258, 1259, 1264, 1266, 1267, 1268, 1269, 1270, 1271, 1272, 1274, 1280, 1282, 1326

4) *Define security requirements*: The fourth step in the process defines plain-language security requirements for the identified weaknesses. Once a mechanism is identified as a potential weakness, designers can articulate a security requirement which addresses how that mechanism could fail as determined from the relevant CWEs and an analysis of the design.

For the M AXI group of weaknesses (i.e., the AXI channels) identified in Step 2, we develop security requirements addressing the existence and the content of information flows between C , the ACW, and P . Since the ACW sits between C and P , there will always be information flows between C and the ACW and the ACW and P . However, the source of these flows dictates their allowable behaviors. Information flows in which the source is C and the destination is P (or vice versa) should only occur when the ACW is in *Supervising Mode* and a legal transaction is issued. In all other instances, the only information flows that should occur are those in which the source is the ACW, the destination is either C or P , and the content of the flow does not deviate from the default AXI values we have selected.

Requirement 1: C cannot receive/send data from/to P which originates while the ACW is in reset mode.

For the config/control group of weaknesses identified in Step 2, we develop security requirements involving the content of registers and signals. Many of the listed CWEs (e.g., 1258, 1266, 1269, and 1271) [3] focus on the failure to properly initialize, set, and clear the contents of security-critical registers/signals, especially on transitions between system states/modes. Considering this, the config/control group of requirements dictate what content is appropriate for registers/signals given the ACW's current mode of operation.

Requirement 2: The configuration/anomaly registers are cleared and set to their default values while the ACW is actively being reset.

5) *Specify Security Properties*: The fifth step in the process specifies a security property template for each of the security requirements. In order to verify a security requirement, it must be manually converted into a formally specified security property which uses explicit values, design signals, and operators to form an evaluable expression. Rather than specifying nearly identical security properties for each design signal that should adhere to a given security requirement, AKER provides a property generation framework which automatically generates these specific properties given a single security property template with placeholder signals and a list of target design signals.

For the security requirements relevant to the M AXI group (Requirement 1), the security property templates we specify are primarily information flow tracking *IFT* properties. IFT properties enable us to tag information from a particular source signal and track it as it flows through our system [18]. For example, the send aspect of the security requirement from Requirement 1 is formalized below using the following template which fails if any information originating from C during active reset flows to P .

```
`signal_from_C` //source
when (ARESETN == 0) //tagging condition
  =/=> //no-flow operator
`signal_to_P` //destination
```

Note that the property involves the no-flow operator ($=/=>$). Hardware information flow properties are a type of hyperproperty [19]. Hyperproperties require specialized verification tools [20]. IFT properties are more challenging to verify than trace properties.

Trace properties are stated over a set of traces, and are commonly used in functional verification. Hyperproperties are stated over sets of traces and are useful for proving noninterference – a crucial aspect of information flow analysis.

For the security requirements relevant to the config/control group (Requirement 2), the security property templates are primarily trace properties which specify what the value of a specific signal/register should be under various conditions. For example, the security requirement is formalized using the following template which fails if the configuration/anomaly registers do not contain their default values after being reset.

```
`reg` == `dflt_val`
unless
(ARESETN != 0 && `acw_w/r_state` != 2'b00)
```

In total, we develop eighteen security property templates for verifying the security of the ACW, which are expanded to hundreds of individual properties in Step 6. Eleven of these templates are related to information flow and seven templates relate to trace properties.

6) *Verify Security Properties:* The final step generates specific security properties and then verifies them via simulation. The eighteen security property templates created in Step 4 and the assets identified in Step 5 are used to automatically generate 316 security properties which are broken down into 164 information flow properties and 152 trace properties. The verification setup for these properties includes a configurable AXI DMA module acting as controller *C*. *C* is wrapped with an ACW. A top testbench module mimics the behavior of the peripheral *P*. The testbench iterates through resets and configurations of the ACW and the DMA with the goal of switching the ACW between operative modes to provide adequate coverage of the necessary conditions for all of the security properties.

Tortuga Logic Radix-S is used for security verification. Each property is written as an assertion using the Tortuga Logic Sentinel security language. Radix-S generates a security model from the security rules and a simple test design. When simulated, this security model will report how many times each individual property assertion fails along with the time at which each failure occurs.

C. Firmware-level Security Verification

One of the key features of AKER access control systems is the simple and fast setup of the local access control policy of the ACWs. This can be setup once in static configuration (e.g., at boot time) or managed at runtime by a *TE*. This operation is critical. Thus, the interactions between the ACWs and the *TE* must be securely validated. To perform firmware verification, we integrate AKER with the OpenTitan [5] HRoT acting as the *TE*. The security verification proposed in this section focuses on firmware-level security verification of AKER, i.e., securely validating the interaction of the *TE* and the ACW. It is worth mentioning that AKER can be easily integrated with other *TE*, such as other HRoTs, trusted processors, etc.

We use the same process introduced in Section III-B to validate the firmware-level security of the interactions between the ACW and the *TE*. There are four entities that we are concerned with: a single controller *C*, a single ACW which wraps *C*, a single peripheral *P*, and the trusted entity *TE*. Unlike the IP-level verification, the ACW's local access control policy *LACP* can be configured dynamically at runtime by the *TE*.

1) *Create Threat Model:* In this scenario, our threat model assumes that the ACW, the *TE*, and *P* are trusted, *C* is untrusted, and, therefore, *C*'s ability to communicate with *P* via the ACW in a manner which does not adhere to the dynamically-configured *LACP* is a threat.

2) *Identify Assets:* In addition to the assets from the IP level, the additional assets we identify are the design signals that make up the five S AXI channels which allow the *TE* to configure the ACW, and the design signals for the ACW's read and write channel interrupt lines.

3) *Identify Potential Weaknesses:* We identified seven relevant CWEs which helped to expand the potential weaknesses in the config/control group from Section III-B. The additional potential weaknesses include the configuration ports which enable the *TE* to set the ACW's *LACP* (i.e., the five S AXI channels) and the two interrupt lines which go from the ACW to the *TE*. Note that the CWEs and potential weaknesses identified for the IP level are still relevant for this scenario but, since we have already examined those, we only focus on weaknesses related to the interactions between the ACW and the *TE* in this section.

Relevant CWEs: 276, 1191, 1193, 1262, 1283, 1290, 1292

4) *Define security requirements:* For the configuration ports identified in Step 3, we develop security requirements addressing the existence and the content of information flows between the *TE* and the ACW's configuration and anomaly registers. Since the *TE* is present to configure the ACW's *LACP*, it should be the source of any information flows which modify the configuration registers. Additionally, since the anomaly registers are populated with illegal transaction metadata by the ACW for the *TE*, the *TE* should not be able to modify the anomaly registers.

Requirement 3: The configuration/anomaly registers contain the default values until they are modified by the *TE* (config.) and/or ACW (illegal req. metadata tracking).

For the interrupt lines identified in Step 3, we develop security requirements addressing the value of signals. The ACW should alert the *TE* whenever there is an illegal transaction by driving the appropriate interrupt line and otherwise it should not drive the interrupts.

Requirement 4: An interrupt to *TE* is generated after the ACW detects an illegal request.

5) *Specify Security Properties:* The requirements relevant to the *TE* and the configuration/anomaly registers are primarily information flow tracking *IFT* properties. For example, the security requirement from Requirement 3 is formalized using the following template which fails if any unauthorized source modifies the configuration regs and anomaly registers after reset.

```
`unauthorized_signal` //source
when (`reg` == `dflt_val`) //tagging cond.
  => //no-flow op.
`reg` //destination
unless (`reg` == `dflt_val`)
```

For the security requirements relevant to the interrupt lines, the security property templates we specify are trace properties. In particular, Requirement 4 is formalized using the following specification which fails if the interrupt line does contain the appropriate value given the ACW's operative mode.

```
`INTR_LINE_W/R` == 1
unless (`acw_w/r_state` != 2'b10)
```

In total, we develop four security property templates for verifying the security of the firmware-level interactions between the ACW and the *TE*. Three of these are information flow properties and one is a trace property. These can all be found in our repository.

6) *Verify Security Properties*: The four security property templates created in Step 5 and the assets identified in Step 2 are used to automatically generate 1,438 security properties which are broken down into 1,436 information flow properties and 2 trace properties. The verification setup for these properties is nearly identical to the IP level setup (Section III-B) except for the presence of the *TE* for configuring the ACW.

D. System-level security verification

Having verified the security of the ACW's interactions at the IP level and firmware level, we now use our six-step process to validate the security of the interactions between multiple ACW-wrapped controllers and several shared SoC resources. This scenario concerns eleven entities: two controllers C_1 and C_2 , two ACWs ACW_1 and ACW_2 wrapping C_1 and C_2 , respectively, three peripherals $P_1 \dots P_3$, an interconnect, and the *TE*. This scenario corresponds to an architecture from Figure 2 when $N = 2$ and $L = 3$. The $LACP_1$ of ACW_1 states that C_1 can read from all regions of $R_1 = \{P_1, P_2\}$ and write to all regions of $W_1 = \{P_1\}$. The $LACP_2$ of ACW_2 states that C_2 can read from all regions of $R_2 = \{P_3\}$ and write to all regions of $W_2 = \{P_2, P_3\}$.

1) *Create Threat Model*: In this scenario, our threat model assumes that ACWs, P_s , and the *TE* are trusted, and that C_1 and C_2 are untrusted. The threat model focuses on the ability of the generic C_i 's to communicate with the generic P_k via the ACW in a manner which does not adhere to the *LACP*.

2) *Identify Assets*: The additional assets we identify as being relevant at this level are all of the design signals within the unauthorized regions for each C_i and the AXI signals which connect each C_i to its respective ACW_i .

3) *Identify Potential Weaknesses*: We identify three additional relevant CWEs which helped to further expand the potential weaknesses from the IP and firmware verification. Since we are validating at the system level, the additional potential weaknesses include the manner in which the *LACP* for ACW_i is set as it relates the generic C_i sharing resources with the generic C_j .

Relevant CWEs: 441, 1189, 1260

4) *Define security requirements*: We develop security requirements addressing the existence and the content of information flows between every pair of C_i and P_k in accordance with each ACW_i 's $LACP_i$. ACW_1 's $LACP_1$ states that there should never be information flows between C_1 and any region of P_3 . ACW_2 's $LACP$ states that there should never be information flows between C_2 and any region of P_1 .

Requirement 5: Any C cannot receive/send data from/to any region not contained within its ACW's LACP.

5) *Specify Security Properties*: The security property templates we specify are all *IFT* properties. For example, the send aspect of Requirement 5 is formalized below using the following template which fails if any information originating from some C_i flows to any unauthorized region.

```
`sig_from_C` //source (always tagged)
=/>
`unauthorized` //destination
```

In total, we develop two *IFT* security property templates for verifying the security of the interactions between multiple ACW-wrapped controllers and multiple shared resources across our system.

Functionality for policy definition	INTC	XMPU	AKER
Protect a limited set of predefined regions	Yes	Yes	Yes
Dynamic allocation of read/write regions	No	Yes	Yes
Definition of private read/write regions	No	No	Yes
Definition of read-only/write-only regions	No	No	Yes
Secure transactions identification	Yes	No	Yes

TABLE I: Comparison of SoC access control systems. The AXI-interconnect-based INTC and the XMPU access control systems available exhibit limitations not seen in with AKER.

6) *Verify Security Properties*: The two security property templates created in step 5 and the assets identified in step 2 are used to automatically generate 76 *IFT* security properties. The verification setup for these properties builds upon the Firmware-level verification from Section III-C by inserting one additional ACW-wrapped controller module, three memory modules to serve as peripherals, and one AXI interconnect to connect the controllers with the peripherals.

IV. EXPERIMENTAL EVALUATION

We evaluate the performance and resource usage of the AKER access control system and verify its functional and security correctness. The first set of experiments in Section IV-A compares the performance and resource usage of an AKER access control system with two typical methods of implementing on-chip access control described in Section II-C. In Section IV-B, we provide a case study of integrating an AKER access control system on the OpenPULP architecture [7].

A. FPGA SoC Experiments

We develop an FPGA SoC architecture on a Xilinx Zynq Ultra-scale+ platform. The architecture has three controller modules C_1 , C_2 , and C_3 implemented as hardware accelerators in the FPGA fabric. C_1 , C_2 , and C_3 are connected to a Xilinx AXI SmartConnect [10], which is connected to a single peripheral resource P_1 – the shared DRAM memory controller exposed as an AXI S bus in the Processing System PS . This architecture is similar to the one shown in Figure 1 with $N = 3$ and $L = 1$. C_1 , C_2 , and C_3 are implemented as three separate high-performance DMA IPs – this choice allows easy configuration and can cover a range of communication behaviors.

We implemented three different access control system: **Design (a)** uses AXI SmartConnect (INTC) (Section II-C1), **Design (b)** implements access control in PS leveraging the Xilinx Memory Protection Unit (XMPU) [13] (Section II-C2), and **Design (c)** is an AKER access control system involving three ACW modules. We leverage one of the processors of the platform for the configuration of the ACWs, which acts as the *TE*. The designs were synthesized using Xilinx Vivado 2018.2. To achieve high accuracy, the performance measurements are done by a custom timer implemented into the FPGA fabric. We also deployed a Xilinx System ILA [21] to verify the correct behavior of the ACW modules.

One of the major drawbacks of implementing the access control within the AXI SmartConnect (Design (a)) is that the access control policy cannot be dynamically modified. Moreover, the Vivado design tool uses predefined addressable regions for the controllers – once set, no additional custom regions can be added in the access control policy of the AXI SmartConnect. Also, the predefined regions have default read/write permissions; no read only regions can be defined.

Design (b) uses the XMPU integrated into the PS to implement the access control system, which enables the definition of up to 16 custom memory regions. The XMPU uses the workaround of the AXI ID signals described in Section II-C2 to identify the source of a specific request and decide whether a request is legal or not

(see [13]). However, the AXI SmartConnect connecting the C to the PS does not propagate the ID signals to the PS [10]. Therefore, even when forcing C_1 , C_2 , and C_3 to issue requests with unique IDs, once the requests are propagated by the AXI SmartConnect to the PS, they lose the ID and therefore the XMPU cannot determine the source of the request. Thus, the XMPU cannot reliably enforce any access control policy that aims to differentiate the requests issued by C_1 , C_2 , and C_3 . This means that even a very simple access control policy defining a private read/write buffer for each C cannot be implemented using the XMPU as the access control system. Also in this case, the regions defined in the XMPU has default read/write privilege that cannot be target for the definition of read-only regions. Table I summarizes some of the features required to the access control system for the implementation of common functionalities required in security policies and the limitations of the methods available on the modern SoC under evaluation. We evaluate the AKER access control system with Designs (a) and (b) to understand relative performance and resource usage. Therefore, we develop a simple access control policy compatible with the limitations of the access control systems of designs (a) and (b) and compare these three designs.

The first experiment compares the performance impact on the memory access time of C_1 , C_2 , and C_3 associated with the three access control systems. We setup a common forbidden region F in memory – any read or write request directed to that region is illegal for any controllers C . We evaluate the memory access time in isolation: C_1 , C_2 , and C_3 are activated separately and access a legal region of the memory for different amounts of data. Figure 4(i) reports the measured memory access times. The results show similar performance in latency and throughput for all the designs. This result confirms that the per-transaction extra one clock cycle introduced by the ACW modules has a negligible impact on performance.

The next experiment tests contention generated by illegal transactions. We keep the same configuration of the previous experiment for C_1 , but we configure C_2 to try to concurrently access the forbidden region F , i.e., it issues illegal requests. C_2 issues a new illegal transaction once the previous one has been replied with an error – this behavior models a controller stuck trying to access an illegal memory region due to a misconfiguration. As discussed in Section II-C2, illegal requests in access control systems implemented at the peripheral (Design (b)) occupy time on the interconnect and therefore impact the performance of legal transactions. The measured average access time for C_1 are reported in Figure 4(ii). The results from Design (b) show that the interference generated by the illegal transactions issued by C_2 impacts the performance of C_1 . In particular, the average measured response time increases by 203% on a 16-word transaction changing from 1.22 μs in Designs (a) and (c) to 3.7 μs in Design (c). We measured a lower impact for longer and consecutive accesses. However, in all the cases we measured an impact of at least 20% on the average response times. In Design (a) and (c) the illegal transactions of C_2 are stopped before entering the network – the results shows how AKER stops any interference generated by illegal transactions while featuring flexibility in the definition of the access control policy.

The final experiment tests a denial of service scenario. C_1 keeps the same configuration from the previous experiment while C_2 is setup to flood the interconnect, issuing continuous illegal requests, thus leveraging the full throughput made available by the AXI SmartConnect to C_2 . In this case, C_2 mimics the behaviour of a misconfigured or malicious high-throughput IP core. The results are reported in Figure 4(iii). The impact on the response times of C_1 in Design (b) is way higher than in experiment (ii): the average measured response time of a 16-word transaction issued by C_1 passes

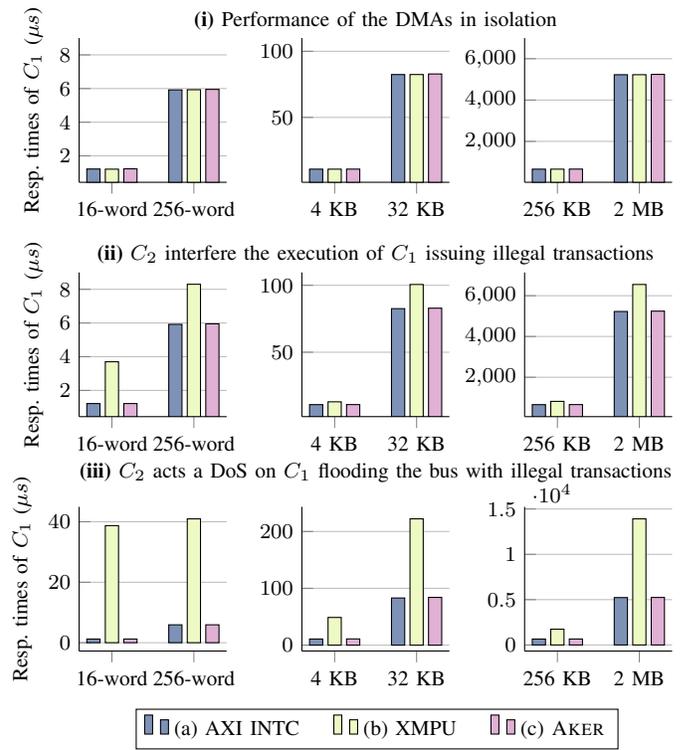


Fig. 4: Performance Evaluation: (i): the three designs act similarly in isolation. (ii): The techniques differ in response time in situations with illegal transaction requests. (iii): A DOS attack by C_2 endangers the availability of the DRAM memory from C_1 in Design (b).

from 1.22 μs of Designs (a) and (c) to 38.72 μs in Design (b), corresponding to an increase of 3074%. Again, the impact decreases on longer and consecutive accesses, however, all of the tested cases showed an impact of at least the 165% on the nominal average response times. Thus, in all the tested scenarios, the response time of C_1 is more than the double with respect to nominal conditions. This experiment shows how a misbehaving IP can create a denial of service when using Design (b) for access control. This issue can be critical in designs integrating software-configurable IPs – malicious software could exploit this issue to act Denial-of-Service of the memory or other resources to the other IPs integrated into the system. Indeed, even if detected at runtime, the access control system implemented in Design (b) does not provide any method to stop the flood of illegal transactions.

Resources	PULP	4 regs	8 regs	16 regs
LUT	156937 (57%)	326 (0.1%)	467 (0.2%)	730 (0.3%)
FF	53354 (10%)	358 (0.1%)	486 (0.1%)	744 (0.1%)

TABLE II: Resource consumption of the ACW module. The area impact of the ACW can be target according to the requirements of the target application.

Table II reports the resource consumption for different configurations of the ACW module implemented for the Xilinx ZYNQ Ultrascale+ platform. The results report the resource consumption of ACW deploying 4 regions (4 regs), 8 regions (8 regs), and 16 regions (16 regs). The results are compared with the resource cost of the PULP SoC platform used in Section IV-B (PULP). The results show that the ACW modules have a very limited impact on resource consumption with respect to the cost of the PULP SoC. Moreover,

the resource consumption can be optimized to meet the requirements of the application.

B. PULP SoC Experiments

The Parallel Ultra-Low-Power (PULP) is an open-source multi-core computing platform comprised of a multicore RISC-V processor. PULP is divided into the SoC domain and the Cluster domain where the SoC performs control and other high level functions while the cluster is aimed at hardware acceleration across eight RISC-V cores.

There are two communication pathways between the SoC and the Cluster. One pathway allows the Cluster to access the SoC, i.e., the Cluster is the Controller and the SoC is a Peripheral. The other communication pathway allows the SoC to access the Cluster – the SoC is the Controller and the Cluster is a Peripheral. These two communication pathways enable the fabric controller core in the SoC domain and the eight cores in the Cluster domain to send/receive information and access the shared L2 memory. Additionally, the PULP’s memory map which includes areas for the Cluster subsystem, the ROM memory, the SoC peripherals subsystem, and the L2 memory is fully addressable from any of the PULP’s nine cores.

The OpenPULP platform does not feature any default access control system for the transactions going from the cluster to the SoC, and vice-versa. Thus, we integrated an AKER access control system using two ACWs to regulate the communication between the PULP’s SoC domain and Cluster domain. Since both pathways use the AXI standard, the process of wrapping their respective AXI M is straightforward and only requires ensuring that the ACW’s ports are connected to the proper signals. Once this is completed, the two ACWs filter all the read/write transactions on the pathways.

We validated the access control policies enforced by the two ACWs via test simulations with various ACW configurations. The test simulations we used include C programs that do not make use of the PULP Cluster and C programs which do make use of the PULP Cluster. As a baseline, we ensured that all test simulations are able to successfully run on the default PULP. For our first validation, we configured both ACWs to allow all read/write transactions and verify that all tests run successfully as with the baseline. For our second validation, we configured both ACWs to block all read/write transactions and verify that the tests which do not make use of the PULP Cluster run successfully and those that do use the Cluster stall while waiting for responses from the decoupled domains. For the remaining validations, we used a combination of configurations to ensure the ACWs are able to enforce access control policies that are more fine-grained than the all-or-nothing approach used in the first two validations. For each validation, we verified results using the testbench output logs and vcd/waveforms (see Figure 5). The design and testing frameworks are available in our repository [6].

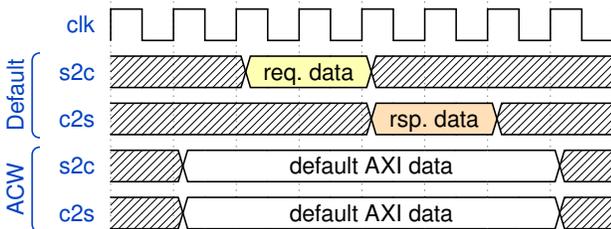


Fig. 5: s2c is the SoC to Cluster pathway. c2s is the Cluster to SoC pathway. The default group shows a portion of the execution of a C program using the Cluster with the default OpenPulp. The ACW group shows the same portion of the execution with the addition of two ACWs configured to block all transactions.

V. RELATED WORKS

Access control systems have been integrated into network-on-chip (NoC) architectures. Fiorin et al. study different manners of integration [22]. Grammatikakis et al. describe a NoC firewall that checks memory accesses in a distributed manner [23]. SurfNoC [24] can isolate mixed-trust users and effectively utilizing the NoC in a time-multiplexed manner. Sepulveda et al. [25] proposed a property-driven method aimed at the specific security verification of NoC routers. While AKER did not specifically focus on NoC architectures, it could be extended to them with some modifications to our methodology.

Several research efforts have been spent by the research community to advance the security of shared bus architectures. Restuccia et al. proposed different solutions to enforce safety and security in AXI architectures including a method to enforce a fair bandwidth distribution among controllers [26], a method to prevent DoS caused by misbehaving/malicious controllers [27], and a hypervisor-level interconnect for the dynamic management of the controllers [28]. Jacob et al. [29] demonstrated how hardware vulnerabilities related to access control can be injected in real systems during the integration of third-party IP modules. A brief discussion of prevention techniques are provided without providing any specific solution. Oberg et al. [30] describe techniques for security verification of I2C and USB. They use hardware information flow tracking to perform verification of a time division multiple access control scheme. Siddiqui et al. [11] and Tan et al. [31] proposed two solutions for the implementation of distributed and decentralized systems aiming to detect anomalous conditions generated by hardware modules. While these solutions can help mitigating misbehaving conditions generated by the hardware module, they are not intended for the implementation of dynamic access control systems. Huffmire et al. [32], [33] describe a memory protection mechanism for enforcing access control policies for FPGAs accessing off-chip memory. Brunel et al. [34] provided a software/hardware system for securing the off-chip memories with static policies during boot phase. Cotret et al. [35] proposed an hardware module for the deployment of distributed firewall systems. It lacks a security verification strategy, it shows high performances impact (18% increase in latency, that can also depends on how the region table is sorted), and lacks of any integration with modern HRoTs for secure configuration.

VI. CONCLUSION

We developed the AKER design and verification framework for SoC access control systems. AKER builds upon the Access Control Wrapper (ACW) that integrates with on-chip controller resources to monitor their memory transactions. AKER provides an extensive property-driven security verification framework. We show how to design, integrate, and verify AKER access control systems into several SoC architectures. We demonstrate that AKER has limited impact on performance while using minimal resources. AKER is easily integrated with a hardware root-of-trust to ensure secure configuration of the the local ACW access control policies. AKER is released as open-source repository [6]. This includes and extensive verification framework with security templates, properties, and testbenches to perform security verification at the IP, firmware, and system levels. The repository also includes design files for the ACW and example integration with OpenTitan, OpenPULP, and a Xilinx FPGA SoC.

VII. ACKNOWLEDGEMENTS

This work was supported in part by the Semiconductor Research Corporation GRC Task 2993.001 and National Science Foundation Award 1718586.

REFERENCES

- [1] F. Restuccia, M. Pagani, A. Biondi, M. Marinoni, and G. Buttazzo, "Modeling and Analysis of Bus Contention for Hardware Accelerators in FPGA SoCs," in *32st Euromicro Conference on Real-Time Systems (ECRTS 2020)*, 2020.
- [2] D. Casini, A. Biondi, G. Nelissen, and G. Buttazzo, "A holistic memory contention analysis for parallel real-time tasks under partitioned scheduling," in *2020 IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*. IEEE, 2020, pp. 239–252.
- [3] *The Common Weakness Enumeration Official Webpage*, MITRE, <https://cwe.mitre.org/>.
- [4] W. Hu, A. Althoff, A. Ardeshiricham, and R. Kastner, "Towards property driven hardware security," in *2016 17th International Workshop on Microprocessor and SOC Test and Verification (MTV)*. IEEE, 2016, pp. 51–56.
- [5] *The OpenTitan Hardware Root of Trust official website*, OpenTitan, <https://opentitan.org/>.
- [6] *Aker Github Repository*, <https://github.com/KastnerRG/AKER-Access-Control>.
- [7] F. Conti, D. Rossi, A. Pullini, I. Loi, and L. Benini, "Pulp: A ultra-low power parallel accelerator for energy-efficient and flexible embedded vision," *Journal of Signal Processing Systems*, vol. 84, no. 3, pp. 339–354, 2016.
- [8] *AMBA® AXI™ and ACE™ Protocol Specification*, ARM, iHI 0022D.
- [9] *SiFive TileLink Specication*, SiFive, v1.8.1.
- [10] *AXI SmartConnect v1.0 LogiCORE IP Product Guide*, Xilinx, pG247.
- [11] F. Siddiqui, M. Hagan, and S. Sezer, "Pro-active policing and policy enforcement architecture for securing mpsoCs," in *2018 31st IEEE International System-on-Chip Conference (SOCC)*. IEEE, 2018, pp. 140–145.
- [12] J. Coburn, S. Ravi, A. Raghunathan, and S. Chakradhar, "Seca: security-enhanced communication architecture," in *Proceedings of the 2005 international conference on Compilers, architectures and synthesis for embedded systems*, 2005, pp. 78–89.
- [13] *Isolation Methods in Zynq UltraScale+ MPSoCs*, Xilinx, xAPP1320.
- [14] A. Basak, S. Bhunia, and S. Ray, "A flexible architecture for systematic implementation of soc security policies," in *2015 IEEE/ACM International Conference on Computer-Aided Design (ICCAD)*. IEEE, 2015, pp. 536–543.
- [15] A. P. D. Nath, S. Ray, A. Basak, and S. Bhunia, "System-on-chip security architecture and cad framework for hardware patch," in *2018 23rd Asia and South Pacific Design Automation Conference (ASP-DAC)*. IEEE, 2018, pp. 733–738.
- [16] K. J. Biba, "Integrity considerations for secure computer systems," MITRE CORP BEDFORD MA, Tech. Rep., 1977.
- [17] S. Aftabjehani, R. Kastner, M. Tehranipoor, F. Farahmandi, J. Oberg, A. Nordstrom, N. Fern, and A. Althoff, "Cad for hardware security - automation is key to adoption of solutions," in *Proceedings of the IEEE VLSI Test Symposium*, 2021.
- [18] W. Hu, A. Ardeshiricham, and R. Kastner, "Hardware information flow tracking," *ACM Computing Surveys (CSUR)*, vol. 54, no. 4, pp. 1–39, 2021.
- [19] M. R. Clarkson and F. B. Schneider, "Hyperproperties," *Journal of Computer Security*, vol. 18, no. 6, pp. 1157–1210, 2010.
- [20] W. Hu, A. Ardeshiricham, M. S. Gobulukoglu, X. Wang, and R. Kastner, "Property specific information flow analysis for hardware security verification," in *Proceedings of the International Conference on Computer-Aided Design*, 2018, pp. 1–8.
- [21] *System Integrated Logic Analyzer v1.0*, Xilinx, 2017, pG261.
- [22] L. Fiorin, G. Palermo, S. Lukovic, V. Catalano, and C. Silvano, "Secure memory accesses on networks-on-chip," *IEEE Transactions on Computers*, vol. 57, no. 9, pp. 1216–1229, 2008.
- [23] M. D. Grammatikakis, K. Papadimitriou, P. Petrakis, A. Papagrigoiriou, G. Kornaros, I. Christoforakis, O. Tomoutzoglou, G. Tsamis, and M. Coppola, "Security in mpsoCs: a noc firewall and an evaluation framework," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 34, no. 8, pp. 1344–1357, 2015.
- [24] H. M. Wassel, Y. Gao, J. K. Oberg, T. Huffmire, R. Kastner, F. T. Chong, and T. Sherwood, "Surfnoc: a low latency and provably non-interfering approach to secure networks-on-chip," *ACM SIGARCH Computer Architecture News*, vol. 41, no. 3, pp. 583–594, 2013.
- [25] J. Sepulveda, D. Aboul-Hassan, G. Sigl, B. Becker, and M. Sauer, "Towards the formal verification of security properties of a network-on-chip router," in *2018 IEEE 23rd European Test Symposium (ETS)*. IEEE, 2018, pp. 1–6.
- [26] F. Restuccia, M. Pagani, A. Biondi, M. Marinoni, and G. Buttazzo, "Is your bus arbiter really fair? restoring fairness in AXI interconnects for FPGA SoCs," *ACM Transactions on Embedded Computing Systems (TECS)*, vol. 18, no. 5s, p. 51, 2019.
- [27] F. Restuccia, A. Biondi, M. Marinoni, and G. Buttazzo, "Safely Preventing Unbounded Delays During Bus Transactions in FPGA-based SoC," in *2020 IEEE 28th Annual International Symposium on Field-Programmable Custom Computing Machines (FCCM)*. IEEE, 2020.
- [28] F. Restuccia, A. Biondi, M. Marinoni, G. Cicero, and G. Buttazzo, "Axi hyperconnect: A predictable, hypervisor-level interconnect for hardware accelerators in fpga soc," in *2020 57th ACM/IEEE Design Automation Conference (DAC)*. IEEE, 2020, pp. 1–6.
- [29] N. Jacob, C. Rolfes, A. Zankl, J. Heyszl, and G. Sigl, "Compromising fpga socs using malicious hardware blocks," in *Design, Automation Test in Europe Conference Exhibition (DATE)*, 2017, 2017, pp. 1122–1127.
- [30] J. Oberg, W. Hu, A. Irturk, M. Tiwari, T. Sherwood, and R. Kastner, "Information flow isolation in I2C and USB," in *2011 48th ACM/EDAC/IEEE Design Automation Conference (DAC)*. IEEE, 2011, pp. 254–259.
- [31] B. Tan, R. Elnaggar, J. M. Fung, R. Karri, and K. Chakrabarty, "Towards hardware-based ip vulnerability detection and post-deployment patching in systems-on-chip," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 2020.
- [32] T. Huffmire, S. Prasad, T. Sherwood, and R. Kastner, "Policy-driven memory protection for reconfigurable hardware," in *European Symposium on Research in Computer Security*. Springer, 2006, pp. 461–478.
- [33] T. Huffmire, T. Sherwood, R. Kastner, and T. Levin, "Enforcing memory policy specifications in reconfigurable hardware," *computers & security*, vol. 27, no. 5-6, pp. 197–215, 2008.
- [34] J. Brunel, R. Pacalet, S. Ouaarab, and G. Duc, "Secbus, a software/hardware architecture for securing external memories," in *2014 2nd IEEE International Conference on Mobile Cloud Computing, Services, and Engineering*, 2014, pp. 277–282.
- [35] P. Cotret, J. Crenne, G. Gogniat, and J. Diguët, "Bus-based mpsoC security through communication protection: A latency-efficient alternative," in *2012 IEEE 20th International Symposium on Field-Programmable Custom Computing Machines*, 2012, pp. 200–207.