Slick: Secure Middleboxes using Shielded Execution

Bohdan Trach†, Alfred Krohmer†, Sergei Arnautov†, Franz Gregor†,
Pramod Bhatotia‡, Christof Fetzer‡
†Technische Universität Dresden ‡University of Edinburgh

Abstract
Cloud computing offers the economies of scale for computational resources with the ease of management, elasticity, and fault tolerance. To take advantage of these benefits, many enterprises are contemplating to outsource the middlebox processing services in the cloud. However, middleboxes that process confidential and private data cannot be securely deployed in the untrusted environment of the (edge) cloud.

To securely outsource middleboxes to the cloud, the state-of-the-art systems advocate network processing over the encrypted traffic. Unfortunately, these systems support only restrictive middlebox functionalities, and incur prohibitively high overheads due to the complex computations involved over the encrypted traffic.

This motivated the design of Slick—a secure middlebox framework for deploying high-performance Network Functions (NFs) on untrusted commodity servers. Slick exposes a generic interface based on CLick to design and implement a wide-range of NFs using its out-of-the-box elements and C++ extensions. Slick leverages ScONE (a shielded execution framework based on INTEL SGX) and INTEL DPDK to securely process confidential data at line rate.

More specifically, Slick provides hardware-assisted memory protection, and configuration and attestation service for seamless and verifiable deployment of middleboxes. We have also added several new features for commonly required functionalities: new specialized CLick elements for secure packet processing, secure shared memory packet transfer for NFs chaining, secure state persistence, an efficient on-NIC timer for SGX enclaves, and memory safety against DPDK-specific lago attacks. Furthermore, we have implemented several SGX-specific optimizations in Slick. Our evaluation shows that Slick achieves near-native throughput and latency.

1 Introduction
Modern enterprises ubiquitously deploy network appliances or "middleboxes" to manage their networking infrastructure. These middleboxes manage a wide-range of workflows for improving the efficiency (e.g., WAN optimizers), performance (e.g., caching, proxies), reliability (e.g., load balancers and monitoring), and security (e.g., firewalls and intrusion detection systems). Due to their wide-spread usage in the networking infrastructure, these middleboxes incur significant deployment, maintenance, and management costs [42].

To overcome these limitations, many enterprises are contemplating to outsource the middlebox processing services in the cloud [31, 42]. Cloud computing offers the economies of scale for computational resources with the ease of management, elasticity, and fault tolerance. The realization of vision: "middleboxes as a service in the cloud" is strengthened by the advancements in software-defined middleboxes, also known as Network Function Virtualization (NFV) [29]. Network Function Virtualization offers a flexible and modular architecture that can be easily deployed on the commodity hardware. Thus, NFV is a perfect candidate to reap the outsourcing benefits of the (edge) cloud computing infrastructure.

However, middleboxes that process confidential and private data cannot be securely deployed in the untrusted environment of the cloud. In the cloud environment, an accidental or, in some cases, intentional action from a cloud administrator could compromise the confidentiality and integrity of execution. These threats of potential violations to the integrity and confidentiality of customer data is often cited as a key barrier to the adoption of cloud services [36].

To securely outsource middleboxes to the cloud, the state-of-the-art systems advocate network processing over the encrypted traffic [25, 43]. However, these systems support only restrictive type of middlebox functionalities, and incur prohibitively high performance overheads since they require complex computations over the encrypted network traffic.

These limitations motivated our work—we strive to answer the following question: How to securely outsource the middlebox processing service on the untrusted third-party platform without sacrificing performance while supporting a wide range of enterprise NFs?

To answer this question, we propose Slick—a secure middlebox framework for deploying high-performance Network Functions (NFs) on untrusted commodity servers. The architecture of Slick is based on four design principles: (1) Security — we aim to provide strong confidentiality and integrity guarantees for the execution of middleboxes against a powerful adversary, (2) Performance — we strive to achieve near-native throughput and latency, (3) Generality — we aim to support a wide range of network functions (same as plaintext processing) with the ease of programmability, and, (4) Transparency — we aim to provide a transparent, portable, and verifiable environment for deploying middleboxes.
Slick leverages Click [23] to provide a flexible and modular framework to build a rich set of NFs using its out-of-the-box elements and C++ extensions. Slick leverages hardware-assisted secure enclaves based on Intel SGX to provide strong confidentiality and integrity properties [14]. To achieve high performance despite the inherent limitations of the SGX architecture, Slick builds on Scone [35] (a shielded execution framework) and Intel DPDK [2] to efficiently process packets in the userspace secure enclave memory. Finally, Slick builds on the container technology with a remote attestation interface [32] to provide a portable deployment and cryptographic verifiable mechanism.

Using the Slick framework, the middlebox owner launches a Slick instance in the cloud and performs remote attestation, passing Slick an encrypted configuration in case of successful attestation. Thereafter, Slick executes user-defined Click elements, which are responsible for reading packets in the userspace directly from NIC, performing network traffic processing, and sending them back to the network. All elements run inside SGX enclave. Packets that must be processed under SGX protection are copied into the enclave explicitly. We efficiently execute the expensive network I/O operations (to-and-from the enclave memory) by integrating Scone with DPDK.

Furthermore, we have designed several new design features for commonly required middlebox functionalities: (a) a remote attestation and configuration service for a seamless and verifiable deployment of middleboxes in the cloud, (b) new Click elements for secure packet processing, (c) an efficient and secure shared memory packet transfer in the multiple SGX enclaves setup for NFVs chaining [20], (d) a secure state persistence layer for fault-tolerance/migration [41], (e) an on-NIC PTP clock as the time source for the SGX enclaves, and (f) a memory protection mechanism to defend against DPDK-specific Iago attacks [13].

We have implemented the aforementioned security features, and also added several SGX-specific performance optimizations to Slick. Lastly, we have evaluated the system using a series of microbenchmarks, and two case-studies: a multiport IP Router, and Intrusion Detection System (IDS). Our evaluation shows that Slick achieves near-native throughput and latency. In order to improve throughput, we limit memory copying by storing most of the packets outside the enclave, using more efficient data structures and preallocating memory. In order to reduce latency, we use NIC timer when necessary, and avoid unnecessary system calls by modifying Click timer event scheduler.

2 Background

In this section, we present a brief necessary background about the three technical building blocks of Slick: shielded execution, DPDK, and Click.

2.1 Shielded Execution

Shielded execution provides strong confidentiality and integrity guarantees for unmodified legacy applications running on untrusted platforms. Our work builds on Scone [35]—a shielded execution framework based on Intel SGX [14].

Intel Software Guard Extensions (SGX). Intel SGX is a set of ISA extensions for Trusted Execution Environments (TEE) released as part of the Skylake architecture. Intel SGX provides an abstraction of secure enclave—a memory region for which the CPU guarantees the confidentiality and integrity of the data and code residing in it. More specifically, the enclave memory is located in the Enclave Page Cache (EPC)—a dedicated memory region protected by MEE, an on-chip Memory Encryption Engine. The MEE encrypts and decrypts cache lines with writes and reads in the EPC, respectively. The processor verifies that the read/write accesses to the EPC are originated from the enclave code. Furthermore, the MEE verifies the integrity of the accessed page to detect memory modifications and rollback attacks.

However, the architecture of SGX suffers from two major limitations: First, the EPC is a limited resource, currently restricted to 128 MB (out of which only 94 MB is available to all enclaves). To overcome this limitation, SGX supports a secure paging mechanism to an unprotected memory. However, the paging mechanism incurs very high overheads depending on the memory access pattern (2x to 2000x). Second, the execution of system calls is prohibited inside the enclave. To execute a system call, the executing thread has to exit the enclave. The system call arguments need to be copied in and out of the enclave memory. Such enclave transitions are expensive—especially, in the context of middleboxes—because of security checks and TLB flushes.

Scone. Scone is a shielded execution framework for unmodified applications based on Intel SGX [35]. In the Scone framework, the legacy applications are statically compiled and linked against a modified standard C library (Scone libc). In this model, application’s address space is confined to the enclave memory, and interaction with the outside world (or the untrusted memory) is performed only via the system call interface. The Scone libc executes system calls outside the enclave on behalf of the shielded application. The Scone framework protects the executing application from the outside world, such as untrusted OS, through shields. In particular, shields copy arguments of system calls inside and outside the enclave and provide functionality to transparently encrypt the data that leaves the enclave perimeter. Furthermore, Scone provides a user-level threading mechanism inside the enclave combined with the asynchronous system call mechanism in which threads outside the enclave asynchronously execute the system calls [45] without forcing the enclave threads to exit the enclave.
2.2 Intel DPDK and Click

**Intel DPDK.** We build on the Intel DPDK library [2] that supports developing high-performance networked systems running on commodity hardware. The DPDK library allows processing of L2 packets from NIC directly in the userspace; thus it completely bypasses the OS networking stack to improve both the throughput and latency.

The DPDK library consists of three main components: Environment Abstraction Layer (EAL), memory management subsystem, and Poll Mode Drivers (PMD). EAL provides a unified way to initialize the central DPDK components (memory management, poll drivers, threading, etc.). The memory management unit of DPDK utilizes huge pages for the buffer management through its own memory allocator (mempool). The mbuf library provides functionality to store and process the raw packet data (which is directly mapped in the userspace virtual memory) in the memory blocks allocated from a mempool. Lastly, a PMD uses the memory rings on the NIC to directly send and receive packets without interrupts, thus achieving high CPU utilization.

**Click.** In addition to DPDK, we leverage Click’s [23] programmable and extensible architecture for the implementation of NFs using its out-of-the-box elements and C++ extensions. In particular, Click provides a dataflow programming language that allows construction of middleboxes as a graph of elements—small, reusable, atomic pieces of network traffic processing functionality. Thereafter, Click routes packets through the elements in the dataflow graph. The modular architecture of Click greatly improves the programmability, productivity, and dependability of middleboxes.

3 Overview

**Basic design.** At a high-level, the core of our system Sllick consists of a simple integration of a DPDK-enabled Click that is running inside the SGX enclave using SCONE. Figure 1 shows the high-level architecture of Sllick.

While designing Sllick, we need to take into account the architectural limitations of Intel SGX. As described in §2.1, an enclave context switch (or exiting the enclave synchronously for issuing system calls) is quite expensive in the SGX architecture. The SCONE framework overcomes this limitation using an asynchronous system call mechanism [45]. While the asynchronous mechanism is good enough for commonly used services like HTTP servers or KV stores—it can not sustain the traffic rates of modern middleboxes. Therefore, we decided to use the userspace DPDK I/O library as a better fit for the SGX enclaves to achieve high performance.

Furthermore, we need to ensure that the memory footprint of Sllick code and data is minimal, due to several reasons: As described in §2.1, enclaves that use more than 94MB of physical memory suffer high performance penalties due to EPC paging (2× to 2000×). In fact, to process data packets at line rate, even stricter resource limit must be obeyed—the working set of the application must fit into the L3 cache. Therefore, our design diligently ensures that we incur minimum cache misses, and avoid EPC paging.

Besides performance reasons, minimizing the code size inside the enclave leads to a smaller Trusted Computing Base (TCB) and allows to reduce the attack surface. The core of Sllick is already quite small (6MB for a statically linked binary section that is loaded in the memory). We decrease its size by removing the unnecessary Click elements at the build time. Importantly, we designed Sllick with the packet-related DPDK data structures running outside of the enclave.

More specifically, when the SCONE runtime starts the application, it automatically places the application code, statically allocated data, and heap in the SGX-protected memory. This mechanism is in contrast the way DPDK operates—it by default allocates memory using x86_64 huge page mechanism, which reduces the TLB miss rate. Such pages are not supported inside the enclave; besides that, NIC can only deliver packets to the unprotected memory, and network traffic entering or leaving machine can be modified by attacker. Therefore, we keep the huge pages enabled in DPDK outside the enclave, and explicitly copy packets that must be processed with SGX protection into the enclave. With this scheme, DPDK-created packet data structures are allocated outside the SGX enclave. We support an efficient data transfer between the DPDK and enclave and processing inside the enclave using the new secure Click elements (detailed in §4.2).

When Sllick starts, it performs remote attestation and obtains the configuration. Sllick initializes the DPDK subsystems, allocates huge page memory and takes the control over NICs that are available. Then, it starts running Click element scheduler, which reads packets from the NIC and passes them along the processing chain until they leave the system or are dropped. Packets that need SGX protection are explicitly copied into enclave.

**Threat model.** We target a scenario where the middleboxes that process confidential and sensitive data are deployed in the untrusted cloud environment (or at the edge computing nodes at ISPs) [42]. Although the cloud providers are usually contractually obligated to not interfere with the compute
and storage units, an accidental leakage, or even a malicious cloud operator might compromise the confidentiality and integrity of the execution [36]. In the context of middleboxes [25, 43], attackers might try to learn the contents of the encrypted data packets and configuration of the system such as cryptographic keys, filtering and classification rules, etc. Furthermore, attackers might try to compromise the integrity of a middlebox by subverting its execution.

To circumvent such attacks, we protect against a very powerful adversary even in the presence of complex layers of software in the virtualized cloud computing infrastructure. More specifically, we assume that the adversary can control the entire system software stack, including the OS or the hypervisor, and is able to launch physical attacks, such as performing memory probes.

However, we note that Slick is not designed to protect against side-channel attacks [48], such as exploiting timing and page fault information. Furthermore, since the underlying infrastructure is controlled by the cloud operator we cannot defend against the denial-of-service attacks.

**System workflow.** Figure 2 shows the system workflow of Slick. As a preparation to the deployment, developers build middlebox container images, and upload them to an image repository (such as Docker Hub [1]) using the Slick toolchain. Network operator, on the other hand, must bootstrap a Configuration and Attestation Service (CAS) on a trusted host, and a Local Attestation Service (LAS) on the host that will be running the middlebox. After this, Slick can be installed on the target machine in the cloud using the container technology—either manually or deployed as a container image from the image repository. Alternatively, it can be installed by transferring a single binary to the target machine.

The Slick framework is bootstrapped using the Configuration and Remote Attestation Service (CAS). The CAS service is launched either inside an SGX enclave of a (already bootstrapped) untrusted machine in the cloud or on a trusted machine under the control of the middlebox operator outside the cloud. Middlebox developers implement the necessary NFs as Slick configurations and send them to the CAS service together with all necessary secrets.

Once the operator launched Slick in the cloud, it will connect to CAS and carry out the remote attestation (detailed in §4.1). If the remote attestation is successful, the Slick instance receives the configuration and necessary secrets. After that, Slick can start processing the network traffic, with all the benefits:

- **Security:** Slick provides strong confidentiality and integrity for the middlebox execution. We leverage hardware-assisted SGX memory enclaves to provide strong security properties.

**Workflow steps:**

1. Build and host middlebox images using the Slick toolchain
2. Launch the CAS service on a trusted host
3. Install the LAS service on a Slick host
4. Install a Slick middlebox from the repository
5. Provide Slick configuration and secrets to CAS
6. Perform remote attestation, configuration, and launch Slick

![Figure 2: Slick system workflow](image)

**Figure 2: Slick system workflow**

- **Performance:** Slick achieves near-native throughput and latency by building a high-performance networking I/O architecture for the shielded execution of middleboxes. We overcome the architectural limitations of Intel SGX enclaves by optimizing the combination of Scone and DPDK.
- **Generality:** Slick supports a wide-range of NFVs, same as supported in the plain-text network processing, without restricting any functionalities. We leverage Slick to provide a general framework to implement a wide-range of NFs.
- **Transparency:** Lastly, Slick provides network operators a portable, configurable, and verifiable architecture for the middlebox deployment in cloud. We build on the container technology with configuration and attestation services for a seamless deployment.

**Limitation.** We note that neither DPDK nor Slick support flow-based stateful traffic. This implies that Slick currently supports NFs that work on L2 and L3; as only restricted processing of L4-L6 traffic is supported. We plan to extend our system to support flow-based traffic with shielded execution by integrating a user-level networking stack [18].

4 **Design Details**

We next present the design details of Slick. Figure 3 shows the detailed architecture of Slick.

4.1 **Configuration and Remote Attestation**

To bootstrap a trusted middlebox system in the cloud, one has to establish trust in the system components. While Intel SGX provides a remote attestation feature, a holistic system must be built for remote attestation and secure configuration of middleboxes [37]. To achieve this goal, we have designed a Configuration and Attestation Service (CAS) for middleboxes. Figure 4 shows the system protocol for the CAS service.
In order to attest an enclave using Intel Remote Attestation, verifier (operator of a Slick instance) connects to the application and requests a quote. The enclave requests a report from SGX hardware and transmits it to the Intel Quoting Enclave (QE), which verifies, signs, and sends back the report. The enclave then forwards it to the verifier. This quote can be verified using the Intel verification service [3].

Our remote attestation system extends Intel’s RA service, and is integrated with a configuration system, which provisions Slick with its configuration in a secure way using a trusted channel established during attestation. This system consists of enclave-level library, Local Attestation Service (LAS), and Configuration and Attestation Service (CAS).

- Enclave library interacts with LAS and CAS to carry out remote attestation, and allows setting environment variables, command-line arguments, and keys for the Scone shielding layer in a secure and confidential manner.
- Local Attestation Service is running on the same machine as Slick middlebox, and acts as a proxy for interaction with the Intel Attestation Service (IAS). It also acts as the intermediate root of trust: once LAS is attested, further Slick instances can be launched even when IAS is unavailable.
- Configuration Attestation Service is running on a single (possibly replicated) node and stores configuration and secrets of the services built with Scone. It maintains information about attested enclave instances, and provisions configuration to applications using the Enclave Library.

To bootstrap the system, the operator launches CAS, either on the host under his control or on the host in the cloud inside an SGX enclave. Then, the CAS service is populated with configurations and secrets using the REST API or a command-line configuration tool. LAS and IAS instances are launched on cloud hosts that will run Slick instances. During startup, each Slick instance establishes a TLS connection to CAS. Simultaneously, it connects to LAS to perform local attestation. In the case the LAS instance is not yet attested, it will attest itself to CAS using Intel Remote Attestation protocol, and then attest Slick instance to CAS using SGX local attestation. Local attestation verifies integrity of the Slick binary, and establishes whether Slick is running under SGX protection. This allows to remove distribution mechanisms (such as Docker Hub) from the TCB. After that, Slick sends the LAS quote to CAS, and a secure channel is established between CAS and Slick. Thereafter, Slick obtains its configuration from the CAS service and transfers control to main Slick code.

### 4.2 Secure Elements

As described in §3, we designed Slick with the packet-related data structures of DPDK running outside the enclave. Therefore, we needed an efficient way to support the communication between DPDK and the enclave memory region. In particular, we have to consider the overheads of accessing the SGX-encrypted pages from the main memory and copying of the data between the protected and unprotected memory regions. When possible, the data packets with plain-text contents should not be needlessly copied into the enclave, as it will degrade the performance. Therefore, we designed specialized secure Slick elements (shown in Table 1) for copying the data packets into/outside the enclave to facilitate efficient communication.
By default, packets are read from NIC queues into the untrusted memory. This reduces the overhead of using SGX when processing packets that are not encrypted and can be safely treated with less security mechanisms involved. Such packets are immediately forwarded or dropped upon header inspection. On the other hand, we must move packets into the enclave memory with explicit copy element. We have implemented such an element (ToEnclave), and use it to construct secure packet processing chains.

We have also added support for the commonly used AES-GCM cipher into Sllick (Seal and Unseal elements). This allows us to construct VPN systems that use modern cryptographic mechanisms. This element was implemented using Intel ISA-L crypto library. In order to allow secure key generation inside the enclave, we have exposed Scon functions for getting SGXSea1 keys to the Sllick internal APIs.

To allow building high-performance IDS systems based using Sllick, we have created and element based on the HyperScan regular expression library. It allows fast matching of a number of regular expressions for the incoming packets, simplifying implementation of systems like Snort [5].

We have also added elements that implement more broad mechanisms: DPDKRing (§4.3) for NFV chaining, and StateFile (§4.4) for state persistence in middleboxes.

4.3 NFVs Chaining

Typically NFVs are chained together to build a dataflow processing graph with multiple Sllick elements, spanning across multiple cores, sockets, and machines [20, 31]. The communication between different cores and sockets happens through the shared memory, and communication across machines via NICs over RDMA/Infiniband. DPDK supports NUMA systems and always explicitly tries to allocate memory from the local socket RAM nodes.
Seal(StateFile)
Seals elements’ state in the StateFile
Unseal(StateFile)
Unseals elements’ state from the StateFile
Persist(timer, StateFile)
Periodically persists the state to StateFile

| Table 2: Slick APIs for state persistence |

existing ring (secondary process) in huge page memory. In Slick, packets pushed towards a DPDKRing element are enqueued into the ring and can be dequeued from the ring in another process for further processing. A bidirectional communication between two processes can be established by using a pair of rings.

4.4 Middlebox State Persistence

Middleboxes often maintain useful state (such as counter values, Ethernet switch mapping, activity logs, routing table, etc.) for fault-tolerance [41], migration [30], diagnostics [47], etc. To securely persist this state, we extend Slick with new APIs (shown in Table 2) for the state persistence in middleboxes. The Seal primitive is used to collect the state that must be persisted from the elements, and write it down in encrypted form to disk. Unseal reads this state from disk, decrypts it and populates the elements with this state.

To configure this functionality, we have added a new configuration element to Slick, called StateFile (see Table 1). Its parameters are file to which state should be written and the key that should be used for encryption. Note that this information is transmitted to Slick instance in the configuration string via remote attestation, and is not accessible outside the enclave. We don’t use Scone file system shield, and instead encrypt and decrypt file as a single block. This ensures confidentiality and integrity of stored data via the use of AES-GCM cipher.

We do not attempt to extract the relevant state transparently. Instead, we rely on programmer providing necessary serialization routines that save only necessary parts of element state. These routines are available in Slick as read and write handlers, and are triggered in the Slick startup procedure after the configuration is loaded, parsed, and initialization of the basic components is finished, or manually via ControlSocket interface of the StateFile element. It’s also possible to trigger them periodically via a timer.

4.5 NIC Time Source

Timer is one of the commonly used functionalities in middleboxes [29, 31]. It is used for a variety of purposes such as measuring performance, scheduling execution of periodically-triggered NFs, etc.

The time measurement can be fine-grained or coarse-grained based on the application requirements. For the fine-grained cycle-level measurements, developers use rdtscp instruction, which is extremely cheap and precise. Whereas for the coarse-grained measurements, applications invoke system calls like gettimeofday or clock_gettime.

However, in the context SGX enclaves, both rdtscp and system calls have unacceptable latency for their use in middleboxes to process the network traffic at line rate. More specifically, the rdtscp instruction is forbidden inside the enclave, and therefore, it causes an enclave exit event; whereas, asynchronous system calls in Scone are submitted though a system call queue that is optimized for the raw throughput, but not latency.

To overcome these limitations, we have opted to use the on-NIC PTP clock as the clock source for the enclave. This clock can be read inside the enclave reasonably fast (0.9 µsec, which is on the same scale of magnitude as reading HPET). Moreover, it neither causes enclave exits nor requires submitting system calls. Furthermore, the on-NIC clock is extremely precise since it is intended to use for the PTP synchronization protocol.

We stress that this time source is not secure, and can be used as a denial of service attack vector by the malicious operation system. However, the same is true for the other time sources—a trusted, efficient and precise time source for SGX enclaves remains an unsolved problem that will likely require changes to the CPU hardware [39].

4.6 DPDK-Specific Iago Attacks

Iago attacks [13] are a serious class of security attacks that can be launched on shielded execution to compromise the confidentiality and integrity properties. In particular, an Iago attack originates through malicious inputs supplied by the untrusted code to the trusted code. In the classical setting, a malicious OS can subvert the execution of an SGX-protected application by exploiting the application’s dependency on correct values of system call return values [11].

The decision (§3) to allocate huge pages for packet buffers and DPDK rings has security implications. The fact that packets are passed through rings by reference, and DPDK buffers contain pointers, opens a new attack surface on Slick. Attackers with access to this memory region could modify pointers to point into the SGX-protected regions and make the enclave inadvertently leak secrets over the network.

To protect against DPDK-specific Iago attacks, we have implemented a pointer validation function. More specifically, the scheme uses an enclave parameter structure that is located inside the enclave memory and defines the enclave memory boundaries. Pointers are validated by checking if they do not point into the enclave memory range \([\text{base}, \text{base} + \text{enclave size}]\). We note that Slick is already protected against the classical syscall-specific Iago attacks through Scone’s shielding interfaces.
This ensures that no pointers possibly pointing to the secrets stored in EPC are accepted through the unprotected huge page memory. Pointers can still be modified by a malicious attacker, but they can only point to the unprotected memory.

As it is possible for an application to enqueue and dequeue arbitrary pointers into DPDK's rte_ring structures, it is not easily possible to integrate this pointer check directly into DPDK. Instead, we implemented these pointer checks in the DPDKRing and FromDPDKDevice ($\S 4.3$) elements. If SLick detects a malicious pointer, it assumes an attack, notifies the application operator and drops the packet.

5 Implementation

5.1 Toolchain
We built SLick's toolchain using DPDK (version 16.11) and CLICK (master branch commit @88680a93). We further integrate it with the Scone runtime to compile SLick. The toolchain is based on the musl-cross-make [4] project, modified to use Scone libc instead of the standard musl-libc. We use gcc version 6.3.0 for the compilation process. This enables us to use both C and C++ code. musl-cross-make is also used to compile native version of CLICK for the evaluation. We used Boost C++ library (version 1.63) to build a static version of the Hyperscan high performance regular expression matching engine (master branch commit 7aff6f61) and incorporated it into SLick. We use WolfSSL library [7] to implement the remote attestation system and StateFile sealing, and packet Seal/Unseal elements. The toolchain contains automated scripts for building and deploying middlebox container images, and setting up SLick and CAS services (as described in the system workflow in §3).

To make the compilation of SLick work with the Scone toolchain, some changes to DPDK were necessary. In particular, we need to remove the helper functions for printing stack traces and provide some glibc-specific structures and macros as well as kernel header files. CLICK is implemented in C++ using mostly high level APIs and required no adaptions.

The resulting SLick binary is 8.2 MB in size, and around 16 MB including minimal runtime stack and heap allocation. This implies that we could run roughly up to six instances of SLick in parallel on one processor without impacting the performance by EPC paging (system-wide EPC limit is 94 MB).

5.2 Memory Management
Scone implements its own, in-enclave memory management, using EPC pages for all malloc and mmap anonymous memory allocation calls. Allocating huge page memory through this allocator is not possible without modifications.

However, accessing huge pages in DPDK does not necessarily require bypassing Scone, because of the specific way DPDK uses to allocate huge pages. Instead of passing MAP_HUGETLB flag to mmap(), it opens shared memory files in the hugetlbfs virtual filesystem and passes those file descriptors to mmap call, which is not protected by Scone. This mmap file-to-memory mapping request is directly passed to the operating system by Scone.

5.3 Optimizations
In order to further improve the performance, especially for the case of DPDK running inside the enclave, we optimized the data path inside CLICK. We used the Linux performance profiling tool perf [6] to find the bottlenecks.

Memory pre-allocation. The FromDPDK element allocated memory for packet descriptor storage on the stack each time the run_task function was called. We pre-allocated this memory once in a constructor.

Branching hints. We inserted GCC-specific unlikely / likely macros in several if-clauses. These get translated to platform specific instructions which instruct the processor to always try the given branch first instead of using its built-in branch prediction.

Modulo operations. We replaced all modulo operations in the data path by compare-and-subtract operations (which are way less expensive in terms of processing time).

Queue optimization. In the ToDPDKDevice CLICK element we replaced the inefficient implementation of the queue (which used std::vector from the C++ standard library) by the rte_ring structure provided by DPDK.

Timer event scheduler optimization. In the CLICK timer event scheduler, we have optimized the code to reduce the amount of clock_gettime system calls. This allowed us to reduce the latency in short element chains to the native level.

6 Evaluation

6.1 Experimental Setup
Testbed. We benchmark our system using two machines: (1) load generator, and (2) SGX-enabled machine. The load generator is a Broadwell Intel Xeon D-1540 (2.00GHz, 8 cores, 16 hyperthreads) machine with 32 GB RAM. The SGX machine under test is Intel Xeon E3-1270 v5 (3.60GHz, 4 cores, 8 hyperthreads) with 32 GB RAM running Linux kernel 4.4. Each core has private 32KB L1 and 256KB L2 caches, and all cores share a 8MB L3 cache. The load generator is connected to the test machine using 40 GbE Intel XL-710 network card. We use pktgen-dpdk for throughput testing. The test machine is configured to use the maximum number of cores. The load generator saturates the link starting with 128 byte packets.

Applications. For the microbenchmarks, we use three basic CLICK elements: (1) Wire, which sends the packet immediately after receiving; (2) EtherMirror, which sends the packet after swapping the source and destination addresses; and (3) Firewall, which does packet filtering based
We first measure the throughput of three microbenchmark applications with varying packet size. Slick is running on four cores. Figure 5, Figure 6, and Figure 7 present the throughput for Wire, Ethermirror, and Firewall, respectively.

The results show that the performance of Slick matches the performance of Click. In the case of Wire application with the packet sizes smaller than 256 bytes, Slick is better than the native version. This is explained by the fact that Click timer event scheduler optimization is missing in the native Click, which removes some system call overhead from the Wire application. The impact is smaller with other applications, because they contain elements that reduce the relative overhead of Click scheduler. We also see that Slick achieves line rate at 512 byte packets.

6.3 Scalability

We next consider the scalability of our system with increasing number of cores. (Our latest SGX-enabled server has maximum of 4 cores / 8 HT. Recently released Intel X-Series will consist of 18 cores.) Figure 8, Figure 9, and Figure 10 present the throughput for Wire, Ethermirror, and Firewall, respectively. The scalability of both Slick and Click is limited. We can see that the performance for both native and Slick peaks at four cores. There are several reasons for this:

- DPDK and Slick work best with hyperthreading disabled.
- Slick runs system call threads to execute system calls asynchronously. When there are no system calls for a long time, they back-off (i.e. yield the CPU). They wake up from back-off periodically, and as result, they preempt in-enclave threads.

6.4 Latency

To evaluate the influence of Slick’s runtime environment on latency, we have also measured the packet processing latency using the following scheme: load generator runs an application, continuously generates a UDP packet and waits for its return spinning. We study packet round trip time measured at the load generator. On the Slick instance, we are running the EtherMirror application. (We omit the results for other applications due to the space constraints.) For this measurements, we did not perform any latency-specific tuning of the environment other than thread pinning, which is enabled by default in DPDK. We expect that a production system with stringent requirements to low latency will use...
The low performance of Slick without optimizations is explained by the fact that Slick executes clock_gettime system calls in the timer event scheduling code. Scone system calls are optimized for raw throughput with a large number of threads, but not for low latency; this makes the latency measurement result 3x worse than the native execution. We have considered the following latency optimizations:

- Reduced system call rate for immediately-scheduled timer events. It removes one system call round-trip from the packet latency.
- Modified scheduler that prioritizes immediately-scheduled events and allows to remove a system call from scheduler if there are no periodic timer events.

One of the surprising results that we have is that each of these optimizations does not have a statistically significant influence when applied individually, which can be explained by the fact that once the system call thread has left the back-off mode, it will execute system calls with low individual overhead. On the other hand, when applied simultaneously, they return the latency to almost-native levels—effect of Scone on the latency is extremely small.

We consider using NIC timer as a separate optimization. One can see that reading NIC timer is a costly operation; it happens twice per packet in our measurements, adding approximately 0.9 + 2 = 1.8µsec to the total latency. On the other hand, it’s much faster than executing clock-reading system calls, and can further improve system timeliness when combined with other optimizations.

### 6.5 Configuration and Attestation

We next evaluate the overheads of the configuration and attestation service in Slick. The measurement results are presented in Table 3. The results show that remote attestation has negligible effect on the Slick startup time. Furthermore, even though TLS session establishment is a costly operation, it is performed once per instance start-up, allowing operator to use a single CAS node for thousands of Slick instances.

### 6.6 ToEnclave Overhead

We next measure the throughput of the new secure ToEnclave element added in Slick, which is used to copy the packet data inside SGX enclave protected memory. We evaluate the impact of this extra data copy by measuring the throughput scaling with varying packet size. Figure 12 and Figure 13 show the results for Wire and EtherMirror, respectively.

As we can see that the overhead of the extra memory copy peaks with small packet sizes. This is due to the fact that for each received packet, operations with rather high overhead must be executed to allocate the packet. One way to reduce this cost would be to batch the memory allocation for all packets. It can be also seen that the overhead with Slick when compared to the native execution is relatively small: Slick with ToEnclave is running within 88% of the native version with extra memory copy in the worst case of small packet sizes, and within 60% of the native Click without ToEnclave element.

### 6.7 NFVs Chaining

To measure the throughput of the NFV chaining scheme, we have implemented a chaining application. The chaining application implements packet communication between

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**Table 3: Overheads of configuration and attestation**

| Phase          | Average Duration, µsec |
|----------------|------------------------|
| Attestation    | 19467                  |
| CAS communication | 19301              |
| LAS communication | 1474               |
| Configuration  | 825.6                  |
| Total time     | 26368                  |

**Figure 9: EtherMirror throughput w/ increasing cores**

**Figure 10: Firewall throughput w/ increasing cores**

**Figure 11: EtherMirror latency measurement**
two Slick instances running on the same machine through a DPDK packet ring. One instance contains an application that receives packets from network and sends them to the other instance via the DPDKRing element. The second instance receives packets from the ring and sends them back through a different DPDKRing element. These packets are received by the first Slick forming a circular ring. Thereafter, the packets are transmitted back to the load generating node. Please note that the packets cross the rings twice. The chaining application showcases the worst-case throughput since the Slick elements are not performing any computation on the network packets.

Figure 14 presents the throughput with varying packet size for the NFV chaining application. The results show that using the ring communication causes a substantial performance drop for Slick independent of the optimizations. This is mostly related to the way Scone runs enclaves—it must allocate constantly-running thread for the service threads created by Slick and DPDK. Due to this, there is interference between the service threads and processing cores, which decreases the throughput and also increases the result variance.

### 6.8 Packet Sealing Performance

We next evaluate the throughput of the Seal/Unseal secure elements. In particular, we use our AES-GCM encryption code running inside the SGX enclave (the same code is used for middlebox state persistence code). Figure 15 presents the throughput of the Seal element with varying packet size. The result shows that the code inside SGX enclave runs within 88% of the native performance irrespective of the optimizations applied. This is explained by the fact that most of the application CPU time is spent doing the encryption. The difference between the native and SGX version can be explained by different thread scheduling strategies used by Scone and native POSIX. In POSIX, threads are pinned to the real CPU cores, while in Scone, the userspace threads inside enclave are pinned to the in-enclave kernel threads. This makes thread pinning non-deterministic—sometimes two threads that are to be pinned to different cores are pinned to sibling hyper-threads.

### 6.9 Case Studies

We next evaluate Slick’s performance with the following two case-studies: (1) IPRouter, and (2) IDS.

**IPRouter.** IPRouter application is an adaptation of a multi-port router ClicK example application to our evaluation hardware. This application first classifies all packets into three categories: ARP requests, ARP replies, and all other packets. ARP requests are answered. ARP replies are dropped. Other packets are passed to a routing table element that sends them to the NIC output port. Figure 16 shows the throughput of the IPRouter application with varying packet size. We can see that Slick has the same performance as ClicK with packet sizes bigger than 256 bytes, and performs within 90% of ClicK with smaller packets.

We also measured the latency of the IPRouter application as presented in Figure 17. We can see that even if the number of elements in the application increases, latency of the application remains the same as the native execution.

**Intrusion Detection System (IDS).** IDS application implements NF that is commonly found in the enterprise network. It pushes the traffic through the firewall, and then performs...
traffic scanning with the Hyper Scan element. Traffic that does not match any pattern is sent to the output, while matching traffic passes through a counter and then dropped.

**Slick** performs as close to the native **Click** execution with a slight performance drop. This drop comes from the general SGX overhead for memory accesses. Due to the space constraints, we omit the latency measurement results for IDS.

7 Related Work

**Software middleboxes.** **Click**’s [23] modular architecture has been leveraged in the research community to build many useful software-based middlebox platforms [10, 12, 19, 19, 27, 29]. Our work also builds on the **Click** architecture, but unlike the previous work, **Slick** focuses on securing the **Click** architecture on the untrusted commodity hardware.

However, most **Click**-based middleboxes operate at L2-L3 layer, with the notable exception of CilMB [26]. To support flow-based abstractions, many state-of-the-art middleboxes [8, 9, 17, 28, 28, 40] support comprehensive applications and use-cases. Since both **Click** and DPDK are geared toward L2-L3 network processing, our current architecture does not support L4-L7 network functions. As part of the future work, we plan to integrate a high-performance user-level networking stack [18] in the Scone framework to support the development of secure higher layer middleboxes.

**Secure middleboxes.** **APLOMB** [42] is one the first systems to showcase that it is a viable alternative, performance- and cost-wise, to outsource middleboxes from the enterprise environment to the cloud. However, **APLOMB** does not consider the security implications of outsourcing in the cloud.

To overcome the limitation of **APLOMB**, the follow up systems, namely **Embark** [25] and **BlindBox** [43], advocate network data processing over the encrypted traffic. In particular, **BlindBox** [43] proposes an encryption scheme based on garbled circuits to support string matching operations over encrypted traffic. However, **BlindBox** supports only restrictive type of middlebox functionalities, such as NFs for deep packet inspection. To overcome this limitation, **Embark** [25] extends **BlindBox** to support a wider range of middlebox functions. However, **Embark** suffers from prohibitively low performance as it involves complex cryptographic computations over the encrypted network traffic. In contrast, **Slick** supports a wide range of network functions (same as plaintext), and achieves a near-native throughput and latency.

The recently published workshop papers [15, 22] have elaborated the challenges and potential usages of SGX in the network applications. In the domain of network-intensive applications, **SGX-Tor** [21] is one of the first systems to use SGX to enhance the security and privacy of Tor. In a similar vein, **CBR** [33] leverages SGX to support privacy-preserving routing. Likewise, the **Slick** project builds the first comprehensive system using **Intel** SGX to secure middleboxes.

**Shielded execution.** Shielded execution provides strong security guarantees for legacy applications running on untrusted platforms [11, 24, 35, 38, 44, 46]. Our work leverages shielded execution based on **Intel** SGX. It is worth noting that unlike the prior usage of shielded execution for commonly used services like HTTP servers or KV stores, we need to adapt the shielded execution to process the network traffic at line rates. To achieve this, **Slick** is the first system that integrates a high-speed packet I/O framework [2, 16, 34] with shielded execution.

8 Conclusion

In this paper, we presented the design, implementation, and evaluation of **Slick**—a secure middlebox framework for deploying high-performance Network Functions (NFs) on untrusted commodity servers. **Slick** exposes a generic interface based on **Click** to design and implement a wide range of NFs using its out-of-the-box elements and C++ extensions. To securely process data at line rate, **Slick** is the first system to integrate a high-performance I/O processing library (**Intel** SGX).
DPDK) with a shielded execution (Scone) framework based on Intel SGX. We have also added several new useful features, and optimizations for secure network processing. Our evaluation using a wide-range of NFs and case-studies show that Slick achieves near-native throughput and latency.

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