TNIC: A Trusted NIC Architecture

A full version

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Abstract

We introduce TNIC, a trusted NIC architecture for building trustworthy distributed systems deployed in heterogeneous, untrusted (Byzantine) cloud environments. TNIC builds a minimal, formally verified, silicon root-of-trust at the network interface level. We strive for three primary design goals: (1) a host CPU-agnostic unified security architecture by providing trustworthy network-level isolation; (2) a minimalistic and verifiable TCB based on a silicon root-of-trust by providing two core properties of transferable authentication and non-equivocation; and (3) a hardware-accelerated trustworthy network stack leveraging SmartNICs. Based on the TNIC architecture and associated network stack, we present a generic set of programming APIs and a recipe for building high-performance, trustworthy, distributed systems for Byzantine settings. We formally verify the safety and security properties of our TNIC while demonstrating its use by building four trustworthy distributed systems. Our evaluation of TNIC shows up to 6× performance improvement compared to CPU-centric TEE systems.

CCS Concepts: • **Security and privacy → Trusted computing**.

Keywords: trusted computing, hardware-software co-design

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1 Introduction

Distributed systems are integral to the third-party cloud infrastructure [4, 18, 29, 33]. While these systems manifest in diverse forms (e.g., storage systems [41, 47, 58, 62, 71, 75, 88], management services [60, 100], computing frameworks [8, 10, 19]) they all must be fast and remain correct upon failures.

Unfortunately, the widespread adoption of the cloud has drastically increased the surface area of attacks and faults [83, 95, 152] that are beyond the traditional fail-stop (or crash fault) model [77]. The modern (untrusted) third-party cloud infrastructure severely suffers from arbitrary (*Byzantine*) faults [113] that can range from malicious (network) attacks to configuration errors and bugs and are capable of irreversibly disrupting the correct execution of the system [65, 83, 95, 152].

A promising solution to build trustworthy distributed systems that can sustain Byzantine failures is based on the *silicon root of trust*—specifically, the Trusted Execution Environments (TEEs) [7, 26, 48, 73, 145]. While the TEEs offer a (single-node) isolated Trusted Computing Base (TCB), we have identified three core challenges (§ 3.3) that complicate their adoption for building trustworthy distributed systems spanning multiple nodes in Byzantine cloud environments.

First, TEEs in heterogeneous cloud environments introduce programmability and security challenges. A cloud environment offers diverse heterogeneous host-side CPUs with different TEEs (e.g., Intel SGX/TDX, AMD SEV-SNP, AWS Nitro Enclaves, Arm TrustZone/CCA, RISC-V Keystone). These heterogeneous host-side TEEs require different programming models and offer varying security properties. Therefore, they cannot (easily) provide a generic substrate for building trustworthy distributed systems. Our work overcomes this challenge by designing a *host CPU-agnostic silicon root of trust* at the network interface (NIC) level (§ 4). We provide a generic programming API (§ 6) and a *recipe* (§ 6.2) for building high-performance, trustworthy distributed systems (§ 7).

Secondly, TEEs with a large TCB are plagued with security vulnerabilities, rendering them non-verifiable. With hundreds of security bugs already uncovered [84], TEEs' large TCBs further increase their security vulnerabilities [111, 135], impeding a formal verification of their security. We overcome this with a *minimalistic verifiable TCB* (§ 4.1). Our TCB resides at the NIC hardware and is equipped with *the lower bound of*

*This work started when the author was at the University of Edinburgh.

security primitives; we provide only two key security properties of non-equivocation and transferable authentication for building trustworthy distributed systems (§ 2.1). Since we strive for a minimal trusted interface, we can (and we did) formally verify the security properties of our TCB (§ 4.4).

Thirdly, TEEs report significant performance bottlenecks. TEEs syscalls execution for (network) I/O is extremely costly [171], whereas even state-of-the-art network stacks showed a lower bound of 4× slowdown [55]. We attack this challenge based on two aspects. First, we build a scalable transformation with our minimal TCB's security properties (§ 6.2) to transform Byzantine faults ($3f+1$) to much cheaper crash faults ($2f+1$) for tolerating f (distributed) Byzantine nodes. Secondly, we design hardware-accelerated offload of the security computation at the NIC level by extending the scope of SmartNICs with *the lower bound of security primitives* (§ 4) while offering kernel-bypass networking (§ 5).

To overcome these challenges, we present TNIC, a trusted NIC architecture for building trustworthy distributed systems deployed in Byzantine cloud environments. TNIC realizes an abstraction of trustworthy network-level isolation by building a hardware-accelerated silicon root of trust at the NIC level. Overall, TNIC follows a layered design:

- **Trusted NIC hardware architecture (§ 4):** We materialize a minimalistic, verifiable, and host-CPU-agnostic TCB at the network interface level as the key component to design trusted distributed systems for Byzantine settings. Our TCB guarantees the security properties of non-equivocation and transferable authentication that suffice to implement an efficient transformation of systems for Byzantine settings. We build TNIC on top of FPGA-based SmartNICs [3]. We formally verify the safety and security guarantees of TNIC protocols using Tamarin Prover [130].
- **Network stack (§ 5) and library (§ 6):** Based on the TNIC architecture, we design a HW-accelerated network stack to access the hardware bypassing kernel for performance. On top of TNIC's network stack, we present a networking library that exposes a simplified programming model. We show *how to use* TNIC APIs to construct a generic transformation of a distributed system operating under the CFT model to target Byzantine settings.
- **Trusted distributed systems using TNIC (§ 7):** We build with TNIC the following (distributed) systems for Byzantine environments: Attested Append-only Memory (A2M) [69], Byzantine Fault Tolerance (BFT) [64], Chain Replication [166], and Accountability with PeerReview [94]—showing the generality of our approach.

We evaluate TNIC with a state-of-the-art software-based network stack, eRPC [105], on top of RDMA [131]/DPDK [24] with two different TEEs (Intel SGX [103] and AMD-sev [48]). Our evaluation shows that TNIC offers 3×—5× lower latency than the software-based approach with the CPU-based TEEs. For trusted distributed systems, TNIC improves throughput by up to 6× compared to their TEE-based implementations.

2 Motivation and Background

We first examine the design requirements for high-performance, trustworthy distributed systems for cloud environments.

2.1 Trustworthy Distributed Systems

Byzantine fault model. In the untrusted cloud infrastructure, arbitrary (Byzantine) faults are a frequent occurrence in the wild [83, 152, 176, 177]. To this end, system designers introduced Byzantine Fault Tolerant (BFT) systems that remain correct even under the presence of (a bounded number of) Byzantine failures [113]. Traditional BFT protocols need *at least* $3f+1$ nodes in order to provide consistent replication while tolerating up to f Byzantine failures. While BFT accurately captures the realistic security needs in the cloud [81], it is rarely adopted in practice [156] due to its complexity and limited performance [53, 154].

Crash fault model. The vast majority of cloud applications operate under the fail-stop (crash fault) model [14, 17, 21, 61, 71], optimistically *assuming* that the entire cloud infrastructure is trusted and only fails by crashing [77]. Compared to BFT replication, Crash Fault Tolerant (CFT) protocols [100, 112, 137, 138], require $2f+1$ replicas to tolerate f (yet non-Byzantine) failures. While CFT systems can offer performance and scalability [87], they are fundamentally incapable of ensuring safety in the presence of non-benign faults, hence, are ill-suited for the modern cloud.

Security properties for BFT. We seek to build BFT systems while reducing their programmability and performance overheads. Our approach, inspired by the theoretical findings of Clement et al. [70], *transforms* CFT systems into BFT systems by providing the *lower bound* of security properties, i.e., *transferable authentication* and *non-equivocation*.

We next explain the two security properties. First, *transferable authentication* allows a node to verify the original sender of a received message, even if it is forwarded by other than the original sender. Assuming that the sender p_i sends an authenticated message m to a recipient p_j, the authenticated message m is accompanied by an authentication token $\sigma(p_i)$ that allows p_j to verify that p_i generated the message, e.g., verify(m,$\sigma(p_i)$). Authentication tokens are unforgeable:

- if p_i is correct, then verify(m,$\sigma(p_i)$) is true if and only if p_i generated m.
- if p_i is faulty, verify(m,$\sigma(p_i)$) $\wedge$ verify(m',$\sigma(p_i)$) $\Rightarrow m=m'$. As such, a compromised p_i cannot produce two valid different messages that can be verified with the same token $\sigma(p_i)$.

As an authentication token is transferable, it allows another recipient p_k to evaluate verify(m,$\sigma(p_i)$) in the same way even when m and $\sigma(p_i)$ are forwarded from p_j.

Second, *non-equivocation* guarantees that a node cannot make conflicting statements to different nodes. Equivocation

also manifests as network adversaries or replay attacks that send invalid messages or re-send valid but stale messages.

The seminal paper [70] proves that, given these two properties, a transformation from any CFT protocol to a BFT protocol is *always* possible without increasing the number of participating nodes; e.g., a reliable broadcast can be implemented to tolerate up to f Byzantine failures in an asynchronous system with $2f+1$ replicas, rather than the conventional $3f+1$.

2.2 High-Performance Distributed Systems

The aforementioned two security properties are sufficient to *correctly transform* (any) CFT distributed system to operate in the BFT model [70, 72]. However, a fundamental design trade-off exists between efficiency and robustness for practical deployments in the cloud. Our work aims to resolve this tension.

Trusted hardware for BFT. System designers established trusted hardware, TEEs, as the most effective way to eliminate a system's Byzantine counterparts [55, 57, 76, 167]. While TEEs can be used to offer BFT, prior research illustrated significant performance and architectural limitations in the context of networked systems [55, 57, 76, 167]. Based on performance and security studies [45, 46], TEEs' overheads in the heterogeneous cloud, in addition to their heterogeneity in programmability and security guarantees, are incapable of offering high-performant trusted networking under the BFT model.

SmartNICs for high-performance and BFT. We leverage the state-of-the-art hardware-level networking accelerators, i.e., SmartNICs [3, 9, 11, 28, 30–32, 40], to address the trade-off between performance and security, overcoming the limitations of TEEs. Our design choice of leveraging SmartNICs is not hypothetical; SmartNIC devices have already been launched by major cloud providers [9, 32, 40], presenting great opportunities for performance thanks to their integrated fully programmable hardware (e.g., ARM cores [11, 28, 31, 40], FPGAs [2, 3, 32]). Precisely, we rely on two promising directions: *(1)* security and network processing offloading at the NIC-level hardware and *(2)* an efficient transformation for BFT.

3 Overview

3.1 System Overview

We propose TNIC, a trusted NIC architecture for high-performance, trustworthy distributed systems, formally guaranteeing their secure and correct execution in the heterogeneous Byzantine cloud infrastructure. TNIC is comprised of three layers (shown in Figure 1): **(1) the TNIC hardware architecture** (green box) that implements trusted network operations on top of SmartNIC devices (§ 4), **(2) the TNIC network stack** (yellow box) that intermediates between the application layer and the TNIC hardware (§ 5), and **(3) the TNIC network library** (blue box) that exposes TNIC's programming APIs (§ 6).

Our TNIC hardware architecture implements the networking IB/RDMA protocol [1] on FPGA-based SmartNICs [3]. It extends the conventional protocol implementation with a minimal hardware module, the attestation kernel, that materializes the security properties of the non-equivocation and transferable authentication. The TNIC network stack configures the TNIC device on the control path while it offers the data path as kernel-bypass device access for low-latency operations. Lastly, the TNIC network library exposes programming APIs built on top of (reliable) one-sided RDMA primitives.

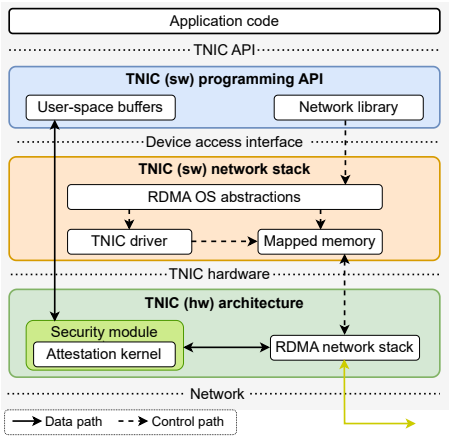

Figure 1. TNIC system overview.

3.2 Threat Model

We inherit the fault and threat model from the classical BFT [65] and trusted computing domains [103]. The cloud infrastructure (machines, network, etc.) can exhibit Byzantine behavior and also being subject to attackers that can control over the host CPU (e.g., the OS, VMM, etc.) and the SmartNICs (post-manufacturing). The adversary can attempt to re-program the SmartNIC, but they cannot compromise the cryptographic primitives [65, 116, 167]. The physical package, supply chain, and manufacturer of the SmartNICs are trusted [107, 179]. The TNIC implementation (bitstream) is synthesized by a trusted IP vendor with a trusted tool flow for covert channels resilience.

Since TNIC does not rely on CPU-based TEEs and its network stack and library run on the unprotected CPU, both software can be compromised by a potentially Byzantine actor on the machine. As such, TNIC does not distinguish between different types of untrusted software components. Whether the network library, the network stack, or the application code is compromised, the node is considered faulty (Byzantine) and must conform to the BFT application system model, which should specify its tolerance to Byzantine failures.

3.3 Design Challenges and Key Ideas

While designing TNIC, we overcome the following challenges:

#1: Heterogeneous hardware. CPU-based TEEs in the cloud infrastructure are heterogeneous with different programmability [51, 56, 150, 163, 164, 172] and security properties [128, 133, 140] that complicate their adoption and the system's correctness [150]. Prior systems [57, 76, 124, 167] *could* not

address this heterogeneity challenge as they require *homogeneous* x86 machines with SGX extensions of a specific version. This is rather unrealistic in modern heterogeneous distributed systems where system designers are compelled to *stitch heterogeneous TEEs together*. TEE's heterogeneity in programmability and security semantics hampers their adoption and adds complexity to ensuring the system's overall correctness.

Key idea: A host CPU-agnostic unified security architecture based on trustworthy network-level isolation. Our TNIC offers a unified and host-agnostic network-interface level isolation that guarantees the specific yet well-defined security properties of the non-equivocation and transferable authentication. TNIC shifts the security properties from CPU-hosted TEEs to NIC hardware, thereby addressing the heterogeneity and programmability issues associated with CPU-based TEEs. TNIC also offers generic programming APIs (§ 6.1) that are used to *correctly* transform a wide variety of distributed systems for Byzantine settings. We demonstrate the power of TNIC with a generic transformation *recipe* (§ 6.2) and its usage to transform prominent distributed systems (§ 7).

#2: Large TCB in the TEE-based silicon root-of-trust. TEEs based on a *silicon root of trust* are promising for building trustworthy systems [55, 57, 76, 167]. Unfortunately, the state-of-the-art TEEs integrate a *large* TCB; for example, we calculate the TCB size of the state-of-the-art Intel TDX [26]. The TEE ports within the trusted hardware the entire Linux kernel (specifically, v5.19 [38]) and "hardens" at least 2000K lines of usable code, leading to a final TCB of 19MB. Such large TCBs have been accused of increasing the area of faults and attacks [111, 135] of commercial TEEs that are already under fire for their security vulnerabilities [25, 27, 42, 52, 143]. Importantly, TEE's large TCBs complicate their security analysis and verification, rendering their security properties *incoherent*.

Key idea: A minimal and formally verifiable silicon root-of-trust with low TCB. In our work, we advocate that a *minimalistic silicon root of trust* (TCB) at the NIC level hardware is the foundation for building verifiable, trustworthy distributed systems. In fact, TNIC builds a minimalistic and verifiable attestation kernel (§ 4.1) that guarantees the TNIC security properties at the SmartNIC hardware. Moreover, we have formally verified the TNIC secure hardware protocols (§ 4.4).

#3: Performance. TEE's overheads are significant in the context of networked systems [55, 76, 89, 167]. Prior research [55] reported 4×—8× performance degradation with even a sophisticated network stack. Others [57, 76, 167] limit performance due to the communication costs between their untrusted and TEE-based counterparts [107]. The actual performance overheads in heterogeneous distributed systems are expected to be more exacerbated [45, 46]. As such, TEEs cannot *naturally* offer high-performant, trusted networking.

Key idea: Hardware-accelerated trustworthy network stack. Our TNIC bridges the gap between performance and security with two design insights. First, TNIC attestation kernel offers the foundations to transform CFT distributed systems to BFT systems without affecting the number of participating nodes, significantly improving scalability. Second, TNIC user-space network stack (§ 5) bypasses the OS and offloads security and network processing to the NIC-level hardware.

4 Trusted NIC Hardware

Figure 2 shows our TNIC hardware architecture that implements trusted network operations on a SmartNIC device. TNIC introduces two key components: *(i)* the attestation kernel that guarantees the non-equivocation and transferable authentication properties over the untrusted network (§ 4.1) and *(ii)* the RoCE protocol kernel that implements the RDMA protocol including transport and network layers (§ 4.2). We also introduce a bootstrapping and a remote attestation protocol for TNIC (§ 4.3) and formally verify them (§ 4.4).

4.1 NIC Attestation Kernel

The attestation kernel *shields* network messages and materializes the properties of non-equivocation and transferable authentication by generating *attestations* for transmitted messages. As shown in Figure 2, the attestation kernel resides in the data pipeline between the RoCE protocol kernel that transmits/receives network messages and the PCIe DMA that transfers data from/to the host memory. The kernel processes the messages as they *flow* from the memory to the network and vice versa to optimize throughput.

Hardware design. The attestation kernel is comprised of three components that represent its state and functionality: the HMAC component that generates the message authentication codes (MAC), the Keystore that stores the keys used by the HMAC module, and the Counters store that keeps the message's latest sent and received timestamp.

The system designer initializes each TNIC device during bootstrapping with a unique identifier (ID) and a shared secret key—ideally, one shared key for each session—stored in static memory (Keystore). The keys are shared and, hence, unknown to the untrusted parties.

TNIC holds two counters per session in the Counters store: `send_cnts`, which holds sending messages, and `recv_cnts`, which holds the latest seen counter value for each session. The counters represent the messages' timestamp and are increased monotonically and deterministically after every send and receive operation to ensure that unique messages are assigned to unique counters for non-equivocation. Consequently, no messages can be lost, re-ordered, or doubly executed.

Algorithm. Algorithm 1 shows the functionality of the attestation kernel. The module implements two core functions: `Attest()`, which generates a unique and verifiable attestation for a message, and `Verify()`, which verifies the attestation of a received message. The message transmission invokes `Attest()`, and likewise, the reception invokes `Verify()`.

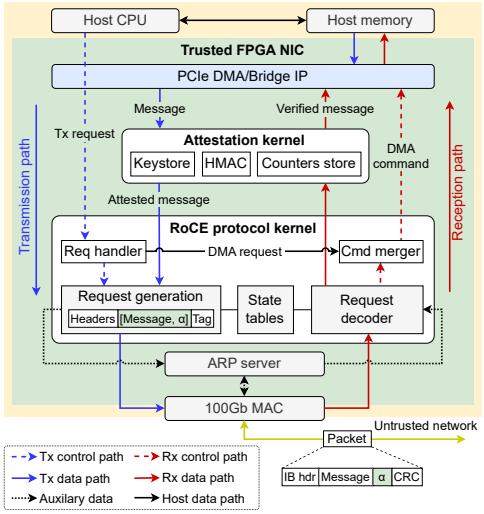

Figure 2. TNIC hardware architecture.

Upon transmission, as shown in Figure 2, the message is first forwarded to the attestation kernel. The attestation kernel executes `Attest()` and generates an *attested* message comprised of the message data and its attestation certificate α. The function calculates α as the HMAC of the message concatenated with the counter `send_cnt` and the device ID (for transferable authentication) with the `key` for that connection (Algo 1: L4). It also increases the next available counter for subsequent future messages (Algo 1: L2). The function forwards the message with its α to the RoCE protocol kernel (Algo 1: L4).

Upon reception, the received message passes through the attestation kernel for verification before it is delivered to the application. Specifically, `Verify()` checks the authenticity and the integrity of the received message by re-calculating the *expected* attestation α' based on the message payload and comparing it with the received attestation α of the message (Algo 1: L7—8). The verification also ensures that the received counter matches the expected counter for that connection to ensure *continuity* (Algo 1: L8).

4.2 RoCE Protocol Kernel

The RoCE protocol kernel implements a reliable transport service on top of the IB Transport Protocol with UDP/IPv4 layers (RoCE v2) [23] (transport and network layers). As shown in Figure 2, to transmit data, the `Req handler` module in the RoCE kernel receives the request opcode (`metadata`) issued by the host. The message is fetched through the PCIe DMA engine and passes through the attestation kernel. The request opcode and the attested message are forwarded to the `Request generation` module that constructs a network packet.

Upon receiving a message from the network, the RoCE kernel parses the packet header and updates the protocol state (stored in the State tables). The attested message is then forwarded to the attestation kernel. The message is delivered to the application's (host) memory upon successful verification.

Algorithm 1: `Attest()` and `Verify()` functions.

```
1  function Attest(c_id, msg){
2      cnt ← send_cnts[c_id]++;
3      α ← hmac(keys[c_id], msg||ID||cnt);
4      return α||msg||ID||cnt;
5  }
6  function Verify(c_id, α||msg||ID||cnt){
7      α' ← hmac(keys[c_id], msg||ID||cnt);
8      if (α' = α && cnt = recv_cnts[c_id]++ )
9          return (α||msg||cnt);
10     assert(False);
11 }
```

Hardware design. The RoCE protocol kernel is also connected to a 100Gb MAC IP and an ARP server IP.

100Gb MAC. The 100Gb MAC kernel implements the link layer connecting TNIC to the network fabric over a 100G Ethernet Subsystem [39]. The kernel also exposes two interfaces for transmitting (Tx) and receiving (Rx) network packets.

ARP server. The ARP server has a lookup table containing MAC and IP address correspondences. Right before the transmission, the RDMA packets at the `Request generation` first pass through a MAC and IP encoding phase, where the `Request generation` module extracts the remote MAC address from the lookup table in the ARP server.

IB protocol. The RoCE protocol kernel implements the reliable version of the IB protocol. Similarly to its original specification [1], the kernel implements State tables to store protocol queues (e.g., receive/send/completion queues) as well as important metadata, i.e., packet sequence numbers (PSNs), message sequence numbers (MSNs), and a Retransmission Timer.

Dataflow. The transmission path is shown with the blue-colored axes in Figure 2. The `Req handler` receives requests issued by the host and initializes a DMA command to fetch the payload data from the host memory to the attestation kernel. Once the attestation kernel forwards the attested message to the `Req handler`, the module passes the message from several states to append the appropriate headers `IB hdr` along with metadata (e.g., RDMA op-code, PSN, QP number). The last part of the processing generates and appends UDP/IP headers (e.g., IP address, UDP port, and packet length). The message is then forwarded to the 100Gb MAC module.

In the reception path (red-colored axes in Figure 2), the `Request decoder` extracts the headers, metadata, and attested message. The message is forwarded to the attestation kernel for verification and finally copied to the host memory.

The message format in TNIC follows the original RDMA specification [1]; only the difference between our TNIC and the original RDMA messages is that the attestation kernel *extends* the payload by appending a 64B attestation α and the metadata. The metadata includes a 4B id for the session id of the sender, a 4B ID for the device id (unique per device), and the appropriate `send_cnt`. This payload extension is negligible and does not harm the network throughput.

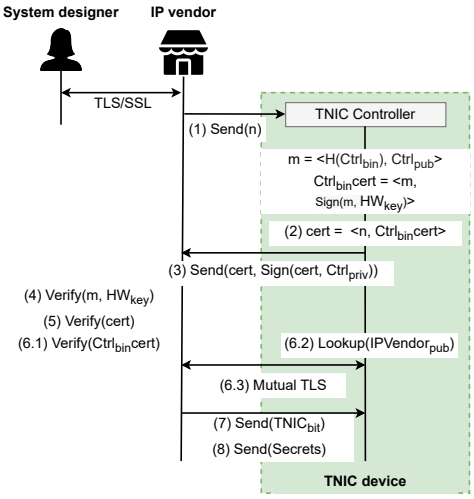

Figure 3. TNIC remote attestation protocol.

4.3 TNIC Attestation Protocol

We design a remote attestation protocol to ensure that the TNIC device is genuine and the TNIC bitstream and secrets are flashed securely in the device.

Boostrapping. The TNIC hardware is securely bootstrapped in an untrusted third-party cloud by the Manufacturer, System designer, and IP vendor, who trust each other. At the device construction, the Manufacturer burns $\texttt{HW}_{key}$, a secret key unique to the device. It is possible with commercial FPGA cards that have access to an AES key and the hash of a public encrypted key embedded in secure, on-chip, non-volatile storage (Intel [34], AMD [16]). The System designer shares the configuration with the IP vendor and instructs the cloud provider to load the (encrypted) FPGA firmware which is then decrypted with the $\texttt{HW}_{key}$. The firmware loads the controller binary $\texttt{Ctrl}_{bin}$, generates a key pair $\texttt{Ctrl}_{pub,priv}$ for the specific device and binary, and signs the measurement of the $\texttt{Ctrl}_{bin}$ and the $\texttt{Ctrl}_{pub}$ with the $\texttt{HW}_{key}$ ($\texttt{Ctrl}_{bin}\texttt{cert}$).

Remote attestation. Figure 3 shows TNIC remote attestation. The IP vendor sends a random nonce n for freshness to the Controller. The IP vendors public key $\texttt{IPVendor}_{pub}$ is embedded into the $\texttt{Ctrl}_{bin}$. The Controller generates a certificate cert over the $\texttt{Ctrl}_{bin}\texttt{cert}$ and n (2) which signs with $\texttt{Ctrl}_{pub}$ and sends it to the IP vendor (3).

The IP vendor verifies the authenticity of the cert (4)—(5) and establishes a TLS connection with the Controller. First, the vendor verifies the authenticity of m with the $\texttt{HW}_{key}$, ensuring that a genuine $\texttt{Ctrl}_{bin}$ and a genuine device has signed m (4). As such, the vendor ensures that the $\texttt{Ctrl}_{bin}$ runs in a genuine TNIC device by verifying that the measurement of the $\texttt{Ctrl}_{bin}$ has been signed with an appropriate device key installed by the Manufacturer. Lastly, the vendor verifies the nonce n and cert to ensure freshness (with the $\texttt{Ctrl}_{pub}$ included in m).

Now, a mutually authenticated TLS connection is established; the IP vendor verifies authenticity by checking for the desired $\texttt{Ctrl}_{pub}$ and the Controller checks for it's embedded $\texttt{IPVendor}_{pub}$ (6.1)—(6.3). Once the TLS connection is established the IP Vendor sends the Controller the secrets and the TNIC bitstream, $\texttt{TNIC}_{bit}$.

4.4 Formal Verification of TNIC Protocols

We formally verify the safety and security properties of TNIC hardware using Tamarin [130]. The proof details are covered in Appendix § B. Our verification consists of a model for bootstrapping, remote attestation, message transmission, and reception, according to Figure 3. This model is augmented with custom *action facts*, which mark the occurrence of defined events in the execution trace. These include:

1. $\mathrm{D}_e(x)$, which marks the end of the attestation phase for endpoint e, with associated connection information x.
2. $\mathrm{S}_e(m)$ and $\mathrm{A}_e(m)$ marking the sending and accepting of a message m, following Algorithm 1, respectively.

The intended temporal relationship of these action facts is expressed using lemmas, which Tamarin then proves using automated deduction and equational reasoning. The relation $a\,@\,t_i$ expresses that action fact a occurred at time t_i. Using this relation, we can express our desired security properties as follows:

Remote attestation. We define the main attestation lemma for any TNIC device *tnic* and associated IP Vendor *ipv*. The lemma holds if, after the last step of the remote attestation protocol, the TNIC device is in a valid, expected state:

$$\forall\, ipv,tnic,c,t_i.\ \mathrm{D}_{ipv}(c)\ @\ t_i \Longrightarrow \exists\, t_j.\ t_j < t_i \wedge \mathrm{D}_{tnic}(c)\ @\ t_j \quad (1)$$

Transferable authentication. We define the lemma, which states that any accepted message was sent by an authentic TNIC device in a valid configuration:

$$\forall\, e1,m,t_i.\ \mathrm{A}_{e1}(m)\ @\ t_i \Longrightarrow \exists\, e2,t_j.\ t_j < t_i \wedge \mathrm{S}_{e2}(m)\ @\ t_j \quad (2)$$

Non-equivocation. We further extend the model by three lemmas that help to reason about non-equivocation. For any message that is accepted, it holds that *(i)* there is no message that was sent before but not accepted:

$$\begin{aligned}\forall\, e1,e2,m_j,t_i,t_j.\ &\mathrm{A}_{e1}(m_j)\ @\ t_i \wedge \mathrm{S}_{e2}(m_j)\ @\ t_j \\ &\Longrightarrow (\forall m_k,t_k.\ t_k < t_j \wedge \mathrm{S}_{e2}(m_k)\ @\ t_k \\ &\Longrightarrow \exists\, t_l.\ t_l < t_i \wedge \mathrm{A}_{e1}(m_k)\ @\ t_l)\end{aligned} \quad (3)$$

(ii) there is no message that was sent after, but accepted before:

$$\begin{aligned}\forall\, e1,m_i,m_j,t_i,t_j.\ &t_i < t_j \wedge \mathrm{A}_{e1}(m_i)\ @\ t_i \wedge \mathrm{A}_{e1}(m_j)\ @\ t_j \\ &\Longrightarrow \exists\, e2,t_k,t_l.\ t_k < t_l \wedge \mathrm{S}_{e2}(m_k)\ @\ t_k \wedge \mathrm{S}_{e2}(m_l)\ @\ t_l\end{aligned} \quad (4)$$

(iii) this message has not been accepted before:

$$\forall\, e1,m,t_i,t_j.\ \mathrm{A}_{e1}(m)\ @\ t_i \wedge \mathrm{A}_{e1}(m)\ @\ t_j \Longrightarrow t_i = t_j \quad (5)$$

Our complete verification includes additional action facts and lemmas to verify properties like the secrecy of private information and the implications of out-of-band key compromises.

To sum up, Tamarin successfully shows that there is no sequence of transitions that leads to any state where our lemmas are violated. Thus, the attestation and transferable authentication lemmas hold for our model, and the counters behave as expected for non-equivocation.

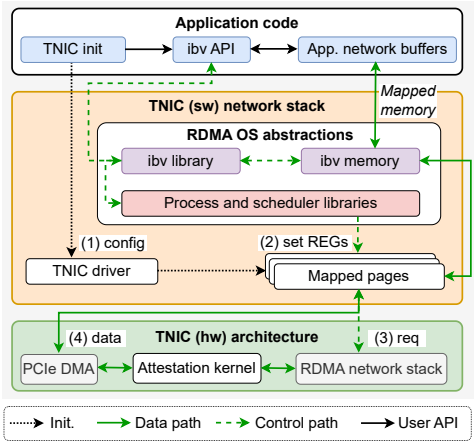

Figure 4. TNIC network system stack.

5 TNIC Network Stack

We build a software TNIC system network stack that operates as the *middle layer* between the TNIC programming APIs (see § 6.1) and the hardware implementation of TNIC. Figure 4 shows an overview of the network stack design that is comprised of two core components: *(1)* the TNIC driver and mapped REGs pages that are responsible for initializing the device and configuring host—device communication and *(2)* the RDMA OS abstractions that execute networking operations.

5.1 TNIC Driver and Mapped REGs Pages

The TNIC driver is invoked at the device initialization, before the remote attestation protocol (§ 4.3), to configure the hardware with its static configuration (the device MAC address, the device QSFP port, and the network IP used by the application).

The driver enables kernel-bypass networking—similar to the original (user-space) RDMA protocol—by mapping the TNIC device to a user-space addresses range, the Mapped REGs pages. TNIC reserves one page at the page granularity of our system for each connected device that is represented as pseudo-devices in `/dev/fpga<ID>`. Read and write access to the pseudo-device is equal to accessing the control and status registers of the FPGA. Applications directly interact with the control path of the TNIC hardware bypassing the host OS.

5.2 RDMA OS Abstractions

The RDMA OS abstractions are a user-space library that enables the networking operations in the TNIC hardware, bypassing the OS kernel for performance. As shown in Figure 4, the RDMA OS library is comprised of two parts: *the network (RDMA) library* (colored in purple) that implements the software part of the RDMA protocol and *the OS library* (colored in red) that schedules the TNIC requests.

Network (RDMA) library. The network (RDMA) library includes all the logic and data (e.g., Tx/Rx queues per connection, local and remote memory addresses, RDMA keys that denote memory access permissions) required to implement the RDMA protocol. It executes the application's networking operations by posting the requests to the hardware. More specifically, it creates an internal representation of the request and the associated data and metadata (i.e., request opcode, remote IP, source/destination addresses, data length, etc.) and writes them into specific offsets in the REGs pages to update the control registers of the TNIC hardware.

As shown in Figure 4, the transmission and reception of requests and responses mandate the allocation of application network buffers. We adopt memory management similar to that in widely used user-space networking libraries [24, 105, 131]. Importantly, the network buffers need to be mapped to a specific TNIC-memory, called the ibv memory. The ibv memory area is allocated at the connection creation in the huge page area by the application through the ibv library. It resides within the application's address space with full read/write permissions and is eligible for DMA transfers.

OS library. The TNIC-OS library is responsible for scheduling the requests and ensuring isolated access to the mapped REG pages. For performance, the TNIC data path eliminates unnecessary data copies throughout the network stack; the data to be sent is directly fetched by the hardware through DMA transfers. The OS library creates a TNIC-process object to represent each TNIC device. This TNIC-process in TNIC is not a separate scheduling entity (i.e., a thread as in classical OSes). In contrast, it is an object handle, exposed to the ibv library but managed by the TNIC-OS library that acquires locks on the respective REG pages to ensure isolated access to the TNIC hardware.

Initialization APIs	
`ibv_qp_conn()`	Creates an ibv struct
`alloc_mem()`	Allocates host ibv memory
`init_lqueue()`	Registers local memory to TNIC
`ibv_sync()`	Exchanges ibv memory addresses
Network APIs	
`local_send/verify()`	Generates/verifies attested messages
`auth_send()`	Transmits an attested message
`poll()`	Polls for incoming messages
`rem_read/write()`	Fetches/writes remote memory

Table 1. TNIC programming APIs.

6 TNIC Network Library

We present TNIC's programming APIs (§ 6.1), and a generic recipe to transform existing distributed systems (§ 6.2).

6.1 Programming APIs

TNIC implements a programming API (Table 1) that resembles the traditional RDMA programming API [105] used in modern distributed systems[80, 87, 91, 106, 109, 127, 136]. We further extend the security semantics, offering the properties of non-equivocation and transferable authentication (§ 2.1).

Initialization APIs. The TNIC application first needs to configure the TNIC system to establish peer-to-peer RDMA connections. The application creates one ibv struct for each connection with `ibv_qp_conn()`, which sets up and stores the

queue pair, the local and remote IP addresses, device UDP ports, and others. The application also invokes `alloc_mem()` to allocate the ibv memory and then register the ibv memory to the TNIC hardware. Lastly, the application synchronizes with the remote machine using `ibv_sync()` to exchange necessary data (e.g., ibv memory address, queue pair numbers).

Network APIs. TNIC executes trusted one-sided, reliable RDMA with the same reliability guarantees as the classical one-sided RDMA over Reliable Connection (RC), i.e., a FIFO ordering (per connection), similar to TCP/IP networking.

TNIC offers `auth_send()` to send an attested message with RDMA reliable writes. We support classical RDMA operations for reads and writes: `rem_read()` and `rem_write()`. The remote side runs `poll()` to fetch the number of completed operations; `poll()` is updated only when the message verification succeeds at the TNIC hardware. We offer local operations for generating and verifying attested messages within a single-node setup: `local_send()` and `local_verify()`.

TNIC does not support a hardware-assisted multicast, but it can offer equivocation-free multicast uni-casting the same attested message generated by `local_send()` as in [116].

6.2 A Generic Transformation Recipe

Transformation properties. We show how to use TNIC APIs to transform an existing (CFT) distributed system into one that targets Byzantine settings. Our transformation is defined as wrapper functions on top of the send and receive operations [70]. For safety, our transformation needs to meet the following properties to provide the same guarantees expected by the original CFT system [70, 97, 98]:

Safety. If a correct receiver receives a message m from a correct sender S, then S must have sent with m.

Integrity. If a correct receiver receives and delivers a message m, then m is a *valid* message.

```
1  void send(P_id, char[] msg) {
2     state = hash(my_state);
3     tx_msg = msg || state || receiver_state;
4     auth_send(follower, tx_msg);
5  }
6  void recv(recv_msg) {
7     auto [att, msg || state || receiver_state] = deliver();
8     [msg, cnt] = verify_msg(msg);
9     verify_sender_state(state);
10    local_verify(receiver_state);
11    verify_system_view(receiver_state); apply(msg);
12 }
```

Listing 1. Generic send and recv wrapper functions using TNIC. TNIC additions are highlighted in orange.

Listing 1 shows our proposed send (L1-5) and recv (L7-13) operations, providing a general method for transforming a CFT system into a BFT system. We assume a two-node scenario where the first node (sender) receives client requests and forwards them to the second node (receiver). For transmission, the sender sends the client message msg, its current state (e.g., the sender's action to the msg), and the receiver's previous state (known to the sender). The receiver's state is optional depending on the consistency guarantees of the derived system and can be used to ensure that both nodes have the same system view.

Upon receiving a valid message (L8-9), the receiver *simulates* the sender's state to verify that the sender's action to the request is as expected (L10). The way to simulate the states depends on the applications, e.g., in our BFT protocol implementation (§ 7), each replica maintains copies of counters that represent the expected counter values for all other participating nodes. The simulation allows nodes to avoid replaying the entire message history in order to reconstruct the system's state, as done in [70]. The receiver also ensures that it does not lag, and both nodes have the same "view" of the system inputs by verifying that the sender has *seen* the receiver's latest state (e.g., message) (L11-12).

Our generic transformation satisfies the requirements listed above. First, TNIC's transferable authentication property directly satisfies the safety requirement. A faulty node cannot impersonate correct nodes; if TNIC validates a message m from a sender, the sender must have sent m. TNIC's reliable network operations ensure liveness properties between correct nodes. Second, our transformation satisfies the integrity property. The integrity property is ensured by validating that the sender's response to the client's request follows the protocol specification. The transferable authentication mechanism allows correct receivers to prove the integrity flow by simulating the sender's output and state, e.g., by maintaining a copy of the sender's state.

Consistency property for replication. Our transformation further needs to meet the consistency property [70]. If correct receivers R_1 and R_2 receive valid messages m_i and m_j respectively from sender S, then either (a) Bpg_i is a prefix of Bpg_j , (b) Bpg_j is a prefix of Bpg_i, or (c) $Bpg_i = Bpg_j$ (where Bpg_x is the process behavior that supports the validity of message m_x).

The consistency requirement is enforced through the TNIC's non-equivocation primitive that assigns a (unique) monotonic sequence number to each outgoing message, enforcing a total order on the sender's outgoing messages. Along with the integrity requirement, the total order can prevent equivocation and suffice for consistency. Importantly, TNIC ensures that correct receivers cannot miss any past messages. Following this, two followers that receive from the same sender (using the equivocation-free multicast discussed in § 8.2) follow the same transition (execution) path. TNIC cannot transform systems with non-deterministic specifications.

7 Trusted Distributed Systems

Using TNIC, we transform the following four distributed systems into BFT systems (see Appendix § C for details).

Attested Append-Only Memory (A2M). We design an Attested Append-Only Memory (A2M) [69] leveraging TNIC,

which can be used to shield and optimize various systems [43, 65, 74, 119]. The original A2M, and hence our implementation over TNIC, builds append-only (trusted) logs, associating each entry with a monotonically increasing sequence number to combat equivocation. While A2M has a large TCB and ports the log within the TEE, our implementation has only a minimal TCB in hardware and it can robustly store the log in the untrusted host memory, improving memory efficiency [116].

As in the original A2M, we build the append and lookup operations. The append calls into TNIC to generate an attestation for the log entry while associating it with a monotonically increased sequence number (sent_cnt). The sequence number denotes the entry's position in the log. The lookup operation retrieves entries locally without verification.

Byzantine Fault Tolerance (BFT). We design a Byzantine Fault-Tolerant protocol (BFT) using TNIC. The protocol builds a replicated counter as a foundational service for various systems [78, 101, 104, 148, 168]. Our system model considers a network of replicas with at most f Byzantine replicas out of $N = 2f+1$ total replicas. One replica serves as the leader, and the others act as followers. The system prevents equivocation through TNIC, which enforces and validates the ordering of messages. This reduces the number of replicas required and the message complexity compared to the classical BFT ($3f+1$).

Clients send increment counter requests to the leader, who performs the requests and broadcasts the change along with a *proof of execution* (PoE) message to followers. The proof of execution is a TNIC-attested message with the original client's request, the leader's counter value, and metadata. The followers leverage their local state machine to detect a faulty leader (or follower) [98]. Subsequently, if and only if a follower has not applied the message before, it applies the incremented counter value to its state machine before forwarding its own PoE message to all other replicas and replying to the client. A quorum of at least $f+1$ identical messages from different replicas guarantees a correctly committed result for the client.

Chain Replication (CR). We design a Byzantine CR system [165] using TNIC as the replication layer of a Key-Value store. As in the CFT version of CR, the replicas, e.g., head, middle, and tail, are connected in a chained fashion.

Clients execute requests by forwarding them to the head. The head orders and executes the request, creating his own *proof of execution message* (PoE), which is sent along the chain. The PoE consists of the original request and the head's output that TNIC attests. Each node in the chain verifies the previous node's PoE, executes the request, and creates its own PoE, which consists of the last PoE and the node's output.

Unlike the CFT CR, local operations in the tail (e.g., reads) are untrusted in the BFT model. Therefore, all operations must traverse the entire chain. Replicas reply to clients with their output after forwarding their PoE message, and clients wait for identical replies from all chained nodes. We discuss the performance-security trade-offs of an alternative TEE-based design of porting the entire CR protocol into the TEE (that would allow clients to read only from the tail) in § 8.3.

System	(host) TEE-free	Tamper-proof
SSL-lib	Yes	No
SSL-server/Intel-x86*/AMD	Yes	No
SGX/AMD-sev	No	Yes
TNIC	Yes	Yes

Table 2. Host-sided baselines and TNIC. (*) We use the term SSL-server for this run unless stated otherwise.

Accountability (PeerReview). Lastly, we design an accountability system with TNIC based on the PeerReview system [94] to *detect* malicious actions in large deployments [134, 161]. We detect faults impacting the system's network messages logged into the participant's tamper-evident log. We frame the protocol within an overlay multicast protocol for streaming systems where the nodes are organized in a tree topology. Witnesses assigned to each node audit the node's log to detect faults or non-responsive nodes. The witnesses replay the log entries, comparing them with a reference deterministic implementation to identify inconsistencies. Our TNIC prevents equivocation at NIC hardware efficiently, which eliminates the expensive all-to-all communication of the original PeerReview that does not use trusted hardware [116].

8 Evaluation

We evaluate TNIC across three dimensions: *(i)* hardware (§ 8.1), *(ii)* network stack (§ 8.2) and *(iii)* distributed systems (§ 8.3).

Evaluation setup. We perform our experiments on a real hardware testbed using two clusters: AMD-FPGA Cluster and Intel Cluster. AMD-FPGA Cluster consists of two machines powered by AMD EPYC 7413 (24 cores, 1.5 GHz) and 251.74 GiB memory. Each machine also has two Alveo U280 cards [3] that are connected through 100 Gbps QSFP28 ports. Intel Cluster consists of three machines powered by Intel(R) Core(TM) i9-9900K (8 cores, 3.2 GHz) with 64 GiB memory and three Intel Corporation Ethernet Controllers (XL710).

8.1 Hardware Evaluation: T-FPGA

Baselines. We evaluate the performance of Attest() of the TNIC's attestation kernel (§ 4.1) compared with four host-sided systems shown in Table 2. For these host-sided versions, we build OpenSSL v3.1 servers that run natively or within a TEE with the same BIOS configuration (AES-NI enabled). The servers attest and forward network messages to the host application. We use the terms Intel-x86 and AMD for a native run of the server process (SSL-server) and SGX and AMD-sev for their tamper-proof versions within a TEE. The TEE baselines follow the same system model as in state-of-the-art hybrid systems [76, 107, 116, 167], where the host BFT application runs on the untrusted CPU and communicates with a separate TEE-based process to generate and verify message attestations. TNIC implements similar abstractions for counter and message attestation. Thus, TNIC does not introduce additional

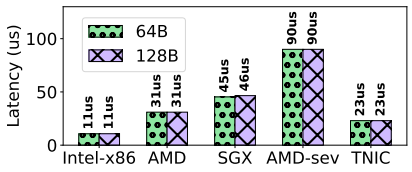

Figure 5. `Attest` function latency.

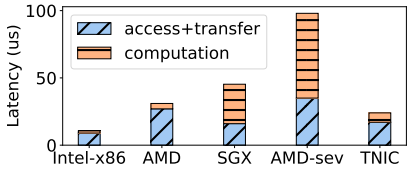

Figure 6. `Attest` latency breakdown.

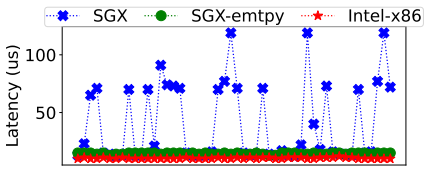

Figure 7. Latency over time (SGX).

protocol alterations compared to them.The server and host process run in the same machine to eliminate network latency and communicate through TCP sockets. We implement SGX using the SCONE framework [51] while AMD-sev runs in a QEMU VM using the official VM image [6]. In addition, we build (non-temper-proof) SSL-lib, which integrates the `Attest` function as a library.

Methodology and experiments. We use Vitis XRT v2022.2 and the shell `xilinx_u280_gen3x16_xdma_base_1` for the stand-alone evaluation of the TNIC attestation kernel: synchronous data transfers between the host and device (U280). We measure and report the average latency and communication costs by executing an empty function body of `Attest()`.

Results. Figure 5 shows the average latency of `Attest()` based on the HMAC algorithm for 64B and 128B data inputs. The latency of `Verify()` is similar, and as such, it is omitted. Our TNIC achieves performance in the microseconds range (23 us) and outperforms its equivalent TEE-based competitors at least by a factor of 2. Importantly, TNIC is approximately 1.2× faster than AMD, which is not tamper-proof.

Figure 6 shows the latency breakdown of `Attest()`. Accessing the TNIC device and TEEs can be expensive, ranging from 30% to 90% of the total operation latency among the systems. Regarding TNIC, the transfer time (16us) accounts for 70% of the execution time. We expect that TNIC effectively eliminates this cost by enabling asynchronous (user-space) DMA data transfers. Regarding the TEE-based systems (SGX, AMD-sev), the communication and system call execution costs account for up to 40% of the total execution. To our surprise, this implies that the HMAC computation within any of the two TEEs experiences more than 30× overheads compared to its native run. To analyze TEEs' behavior, we instrument the client's code to measure the operations' individual latency at various periods of time during the experiment accurately.

Figure 7 illustrates the individual operation latency, where SGX-empty indicates SGX without HMAC computation. As shown in Figure 7, the HMAC execution within the TEE often experiences huge latency spikes. We attribute this behavior to the scheduling effects and asynchronous exitless system calls inherent in our SGX framework, SCONE [51]. We observe similar latency variations during executions on AMD systems, spiking up to 200–500 us.

8.2 Software Evaluation: TNIC Network Stack

Baselines. To evaluate the TNIC performance, we discuss (1) the effectiveness of offloading the network stack to the TNIC hardware and (2) the overheads incurred by the CFT systems

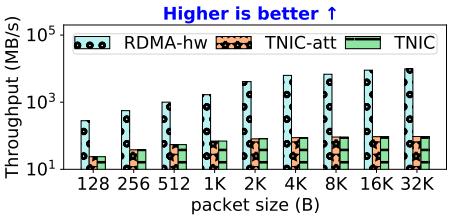

Figure 8. Throughput of send operations across the three selected network stacks.

transformation for the BFT model. We compare TNIC across four other software/hardware network stacks with different security properties as follows: *(i)* RDMA-hw, an untrusted RoCE protocol on FPGAs, *(ii)* DRCT-IO (direct I/O), untrusted software-based kernel-bypass stack, *(iii)* DRCT-IO-att, altered DRCT-IO that offers trust by sending attested messages but does not verify them, and *(iv)* TNIC-att, altered TNIC that similarly sends attested messages without verification. We build *(i)* RDMA-hw on top of Coyote [15] network stack similarly to TNIC. For *(ii)* *(iii)* DRCT-IOs, we base our design on eRPC [105] with DPDK [24] that offers similar reliability guarantees with RDMA-hw. The hardware network stacks run on AMD-FPGA Cluster, whereas the rest run on Intel Cluster.

Methodology and experiments. Our experiments measure the latency and throughput for respective network stacks, which run through a single-threaded client-server implementation. For the latency measurement, the client sends one operation at a time, whereas for the throughput measurement, one client can have multiple outstanding operations.

Results. Figure 9 and 8 show the latency and throughput of the send operation with various packet sizes. First, regarding (1) the effectiveness of network stack offloading, RDMA-hw is 3×—5× faster than DRCT-IO, which indicates that the network offloading boosts performance. Although DRCT-IO offers minimal latency (16-16.6us) for small packet sizes up to 1 KiB due to its zero-copy transmission/reception optimizations [105], they are only effective for up to 1460B (MTU is 1500B, but 40B are reserved for metadata), and RDMA-hw still achieves 3× lower latency (5-5.5us). For bigger data transfers, the RDMA-hw latency increases steadily up to 19 us, whereas DRCT-IO does not scale well with latencies up to 100us.

Second, regarding (2) the TNIC performance overhead, TNIC offers trusted networking with 3×—20× higher latencies than the untrusted RDMA-hw. The latency increase stems from the HMAC calculation of the TNIC hardware. As this algorithm fundamentally cannot be parallelized, the higher the message size, the higher the latency our TNIC incurs. More specifically,

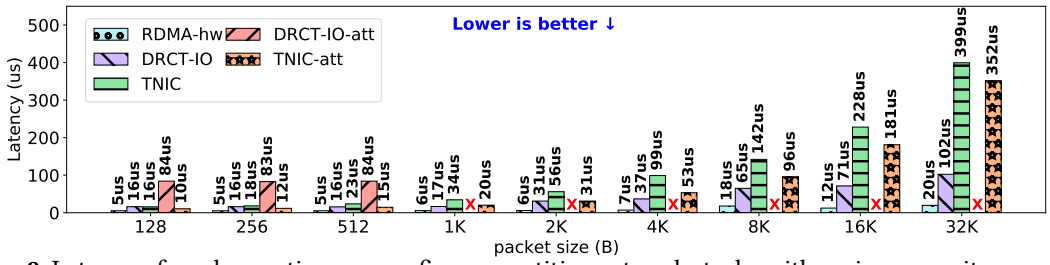

Figure 9. Latency of send operations across five competitive network stacks with various security properties.

for packet sizes less than 1 KiB, doubling the packet size in TNIC results in a 13%—20% increment in the overall latency. For packet sizes bigger or equal to 1 KiB, doubling the packet size increases the latency by 30%—40%. Compared to DRCT-IO-att (82us), TNIC is up to 5.6× faster. Importantly, DRCT-IO-att reports extreme latencies (2000us or more) for packet sizes larger than 521B, which are omitted to avoid plot distortion. We attribute these latencies to the scheduling effects of SCONE [51].

8.3 Distributed Systems Evaluation

We next evaluate four distributed systems described in § 7.

Methodology and experiments. We execute all four of our codebases on Intel Cluster in three servers (as the minimum required setup capable of withstanding a single failure, $N = 2f+1$, where $f = 1$). We only use a single port of the U280 for network communication because of a limitation introduced in our system by the Coyote codebase [15], on top of which we base TNIC implementation. Due to our limited resources, we cannot install Alveo U280 cards on all these servers. Instead, we build our codebase using the DRCT-IO stack (detailed in § 8.2) and inject busy waits to emulate the delays incurred by TNIC for generating and verifying attested messages.

We evaluate each codebase using five systems that generate and verify the attestations: *(i)* SSL-lib (no tamper-proof), *(ii)* SSL-server (no tamper-proof), *(iii)* SGX, *(iv)* AMD-sev, and *(v)* TNIC. To perform a fair comparison, we integrate into our codebases a library that accurately emulates all latencies (measured in § 8.1) within the CPU. For the AMD latency, we use 30us, representing the lower bound of the latencies measured in § 8.1. We do not emulate the SSL-lib latency.

Given that DRCT-IO, which is used for the emulation, is at least 3× slower than the hardware RDMA network stack (RDMA-hw), the latencies outlined in this section are anticipated to reflect the upper limit for all four systems with TNIC.

We additionally evaluate two TEEs-hosted CFT replication protocols (TEEs-Raft and TEEs-CR) where the entire protocol codebase (Raft [138] and Chain replication [166] respectively) resides within the TEE. We compare the TEEs-hosted systems with TNIC and discuss the trade-offs between their threat model, TCB, and performance.

A2M. We first evaluate our TNIC-A2M system. We evaluate two TEE baselines: SGX-lib, which places the entire log within the TEE, and AMD-sev, which places the attested log outside the TEE as in the implementation of TrInc [116] and has been shown to be effective. In this experiment, we construct a 9.3GiB log with 100 million entries and then lookup them sequentially/individually.

	Throughput (Op/s)		Latency (us)	
System	append	lookup	append	lookup
SSL-lib	790K	256M	1.26	0.0039
SGX-lib	380K	3.8M	2.6	0.26
AMD-sev	30K	263M	32.37	0.0038
TNIC	158K	257M	6.34	0.0039

Table 3. Throughput and latency of A2M.

Results. Table 3 shows the throughput and mean latency of the append/lookup operations. The native execution (SSL-lib) achieves the highest throughput as it incurs no communication costs. Compared to SSL-lib, SGX-lib experiences only a 2× slowdown because we avoid the costly communication w.r.t. an SGX-based server implementation. On the other hand, AMD-sev, which runs the SSL server, incurs a 15× slowdown. Lastly, TNIC incurs 5× and 2.4× slowdown compared to SSL-lib and SGX-lib, respectively, due to the HMAC calculation.

Regarding the lookup operation, SSL-lib, AMD-sev, and TNIC report similar throughput and latency because they lookup untrusted host memory for the requested entry. However, SGX-lib reports a 66× slowdown due to its trusted memory size constraints and expensive paging mechanism [89] because we have to support a log of 9GB within the SGX enclave that only provides 94MB of memory. In contrast, AMD-sev is faster as it only accesses the untrusted host memory. Similar findings have also been demonstrated in [116]. As a result, while TNIC increases append latencies, it greatly optimizes lookup latencies due to its minimal TCB.

BFT. We evaluate the performance of our BFT protocol with various network batching factors. We implement network batching as part of the application's message format.

Results. Figure 10 shows the throughput and latency of the protocol, which highlights that TNIC significantly outperforms TEE-based versions (SGX, AMD-sev), improving the throughput and latency 4—6×. On the other hand, TNIC incurs 2.4× throughput overhead and up to 7× higher latency compared to SSL-lib. We recall that SSL-lib is not tamper-proof (Table 2) and eliminates the communication overheads incurred by other tamper-proof solutions (SGX, AMD-sev).

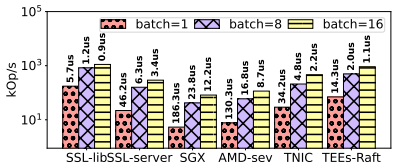

Figure 10. Throughput (and latency numbers) of BFT.

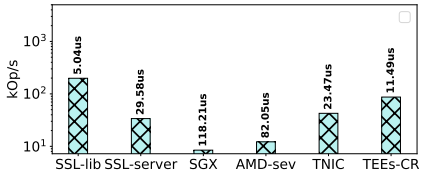

Figure 11. Throughput (and latency numbers) of Chain Replication.

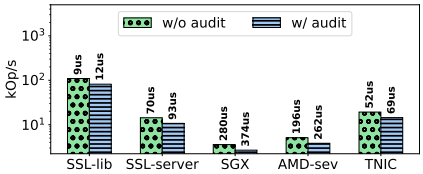

Figure 12. Throughput (and latency numbers) of PeerReview.

We also observe that batching improves the throughput and latency proportionally to the number of batched messages. For all except SSL-lib, the batching factors equal to 8 and 16 achieve 7× and 15× higher throughput than without batching, respectively. For SSL-lib, they are moderately effective: approximately 4—6× faster. It is primarily because the native execution of the attestation function is fast enough to saturate the network bandwidth. As such, conventional techniques can drastically eliminate the overheads for BFT and improve TNIC's adoption into practical systems.

CR. In this experiment, we evaluate the performance of our CR. We allocate one message structure per client request comprising 60B context, 4B operation type, and a 32B signature.

Results. Figure 11 shows the throughput and latency of our Chain Replication. We highlight that our TNIC is 5× and 3.4× faster than SGX and AMD-sev, respectively. While TNIC incurs 4.6× overheads compared to SSL-lib, it is 30% faster than SSL-server, which is not tamper-proof. The performance benefit stems primarily from hardware acceleration by the TNIC's attestation kernel on the transmission/reception data path.

PeerReview. We evaluate our PeerReview system's performance by both activating and deactivating the audit protocol. The system uses one witness for the source node that *periodically* audits its log. In our experiments, the witness audits the log after every send operation in the source node until both clients acknowledge the receipt of all source messages.

Results. Figure 12 shows the throughput and latency of our PeerReview system with and without enabling the audit protocol. Without the audit protocol, the TEE-based systems (SGX, AMD-sev) result in up to 30× slower throughput than SSL-lib, whereas our TNIC mitigates the overheads: 3—5× better throughput compared to AMD-sev and SGX.

Similarly, TNIC outperforms AMD-sev and SGX by 3.7—5× with the audit protocol. Importantly, when using TNIC, the audit protocol itself consumes about 25% (17us) of the overall latency, leading to 1.33× performance slowdown. However, even with the audit protocol, TNIC offers 3.7—5.42× lower latency compared to its TEE-based competitors.

TEEs-hosted baselines. We compare TNIC with TEEs-hosted systems implementing two prototypes based on the failure-free execution of Raft (TEEs-Raft) and CR (TEEs-CR). The code runs within three AMD-sev machines. Prior works [49, 55] suggested this setup for performance—however, at the cost of (1) significantly increased TCB size and (2) a weaker threat model from the application perspective. Table 4 summarizes the security costs. Regarding (1), the TCB of TEEs-hosted systems includes the entire OS [79], OpenSSL libraries for messages authentication [20] (labeled as Att. kernel), and the application codebase, which is over 2M LoCs in total. In contrast, TNIC's TCB only includes our hardware attestation kernel, which is 2,114 LoC of HLS/HDL code. It is only 0.09% of TEE-hosted systems. Regarding (2), the TEE-hosted application can only fail by crashing; it can be thought to remain protected from a potentially Byzantine cloud environment, whereas TNIC targets BFT settings, handling up to f arbitrary failures.

System	Threat model	TCB size (LoC) OS	Att. kernel	App	Total
TEEs-Raft	CFT	2,307K	1,268	856	2,309K
TEEs-CR	CFT	2,307K	1,268	992	2,309K
TNIC	BFT	-	2,114	-	2,114

Table 4. TNIC compared with TEE-hosted applications.

We compare TEE-Raft with our TNIC-based BFT (Figure 10) as both are broadcast-based protocols, and TEEs-CR with our TNIC-based CR (Figure 11) as both require all messages to traverse the entire chain of nodes. TEE-Raft achieves approximately 2.5× higher throughput than TNIC-based BFT. The performance difference is primarily due to Raft's one-phase commitment compared to our TNIC-based BFT. Similarly, TEE-CR achieves 2× higher throughput than the TNIC-based CR. While both versions of CR involve the same number of network Round-Trip Times (RTTs), TNIC involves a higher number of the attestation kernel invocations to verify all the chained messages in the PoE.

8.4 FPGA Resource Usage

Lastly, we perform a resource utilization analysis to show TNIC's scalability capabilities. We measure the resource consumption of TNIC's primary hardware components [96] and estimate maximum connections on the latest FPGA.

Table 5 shows the resource consumption details. The overall TNIC design consumes 16.6% of LUTs, 16.3% of Flip-Flops (FF), and 16.6% of RAMB36 (3.46 % of the entire on-chip memory) on the U280 FPGA. Note that TNIC only requires commodity FPGA NIC designs to add the attestation kernel, whose utilization is comparable with the other modules, XDMA and RoCE.

Figure 13 shows the scaling capabilities of TNIC hardware. As the number of network connections increases, we only need to replicate the attestation kernel because the XDMA

Name	LUT (%)		FF (%)		RAMB36 (%)	
U280	1303680	(100)	2607360	(100)	2016	(100)
TNIC	216905	(16.6)	423891	(16.3)	335	(16.6)
XDMA	48258	(3.7)	50701	(1.9)	64	(3.1)
Att. kernel	34138	(2.6)	56914	(2.2)	81	(4.0)
RoCE	30379	(2.3)	75804	(2.9)	46	(2.3)
CMAC	1484	(0.1)	3433	(0.1)	0	(0.0)

Table 5. TNIC's resource usage. The relative (%) compares with the U280 FPGA capacity. TNIC means the entire design.

and CMAC modules are independent of the number of connections, and the RoCE kernel is configured to hold up to 500 connections [153]. The result demonstrates that TNIC can support up to 32 concurrent connections on a single U280 FPGA.

8.5 Discussion

TNIC's applicability. As FPGA-based SmartNICs are widely adopted by major cloud providers for hardware acceleration [85], we believe that TNIC has the potential for broader industry application. In addition, ASIC-based NICs can also provide the same functionalities by integrating TNIC's hardware modules into an optimized System-on-Chip (SoC).

Use cases. The paper deliberately focuses on distributed cloud applications as TNIC's primary use cases. Trust in shared third-party clouds is a more critical concern than in other environments, posing unique challenges in trust, performance, and scalability. While the current scope is specific, the underlying principles could extend to other use cases, such as HPC or on-premise computing.

Message drops. TNIC guarantees packet retransmission between two correct nodes until their successful reception extending a RoCE implementation that supports reliable operations. The application need not re-send the message as it receives a different sequence number, which is not accepted (or verified) by the remote TNIC until all preceding messages have been received.

View-change and recovery. Detailing view-change and recovery in TNIC protocols are beyond the scope of our work. TNIC could adopt similar techniques as in TrInc [117] without disrupting these operations. In a new leader's election, replicas can establish new connections with new identifiers. As such, previous connections will not block execution, and state transfers, e.g., view-change, can be performed effectively.

PCIe transaction encryption. TNIC encrypts PCIe transactions for CPU-to-device communication, allowing attackers to modify the PCIe transactions. This vulnerability is not unique to TNIC; it applies to any network stack, including the OS-based ones, since the *untrusted* OS drives PCIe transactions.

9 Related work

Trustworthy distributed systems. Classical BFT systems [44, 54, 59, 65–67, 157, 162] provide BFT guarantees at the cost of high complexity, performance, and scalability overheads.

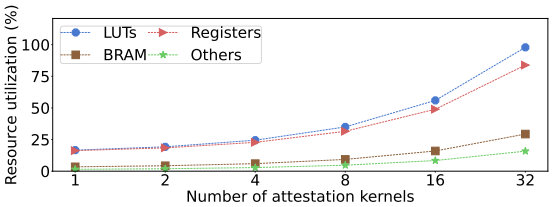

Figure 13. The scalability analysis of TNIC hardware. The resource usage is normalized to the U280 FPGA capacity.

TNIC bridges the gap between BFT and prior limitations, designing a *silicon root-of-trust* with generic trusted networking abstractions that materialize the BFT security properties.

Trusted hardware for distributed systems. Trustworthy systems [55, 76, 76, 89, 92, 144, 167] leverage trusted hardware to optimize the performance of classical BFT at the cost of generalization and easy adoption. The systems suffer from high latencies (50us—105ms) [107, 116], build large TCBs [55, 89], and rely on specific TEEs [57, 167]. In contrast, our TNIC aims to offer performance and generality, while our minimalistic TCB is verifiable and unified in the heterogeneous cloud.

SmartNIC-assisted systems. Networked systems offer fast network operations with emerging (programmable) SmartNIC devices [3, 9, 11, 28, 30–32, 40]. Some of them offload the network functions to the hardware and reduce the host processing and energy overheads [50, 85, 90, 102, 114, 122, 132, 142, 151, 155, 158, 159] or re-design generic networking protocols, from RDMA/RoCE to TCP/IP network stacks, on top of FPGA-based SmartNICs for performance [5, 15, 86, 99, 146, 153, 170]. Others [110, 115, 118, 121, 123, 125, 126, 129, 139, 141, 147, 149] build generic execution frameworks to optimize various distributed systems. Our TNIC follows a similar approach by building a high-performant unified network stack with SmartNICs and extending its security semantics with the properties of non-equivocation and transferable authentication.

Programmable HW for network security. Programmable hardware, SmartNICs, and switches are used to shield networking. Recent systems [108, 160, 169, 175, 178] leverage programmable switches and FPGAs to offload security processing and boost performance in the context of blockchain systems [160] or security functions (e.g., access control, DNS traffic inspection) [108, 175, 178]. Our TNIC similarly offloads security into the hardware, but it carefully uses SmartNICs to overcome the processing bottlenecks of the switches.

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A Artifact Appendix

A.1 Abstract

Our artifacts include the TNIC codebase as well as the software artifact with the four TNIC applications, i.e., A2M, BFT, CR, and PeerReview. In addition, we provide the codebases of all the microbenchmarks we discuss in the paper including those of the TEE-based systems. Lastly, we attach the security proofs of TNIC system operations and attestation protocol based on Tamarin [130]. This appendix provides the necessary information to set up, build, and run the experiments we present in the paper.

A.2 Artifact check-list (meta-information)

- **Program:** TNIC hardware implementation codebase. TNIC software codebases that include the systems where TNIC has been applied (run in emulated hardware) and microbenchmarks (e.g., network benchmark). TNIC's security proofs based on Tamarin [130].
- **Compilation:** Requires Vitis HLS [173], Vivado [174], CMake, C++, Boost, eRPC [105], DPDK [24], Tamarin [130].
- **Run-time environment:** Requires NixOS, 5.15.4, SCONE [51] (for SGX-based experiments).
- **Hardware:** Requires Alveo U280 cards [3], Intel(R) Core(TM) i9-9900K with Intel Corporation Ethernet Controllers (XL710) (or any other DPDK compatible NIC) and AMD EPYC 7413.
- **Execution:** The time of the experiments are configurable. Each of our experiments did not take more than 10 minutes. However, the compilation and synthesis phases of the TNIC hardware implementation might take up to 4 hours.
- **Metrics:** Throughput and latency
- **Publicly available:** Yes.
- **Code licenses:** MIT License. TNIC doesn't use any external license.
- **Archived (DOI):** 10.5281/zenodo.14775354

A.3 Description

A.3.1 How to access. The open-source version of the TNIC codebase can be found on GitHub at the following address:
https://github.com/TUM-DSE/TNIC-main.git

A.3.2 Hardware dependencies. For AMD-SEV and TNIC-hardware setups, you need three machines with AMD EPYC 7413 CPU. Each machine is equipped with an Alveo U280 card [3] and one of every U280's QSFP28 ports connects to the 100Gbps network. For Intel SGX setups, you need machines with Intel(R) Core(TM) i9-9900K with Intel Corporation Ethernet Controllers (XL710) (or any other DPDK compatible NIC) for network connection.

A.3.3 Software dependencies. The software build process involves building the low-level Linux kernel driver and the high-level user application layers. All codebases run on top of NixOS, 5.15.4. We provide the appropriate `.nix` files to set up a `nix-shell` environment with all necessary system dependencies.

The code has been built with `Makefile` and `cmake`. The applications, as well as the TEE-based code and application layer, are written in C++17. We depend on Boost libraries and gflgas for the parsing of the command line arguments. We rely on several other dependencies, which we explain in our README files, including; SCONE [51] for SGX-based experiments, Vivado [174] and Vitis HLS [173] for building TNIC hardware, eRPC [105], DPDK [24], and Tamarin [130].

A.4 Installation

The artifact is linked to the repository as submodules. Each repository provides analytical instructions in their `README.md` files of how to build and run the binaries.

To build the TNIC's hardware implementation, please follow the instructions provided in [12].

To build the software including the driver and the benchmarks, please follow the instructions in [13].

To run the experiments for the TNIC hardware implementation, you need to first load the TNIC's kernel module and then run the compiled binary. Detailed instructions are available in [22].

Similar instructions have been documented for the applications [36] and the security proofs [37].

A.5 Evaluation and expected results

Each of the experiments will output information about its progress; this is a hint that the script is still running and hasn't halted. The output of the experiment reports important measurements about the execution. The results are expected not to vary significantly (less than 5%) when compared to the results presented in the paper. However, as discussed, we observed quite a significant variance in some TEE-based systems (Intel SGX and AMD-SEV).

A.6 Methodology

Submission, reviewing, and badging methodology:

- https://www.acm.org/publications/policies/artifact-review-badging
- http://cTuning.org/ae/submission-20201122.html
- http://cTuning.org/ae/reviewing-20201122.html

B Formal verification Proofs

In this appendix, we also present the detailed security proofs for TNIC security protocols using the Tamarin Prover [130].

Proof artifact. The complete proofs, including the detailed formal models used to generate them, can be found under the following link:
https://github.com/TUM-DSE/TNIC-proofs.git

Symbolic model. We prove the security properties of TNIC in a symbolic model because Tamarin analyzes protocols in symbolic models and can prove properties by verifying user-defined lemmas. We leverage Tamarin's built-in primitives

and automated and interactive analysis to verify the security protocols.

We impose a set of assumptions on our proofs motivated by Tamarin's symbolic model: *(i)* The symbolic model does not reason about bitstrings directly. Instead, it assumes a set of atomic terms and functions that operate on these terms. All messages that are part of the model are composed of such atomic terms and functions applied on these terms *(ii)* These cryptographic functions are assumed to be perfect with no side-effects, e.g., hash functions are irreversible, and hash collisions are impossible. This allows for proving lemmas without considering the probabilities of violating specific properties and thus significantly reducing the complexity. The computational model is an alternative to the symbolic model that considers such probabilities. *(iii)* Attackers can read and delete all messages that are sent on the network and modify them in accordance with the set of defined functions.

Tamarin works on symbolic models specified using multiset rewriting rules that operate on the system's state. Different states of the system are expressed as a set of facts with rules capturing the available transitions from one system state to another. Rules are used to model the actions of agents running the protocol and the adversary's capabilities. In addition to the rules, Tamarin also makes use of restrictions. Restrictions further refine the sources of facts in the protocol to improve the efficiency of the proof generation.

Our verification work relies on properties of the already analyzed TLS handshake [35]. It provides a model and lemmas for the security properties of the protocols presented in this paper.

To prove the correctness of our lemmas, Tamarin computes possible executions for each rule. Tamarin employs constraint solving to refine its knowledge about the sequence of protocol transitions. To check the correctness of the protocol model we also employ sanity lemmas which ensure that there exists a sequence of transitions to reach a predefined valid state. These lemmas ensure that the protocol can be executed as intended.

In the following paragraphs, we give an overview of the rules and lemmas used to model the TNIC protocols.

Rules. The bootstrapping rules, in accordance with the bootstrapping steps in Section 4.3:

- *bootstrapping_1*: Models step (1), the generation and burning of the hardware key by the TNIC manufacturer.
- *bootstrapping_2*: Models step (2), the loading and verification of firmware from the insecure storage medium.
- *bootstrapping_3_4_5*: Models step (3-5), the loading, key and certificate generation of the controller.
- *publish_firmware*: Models the hardware manufacturer publishing a new firmware version.
- *get_tnic_public_key*: Models the retrieval of the public TNIC key for verification.
- *compromise_tnic_private_key*: Models an attacker compromising a specific TNIC device and retrieving the private key.

The attestation rules, in accordance with the attestation steps in Section 4.3:

- *attestation_6_7*: Models step (6-7), the receiving of the configuration data from the protocol designer, and the start of the secure channel establishment with the TNIC device.
- *attestation_8a*: Models step (8) on the TNIC side.
- *attestation_8b_9*: Models step (8) on the IP Vendor side and step (9), the sending of the encrypted configuration bitstream.
- *attestation_10_11_12*: Models step (10-12), the report generation of the TNIC device.
- *attestation_13_14_15_16*: Models step (13-16), the report retrieval and verification, as well as the sending of the bitstream encryption key.
- *attestation_17*: Models step (17), the decryption and configuration of the bitstream, as well as the acknowledgment.
- *attestation_18*: Models the final step of the IP Vendor after which the attestation protocol is completed.
- *add_bitstream*: Models the addition of a new bitstream to the IP Vendor, which potentially contains sensitive information.

The communication rules, in accordance with the functions provided in Algorithm 1:

- *init_ctrs*: Models the initialization of the send and receive counters for each session. Is restricted to guarantee the uniqueness of the session counters.
- *send_msg*: Models send an arbitrary message by attesting it before sending it over the secure channel. Is restricted to guarantee the session counters are increased.
- *recv_msg*: Models receive an arbitrary message by only accepting it after a successful verification.

Lemmas. The sanity lemmas, which ensure the protocol can be executed as intended:

- *sanity* (verified in 26 steps): Ensures that the protocol allows for successfully completing the bootstrapping & attestation phase, such that the IP Vendor and uncompromised TNIC device are in an expected state.
- *send_sanity* (verified in 23 steps): Ensures that the protocol allows for successfully verifying a message sent during the communication phase after two TNIC devices are successfully initialized.

The attestation lemmas, which ensure the bootstrapping & attestation phase behaves as expected:

- *HW_key_priv_secret* (verified in 3 steps): Ensures that the private key of the TNIC device is not obtainable from any messages sent as part of the TNIC protocols of the model.
- *S_key_secret* (verified in 97 steps): Ensures all symmetric keys established during initialization phases are secret. It also ensures that past symmetric keys stay

System	N	f ($N=3$)	Byzantine faults
A2M	1	0	Prevention
BFT	$2f+1$	$f=1$	Prevention
Chain Replication	$f+1$	$f=2$	Prevention
PeerReview	$f+1$	$f=2$	Detection

Table 6. Properties of the four trustworthy distributed systems implemented with TNIC.

secret even if the hardware key is compromised in the future after the session is completed.
- *bitstream_secret* (verified in 83 steps): Ensures all bitstreams shared during initialization phases are secret. It also ensures that past shared bitstreams stay secret even if the hardware key is compromised in the future after the session is completed.
- *initialization_attested* (verified in 5540 steps): Ensures that after the IP Vendor finished the attestation during the initialization phase, the TNIC device is in an expected state and loaded the correct configuration.

The transferable authentication lemma:
- *verified_msg_is_auth* (verified in 31795 steps): Ensuring that each message that is successfully accepted by a TNIC device is sent by a genuine TNIC device, assuming the hardware of the TNIC devices was not compromised.

The non-equivocation lemmas:
- *no_lost_messages* (verified in four steps): Ensures that for all messages that are successfully accepted by a genuine TNIC device, there are no messages that were sent before but not accepted by the same TNIC device.
- *no_message_reordering* (verified in 5447 steps): Ensures that for all messages that are successfully accepted by a genuine TNIC device, there are no messages that were sent after that message but accepted before.
- *no_double_messages* (verified in 10850 steps): Ensures that a genuine TNIC device does not accept the same message multiple times.

C Protocols Implementation

We next present the implementation details of four distributed systems shown in Table 6 using TNIC, presented in Section 7.

C.1 Clients

Clients in a TNIC distributed system execute requests by sending singed request messages to TNIC nodes through the network. TNIC assumes Byzantine (untrusted) clients; as such, its installed shared keys cannot be outsourced. We assume that at the initialization, the System Designer also loads to TNIC devices a (per-device) key pair $C_{pub,priv}$ where the C_{pub} is distributed to clients. TNIC then replies to a client by verifying the (under transmission) attested message and signing it with C_{priv}. As such, TNIC is restricted to only sending valid attested messages to clients where clients can prove the transferable authentication and validity of the message. The only attack vector open to a Byzantine machine is to try to equivocate by sending a stale, valid, attested message that does not reflect the current execution round. However, clients can detect this by verifying that the original request is theirs.

C.2 Attested Append-Only Memory (A2M)

We designed a single-node trusted log system based on the A2M system (Attested Append-Only Memory) [69] using TNIC. A2M has been proven to be an effective building block in improving the scalability and performance of various classical BFT systems [43, 65, 120]. We show the *how* to use TNIC to build this foundational system while we also show that TNIC minimizes the system's TCB jointly with the performance improvements demonstrated in § 8.

System model. Our TNIC version and the original A2M systems are single-node systems that target a similar goal; they both build a trusted append-only log as an effective mechanism to combat equivocation. The clients can only append entries to a log; each log entry is associated with a monotonically increasing sequence number. Each data item, e.g., a network message, is bound to a unique sequence number, a well-known approach for equivocation-free operations [57, 70].

A2M was originally built using CPU-side TEEs—specifically, Intel SGX— whereas we build its TNIC derivative. While the original A2M system keeps its entire state and the log within the TEE, we use TNIC to keep the (trusted) log in the untrusted memory. As such, in contrast to the original A2M, TNIC effectively reduces the overall system's TCB. Our evaluation showed that naively porting the application within the TEE has adverse performance implications in lookup operations.

Execution. Similarly to A2M, we expose three core operations: the `append`, `lookup`, and `truncate` operations to add, retrieve, and delete items of the log, respectively. A2M stores the lowest and highest sequence numbers for each log. Upon appending an entry, A2M increases the highest sequence number and associates it with the newly appended entry. When truncating the log, the system advances the lowest sequence number accordingly. We next discuss how we designed the operations using TNIC APIs.

Append operation. The `append(id,ctx)` operation takes a data item, `ctx`, and appends it to the log with identifier `id`. A log entry at index `i` is comprised of three items: the sequence number of that entry (`i`), the context of the entry (`ctx`), and the *authenticator* field, namely the digest of the `ctx||i` as in [116]. In our implementation, we additionally support the original A2M *authenticator* format calculated as the cumulative digest `c_digest[i]` for that entry which is calculated as `c_digest[i]=hash(ctx||sq||c_digest[i-1])` where `c_digest[0]=0`. The sequence number `i` is then increased to distinguish any entry that will be appended in the future.

Lookup operation. The `lookup(id, i)` retrieves the log entry at index `i` of log with identifier `id`. Compared to A2M, where lookups are compelled to access the trusted hardware,

Algorithm 2: Attested Append-Only Memory (A2M) using TNIC.

```
1  function append(id, ctx){
2      [α,i,ctx] ← local_send(id,ctx);
3      log[id].append(log_entry(α,i,ctx));
4      return [α,i,ctx];
5  }
6  function lookup(id, i){
7      return log[id].get(i);
8  }
9  function truncate(id, head, z){
10     [α,tail,ctx] ← append(id, TRNC||id||z||head);
11     e ← append(MANIFEST,[α,tail,ctx]);
12     return e;
13 }
14 function verify_lookup(id, e, head, tail){
15     assert(e.i>=tail);
16     local_verify(id, e);
17 }
```

TNIC-log only performs a local memory access. The function does not verify whether the entry is legitimate. Developers need to implement the `verify_lookup(id, entry, head, tail)` to verify the attestation. The boundaries of the log (i.e., `head` and `tail`) can constantly be retrieved by replaying a specific log, which keeps the state changes, the MANIFEST. We explain how MANIFEST works in the next paragraph.

Truncate operation. The `truncate(id, head, z)`, where `z` is a nonce provided by the client for freshness, "forgets" all log entries with sequence numbers lower than `head`. A non-Byzantine client can never successfully verify a forgotten log entry. To do that, TNIC-log uses an additional log MANIFEST, which keeps the logs' state changes. First, the operation attests to the *tail* of the log by appending a specific entry, which includes the nonce for a correct client to be later able to verify the operation. Then, the algorithm will append the last attested message of the log to the MANIFEST log and return the attested message for the second append. To retrieve the boundaries of a log, clients can always attest to the tail of the MANIFEST and read backward until they find a TRNC entry.

System design takeaway. TNIC minimizes the required TCB in the A2M system while offering faster lookup operations than its original version.

C.3 Byzantine Fault Tolerance (BFT)

As a second example of TNIC applications, we build a Byzantine Fault-Tolerant protocol (BFT) that implements a robust counter based on *state machine replication* (SMR). Clients send increment counter requests to the SMR and receive the updated value of the counter. Despite its simplicity, this particular system can represent an ordering service, which is a fundamental building block of various distributed applications ranging from event logging and database systems to serverless and blockchain [78, 101, 104, 148, 168]. Our BFT combats equivocation by leveraging the attestation kernel of TNIC. As such, via TNIC, it reduces *(i)* the number of replicas and *(ii)* the message complexity (and latency) required by classical BFT.

System model. We consider a system of $N = 2f+1$ replicas (or *nodes*) that communicate with each other over unreliable point-to-point network links. At most f of these replicas can be Byzantine (aka *faulty*), i.e., can behave arbitrarily. The rest of the replicas are *correct*. Recall that classical BFT protocols require an extra set of f replicas, in total $3f+1$, to handle f Byzantine failures. One of the replicas is the *leader* that drives the protocol, whereas the remaining replicas are (passive) followers. There is only a single active leader at a time.

For liveness, we assume a partial synchrony model [68, 82]. We have only explored deterministic protocol specifications; the correct replicas begin in the same state, and receiving the same inputs in the same order will arrive at the same state, generating the same outputs. Lastly, as in classical BFT protocols, we cannot prevent Byzantine clients who otherwise follow the protocol from overwriting correct clients' data.

Execution. We implement BFT with TNIC as a leader-based SMR protocol for a Byzantine model that stores and increases the counter's value. The leader receives clients' requests to increment the counter. The leader, in turn, executes the protocol and applies the changes to its state machine—in our case, the leader computes and stores the next available counter value. Subsequently, the leader broadcasts the request along with some metadata to the passive followers. The metadata includes, among others, the leader's calculated output in response to the client's command, namely, the increased counter value the leader has calculated.

The followers, in turn, execute and apply the incremented counter value to their state machines. However, they first attest to the leader's (and other followers') actions to detect misbehavior. Importantly, followers validate if the state (counter) of the replicas (including the leader and all other replicas) match the expected value.

After a follower applies the increments to its local counter, it replies to the client. In addition, it forwards the leader's request to every other replica to ensure that all correct replicas will eventually receive and apply the same command. Replicas that have already applied the request ignore it; otherwise, they validate it and apply it. The leader, upon successful validation, will also reply to the client. The client can trust the result if they receive identical replies from a majority quorum, i.e., at least $f+1$ identical messages from different replicas (including the leader). This guarantees that at least one correct replica has responded with the correct result.

Failure handling. Our strategy to verify the replica's execution jointly with the primitives of non-equivocation and transferable authentication offered by TNIC shields the protocol against Byzantine behavior. The leader cannot equivocate;

even if it attempts to send different requests for the same round to different followers, executing the `local_send()` will assign different counter values, which healthy followers will detect. As such, a leader in that case will be exposed.

Likewise, the equivocation mechanism allows correct followers to discard stale message requests sent through replay attacks on the network. If a follower is Byzantine, a healthy leader or replica can detect it. For $f \geq 2$, it is impossible for a faulty leader and, at most, $f-1$ remaining Byzantine followers to compromise the protocol. Either these faults will be detected by a healthy replica during the validation phase, or the protocol will be unavailable, i.e., if the leader in purpose only communicates with the Byzantine followers. This directly affects BFT correctness requirements; a client will never get at least $f+1$ matching replies. Even in the extreme case of a network partition or a faulty leader that purposely excludes some healthy replicas from its multicast group, when the network is restored, these replicas will not accept any future messages unless they receive all missed ones. Suppose the leader fails in the middle of the broadcast. In that case, the last step in the follower's protocol ensures that if a correct replica accepts the requests, all correct replicas will eventually apply the same request. Since the reliability aspect and FIFO ordering are implemented in hardware, healthy replicas will ultimately receive all past messages in the proper order. For protocols to progress in the case of a faulty leader, they must pass through a recovery protocol or view-change protocols similar to those described in previous works [65, 167]. Recovering is beyond the scope of this work, and as such, we did not implement it.

System design takeaway. TNIC optimizes the replication factor and the message rounds compared to classical BFT.

C.4 Chain Replication (CR)

We implement a Byzantine Chain Replication using TNIC that represents the replication layer of a Key-Value store. Chain Replication is a foundational protocol for building state machine replication and initially operates under the CFT model using $f+1$ nodes to tolerate up to f failures. We show *how* to use TNIC to shield the protocol without changes to the core of the algorithm (states, rounds, etc.) while keeping the same replication factor.

System model. We make the same assumptions for the system as in the previous BFT system. For error detection and reconfiguration, we assume a centralized (trusted) configuration service as in [165] that generates new configurations upon receiving reconfiguration requests from replicas. Recall that the classical Chain Replication under the CFT model relies on reliable failure detectors [166]. For liveness, we also assume that the configuration service will eventually create a configuration of correct replicas that do not intentionally issue reconfiguration requests to perform Denial-of-Service attacks.

Clients send requests to `put` or `get` a value and receive the result. The replicas (e.g., head, middle, and *tail* nodes) are

Algorithm 3: BFT using TNIC.

```
1  function leader(req) {
2      output ← execute(req);
3      msg ← req||output;
4      attested_msg ← local_send(msg);
5      rem_write(FOLLOWERS[:], attested_msg);
6      upon reception of ack from FOLLOWERS:
7          [α || f_attested_msg || f_output || f_id]
8                ← upon_delivery(ack);
9          assert(validate_follower(f_attested_msg,
10               f_output));
11         incr_req_acks_if_not_incr_before(f_id);
12     auth_send(CLIENT,msg);
13 }
14 function follower() {
15     upon reception of attested_msg:
16         [α || req || output] ←
17              upon_delivery(attested_msg);
18         assert(validate_sender(req, output));
19         if (in_order_not_applied(req))
20             current_output ← execute(req);
21             f_attested_msg ←
               local_send(req||current_output);
22             ack ← f_attested_msg
23             auth_send(LEADER, ack);
24             auth_send(CLIENT ∪ FOLLOWERS[:],
25                       f_attested_msg);
26 }
```

chained, and the requests flow from the head node to the tail through the intermediate middle replicas.

Malicious primaries, i.e., the head that does not forward the message intentionally, are detected on the client's side and trigger reconfiguration [65, 167].

Execution. To execute a request `req`, e.g., `put`/`get`, a client first obtains the current configuration from the configuration service and sends the `req` to the head of the chain. The head orders and executes the request, and then it creates a *proof of execution message*, which is sent along the chain. The proof of execution includes the `req` and the leader's action (`out`) in response to that request. In our case, the leader sends the `req` along with the assigned commit index. The message is then sent (signed) to the middle node that follows in the chain.

The middle node checks the message's validity by verifying that the head's output is correct, executes the `req`, and forwards the request to the following replica. Similarly, every other node executes the original request, verifies the output of all previous nodes, and sends the original request and a vector of all previous outputs. A replica must construct a *proof of execution message* that achieves one goal. t allows the following replicas in the chain to verify all previous replicas. s such the messages is of the form $<<<\texttt{req}, \texttt{out}_{leader}>_{\sigma_0}, \texttt{out}_{middle1}>_{\sigma_1},$

Algorithm 4: Chain Replication using TNIC.

```
1  function head_operation(req) {
2      output ← execute(req);
3      msg ← req||output;
4      auth_send(MIDDLE,msg);
5      auth_send(CLIENT,msg);
6  }
7  function middle_tail_operation(msg) {
8      assert(validate_chain(msg));
9      output ← execute(req);
10     chained_msg ← msg||output;
11     if (!TAIL)
12         auth_send(MIDDLE,chained_msg);
13     auth_send(CLIENT,req||output);
14 }
15 function validate(msg) {
16     len ← sz;
17     [req, out, cmt] ← unmarshall(msg[0:len]);
18     assert(memcmp(req, out));
19     assert((cmt == expected_cmt));
20     for (i = 1; i < NODE_ID; i++) {
21         [out, cmt] ← unmarshall(msg[len:len+sz]);
22         assert(memcmp(req, out));
23         assert((cmt == expected_cmt));
24         len ← len + sz;
25     return True;
26 }
```

.., $\texttt{out}_{tail}>_{\sigma_N}$. The tail is the last node in the chain that will execute and verify the execution of the request.

In contrast to the CFT version of the Chain Replication protocol, local operations in the tail, `get` or `ack` in a `put` request cannot be trusted. As such, the replicas in the chain need to reply to the clients with their output after they have forwarded their proof of execution message. Clients can wait for at least f replicas replies and the tail reply to collide. Clients can execute the `get` requests similarly to `write` requests, traversing the entire chain, or clients can consult the majority and broadcast the request to $f+1$ replicas, including the tail.

Failure handling. By the protocol definition, all nodes will see and execute all messages in the same order imposed by the head node. As such, all correct replicas will always be in the same state. In addition, network partitions that may split the chain into two (or more) individual chains that operate independently cannot affect safety: the clients must verify at least $f+1$ identical replies. Suppose a correct replica or a client detects a violation (by examining the proof of execution message or having to hear for too long from a node). In that case, they can expose the faulty node and request a reconfiguration.

System design takeaway. TNIC *seamlessly* shields the Chain Replication system for Byzantine settings with the same replication factor as the original CFT system.

C.5 Accountability (PeerReview)

We implement an accountability protocol based on the PeerReview system [93, 94]. Compared to the previous three BFT systems that prohibit an improper action from taking effect, accountability protocols [93, 94, 98] slightly weaken the system (fault) model in favor of performance and scalability. Specifically, our protocol *allows* Byzantine faults to happen (e.g., correct nodes might be convinced by a malicious replica to permanently delete data). Still, it guarantees that malicious actions can always be detected. Accountability protocols can be applied to different systems as generic guards that trade security for performance [94], e.g., NFS, BitTorrent, etc.

The original version of the system did not use trusted components. t incurs a high message complexity, i.e., *all-to-all* communication to combat equivocation. We use TNIC to improve that message complexity.

System model. We only detect faults that directly or indirectly affect a message, implying that *(i)* correct nodes can observe all messages sent and received by that node and *(ii)* Byzantine faults that are not observable through the network cannot be detected. For example, a faulty storage node might report that it is out of disk space, which cannot be verified without knowing the actual state of its disks.

We further assume that each protocol participant acts according to a deterministic specification protocol. As such, detection can be accomplished even with a single correct machine, requiring only $f+1$ machines. This does not contradict the impossibility results for agreement [82] because detection systems do not guarantee safety.

Execution. The participants communicate through network messages generated by TNIC. In addition, each participant maintains a *tamper-evident* log that stores all messages sent and received by that node as a chain. A log entry is associated with an entry index, the entry data, and an authenticator, calculated as the signed hash of the tail of the log and the current entry data.

We frame our protocol in the context of an overlay multicast protocol [63] widely used in streaming systems. The nodes are organized as a tree where the streaming content (e.g., audio, video) flows from a source, i.e., *root* node, to clients (*children* nodes). To support many clients, each can be a source to other clients, which will be connected as children nodes.

In our implementation, we consider nodes in a tree topology. The tree's height equals one, comprising one source node and two client (children) nodes connected to the source. Algorithm 5 (§ C) shows the operations of our implemented accountability protocol. hen the source sends a context (executes the `root()` function), it implicitly includes a signed statement that this message has a particular sequence number (generated by TNIC). he clients execute the `child()` function that validates the received message, logs the received message, executes the result, and responds to the source.

Algorithm 5: PeerReview using TNIC.

```
1  function root(ctx){
2      auth_send(CHILD,ctx);
3      upon reception of response:;
4          assert(validate_reception(response));
5          log(response);
6  }
7  function child(α||cmd||seq){
8      assert(validate_reception(α||cmd||seq));
9      log(α||cmd||seq);
10     result ← execute(cmt);
11     response ← log(result||cmd);
12     auth_send(ROOT, response);
13 }
14 function log_audit(){
15     while last_id < log_tail{
16         entry ← validate_log_entry_at(last_id);
17         last_id++;
18         assert(replay(entry));
19     }
20 }
```

Each node is assigned to a set of *witness* processes to detect faults. Similarly to the original system, we assume that the set of nodes and its witnesses set *always* contain a correct process. The witnesses audit and monitor the node's log. To detect destructive behaviors (or expose non-responsive nodes), the witnesses read the node's log and replay it to run the participant's state machine. As such, they ensure the participant's state is consistent with proper operation.

Specifically, each witness for a participant node keeps track of n, a log sequence number, and s, the state that the participant should have been in after sending or receiving the message in log entry n. t initializes n to 0 and s to the initial state of the participant.

Whenever a witness wants to audit a node, it sends its n and a nonce (for freshness). The participant returns an attestation of all entries between n and its current log entry using the nonce. The witness then runs the reference implementation, starting at state *s*, and progressing through all the log entries. f the reference implementation sends the same messages in the log, then the witness updates n, which is the state of the reference implementation at that point. If not, then the witness has proof it can present of the participant's failure to act correctly.

The original PeerReview system requires a receiver node to forward messages to the original sender's witnesses so they can ensure this message is *legitimate*, i.e., it appears in the sender's log. No other conflicting message is sent to another peer (equivocation). As such, a peer must communicate (in every round) with the witness set of any other peer, leading to a quadratic message complexity. TNIC eliminates the overhead; a participant that sends or receives a message needs to attest and append the message and its attestation in each log. A participant can process received messages only if they are accompanied by attestations generated by the sender's TNIC hardware.

System design takeaway. TNIC can be used to optimize the message complexity in accountable systems.

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