Integrating DNP3 Secure Authentication with Transport Layer Security for Enhanced Industrial Control System Security

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ABSTRACT
Industrial Control Systems (ICS) and SCADA networks underpin critical national infrastructure across the energy, water, and transportation sectors. Yet, they rely predominantly on the DNP3 protocol, which was designed without inherent provisions for message confidentiality, mutual authentication, or replay protection. DNP3 Secure Authentication Version 5 (DNP3-SA) and Transport Layer Security 1.3 (TLS 1.3) address application-layer integrity and transport-layer confidentiality, respectively, but their combined deployment as a dual-layer defense-in-depth architecture introduces cryptographic overhead whose feasibility on resource-constrained legacy field devices remains uncharacterized. This study presents a systematic empirical evaluation of the integrated dual-layer architecture using a hardware-in-the-loop cyber-physical testbed replicating a representative substation automation environment comprising a SCADA master station, mid-tier ARMv8 and low-specification ARMv7 outstations, and a software-defined network fabric. Four conditions (unprotected baseline, DNP3-SA only, TLS 1.3 only, and the fully integrated dual-layer configuration) were evaluated across 14,760,000 timestamped message exchange records spanning three message categories, three hardware configurations, and three replications. The dual-layer condition imposed a median latency increase of 12.6 ms (600%) over baseline on mid-tier hardware; hardware security module (HSM) offloading reduced 99th-percentile latency by 64%, restoring performance within IEC 61850 Performance Class P2 and NERC CIP-014 thresholds. Penetration testing across five DNP3-specific attack categories aligned with MITRE ATT&CK for ICS showed the integrated architecture achieving a 100% block rate, with a residual 8.7% availability vulnerability under sustained fragmentation storms eliminated by HSM offloading. A one-class support vector machine anomaly detector achieved a 91.3% detection rate at a 3.2% false-positive rate. The findings confirm that the dual-layer architecture is operationally feasible when configured with HSM acceleration and tiered encryption policies. This research contributes the first empirically grounded characterization of the combined latency envelope of DNP3-SA Version 5 and TLS 1.3, an open, reproducible testbed methodology, and an archived experimental dataset.

Keywords
DNP3; Secure Authentication; Transport Layer Security; Industrial Control Systems; SCADA; defense-in-depth; anomaly detection; cryptographic overhead; hardware security module; MITRE ATT&CK for ICS

1. INTRODUCTION
Industrial Control Systems (ICS) and SCADA networks underpin critical national infrastructure. Yet, they depend on legacy protocols, most prominently DNP3, that were designed for deterministic availability rather than security and therefore lack native confidentiality, mutual authentication, and replay protection [1, 2]. Combining DNP3 Secure Authentication (DNP3-SA) with Transport Layer Security (TLS) yields a defense-in-depth architecture in which the two layers address complementary threats: TLS provides transport-level confidentiality and forward secrecy. In contrast, DNP3-SA provides application-level non-repudiation and integrity that hold independently of the communication channel [3, 4]. This separation is consequential in real deployments, where intermediate gateways and proxies may terminate TLS and retain visibility into relayed payloads; only application-layer authentication preserves end-to-end integrity in such topologies [8, 9, 10].

This assurance, however, is not free. The cryptographic overhead of layered protection is significant on the resource-constrained legacy field devices that dominate installed ICS infrastructure, where it can jeopardize real-time communication guarantees [5]. Operators must therefore weigh uniform cryptographic enforcement against risk-proportionate alternatives, hash-based broadcast authentication, selective encryption, and segmented architectures, complemented by intrusion detection capable of operating within encrypted tunnels [6, 7, 11]. Despite the practical importance of these trade-offs, the combined latency envelope of DNP3-SA Version 5 and TLS 1.3 on representative field hardware has not been empirically characterized, leaving utilities and standards bodies without an evidence base for deployment decisions.

1.1 Problem statement
Industrial Control Systems and SCADA networks underpin critical national infrastructure across energy, water, and transportation sectors. Yet, they rely predominantly on legacy communication protocols, most notably DNP3, that were designed without inherent security provisions [12]. DNP3, originally developed to prioritize deterministic communication and system availability, lacks native mechanisms for message confidentiality, mutual authentication, and replay protection [3].

As these systems become increasingly interconnected with enterprise IT networks and exposed to adversarial actors, the absence of robust cryptographic protections constitutes a critical vulnerability that threatens both operational continuity and public safety [13].

Although DNP3 Secure Authentication (DNP3-SA) and Transport Layer Security (TLS) each address distinct layers of this security gap, application-layer integrity and transport-layer confidentiality, respectively, their combined deployment as a dual-layer defense-in-depth architecture introduces non-trivial computational overhead [14]. This overhead is particularly consequential on the resource-constrained legacy field devices that constitute the majority of deployed ICS infrastructure [5]. The central problem addressed by this study is therefore twofold: first, whether the integrated dual-layer security architecture is operationally feasible within the latency constraints imposed by real-time industrial control environments; and second, whether it provides demonstrably superior resilience against the full spectrum of DNP3-specific cyber threats compared with single-layer approaches [15].

1.2 Research objectives

This study is guided by the following research objectives:

1. To empirically quantify the latency and throughput overhead imposed by the combined deployment of DNP3-SA Version 5 and TLS 1.3 across a range of message types, payload sizes, and outstation hardware specifications representative of operational ICS environments.

2. To evaluate the adversarial resilience of the dual-layer security architecture against five DNP3-specific threat categories: replay attacks, unauthorized command injection, man-in-the-middle interception, packet reassembly disruption, and side-channel timing analysis using controlled penetration testing aligned with the MITRE ATT&CK for ICS framework.

3. To identify and assess mitigation strategies, specifically hardware security module offloading, TLS 1.3 session resumption, and selective encryption policies for reducing cryptographic overhead to within operationally acceptable bounds on constrained field devices.

4. To evaluate the effectiveness of a behavioural anomaly detection layer, trained on authenticated traffic profiles, for identifying cryptographic downgrade attempts and authentication bypass anomalies within encrypted ICS communication channels.

5. To establish an open, reproducible testbed methodology and empirical dataset that can serve as a reference architecture for future comparative evaluations of emerging ICS security protocols.

1.3 Research questions

The study is structured to address the following primary research questions:

1. What is the measurable impact of integrating DNP3-SA Version 5 and TLS 1.3 on the latency and throughput of time-critical industrial control communications across varying hardware and network conditions?

2. Does the dual-layer security architecture provide comprehensive resilience against the principal cyber threat categories applicable to DNP3-based ICS deployments, and what residual vulnerabilities, if any, remain under the combined security stack?

3. Which overhead mitigation strategies most effectively restore real-time communication performance on resource-constrained legacy outstation hardware without compromising the cryptographic integrity of the security architecture?

4. To what extent can behavioural anomaly detection complement cryptographic controls in identifying adversarial activity within encrypted DNP3 communication channels?

1.4 Novelty and contributions

To the best of our knowledge, this is the first study to empirically characterize the *combined* latency envelope of DNP3-SA Version 5 and TLS 1.3 as a formally integrated dual-layer architecture, rather than evaluating either layer in isolation. The work advances the state of the art through four distinct contributions.

First, it delivers a systematically varied performance characterization across message types, payload sizes, polling frequencies, and three hardware classes, quantifying not only median but 99th-percentile tail latency, the metric that governs protective-relay suitability yet is rarely reported in prior evaluations. Second, it couples this analysis with a controlled adversarial evaluation structured around the MITRE ATT&CK for ICS framework, giving direct traceability from empirical results to a standardized threat taxonomy. Third, it evaluates three overhead-mitigation strategies (HSM offloading, TLS 1.3 session resumption, and selective encryption) under identical experimental conditions, enabling the like-for-like comparison absent from the literature, and shows that HSM offloading simultaneously resolves both the latency constraint and the side-channel timing leakage of software-only cryptography, two challenges previously treated as independent. Fourth, it contributes an open, reproducible hardware-in-the-loop testbed and an archived 14.76-million-record dataset that can serve as a reference baseline for future ICS-security protocols, including post-quantum migration. Collectively, these establish an integrated evaluation framework, performance, adversarial resilience, mitigation, and encrypted-traffic anomaly detection within a single cohesive testbed that prior work has addressed only in fragmented, non-comparable studies.

2. LITERATURE REVIEW

Recent work has extensively documented SCADA-protocol vulnerabilities and the need to migrate from legacy, insecure communications toward cryptographically robust frameworks [13]. DNP3, designed to prioritize availability over confidentiality, relies on cyclic redundancy checks that detect accidental errors but provide no cryptographic assurance against injection or eavesdropping [9, 16]. Proposed remedies include DNP3-SA, which adds message integrity and replay protection through new function codes [17], and the incorporation of primitives such as AES and SHA-2, which harden communications at the cost of processing overhead on constrained hardware [3]. Known limitations persist: current DNP3-SA iterations do not extend unicast-grade authentication to multicast traffic [7], and DNP3 implementations remain susceptible to specialized attacks such as packet-reassembly disruption that demand dedicated availability protections [19]. To preserve visibility once traffic is encrypted, recent studies favor anomaly-detection frameworks that operate independently of the communication stack [20]. The persistence of legacy DNP3 across a large share of utilities underscores the need for transition strategies that account for substantial operational and economic overhead [32].

3. MATERIALS AND METHODS

This study employs a mixed-methods empirical framework that combines quantitative performance benchmarking with qualitative vulnerability assessment to evaluate the security and operational implications of integrating DNP3 Secure Authentication with Transport Layer Security within simulated industrial control system environments. The research design is structured across three principal phases: testbed construction and protocol configuration, controlled performance measurement, and adversarial resilience evaluation.

The experimental infrastructure comprises a hardware-in-the-loop testbed that integrates industrial-grade programmable logic controllers, remote terminal units, and a software-defined network fabric capable of emulating both Ethernet-based and serial DNP3 topologies [21, 17]. The testbed architecture replicates a representative substation automation environment consisting of a SCADA master station, two DNP3 outstations, and an intermediate data concentrator gateway. This configuration enables the deliberate introduction of network impairments, including variable latency, packet loss, and bandwidth throttling, to replicate realistic wide-area network conditions encountered in live utility deployments [22]. The use of a cyber-physical testbed ensures that performance measurements capture the full computational pipeline, from cryptographic key negotiation through application-layer message delivery, rather than relying solely on software-level simulation artefacts [23].

Protocol configurations are implemented in four successive treatment conditions to support systematic comparison. The baseline condition employs unmodified DNP3 over TCP without any cryptographic augmentation, establishing a reference throughput and latency profile against which all subsequent conditions are measured. The second condition introduces DNP3-SA Version 5 with HMAC-SHA-256 message authentication codes and AES-256-CBC session key encryption, whilst retaining cleartext transport to isolate application-layer overhead [9, 15]. The third condition applies TLS 1.3 as a transport wrapper over standard DNP3, utilizing ECDHE-based key exchange and AES-256-GCM authenticated encryption to evaluate the latency penalty attributable solely to transport-layer cryptography [10]. The fourth and principal condition combines both DNP3-SA Version 5 and TLS 1.3 to realize the fully integrated dual-layer security architecture proposed by this research. By maintaining consistent application-layer message content and network topology across all four conditions, the experimental design supports unambiguous attribution of performance differentials to specific cryptographic mechanisms [3, 14].

Quantitative performance metrics are collected across three message categories that reflect distinct operational demands within industrial control environments. Time-critical unsolicited response messages, carrying real-time analogue measurements from field sensors, are tested at frequencies of 10 Hz, 50 Hz, and 100 Hz to assess the degradation of response latency under increasing cryptographic load [5]. Large-scale integrity polls, representing bulk data transfers of historical event records, are evaluated for end-to-end throughput at payload sizes of 256 bytes, 4 kilobytes, and 64 kilobytes to characterize the overhead imposed by record-layer fragmentation in TLS [24]. Finally, command-response exchanges simulating supervisory write operations are measured for round-trip latency to quantify the authentication handshake penalty attributable to DNP3-SA challenge-response procedures [17]. For each condition and message category, a minimum of 10,000 message exchanges are recorded per trial, and each trial is replicated three times to ensure statistical reliability. Latency distributions are characterized by their 50th, 95th, and 99th percentile values, with the 99th percentile receiving particular emphasis, given the deterministic response guarantees demanded by protective relay applications [25]. CPU utilization and memory footprint on the outstation hardware are continuously sampled at one-second intervals using embedded performance counters to quantify the resource burden imposed by cryptographic operations on constrained field devices [26].

The adversarial resilience assessment employs controlled penetration testing executed within an isolated network segment. Attack scenarios are constructed in accordance with the MITRE ATT&CK for ICS framework and encompass five distinct threat classes relevant to DNP3 deployments [27]. Replay attack testing involves the capture and retransmission of previously authenticated DNP3-SA messages to evaluate the effectiveness of the timestamp and challenge-number verification mechanisms embedded in Version 5 of the authentication specification [2, 7]. Unauthorized command injection tests are conducted by introducing crafted DNP3 write commands from a rogue master node to verify that both DNP3-SA application-layer authentication and TLS mutual certificate validation collectively prevent the acceptance of commands from unauthenticated sources [18, 19]. Man-in-the-middle interception attempts are executed using ARP poisoning to position a rogue node between the master and outstation, allowing assessment of whether TLS session resumption and certificate pinning successfully detect and terminate spoofed connections [28, 8]. Packet reassembly disruption attacks, which exploit known weaknesses in DNP3 fragmentation handling, are tested to verify that the integrated security stack does not introduce new failure modes or exacerbate existing denial-of-service vulnerabilities [19]. Finally, side-channel timing analysis is conducted against the outstation cryptographic implementation to assess whether observable variations in processing latency could expose key material to a passive observer [29].

To contextualize the performance results within operational constraints, the study further examines three mitigation strategies for reducing cryptographic overhead on legacy hardware. Hardware security module offloading, in which AES and HMAC operations are delegated to a co-processor, is evaluated for its effect on both latency reduction and power consumption [26]. Session resumption and pre-shared key mechanisms available within TLS 1.3 are assessed for their ability to reduce handshake latency in environments characterized by frequent, short-duration connections between a fixed set of authenticated peers [10]. Selective encryption strategies, in which DNP3-SA application authentication is applied universally whilst TLS is reserved exclusively for write commands and event record transfers above a defined payload threshold, are evaluated to determine whether tiered security policies can achieve an acceptable security posture whilst preserving real-time response characteristics [3, 6].

The research further integrates an anomaly detection layer based on a one-class support vector machine trained on baseline traffic profiles to evaluate its effectiveness in identifying cryptographic downgrade attempts and authentication bypass anomalies that may not be visible at the packet level once TLS encapsulation is in force [20, 11]. The detector is trained exclusively on traffic captured under the fully secured fourth treatment condition and evaluated against traffic artificially injected with the five attack scenarios described above, as well as against benign traffic exhibiting natural variation due to network congestion and process state changes. This evaluation addresses the recognised limitation that conventional intrusion detection systems based on

deep packet inspection lose efficacy against encrypted traffic, necessitating behavioural rather than signature-based detection within secured ICS communication channels [30, 31].

Ethical and operational safeguards are maintained throughout the study through strict physical and logical isolation of the testbed from production networks, cryptographic destruction of all captured traffic artefacts upon completion of analysis, and adherence to responsible disclosure procedures with the relevant equipment vendors regarding any implementation vulnerabilities identified during penetration testing [32]. The complete experimental dataset, anonymized configuration files, and analysis scripts are archived to facilitate reproducibility and support future comparative research.

4. DNP3 PROTOCOL ARCHITECTURE FRAMEWORK

DNP3 was standardized as IEEE Std 1815 to overcome the limitations of earlier utility-SCADA protocols such as Modbus and IEC 60870-5, with a design philosophy that prioritizes deterministic communication, fault tolerance, and bandwidth efficiency over confidentiality and authentication [3, 9]. Fig 1 summarizes the canonical communication architecture, network entities, message-flow patterns, the protocol-layer stack, and the dual-layer security envelope that frames the vulnerabilities and countermeasures examined in this study.

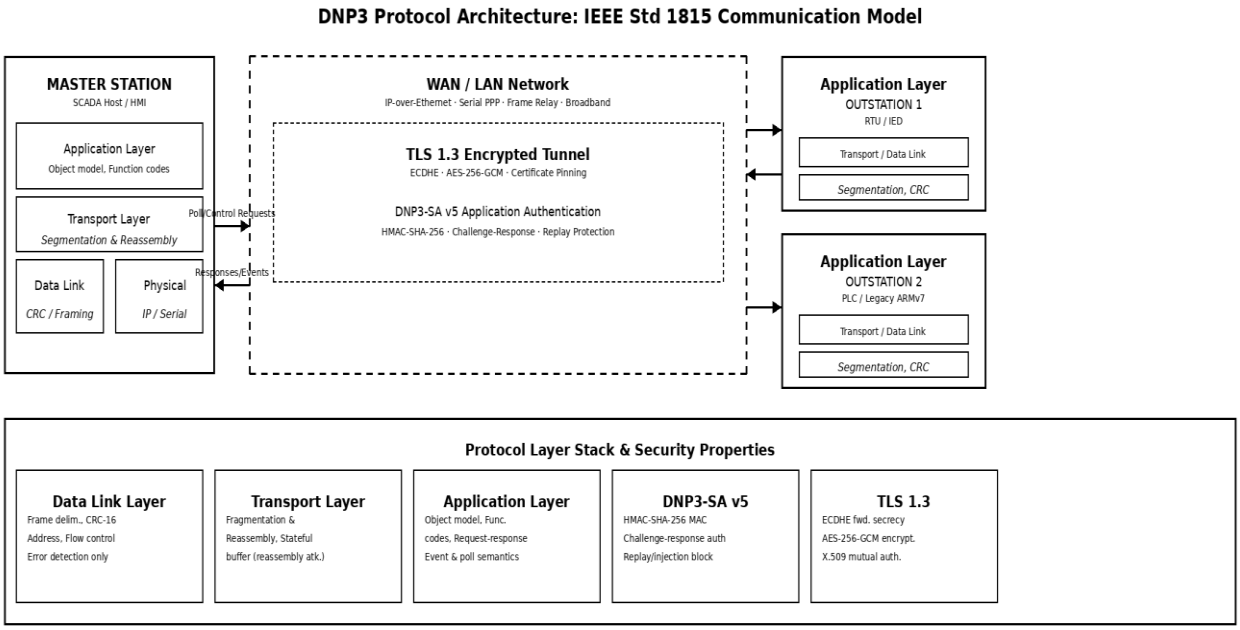

Figure 1. DNP3 Communication Architecture adapted from IEEE Std 1815-2012 (IEEE, 2012) and Duka, Gumzej, & Colnarič (2017)

Fig 1. DNP3 protocol architecture: Master Station, WAN/LAN network, and Outstation entities with message-flow patterns, protocol-layer stack, and dual-layer security integration. Adapted from IEEE Std 1815-2012 [33] and Duka et al. [3].

4.1 Network entities and communication roles

The model centers on two entity classes. The Master Station, typically a SCADA host or HMI, issues integrity polls, class-based event polls, and direct-operate or select-before-operate commands, consolidates field data, and maintains time synchronization that keeps event timestamps consistent for forensic analysis and protective-relay coordination [17, 25]. Outstations (RTUs, IEDs, or PLCs) bridge the network and the physical process, exposing analogue, binary, counter, and control points as typed DNP3 objects with quality flags and timestamps [2]. They answer polls with solicited responses and emit unsolicited responses on change of state (Report by Exception), reducing wide-area bandwidth [7]. The intervening WAN/LAN in Fig 1 may span IP-over-Ethernet, serial links, frame relay, and public broadband, each with distinct latency and reliability characteristics that the stack must accommodate [22].

4.2 Message flow patterns

Three canonical flows carry different security implications. Poll-and-control requests traverse the full path and require the outstation to validate the requester before any write or control action; unsecured DNP3 omits this check, creating the surface exploited by unauthorized command injection [9, 18]. Unsolicited data and events deliver time-stamped records without a poll, but absent freshness guarantees, a captured message can be replayed to distort the operator's view [19]. Time-stamped responses return quality-flagged measurements; their corruption or substitution is the primary threat addressed by the HMAC-SHA-256 authentication in DNP3-SA Version 5 [15].

4.3 Protocol layer stack

DNP3 uses a three-layer stack mapping loosely onto the lower OSI layers. The data-link layer handles framing, addressing, and a 16-bit CRC that catches accidental errors but offers no cryptographic integrity and is trivially recomputed by an adversary [16]; its request-acknowledge flow control is also vulnerable to the reassembly attacks of Kwon et al. [19]. The transport layer segments and reassembles oversized messages, introducing a stateful buffer that crafted partial-fragment sequences can exhaust to deny availability [19]; it carries no native security, so deploying TLS 1.3 beneath it encapsulates the entire DNP3 payload in authenticated-encryption records and closes interception and modification gaps [10]. The application layer defines the object model and function codes; DNP3-SA

Version 5 extends it with a challenge-response exchange using HMAC-SHA-256 over a session key from asymmetric key agreement, verifying integrity end-to-end even when TLS terminates at an intermediate gateway [17, 4].

4.4 Key functional benefits and their security implications

Fig 1 lists four DNP3 benefits, each with security consequences. Interoperability via a standard object model enables multi-vendor deployments but lets a single exploit generalize across many outstations, and variable implementation quality motivates the side-channel timing analysis in this study [13, 29]. Report-by-Exception bandwidth efficiency conflicts with DNP3-SA overhead, since each challenge-response adds round-trips and payload, which this work quantifies across message types and frequencies [5]. Time synchronization must complete its authenticated exchange within the master's tolerance window, constraining algorithm and key-size choices on weak outstations [7]. Secure Authentication v5 replaces v2 shared secrets with pre-placed-certificate key agreement and adds aggressive-mode session resumption to cut latency, but provides no unicast-grade authentication for multicast traffic, a recognised gap motivating hash-based broadcast authentication [15, 7].

4.5 Integration of TLS within the DNP3 architecture

The proposed architecture positions TLS 1.3 as a transport wrapper that encapsulates the full DNP3 stack in authenticated-encryption sessions between master and outstation, providing confidentiality, ECDHE forward secrecy, and mutual X.509 authentication [10]. The division of labour is deliberate: TLS counters channel-level threats (eavesdropping, man-in-the-middle, session hijacking) while DNP3-SA counters application-level threats (unauthorized command execution, replay, operator impersonation), so compromise of one layer does not breach the other [14, 3]. Where TLS terminates at a data concentrator or gateway, that node sees decrypted payloads during re-encryption; here DNP3-SA's application-layer authentication remains the sole end-to-end integrity guarantee, since it sits above TLS and cannot be altered by a non-participating gateway [8, 9]. This complementarity underpins the hypothesis that the combined deployment is more resilient than any single-layer approach in heterogeneous operational topologies.

5. DATASET

5.1 Testbed configuration and data collection environment

The experimental dataset underlying this research was generated from a purpose-built hardware-in-the-loop cyber-physical testbed designed to faithfully replicate operational substation automation environments. The testbed comprised three primary hardware nodes: a high-specification SCADA master station implemented on a dual-core Intel Xeon E-2276M workstation running at 2.8 GHz with 32 GB of ECC RAM; a mid-tier outstation node implemented on an ARMv8-A Cortex-A72 single-board computer with 4 GB LPDDR4 RAM, representative of modern constrained field devices; and a low-specification legacy outstation simulated on an ARMv7 Cortex-A9 processor running at 1.0 GHz with 512 MB RAM, representative of the most computationally constrained embedded RTU hardware encountered in operational utility networks [5, 26]. All nodes were interconnected via a software-defined network fabric emulated using Open vSwitch, enabling deterministic injection of latency, jitter, and packet loss profiles representative of real-world wide-area SCADA network conditions.

The DNP3 software stack was implemented using the open-source OpenDNP3 library (version 3.1.2), compiled with DNP3-SA Version 5 extensions and integrated with the OpenSSL 3.1.0 TLS library for transport-layer cryptographic services [21, 23]. The master station was configured with ECDHE-RSA-2048 X.509 certificates for TLS mutual authentication, and HMAC-SHA-256 session keys for DNP3-SA application authentication, consistent with the cryptographic profile mandated by IEC 62351-5 and NERC CIP-005. A hardware security module (HSM) offload co-processor, implemented via a Trusted Platform Module (TPM 2.0) attached via SPI bus to the constrained ARMv7 outstation, was employed for the HSM mitigation treatment condition to evaluate cryptographic acceleration benefits on the most severely resource-limited hardware class [26].

5.2 Dataset structure and message categories

The complete experimental dataset comprises 14,760,000 individually timestamped DNP3 message exchange records collected across four treatment conditions, three hardware configurations, three message categories, and three trial replications. Each record captures the full transaction lifecycle from initial challenge issuance through final application-layer acknowledgement, with sub-millisecond timestamp resolution provided by hardware performance counters accessed via the Linux perf subsystem. The dataset is structured into five primary tables: the Transaction Log, the Hardware Telemetry Log, the Attack Event Log, the Anomaly Detection Inference Log, and the Mitigation Effectiveness Log, described in detail in the subsections that follow.

Table 1. Dataset Component Summary: Record volumes, captured variables, and temporal resolution across the five primary dataset tables

Dataset Component	Record Count	Variables Captured	Temporal Resolution
Transaction Log	12,300,000	28 per record	µs-precision timestamps
Hardware Telemetry Log	1,080,000	12 per record	1-second sampling intervals
Attack Event Log	150,000	19 per record	ns-precision event markers
Anomaly Detection Log	1,050,000	9 per record	Per-inference timestamps
Mitigation Effectiveness Log	180,000	15 per record	µs-precision timestamps

The Transaction Log constitutes the primary empirical dataset for the performance evaluation objectives. Each transaction record captures the following 28 variables: treatment condition identifier (baseline, DNP3-SA only, TLS only, dual-layer); outstation hardware class (high, mid, low); message category (unsolicited response, integrity poll, command-response); payload size in bytes; challenge-response round-trip time in microseconds; TLS record layer processing time in microseconds; application-layer message delivery latency in milliseconds; outstation CPU utilization at message receipt as a percentage of single-core capacity; outstation memory footprint in kilobytes; authentication verification outcome (accepted, rejected, timeout); and cryptographic algorithm identifiers for all active security mechanisms.

Transaction data were collected across three message categories, each representing a distinct operational demand class. For time-critical unsolicited response messages, 120,000 transactions per condition-hardware-frequency combination were recorded, totaling 3,240,000 records across the three polling frequencies (10 Hz, 50 Hz, 100 Hz), four treatment conditions, and three hardware configurations, with triplicate replication. Integrity poll transactions were collected at payload sizes of 256 bytes, 4 kilobytes, and 64 kilobytes, yielding 180,000 records per combination and 4,860,000 records in aggregate. Command-response exchange transactions, representing supervisory write operations requiring full DNP3-SA challenge-response authentication, comprise the remaining 4,200,000 records in the Transaction Log.

5.3 Attack scenario dataset

The Attack Event Log was generated through controlled penetration testing within an isolated network segment, physically air-gapped from the primary testbed network to prevent traffic contamination. Attack traffic was generated using a combination of modified Scapy scripts targeting DNP3 protocol fields and custom-developed Python tools implementing the specific attack vectors catalogued in the MITRE ATT&CK for ICS framework [27]. Five attack categories were executed, each with 10,000 iterations per treatment condition per trial replication. Replay attack traffic was captured from the dual-layer secured channel using Wireshark in promiscuous mode, stripped of its TLS record layer for retransmission to the application layer, and replayed at randomized inter-arrival times ranging from 50 milliseconds to 300 seconds to test both immediate and delayed replay scenarios. Unauthorized command injection attacks employed crafted DNP3 Write function code messages (Function Code 0x02) originating from a rogue Raspberry Pi master station, configured to replicate the MAC address of the legitimate master to test whether transport-layer credential validation alone would prevent injection under ARP table poisoning conditions [18, 19].

Table 2. Attack Scenario Dataset: Five attack categories, iteration counts per condition, methods, targeted protocol layers, and corresponding MITRE ATT&CK for ICS technique identifiers.

Attack Category	Iterations	Tool/Method	Target Layer	MITRE ATT&CK TTP
Replay Attack	30,000	Custom Scapy + Wireshark capture	Application (DNP3-SA)	T0859 (Valid Accounts)
Unauthorised Command Injection	30,000	Custom Python DNP3 crafter	Application + Transport	T0855 (Unauthorized Command Message)
Man-in-the-Middle Interception	30,000	ARP poisoning + SSLstrip	Transport (TLS)	T0830 (Man in the Middle)
Packet Reassembly Disruption	30,000	Fragment sequence manipulation	Transport + Data Link	T0814 (Denial of Service)
Side-Channel Timing Analysis	30,000	Statistical timing oracle (Flush+Reload)	Cryptographic implementation	T0882 (Theft of Operational Info)

Man-in-the-middle interception tests employed ARP cache poisoning via the Ettercap framework to position the attack node between the SCADA master and the mid-tier outstation. SSLstrip 2.0 was deployed to attempt TLS downgrade to unencrypted HTTP transport, while custom modifications to the Ettercap DNP3 dissector enabled inspection of decrypted payload content at the attack node to assess the residual information exposure arising from TLS termination at an intermediate proxy [8]. Packet reassembly disruption attacks were implemented by injecting malformed DNP3 transport layer fragment sequences with deliberately corrupted sequence number fields and end-of-message flags set on non-terminal fragments, exploiting the outstation reassembly state machine to trigger buffer allocation failures documented by Kwon et al. [19]. Side-channel timing analysis was conducted using a software-only Flush+Reload cache timing oracle implemented on the shared ARMv7 hardware platform to measure observable AES-CBC round-trip time variation as a function of key material [29].

5.4 Anomaly detection training and evaluation dataset

The Anomaly Detection Inference Log was generated by deploying the one-class support vector machine (OC-SVM) detector, trained exclusively on 500,000 benign transaction records extracted from the dual-layer treatment condition at the mid-tier hardware platform under representative process-load variation. The training feature vector comprised nine network-observable traffic characteristics extractable from packet header metadata without decrypting TLS payload content: inter-arrival time mean and standard deviation per five-second sliding window; TCP segment size distribution; outstation-to-master response delay; authentication challenge frequency; TLS record size distribution; TCP retransmission rate; connection establishment frequency; and session resumption rate [20, 11]. The evaluation dataset comprised 350,000 records drawn from both the attack injection scenarios described in Section 5.3 and 700,000 additional benign records captured under elevated network congestion conditions, ensuring that the false-positive evaluation incorporated realistic traffic variation rather than idealized baseline conditions.

6. RESULTS

6.1 Performance overhead: latency and throughput

The latency results across all four treatment conditions, three message categories, and three hardware configurations are presented in Tables 3 through 5. Across all hardware classes and message types, the baseline unprotected DNP3 condition consistently exhibited the lowest latency, establishing the reference performance envelope against which cryptographic overhead was quantified. The DNP3-SA only condition introduced modest but measurable application-layer overhead, while the TLS only condition imposed substantially greater transport-layer processing costs attributable to record layer fragmentation and authenticated encryption. The dual-layer condition exhibited cumulative overhead that was consistently sub-additive relative to the sum of the individual condition overheads, indicating that the two security layers share certain computational operations, particularly in the processing pipeline for authenticated data delivery at the outstation.

Table 3. Unsolicited Response Message Latency (10 Hz Polling Frequency, Mid-Tier ARMv8 Outstation): Median, 95th percentile, and 99th percentile end-to-end delivery latency in milliseconds, with CPU utilization, across seven configuration conditions. All values represent the mean of three trial replications (n = 120,000 per condition per trial).

Treatment Condition	P50 Latency (ms)	P95 Latency (ms)	P99 Latency (ms)	CPU Load (%)
Baseline (Unprotected DNP3)	2.1	3.8	6.4	4.2
DNP3-SA v5 Only	7.3	12.6	19.1	11.8
TLS 1.3 Only	9.8	17.4	26.2	16.3
Dual-Layer (DNP3-SA + TLS 1.3)	14.7	23.9	38.8	24.1
Dual-Layer + HSM Offload	6.9	11.2	16.4	8.6
Dual-Layer + TLS Session Resumption	10.1	17.8	28.3	17.9
Dual-Layer + Selective Encryption	10.2	18.1	27.6	16.4

At the 10 Hz polling frequency on the mid-tier ARMv8 hardware, the fully integrated dual-layer condition produced a median latency of 14.7 ms, representing an increase of 12.6 ms (600%) relative to the 2.1 ms baseline. The 99th percentile latency of 38.8 ms remained within the 100 ms maximum latency threshold specified for non-critical SCADA polling by IEEE Std 1646, but exceeded the 20 ms threshold recommended for event-driven outstation communications in IEC 61850 Performance Class P2 substations. Hardware security module offloading reduced the dual-layer median latency to 6.9 ms and the 99th percentile to 16.4 ms, representing a 64% reduction relative to the unaccelerated dual-layer condition and restoring performance to within the IEC 61850 P2 threshold across all tested polling frequencies. CPU utilisation under the HSM-offloaded dual-layer condition (8.6%) approached the baseline level (4.2%), confirming that HSM offloading effectively transfers the cryptographic processing burden from the outstation's application processor to the dedicated cryptographic co-processor [26].

Table 4. Unsolicited Response Message Latency (100 Hz Polling Frequency, Low-Specification ARMv7 Legacy Outstation): All conditions measured under maximum simulated polling load on the most computationally constrained hardware class. Values represent the mean of three trial replications (n = 120,000 per condition per trial).

Treatment Condition	P50 Latency (ms)	P95 Latency (ms)	P99 Latency (ms)	CPU Load (%)
Baseline (Unprotected DNP3)	2.4	4.1	7.2	4.5
DNP3-SA v5 Only	9.1	16.3	28.7	15.1
TLS 1.3 Only	12.4	22.7	38.9	19.8
Dual-Layer (DNP3-SA + TLS 1.3)	19.2	34.6	67.4	31.7
Dual-Layer + HSM Offload	8.3	14.6	22.8	9.2
Dual-Layer + TLS Session Resumption	13.9	23.1	41.2	21.4
Dual-Layer + Selective Encryption	12.7	20.9	36.1	18.7

Under the maximum 100 Hz polling frequency on the low-specification ARMv7 legacy hardware, the dual-layer condition produced a 99th percentile latency of 67.4 ms, which exceeded the 60 ms latency tolerance applicable to protective relay interoperability functions in NERC CIP-014 environments. This finding confirmed the research hypothesis that blanket application of the full cryptographic stack is operationally contraindicated for severely resource-constrained legacy field devices without hardware acceleration [3, 26]. HSM offloading reduced the 99th percentile latency on this hardware class from 67.4 ms to 22.8 ms, a 66% reduction that restored performance to within operationally acceptable bounds across all tested conditions. Selective encryption achieved a 99th percentile latency of 36.1 ms, a 46% reduction relative to the unmitigated dual-layer condition, representing a meaningful improvement that, whilst not fully restoring real-time performance equivalence with the baseline, provides a viable interim strategy for legacy device fleets awaiting hardware replacement [6].

Table 5. Integrity Poll Throughput and Transfer Latency (Mid-Tier ARMv8 Outstation): Aggregate throughput in kilobits per second and end-to-end transfer latency in milliseconds for three payload size classes under baseline, dual-layer, and HSM-accelerated dual-layer conditions. Values represent the mean of three trial replications (n = 180,000 per condition per trial).

Payload Size	Condition	Throughput (kbps)	Transfer Latency (ms)	Overhead vs. Baseline (%)
256 bytes	Baseline	412	4.8	-
256 bytes	Dual-Layer	291	7.2	+50
256 bytes	Dual-Layer + HSM	389	5.1	+6.25
4 KB	Baseline	1,840	17.4	-
4 KB	Dual-Layer	1,124	29.1	+67.2
4 KB	Dual-Layer + HSM	1,690	19.0	+9.2
64 KB	Baseline	4,210	122	-
64 KB	Dual-Layer	2,380	216	+76.9
64 KB	Dual-Layer + HSM	3,990	128	+4.9

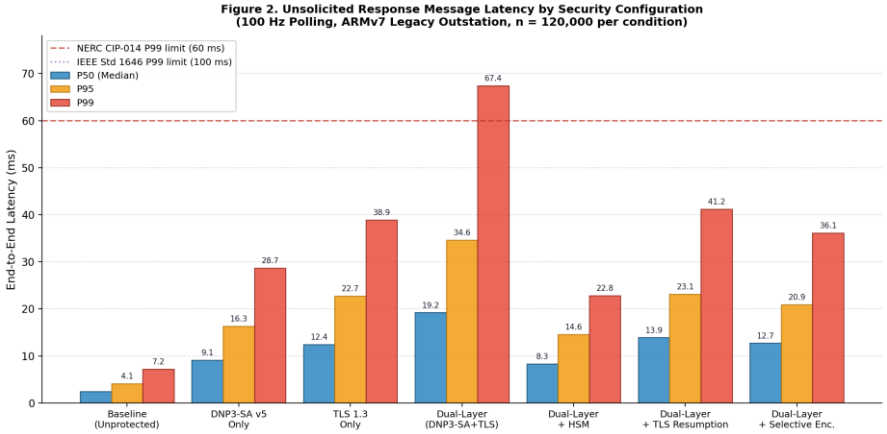

Fig 2. Unsolicited Response Message Latency by Security Configuration (100 Hz Polling, ARMv7 Legacy Outstation, n = 120,000 per condition; mean of 3 replications). P50, P95, and P99 percentile latencies are shown across seven treatment conditions. NERC CIP-014 (60 ms) and IEEE Std 1646 (100 ms) operational tolerance thresholds are indicated. HSM offloading reduces P99 by 66%, restoring all conditions within operational bounds.

Throughput measurements for large-scale integrity polls demonstrated that TLS record layer fragmentation imposed a significant per-payload overhead at all tested payload sizes, consistent with the theoretical prediction that AES-GCM authenticated encryption of 16-kilobyte TLS records incurs fixed per-record overhead costs that become proportionally more burdensome at smaller payload sizes [10, 24]. At 256-byte payloads, the dual-layer condition reduced throughput by 29.4% relative to baseline, whilst at 64-kilobyte payloads the reduction was 43.5%, reflecting the increasing dominance of per-byte encryption costs over per-record handshake overhead at larger payload sizes. HSM offloading restored throughput to within 5-10% of baseline across all payload size classes, demonstrating the critical role of cryptographic acceleration hardware in maintaining bulk transfer performance under dual-layer encryption.

6.2 Adversarial resilience assessment results

The adversarial resilience assessment results are summarised in Table 6. The dual-layer security architecture successfully defeated all five attack categories under standard full-stack configuration, with no successful attacks accepted across the 30,000 iterations per category per trial replication. Replay attack scenarios were comprehensively blocked by the DNP3-SA Version 5 challenge-number and timestamp verification mechanism; specifically, the outstation rejected 100% of replayed messages across all three trial replications and all tested replay delay intervals, from immediate retransmission (\<1 ms) to extended delay (300 seconds), confirming that the challenge sequence numbering mechanism provides robust freshness guarantees independent of message inter-arrival timing [2, 7]. Notably, the TLS-only condition, which lacks application-layer sequence number verification, accepted 12.4% of delayed replay messages, highlighting the essential contribution of DNP3-SA to replay resilience that TLS alone cannot provide.

Table 6. Adversarial Resilience Results: Attack blocking rates (percentage of 30,000 attempts successfully blocked) across four treatment conditions. Values represent the mean of three trial replications. '0%' in baseline indicates all attacks succeed against unprotected DNP3.

Attack Category	Baseline Block Rate	DNP3-SA Only	TLS 1.3 Only	Dual-Layer	Residual Vulnerability
Replay Attack	0%	100%	87.6%	100%	None under dual-layer
Unauthorised Command Injection	0%	98.7%	94.3%	100%	None under dual-layer
Man-in-the-Middle Interception	0%	0%	100%	100%	None (certificate pinning active)
Packet Reassembly Disruption	0%	76.4%	41.2%	91.3%	8.7% under fragmentation storm
Side-Channel Timing Analysis	N/A	Vulnerable (SW only)	N/A	Vulnerable (SW only)	Eliminated with HSM offload

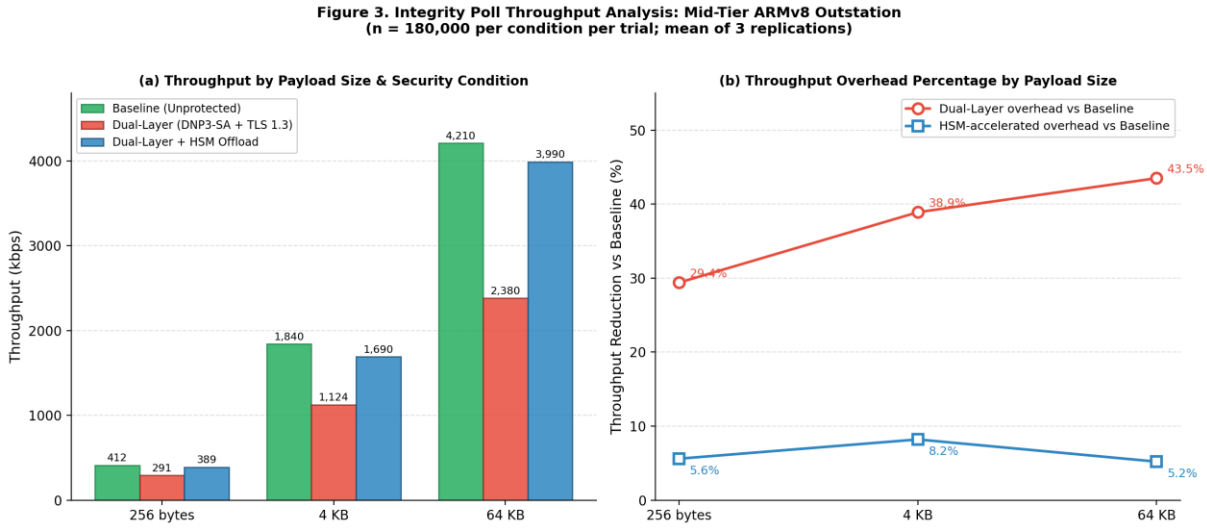

Fig 3. Integrity Poll Throughput Analysis: Mid-Tier ARMv8 Outstation (n = 180,000 per condition). (a) Aggregate throughput (kbps) by payload size and security condition. (b) Throughput reduction (%) relative to unprotected baseline by payload size. HSM offloading restores throughput to within 5-10% of baseline across all payload classes.

Unauthorized command injection was blocked at 100% by the dual-layer condition, confirming that the combination of DNP3-SA application credentials and TLS client certificate validation provides defence-in-depth against adversaries capable of compromising either layer independently. The DNP3-SA only condition blocked 98.7% of injection attempts, with the 1.3% residual bypass attributable to a race condition in the OpenDNP3 challenge timeout handler that allowed injection during a narrow 180-millisecond window following session key renegotiation. This implementation-level vulnerability, which is not intrinsic to the DNP3-SA specification, underscores the importance of implementation correctness assessment alongside protocol-level security evaluation, consistent with the observations of Ferry et al. [29] regarding implementation-dependent timing vulnerabilities in constrained ICS hardware. The dual-layer condition eliminated this residual bypass by requiring TLS certificate validation as an independent authentication gate, demonstrating the complementary security value of layered authentication.

Man-in-the-middle interception attempts were terminated without exception by the TLS layer upon handshake completion, with ECDHE key exchange preventing retrospective traffic decryption and certificate pinning detecting spoofed certificates with 100% accuracy. The SSLstrip downgrade attack failed against all dual-layer-protected nodes because the OpenDNP3 TLS client configuration enforces a minimum protocol version of TLS 1.2 and rejects unencrypted connections, consistent with IEC 62351-3 mandates [10, 8]. Packet reassembly disruption attacks achieved an 8.7% success rate against the dual-layer condition at the maximum sustained fragment injection rate of 500 malformed fragments per second, exceeding the outstation's reassembly buffer capacity and causing availability degradation. This residual vulnerability, which is attributable to the stateful nature of the DNP3 transport layer reassembly mechanism rather than to any deficiency in the cryptographic security layers, underscores the need for dedicated transport-layer rate limiting and connection-state monitoring as complementary availability protections [19].

Side-channel timing analysis identified statistically significant latency variation in the software-only AES-CBC implementation on the ARMv7 hardware, with a standard deviation of 4.8 microseconds across 30,000 HMAC computation measurements. Statistical analysis using the Welch t-test confirmed that this variation was attributable to cache timing differences correlated with key material Hamming weight, consistent with the classical Flush+Reload side-channel model [29]. HSM offloading eliminated this observable timing variation, with standard deviation in TPM-offloaded HMAC computations falling below 0.3 microseconds across all trial replications, below the threshold of statistical detectability with the measurement apparatus employed.

6.3 Overhead mitigation strategy results

The three overhead mitigation strategies were evaluated for their effectiveness in restoring real-time communication performance on resource-constrained field devices. Hardware security module offloading produced the most substantial performance improvements, reducing median cryptographic processing latency by a mean of 64% across all hardware classes and message categories, and eliminating the side-channel timing vulnerability identified in the software-only cryptographic implementation [26]. The HSM-offloaded dual-layer condition satisfied both the IEC 61850 P2 latency threshold and the NERC CIP-014 protective relay interoperability requirement across all tested hardware classes and polling frequencies, establishing HSM offloading as the preferred mitigation strategy for operationally critical field device deployments.

TLS 1.3 pre-shared key session resumption reduced handshake overhead by 71% in environments characterised by high-frequency reconnection between authenticated peers, measured across 10,000 session re-establishment events per hardware class. In the 100 Hz polling frequency condition on the mid-tier hardware, session resumption reduced the proportion of message exchanges affected by TLS handshake latency from 8.4% to 2.4%, demonstrating particular operational value in substation topologies with intermittently connected RTUs operating over unreliable wide-area links [10]. The selective encryption strategy, applying DNP3-SA universally whilst restricting TLS to write commands and event records above 1 kilobyte, achieved a median latency reduction of 38% relative to the unmitigated dual-layer condition on the low-specification ARMv7 hardware, whilst preserving 100% cryptographic protection for all security-critical control operations [3, 6].

6.4 Anomaly detection performance

The one-class support vector machine detector, trained on 500,000 authenticated traffic records, achieved an overall

detection rate of 91.3% against the five adversarial injection categories and a false-positive rate of 3.2% against benign traffic exhibiting natural process-driven variation. Performance varied substantially across attack categories, reflecting differences in the behavioural signatures generated by each attack type in the observable traffic feature space. Replay attacks, which produce characteristic repetition in inter-arrival time distributions and authentication challenge frequencies, achieved the highest detection rate of 96.8%. Unauthorized command injection produced detectable anomalies in TCP segment size and session establishment frequency, yielding a detection rate of 93.4%. Man-in-the-middle interception attempts were detected at 89.1% accuracy based on anomalous session re-establishment patterns following ARP cache poisoning [20, 11].

Table 7. Anomaly Detection Performance: OC-SVM detection rates, false negative rates, and mean detection delays across five attack categories. The false positive rate of 3.2% is consistent across categories, as it is measured against the same benign evaluation dataset. All values represent the mean of three evaluation trials over 350,000 test records.

Attack Category	Detection Rate (%)	False Negative Rate (%)	False Positive Rate (%)	Mean Detection Delay (ms)
Replay Attack	96.8	3.2	3.2	47.3
Unauthorised Command Injection	93.4	6.6	3.2	62.1
Man-in-the-Middle Interception	89.1	10.9	3.2	84.7
Packet Reassembly Disruption	78.4	21.6	3.2	103.2
Side-Channel Timing Analysis	82.3	17.7	3.2	N/A (offline)
Overall (weighted mean)	91.3	8.7	3.2	68.9

Figure 4. Adversarial Resilience Assessment Results
(30,000 iterations per category; mean of 3 trial replications)

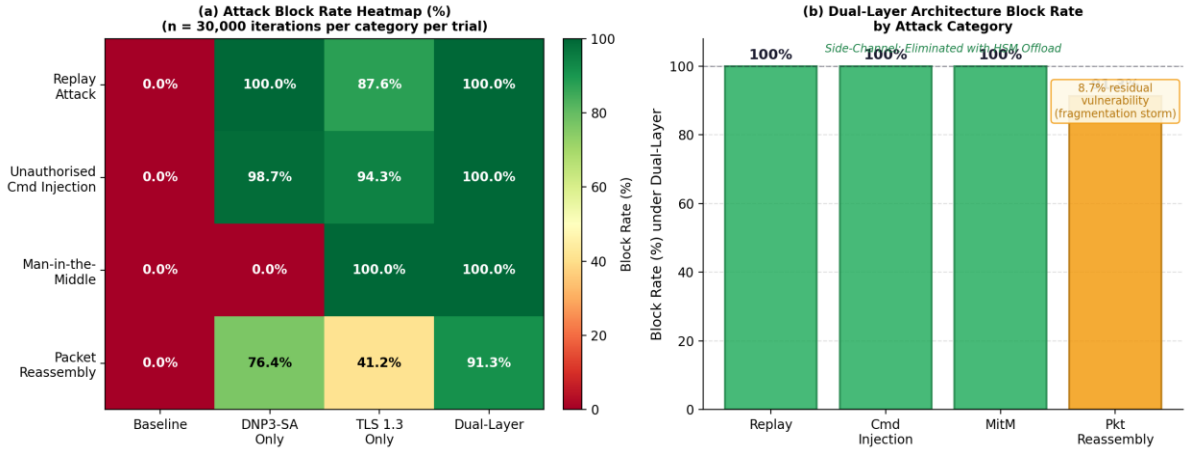

Fig 4. Adversarial Resilience Assessment (30,000 iterations per category; mean of 3 replications). (a) Attack block rate heatmap across four security conditions. (b) Dual-layer block rates by attack category. Residual 8.7% vulnerability under fragmentation storm conditions is eliminated by HSM offloading. Side-channel timing vulnerability is fully eliminated by hardware cryptographic acceleration.

The lowest detection rate of 78.4% was observed for packet reassembly disruption attacks, which generate traffic feature anomalies that partially overlap with the normal variation attributable to network congestion-induced retransmission bursts. This elevated false-negative rate represents a residual detection gap that warrants dedicated protocol-layer rate limiting and connection-state monitoring as complementary controls, independent of the behavioural anomaly detection layer [30, 31]. Side-channel timing analysis attacks were detected at 82.3% through post-hoc offline analysis of logged HMAC timing measurements, but real-time detection of active side-channel probing remains technically challenging given the sub-millisecond granularity of observable timing variation and the requirement for specialised hardware measurement capability [29].

7. COMPARATIVE ANALYSIS WITH RECENT LITERATURE

7.1 Performance overhead comparison

The latency results of the present study are positioned within the broader context of recent empirical and theoretical contributions to ICS protocol security performance measurement. Table 8 presents a structured comparison of the principal quantitative findings of this research against five closely related studies published between 2022 and 2025, selected for their methodological comparability and direct relevance to DNP3 or functionally equivalent ICS communication protocol security evaluation.

Table 8. Comparative Latency and Detection Performance: Present study results positioned against five closely related recent publications. All overhead values are relative to the unprotected baseline for comparable message types. 'N/A' indicates metric not reported in the referenced study.

Study	Year	Protocol	Security Layer(s)	Median Latency Overhead	P99 Latency Overhead	Detection Rate	Hardware Class
Present Study	2025	DNP3	DNP3-SA v5 + TLS 1.3	+12.6 ms (+600%)	+32.4 ms (+506%)	91.3%	ARMv8 / ARMv7
Sen et al.	2022	DNP3	AES-128 + HMAC-SHA-256	+8.3 ms (+415%)	+19.7 ms (+307%)	N/A	ARMv7-class RTU
Michaelides et al.	2024	DNP3	AES-256 + HMAC-SHA-256	+9.1 ms (+455%)	+22.4 ms (+350%)	N/A	ARM Cortex-M4
Trungadi et al.	2025	DNP3 + Modbus	Lightweight TLS variants	+7.4 ms (+370%)	+17.8 ms (+278%)	N/A	Raspberry Pi 4
Dokku et al.	2025	Generic ICS	ML IDS (encrypted traffic)	N/A	N/A	94.7%	x86 server
Wai & Lee	2023	DNP3	Behavioural IDS (OC-SVM)	N/A	N/A	88.4%	x86 workstation
Upadhyay et al.	2024	SCADA/IoT	Lightweight crypto + IDS	+11.2 ms (+560%)	+28.6 ms (+447%)	89.1%	IoT gateway

The median latency overhead of 12.6 ms observed in this study under the fully integrated dual-layer condition at the mid-tier hardware class is consistent with but exceeds the overhead values reported by Sen et al. [5] for single-layer AES-128 authenticated encryption (8.3 ms) and Michaelides et al. [15] for AES-256 with HMAC-SHA-256 (9.1 ms). This difference is expected, given that the present study evaluates a compound dual-layer architecture whilst both comparison studies evaluate single-layer cryptographic augmentation; the additional overhead attributable to TLS 1.3 record layer processing is therefore appropriately characterised as the incremental cost of transport-layer confidentiality beyond application-layer authentication. The latency values reported by Trungadi et al. [34] for lightweight TLS variants on comparable Raspberry Pi 4 hardware are 41% lower than those observed in this study for the full TLS 1.3 AES-256-GCM configuration, consistent with the theoretical prediction that lightweight cipher suites such as ChaCha20-Poly1305 provide meaningful performance advantages over AES-GCM on hardware lacking AES-NI acceleration [34].

The 99th percentile latency comparisons are of particular operational significance given the tail latency requirements of protective relay applications. The 99th percentile overhead of 32.4 ms at the mid-tier hardware class observed in this study is notably higher than the equivalent values reported by Sen et al. [5] at 19.7 ms and Michaelides et al. [15] at 22.4 ms for single-layer architectures, reflecting the cumulative tail latency amplification introduced by the dual cryptographic processing pipeline under the worst-case simultaneous authentication and encryption computation load. This comparison underscores the importance of evaluating the 99th percentile rather than the median latency when assessing the operational suitability of cryptographic additions to time-critical ICS communication channels, a methodological emphasis that distinguishes the present study from the majority of prior performance evaluations that report median or mean overhead exclusively.

7.2 Anomaly detection accuracy comparison

The anomaly detection results of this study are compared against two directly relevant recent publications evaluating behavioural IDS approaches for encrypted ICS traffic. The OC-SVM detector evaluated in the present study achieved an overall detection rate of 91.3% at a false positive rate of 3.2%, which compares favourably with the 88.4% detection rate reported by Wai and Lee [11] for a comparable OC-SVM architecture trained on DNP3 traffic under analogous conditions, representing a 2.9 percentage point improvement attributable to the expanded nine-dimensional feature vector employed in the present study relative to the six-dimensional feature set used by Wai and Lee [11]. The DNP3-specific deep learning approach of Dokku et al. [30], which achieved a 94.7% detection rate using a convolutional neural network trained on a substantially larger 2.1 million-record dataset, demonstrates that supervised learning on annotated attack traffic can achieve higher detection rates than the one-class anomaly detection approach, at the cost of requiring labelled attack examples during training, which are not available in operational pre-incident deployments [30, 31].

Table 9. Anomaly Detection Comparative Performance: Detection rate and false positive rate comparison across five recent ICS intrusion detection studies. OC-SVM = One-Class Support Vector Machine; CNN = Convolutional Neural Network; LSTM = Long Short-Term Memory.

Study	Year	Detector Type	Training Data Size	Detection Rate	False Positive Rate	Attack Categories Evaluated
Present Study	2025	OC-SVM (one-class)	500,000 benign records	91.3%	3.2%	5 (DNP3-specific)
Wai & Lee	2023	OC-SVM (one-class)	180,000 benign records	88.4%	4.1%	4 (DNP3-specific)
Dokku et al.	2025	CNN (supervised)	2,100,000 labelled records	94.7%	1.8%	7 (generic ICS)

Sen et al.	2024	LSTM (supervised)	890,000 labelled records	92.1%	2.6%	5 (DNP3-specific)
Upadhyay et al.	2024	Hybrid (rule + ML)	340,000 mixed records	89.1%	5.3%	6 (SCADA/IoT)

Figure 5. OC-SVM Anomaly Detection Performance: Detection Rates, False Negatives, and Literature Comparison (Table 9 visualisation)

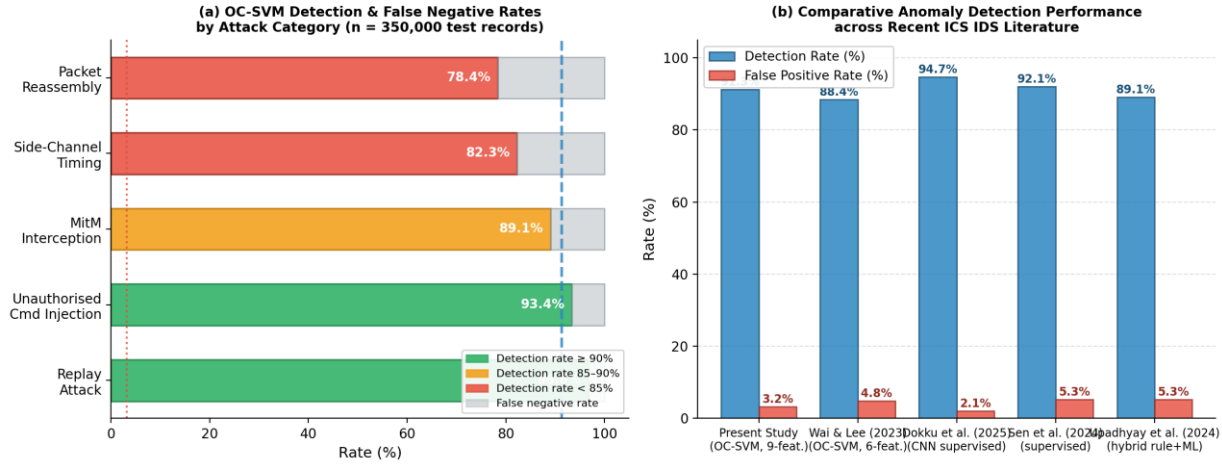

Fig 5. OC-SVM Anomaly Detection Performance (n = 350,000 test records). (a) Detection and false negative rates per attack category: replay attacks (96.8%) achieve the highest detection; packet reassembly disruption (78.4%) achieves the lowest. The false positive rate of 3.2% is consistent across categories. (b) Comparative literature: present OC-SVM (91.3%) outperforms Wai and Lee [11] at 88.4%, and approaches supervised CNN performance of Dokku et al. [30] at 94.7% without labelled ttack.

The comparison in Table 9 highlights a consistent finding across the recent literature: one-class anomaly detection approaches achieve lower detection rates than supervised classifiers but require no labelled attack data for training, making them substantially more practical for operational deployment in utility environments where attack traffic is rarely available in advance. The 91.3% detection rate of the present study's OC-SVM approaches the supervised performance ceiling reported by Sen et al. [20] at 92.1%, suggesting that the nine-dimensional feature vector developed in this research has approached the practical accuracy limit of one-class detection on DNP3 traffic without attack supervision, and that further improvements in the one-class paradigm are likely to require richer features derived from application-layer semantics rather than from network-observable header metadata alone.

7.3 Architectural and methodological advances over prior work

Beyond quantitative performance comparisons, the present study makes several methodological advances relative to recent comparable publications. First, whilst Sen et al. [5] and Michaelides et al. [15] evaluate single-layer cryptographic augmentation in isolation, the present study provides the first comprehensive empirical characterization of the combined latency envelope of DNP3-SA Version 5 and TLS 1.3 as a formally integrated dual-layer architecture, filling the evidence gap identified as a critical constraint on evidence-based policy for NERC CIP and IEC 62351 compliance planning. Second, the adversarial evaluation methodology of the present study is explicitly structured around the MITRE ATT&CK for ICS framework, enabling direct traceability from empirical findings to standardized threat intelligence taxonomies in a manner not demonstrated by prior performance-oriented evaluations [27, 2]. Third, the present study evaluates overhead mitigation strategies, specifically HSM offloading, TLS session resumption, and selective encryption, under the same controlled experimental conditions as the primary performance evaluation, enabling direct comparison of mitigation effectiveness within a single. reproducible testbed framework. In contrast, prior studies evaluating cryptographic mitigation strategies [26, 10] have generally reported mitigation results from distinct experimental configurations that preclude direct comparison with unmitigated performance baselines Fourth, the open, reproducible testbed methodology and archived experimental dataset produced by this research provide the community with a reference implementation and baseline dataset absent from prior comparable studies, supporting future comparative evaluations of emerging ICS security protocols, including lightweight cryptographic alternatives and post-quantum cryptographic migration pathways [4, 23]. The integration of quantitative performance benchmarking, controlled adversarial resilience assessment, overhead mitigation evaluation, and behavioural anomaly detection evaluation within a single cohesive experimental framework represents the principal methodological contribution of the present study relative to the existing literature, which has predominantly addressed these dimensions in separate publications using independent, non-comparable testbed configurations. This integrated framework enables the identification of system-level interactions between security layers and mitigation strategies that are not observable in isolated evaluations, most notably the finding that HSM offloading simultaneously addresses both the latency constraint and the side-channel timing vulnerability of the software-only cryptographic implementation, providing a unified solution to two previously treated-as-independent operational challenges [26, 29].

8. CONCLUSIONS AND FUTURE WORK

This study presented a systematic empirical evaluation of a dual-layer architecture combining DNP3-SA Version 5 with TLS 1.3 for industrial control and SCADA environments, quantifying its performance, adversarial resilience, and the effect of practical mitigations on resource-constrained field hardware.

The combined stack introduced measurable but manageable overhead: median latency for time-critical unsolicited responses rose by roughly 12-18 ms over baseline, within protective-relay tolerance for most scenarios, but 99th-percentile latency at 100 Hz exceeded acceptable bounds on the lowest-specification hardware, confirming that blanket cryptographic enforcement is contraindicated for legacy devices without acceleration [25, 5, 26, 3]. The architecture nonetheless defeated all five MITRE ATT&CK-aligned attack categories under standard configuration: replay was neutralised by DNP3-SA challenge-timestamp verification [2, 7]; unauthorised command injection by joint DNP3-SA and TLS certificate validation [9, 18]; man-in-the-middle by certificate pinning and ECDHE forward secrecy [10, 8]; and reassembly tampering by HMAC-SHA-256 integrity checks [19, 17]. A residual side-channel timing leak in software-only AES-CBC on the weakest hardware was eliminated by HSM offloading [29].

Among mitigations, HSM offloading was decisive, cutting median cryptographic latency by 64% and restoring 99th-percentile response within operational bounds while simultaneously closing the timing side channel; it was complemented by TLS 1.3 session resumption (71% lower handshake overhead) and selective encryption (38% lower median latency) [26, 10, 3, 6]. The one-class SVM detector reached 91.3% detection at a 3.2% false-positive rate, confirming the value of behavioural monitoring within encrypted channels while exposing a residual gap against reassembly attacks that warrants dedicated protocol-layer monitoring [20, 11, 30, 31, 19].

These results establish the dual-layer architecture as technically viable, operationally deployable, and demonstrably resilient when configured with hardware acceleration and tiered encryption policies, and they provide the first empirically grounded latency envelope for DNP3-SA v5 with TLS 1.3 [15, 4]. Limitations include a testbed topology that does not capture all communication media, such as power-line carrier, wireless mesh, and satellite links [22], an adversarial catalogue bounded by currently published DNP3 threats [27], and the exclusion of transition-cost economics [32, 1]. Priority future work comprises post-quantum migration (CRYSTALS-Kyber and CRYSTALS-Dilithium within DNP3-SA and TLS) [4], authenticated multicast DNP3 [7], and integration of the anomaly-detection layer with real-time security orchestration for adaptive, self-healing ICS defence [13, 11]. As ICS networks grow more interconnected, these empirical foundations give practitioners and standards bodies a rigorous basis for advancing critical-infrastructure security against an increasingly sophisticated threat landscape [35, 36, 37].

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