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Article

REAL-TIME CYBERSECURITY INTEGRATION IN PLCS AND IOT GATEWAYS: A PERFORMANCE-CONSCIOUS APPROACH TO ENCRYPTION, AUTHENTICATION, AND INTRUSION DETECTION

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ABSTRACT
The integration of real-time cybersecurity mechanisms into embedded systems has become a critical priority in the context of Industry 4.0, where programmable logic controllers (PLCs) and Internet of Things (IoT) gateways serve as foundational components of industrial automation. These devices are increasingly exposed to cyber-physical threats as they connect to broader networked infrastructures, yet their computational constraints and real-time operational requirements often preclude the use of conventional security measures. This study proposes and evaluates a performance-conscious cybersecurity framework designed to embed lightweight encryption, mutual authentication, and decentralized intrusion detection directly within industrial control devices. The research methodology involved the development of a modular security architecture tested on commercial-grade PLCs and IoT gateways, utilizing communication protocols such as Modbus/TCP, OPC UA, MQTT, and Profinet. Lightweight encryption algorithms, including SPECK, LEA, and ChaCha20, were implemented alongside elliptic curve-based authentication schemes to assess their latency, throughput, and system resource impact. Additionally, hybrid intrusion detection models—combining statistical baselining and anomaly detection—were deployed locally on embedded nodes to monitor network behavior in real time. The findings demonstrate that full-spectrum security can be achieved in embedded systems without disrupting deterministic control cycles. Encryption tasks remained within sub-millisecond boundaries, mutual authentication completed with minimal handshake delay, and intrusion detection maintained over 94% accuracy with low false positives. Resource utilization across CPU, memory, and power remained within device tolerances, and the architecture sustained operational stability during prolonged testing. The study confirms that embedded cybersecurity, when implemented with algorithmic efficiency and system-aware scheduling, can coexist with mission-critical automation processes. This work challenges the conventional reliance on perimeter defenses and post-factum monitoring, offering instead a secure-by-design approach that integrates security functions natively within embedded industrial systems. The proposed framework supports scalable deployment, protocol interoperability, and long-term resilience, advancing the field toward real-time, embedded protection for critical infrastructure environments.

KEYWORDS
Real-Time Cybersecurity; Programmable Logic Controllers (PLCs); IoT Gateways; Intrusion Detection Systems (IDS); Lightweight Encryption;

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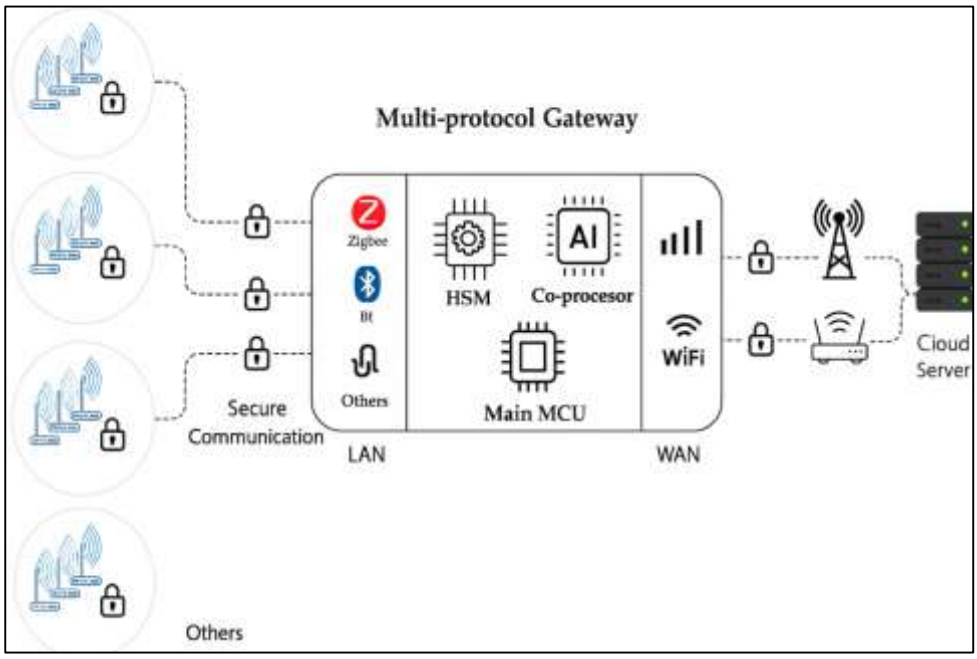
INTRODUCTION

Cybersecurity in industrial environments is fundamentally defined as the application of technologies, processes, and controls to protect industrial systems from cyber threats that aim to access, alter, or destroy sensitive data and disrupt operations. In the context of Industry 4.0, the incorporation of Programmable Logic Controllers (PLCs) and Internet of Things (IoT) gateways into industrial infrastructure has redefined cybersecurity challenges and necessitated real-time, resource-efficient solutions (Costa et al., 2021). A PLC is a ruggedized digital computer used for automation of electromechanical processes, while an IoT gateway serves as an interface between IoT devices and external networks, handling data protocol conversion, local storage, and security filtering (de Oliveira et al., 2022). As these systems increasingly interconnect through industrial Ethernet, wireless protocols, and cloud-based SCADA interfaces, they become vulnerable to a new array of threats, from network intrusion to data exfiltration (Su et al., 2019). Moreover, encryption, authentication, and intrusion detection represent three foundational pillars of any cybersecurity architecture. Encryption ensures data confidentiality by converting information into unreadable code for unauthorized users (Carcangiu et al., 2011). Authentication confirms the identity of devices or users attempting access, while intrusion detection systems (IDS) monitor network and system activities to identify malicious behaviors. These techniques must be implemented in a way that minimally impacts the performance and determinism of time-sensitive industrial applications. Unlike enterprise environments, where latency tolerance is higher, PLC-based systems require sub-millisecond communication delays to ensure real-time operation of actuators, sensors, and feedback loops. The intersection of real-time constraints and security imperatives defines a uniquely complex problem space.

Figure 1: Secure Multi-Protocol Gateway Architecture for Real-Time Industrial IoT Communication



Globally, the proliferation of cyber threats targeting critical infrastructure such as power grids, water treatment facilities, transportation systems, and manufacturing plants has underscored the urgent need for resilient cybersecurity integration in industrial automation. Attacks like Stuxnet, the Triton malware incident, and the Colonial Pipeline ransomware attack have demonstrated the severe geopolitical and economic consequences of vulnerabilities in PLCs and control networks. The International Telecommunication Union (ITU) and the International Society of Automation (ISA) have developed frameworks such as the ISA/IEC 62443 series to standardize security controls across industrial sectors (Tonello & Versolatto, 2011). However, compliance alone does not guarantee real-time applicability or performance-aware deployment. The internationalization of supply chains and remote operational management has further expanded the attack surface. As organizations across Europe, North America, and East Asia implement smart factories and cloud-integrated automation

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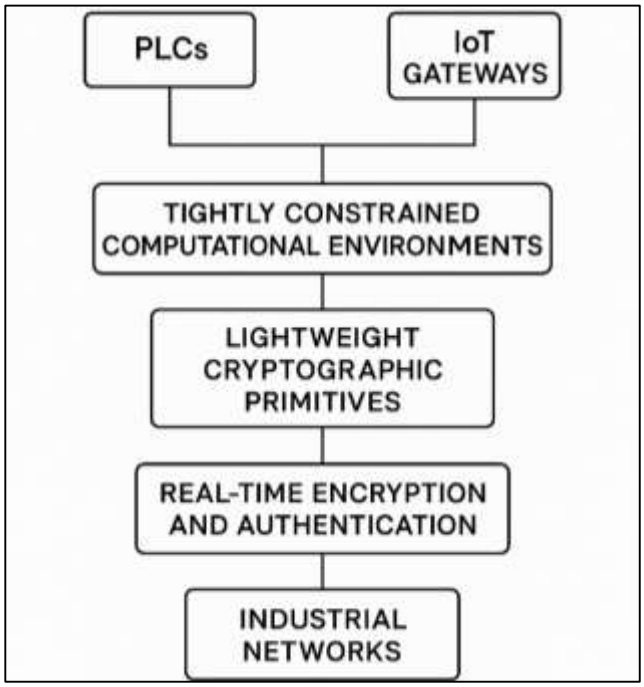
systems, the potential impact of a single breach is magnified (Sung & Bojanczyk, 2010). Multinational corporations are now more reliant on secure edge computing and decentralized control structures, where IoT gateways mediate data exchange between isolated field devices and centralized analytics platforms (Picorone et al., 2020). This topology increases the complexity of security protocols, particularly in settings where bandwidth, processing power, and energy consumption are tightly constrained (Oliveira et al., 2022). Consequently, the international relevance of real-time cybersecurity in embedded industrial systems extends beyond technical resilience; it is a matter of national security, economic stability, and regulatory compliance. Moreover, PLCs and IoT gateways operate within tightly constrained computational environments, often with limited memory, processor speed, and energy availability. Most PLCs rely on microcontrollers or application-specific integrated circuits (ASICs) that prioritize reliability and deterministic execution over general-purpose computing. Unlike modern CPUs that can support complex encryption and authentication routines natively, PLCs must execute tasks with low jitter and predictable response times. Similarly, IoT gateways act as lightweight edge devices tasked with protocol translation, buffering, and preliminary data processing—all while maintaining low latency (Picorone et al., 2020). Adding computationally intensive security layers, such as RSA-based public-key cryptography or full-stack deep packet inspection, could impair their primary automation functions.

Figure 2: Flowchart of Real-Time Cybersecurity Integration in Embedded Industrial Systems



Additionally, these devices often operate on real-time operating systems (RTOS) or bare-metal firmware, lacking the kernel-level support for modular cryptographic libraries or security APIs commonly found in Linux or Windows-based systems. Implementing real-time encryption and authentication requires not only the selection of lightweight cryptographic primitives—such as SPECK, SIMON, or ChaCha20—but also the architectural accommodation of cryptographic co-processors or trusted execution environments (TEEs) like ARM TrustZone (Camponogara et al., 2019). These adaptations must be made without sacrificing throughput, data integrity, or synchronization across industrial networks, which often operate on protocols like Modbus/TCP, EtherCAT, or Profinet (Zhang et al., 2025).

The security threats faced by embedded systems in industrial automation are both diverse and sophisticated. Common attack vectors include man-in-the-middle (MITM) attacks, firmware manipulation, unauthorized access, denial-of-service (DoS) attacks, and data injection targeting process integrity. These threats exploit insecure protocols, hardcoded credentials, outdated firmware, or unsecured remote access paths. Unlike traditional IT systems that can be patched or

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rebooted with minimal disruption, industrial control systems (ICS) require continuous uptime, making real-time, non-intrusive security interventions critical (Kashef et al., 2016). Intrusion detection in this context is complicated by the deterministic behavior of industrial protocols. While this determinism can aid in anomaly detection, it also necessitates high specificity in threat modeling to avoid false positives that could trigger unwarranted system halts or alarms. Furthermore, many PLCs communicate over broadcast-based fieldbus systems or unsecured serial interfaces, making them vulnerable to physical-layer exploits. IDS solutions must therefore be designed to account for both cyber and cyber-physical attack surfaces and be capable of real-time decision-making under strict resource constraints (Gallo et al., 2020).

Integrating encryption in real-time systems introduces significant design challenges, particularly around balancing cryptographic strength with processing efficiency. Conventional algorithms such as RSA or AES-256, while robust, require substantial computational resources and introduce latency that is often unacceptable in industrial settings. Research into lightweight encryption mechanisms, such as PRESENT, HIGHT, and LEA, has shown promise for embedded deployments, offering reduced block sizes and simplified operations suitable for low-power processors. Symmetric-key algorithms are generally favored over asymmetric ones in embedded contexts due to their lower computational cost, although key management remains a persistent concern. Hardware-assisted encryption—using devices such as cryptographic accelerators or secure elements—can offload security functions from the main processor and ensure compliance with real-time constraints. However, such approaches require early-stage design integration and are not always feasible for legacy systems. Stream ciphers and authenticated encryption with associated data (AEAD) modes such as GCM or CCM can help reduce latency and memory usage, especially when combined with session-level key negotiation strategies (Antoniali & Tonello, 2014). The encryption scheme must also accommodate packet fragmentation, out-of-order delivery, and retransmission behavior typical in industrial communication stacks (Naz et al., 2019; Noreen & Baig, 2013).

Authentication protocols in industrial IoT must achieve mutual identity verification with minimal computational and communication overhead. Lightweight alternatives to traditional PKI systems, such as Elliptic Curve Cryptography (ECC), offer enhanced efficiency in key generation and exchange while maintaining strong cryptographic guarantees. Protocols like Datagram Transport Layer Security (DTLS) and lightweight mutual authentication (LMA) frameworks have been adapted for constrained application protocols like CoAP (Chrysochos et al., 2016). Token-based mechanisms and pre-shared keys are also common, though they suffer from limited scalability and revocation challenges (Noreen & Baig, 2013). Furthermore, time-based one-time passwords (TOTP) and hardware-backed identity modules, such as Trusted Platform Modules (TPM), have shown utility in protecting device integrity during remote provisioning and firmware updates (Naz et al., 2019). A critical requirement for authentication schemes in PLCs and gateways is session resumption and fast handshake capabilities that minimize connection setup time (Hale et al., 2020; Shen et al., 2022). These protocols must be implemented without hindering the primary control tasks of the system and should allow for non-blocking operations and re-authentication during communication loss (Tonello & Pittolo, 2015). Authentication must not be an afterthought but an integral component of the security architecture, interacting seamlessly with encryption and access control policies.

Intrusion Detection Systems (IDS) for PLCs and IoT gateways must be capable of detecting both known and unknown threats in real time, while maintaining minimal impact on system resources and communication latency. Traditional signature-based systems, though effective against known exploits, often fail to detect zero-day attacks or sophisticated anomalies that exploit protocol-specific behaviors (Papadopoulos et al., 2013). In contrast, anomaly-based IDS approaches—especially those leveraging machine learning and statistical modeling—have been shown to offer high detection rates with adaptability to evolving threat patterns (Gallo et al., 2020). However, deploying such systems in embedded industrial contexts presents challenges around training data availability, false positive management, and computational constraints (Dib et al., 2018). Recent advances in edge AI and federated learning have introduced models that can be distributed across IoT gateways, allowing localized threat analysis without central data aggregation (Antoniali & Tonello, 2014). These systems can learn from contextual patterns such as device behavior, command frequency, and temporal sequencing of messages, providing a richer basis for anomaly scoring (Noreen & Baig, 2013). Furthermore, hybrid IDS designs—combining signature and anomaly detection—have demonstrated enhanced robustness in industrial applications (Naz et al., 2019). The

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IDS must also be compatible with constrained devices and operate on passively mirrored traffic to ensure non-intrusiveness (Colen et al., 2013). As such, the design of IDS for PLCs and gateways must strike a critical balance between detection fidelity, system responsiveness, and operational continuity.

The principal objective of this study is to develop and evaluate a comprehensive, real-time cybersecurity framework for programmable logic controllers (PLCs) and Internet of Things (IoT) gateways that addresses the critical need for performance-conscious integration of encryption, authentication, and intrusion detection mechanisms in industrial control systems. This research seeks to bridge the technological and operational gap between cybersecurity imperatives and the resource limitations of embedded industrial devices. It aims to construct a security model that preserves system determinism, communication speed, and computational efficiency while ensuring robust defense against both cyber and cyber-physical threats. The study further strives to identify and validate lightweight cryptographic algorithms suitable for real-time data encryption on constrained devices, as well as streamlined authentication protocols that can operate with minimal handshake delays and resource consumption. In addition, it intends to design and implement a real-time intrusion detection system capable of identifying anomalies and malicious activities within industrial communication networks without interrupting normal operations or exceeding hardware limitations. The research is guided by the need to maintain a balance between security assurance and operational continuity, emphasizing modularity, scalability, and low-latency performance. Experimental validation will be carried out using a testbed that simulates real-world industrial environments, including typical field devices, communication protocols, and attack scenarios. Performance metrics such as latency, throughput, CPU utilization, and detection accuracy will be systematically evaluated to measure the efficacy and efficiency of the proposed approach. Ultimately, the objective is to offer an integrated, practically deployable security solution that enhances the cyber resilience of industrial automation systems while respecting their inherent constraints and real-time operational demands. This objective is informed by the growing international urgency to protect critical infrastructure from increasingly sophisticated cyberattacks and the pressing need for solutions that can be implemented at the edge of industrial networks.

LITERATURE REVIEW

The intersection of Customer Relationship Management (CRM) and Data-Driven Decision-Making (DDD) represents a convergence of strategic, operational, and technological paradigms within modern enterprise systems. CRM systems, traditionally used for managing customer interactions, have evolved into sophisticated platforms that support real-time analytics, predictive modeling, and cross-functional collaboration. Concurrently, the rise of DDD as a managerial philosophy and practice has transformed how organizations approach planning, performance tracking, and customer engagement. While extensive research has been conducted on CRM and DDD independently, there remains a need for an integrated synthesis that examines their joint implementation, strategic alignment, and impact on organizational performance. This literature review addresses this gap by systematically analyzing empirical and theoretical contributions across multiple domains including marketing, information systems, organizational behavior, and strategic management. The review is structured around key themes that reflect both the conceptual development and applied outcomes of CRM-DDD integration. Special emphasis is placed on the role of analytics, artificial intelligence, organizational enablers, and sector-specific deployment. Through this review, we aim to uncover how CRM and DDD co-evolve within enterprise settings, the mechanisms by which they generate value, and the conditions under which they succeed or fail.

Cybersecurity in Industrial Automation

The evolution of industrial automation has shifted the cybersecurity paradigm from isolated protection to complex, interconnected defense strategies. Traditional industrial control systems (ICS), once characterized by air-gapped architectures, have transitioned toward interconnected systems integrated with corporate IT networks and external cloud platforms (Syafrizal et al., 2022). This convergence, driven by Industry 4.0 initiatives, introduces a multifaceted attack surface that demands a reconsideration of security priorities. PLCs and other embedded devices—central to automated manufacturing, critical infrastructure, and process control—are increasingly targeted due to their weak cryptographic support, static credentials, and insecure communication protocols (Manikandan et al., 2024). Unlike conventional IT systems, these devices often lack robust memory protection and operate without encryption or authentication protocols by default. Compounding

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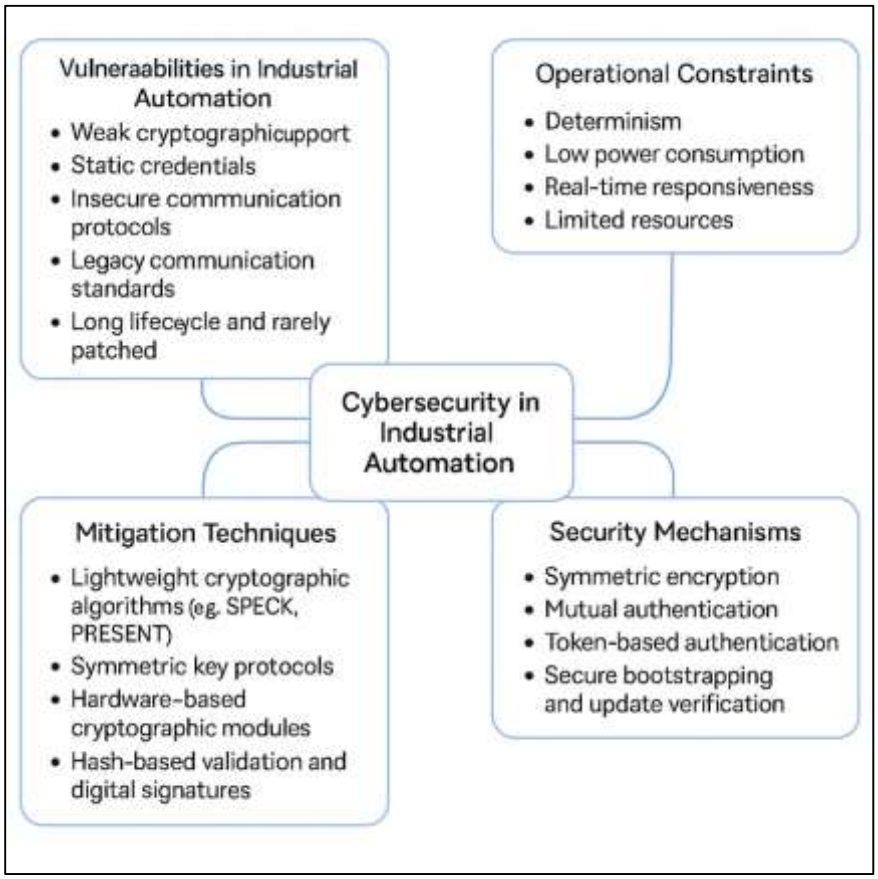
this vulnerability is the long lifecycle of industrial systems, which are rarely patched due to downtime constraints, leaving them exposed to well-known threats such as the Stuxnet worm, Triton malware, and BlackEnergy attacks.

Figure 3: Cybersecurity in Industrial Automation



Moreover, embedded devices like PLCs, industrial sensors, and IoT gateways are governed by strict operational constraints that fundamentally challenge traditional cybersecurity implementation. These devices prioritize determinism, low power consumption, and real-time responsiveness over computational flexibility, which makes integrating complex security mechanisms such as standard encryption suites or authentication layers especially difficult (Bernabe & Skarmeta, 2019). Most embedded control systems operate with fixed clock speeds, limited RAM, and small program memory footprints, often running real-time operating systems (RTOS) that lack support for modern cryptographic APIs or virtualization (Djebbar & Nordström, 2023). As a result, embedded security solutions must balance computational efficiency with resilience against threats like firmware tampering, data interception, or command injection. The incompatibility of traditional IT security frameworks with embedded environments is also evident in key management and authentication. Public-key infrastructure (PKI), while effective in enterprise environments, demands processing power and memory that many PLCs cannot afford without compromising real-time control loops. Consequently, researchers have turned toward lightweight cryptographic algorithms such as SPECK, SIMON, PRESENT, and LEA, which require fewer operations and less memory to execute while maintaining acceptable security margins. These ciphers are often paired with symmetric key protocols and pre-shared keys to mitigate the burden of asymmetric encryption. Similarly, the use of hardware-based cryptographic modules such as ARM TrustZone or Trusted Platform Modules (TPMs) has been proposed to offload security operations from the main processor and ensure the integrity of boot processes, firmware updates, and remote authentication. Despite these adaptations, studies emphasize the risk of performance degradation when even optimized security layers are introduced. Benchmarks have shown that minor increases in packet processing latency or memory consumption

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can lead to timing mismatches or system instability in tightly synchronized industrial systems (Parker et al., 2023). This performance-security trade-off remains a central theme in cybersecurity research for embedded systems, particularly in sectors like power distribution, water treatment, and manufacturing, where real-time reliability is paramount.

PLCs and IoT Gateways

Programmable Logic Controllers (PLCs) form the core of industrial automation systems due to their reliability, ruggedness, and ability to execute deterministic control logic under harsh environmental conditions. Originally designed to replace hardwired relay-based systems, PLCs now manage a vast array of tasks including machine sequencing, feedback control, interlocks, and safety mechanisms across various industrial sectors (Kasprzyczak et al., 2025). Modern PLCs operate on scan cycles where the controller sequentially reads inputs, executes logic, and updates outputs, typically within a few milliseconds. This real-time operation is critical to maintaining process synchronization and equipment safety. Architecturally, PLCs are built around microcontrollers or digital signal processors (DSPs), supported by non-volatile memory for program retention and real-time operating systems (RTOS) for deterministic task scheduling. They are connected to field devices via industrial buses such as Profibus, CAN, or Ethernet/IP, which often lack native security mechanisms. Despite their robust functionality, PLCs were not originally designed with cybersecurity in mind, creating systemic vulnerabilities when integrated into modern networked environments. Hardcoded credentials, plaintext communication, and firmware-level vulnerabilities expose them to manipulation, denial-of-service attacks, and remote code execution (Śliwiński & Piesik, 2021). Legacy PLCs often lack encryption support or access control lists (ACLs), leaving them susceptible to unauthorized reprogramming or packet injection. Even newer models that include encryption capabilities are limited by processing and memory constraints that make full implementation of security protocols impractical. The rigidity of real-time operations further restricts the feasibility of integrating computationally intensive security measures like RSA encryption or machine learning-based anomaly detection. Moreover, PLC firmware updates are infrequent and often manual due to concerns about downtime or process disruption, leaving systems vulnerable to known exploits for extended periods. These limitations make PLCs attractive targets for attackers seeking to compromise industrial control systems with high-impact, low-cost cyberattacks. Security solutions for PLCs must therefore prioritize computational efficiency and architectural compatibility while preserving the core characteristics of real-time reliability, low-latency response, and environmental resilience (Madnick et al., 2023). The secure design and operation of PLCs continue to be a major focus in industrial cybersecurity literature as researchers aim to reconcile deterministic control with dynamic threat mitigation.

IoT gateways serve as critical intermediaries between edge devices and centralized cloud or supervisory control systems, performing protocol translation, edge analytics, local storage, and cybersecurity enforcement. In industrial environments, these gateways must bridge the gap between resource-constrained field devices such as sensors, actuators, and PLCs, and higher-level enterprise platforms that require standardized and secure data formats (Qi et al., 2018). Architecturally, industrial IoT (IIoT) gateways incorporate multi-protocol support including Modbus, OPC UA, MQTT, CoAP, and REST, enabling them to normalize and route data efficiently across heterogeneous network segments. They are often equipped with lightweight processing capabilities and run embedded Linux or specialized firmware to support deterministic data processing, even under fluctuating network conditions. Beyond communication, IoT gateways are increasingly tasked with implementing security features such as firewalls, intrusion detection systems (IDS), and encryption services, especially in settings where endpoint devices lack the computational resources for autonomous protection (Laan et al., 2025). These functions elevate the gateway from a mere router to a cybersecurity enforcement node, creating opportunities for distributed threat detection and response. However, their positioning at the network edge also exposes them to risks, as compromised gateways can act as pivot points for lateral movement and attack propagation. The complexity of gateway tasks and the limited availability of resources necessitate lightweight, context-aware security solutions that can adapt dynamically to the system load and operational context (Manson & Anderson, 2017). The importance of secure bootstrapping, firmware verification, and remote attestation in IoT gateways has also gained scholarly attention, particularly in ensuring the trustworthiness of gateway software and hardware integrity (Hogan & Piccarreta, 2018). While some vendors provide support for TPM or secure enclaves, their integration and standardization

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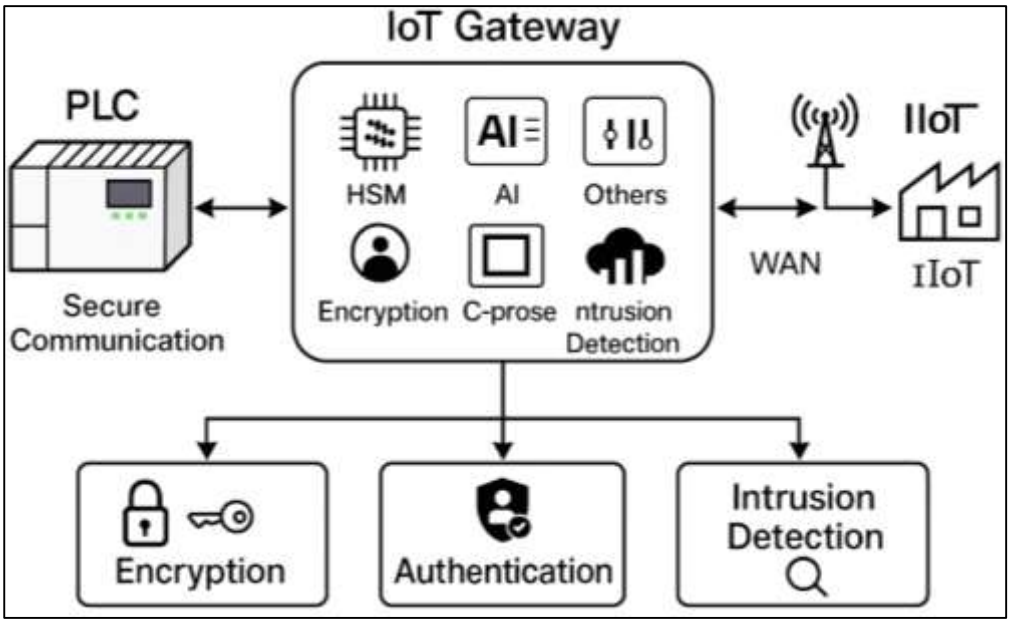
remain limited across industrial applications. Researchers emphasize that IoT gateways should act as collaborative nodes within a hierarchical defense architecture, interacting with both upstream analytics systems and downstream embedded controllers to ensure holistic security coverage (Laan et al., 2024). As such, the literature identifies the dual role of gateways—as communication orchestrators and cybersecurity sentinels—as central to the resilience of future industrial networks.

Figure 4: PLCs and IoT Gateways



PLCs and IoT gateways, due to their central roles in control and communication, represent high-value targets in industrial automation ecosystems. Their increasing exposure to external networks and remote management interfaces has introduced a multitude of vulnerabilities that are routinely exploited by malicious actors. Studies have documented common weaknesses in PLC deployments, including insecure default configurations, exposed debug interfaces, and firmware vulnerabilities that allow unauthorized code execution or memory corruption (Qi et al., 2018). These weaknesses are exacerbated in networked environments where unencrypted data transmission, lack of authentication, and insecure web interfaces leave devices open to manipulation. IoT gateways suffer similar weaknesses due to their multi-role functionality. As they must concurrently perform edge computing, traffic routing, and policy enforcement, security misconfigurations can result in privilege escalation, data leakage, or denial-of-service attacks. For instance, researchers have found that many gateways are deployed without proper segmentation from critical networks, allowing attackers who compromise a gateway to gain access to upstream PLCs and SCADA systems. Threat vectors also include supply chain attacks during device provisioning, exploitation of outdated libraries or firmware, and abuse of third-party APIs that are embedded for cloud connectivity (Madnick et al., 2023).

Modbus, OPC UA, MQTT, Profinet.

Industrial communication protocols such as Modbus, OPC UA, MQTT, and Profinet play essential roles in facilitating data exchange across automation environments, yet their cybersecurity postures vary dramatically based on design intent, architectural evolution, and application scope. Modbus, developed in the late 1970s for serial communication and later adapted to TCP/IP, exemplifies the challenges posed by legacy systems lacking native security. It operates on a master-slave model and transmits unencrypted, unauthenticated data, making it vulnerable to eavesdropping, replay, injection, and manipulation attacks (Tabaa et al., 2018). Despite its simplicity and wide adoption, Modbus remains highly insecure by modern standards, as it lacks mechanisms for data integrity, device authentication, or session validation. In contrast, OPC UA emerged as a secure, service-oriented alternative. Designed with encryption, mutual authentication, and role-based access control, it provides structured data modeling and integration flexibility across embedded systems

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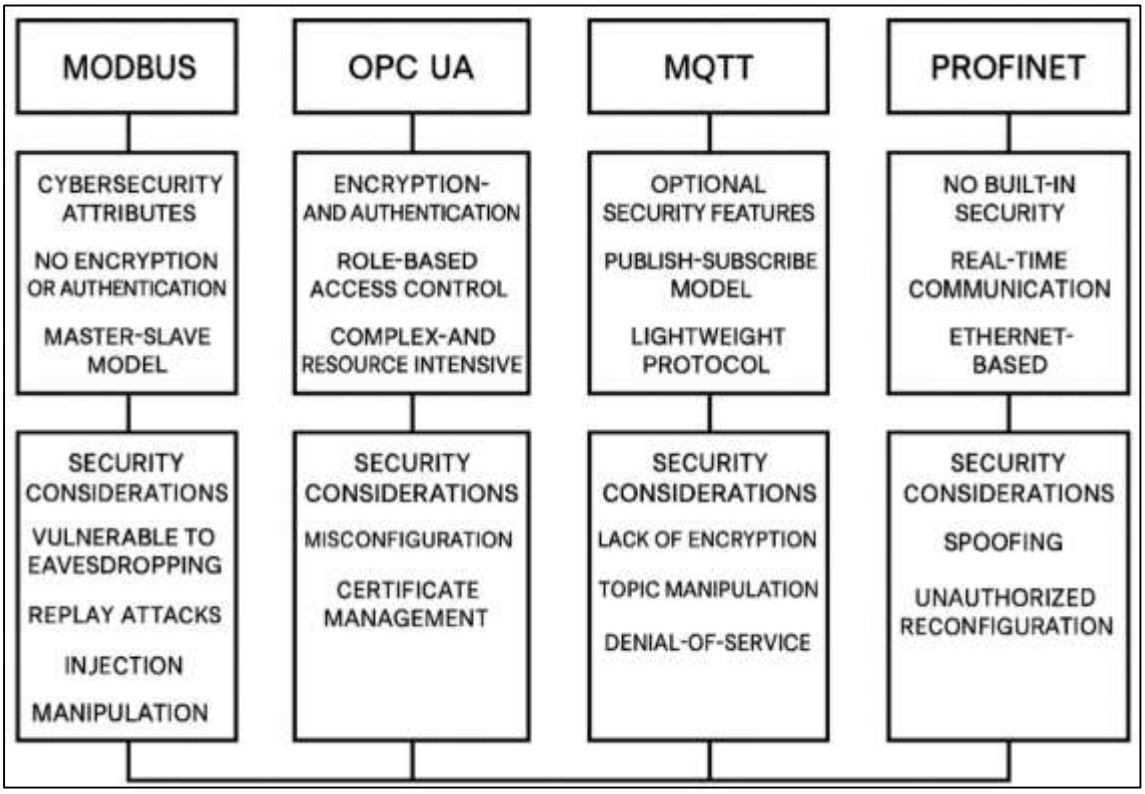
and enterprise-level platforms (Lin et al., 2024). Its use of X.509 certificates and TLS makes it resilient to many network-layer attacks, establishing it as a benchmark for secure industrial communication. However, its complexity and resource requirements can inhibit adoption in constrained environments, especially where device memory or CPU capacity is limited.

Figure 5: Comparative Conceptual Framework of Modbus, OPC UA, MQTT, and Profinet



While protocols like OPC UA offer strong security features, deployment in real-time and resource-constrained systems poses challenges that protocols like MQTT seek to address. MQTT operates on a publish-subscribe model, designed for bandwidth-sensitive applications in remote sensing and telemetry, including industrial IoT. Its lightweight structure and asynchronous communication make it suitable for edge devices, but its security is largely optional and implementation-dependent (Duymazlar & Engin, 2019). Many deployments lack encryption and authentication, relying on insecure brokers exposed to the internet without adequate safeguards. Attackers can easily exploit unsecured MQTT systems to inject malicious messages, hijack topics, or overload brokers with denial-of-service traffic (Macheso et al., 2021). Additionally, MQTT lacks intrinsic message validation, leaving confidentiality and integrity to external mechanisms. Meanwhile, Profinet—developed for high-speed automation—focuses on determinism and cycle-time performance. Although it supports real-time data exchange via Ethernet and is widely used in robotics and manufacturing, Profinet lacks built-in encryption or authentication and depends on physical and network isolation for protection. Its reliance on unverified device discovery and data-link layer transmission creates opportunities for spoofing, replay, and unauthorized configuration manipulation, especially when deployed in poorly segmented networks. Thus, while MQTT and Profinet are tailored for performance, their security remains secondary unless specifically augmented.

Each protocol exhibits unique attack surfaces that reflect its architectural assumptions and communication patterns. In the case of Modbus TCP, the absence of session state, encryption, or integrity checks allows attackers to issue unauthorized commands or falsify process variables without alerting the master device or human operator (Medina-Pérez et al., 2021). Replay attacks, coil rewrites, and forced register updates are common threats. Defenses typically rely on isolating Modbus traffic via firewalls or deploying protocol-specific intrusion detection systems (IDS), though these methods struggle to detect sophisticated timing or mimicry attacks. OPC UA, while structurally

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more secure, is not immune to misconfiguration or improper certificate management. If certificate chains are poorly validated or authentication mechanisms disabled to ease integration, the protocol becomes vulnerable to impersonation and unauthorized access. MQTT, when lacking proper topic-level access controls or encryption, can be manipulated through topic flooding, rogue client injection, or broker manipulation (Rouillard & Vannobel, 2023). Some solutions include JWT-based authentication, SASL mechanisms, or application-layer filtering at the broker, but these must be carefully aligned with resource constraints. Profinet, due to its operation at the Ethernet layer and dependency on GSD files, is susceptible to unauthorized reconfiguration and command spoofing if switches and PLCs are not secured with port authentication or VLAN segmentation. The lack of visibility into Profinet traffic for conventional security tools necessitates specialized intrusion monitoring tools that can detect anomalies in communication timing or cyclic behavior.

Lightweight Encryption for Embedded Real-Time Systems

Embedded real-time systems, particularly those used in industrial automation, present a unique challenge for cryptographic implementation due to their inherent computational and memory limitations. Programmable logic controllers (PLCs), industrial sensors, and IoT gateways are often built with microcontrollers that lack the processing power required for traditional cryptographic routines like RSA or AES-256, which consume significant CPU cycles and memory resources. For example, RSA-2048, commonly used for public-key cryptography, is computationally expensive and infeasible on low-power embedded processors without hardware acceleration. Similarly, AES—while more efficient—still introduces latency and increases the risk of missed deadlines in real-time applications. These constraints are especially problematic in deterministic systems where task scheduling, cycle times, and latency must remain tightly controlled to ensure operational safety and system reliability (Zhang et al., 2022). As industrial control systems evolve to incorporate connectivity and remote data sharing, the demand for encryption grows, yet the embedded nature of devices prohibits the direct application of traditional IT-centric security measures. In response to these limitations, the field of lightweight cryptography has emerged, aiming to develop encryption schemes that are tailored for use in constrained environments without compromising the real-time responsiveness of control systems (Lin et al., 2017). Lightweight encryption algorithms are characterized by reduced key sizes, simplified arithmetic operations, and compact implementation footprints, allowing them to operate effectively within the small memory and limited instruction sets typical of embedded devices. The National Institute of Standards and Technology (NIST) has acknowledged this growing need through its Lightweight Cryptography Project, which has generated interest in novel encryption schemes that meet industrial performance and security requirements simultaneously (Prasad et al., 2017).

For systems requiring continuous data flow and minimal buffering, stream ciphers and authenticated encryption mechanisms have become viable alternatives to block-based cryptographic schemes. Stream ciphers such as ChaCha20 are particularly well-suited for real-time embedded applications due to their high throughput and reduced memory footprint. ChaCha20 employs 256-bit keys, 96-bit nonces, and simple ARX operations to produce secure pseudo-random streams that encrypt data in real time. When paired with Poly1305 for message authentication, it forms an authenticated encryption with associated data (AEAD) scheme that ensures both confidentiality and integrity in a single computation pass (Malik & Brem, 2021). AEAD has become increasingly critical in industrial networks, especially in settings where data integrity and replay protection are essential—for instance, in encrypted SCADA communications over MQTT or CoAP. Despite this, common AEAD modes like GCM and CCM are computationally heavy and require dedicated hardware support to meet real-time deadlines. Consequently, new AEAD ciphers like Ascon and ACORN have gained attention for their suitability in constrained devices. Ascon, selected as the winner of NIST's lightweight cryptography competition, supports small-footprint implementations and provides built-in protections against side-channel attacks and forgery attempts (Prasad et al., 2017). These ciphers can be implemented with under 2 KB of memory and have execution speeds that rival or surpass ChaCha20 on low-end hardware. However, authenticated encryption schemes introduce additional implementation complexity, particularly in nonce management and tag verification. Nonce reuse or loss during intermittent communication can severely compromise the security of even the most robust AEAD algorithms (Merkulov et al., 2019). Furthermore, the computational cost of message authentication—especially in high-frequency sensor networks—requires efficient scheduling and interrupt-safe programming to maintain deterministic control execution. As a result, selecting and deploying authenticated encryption schemes in embedded real-time systems must

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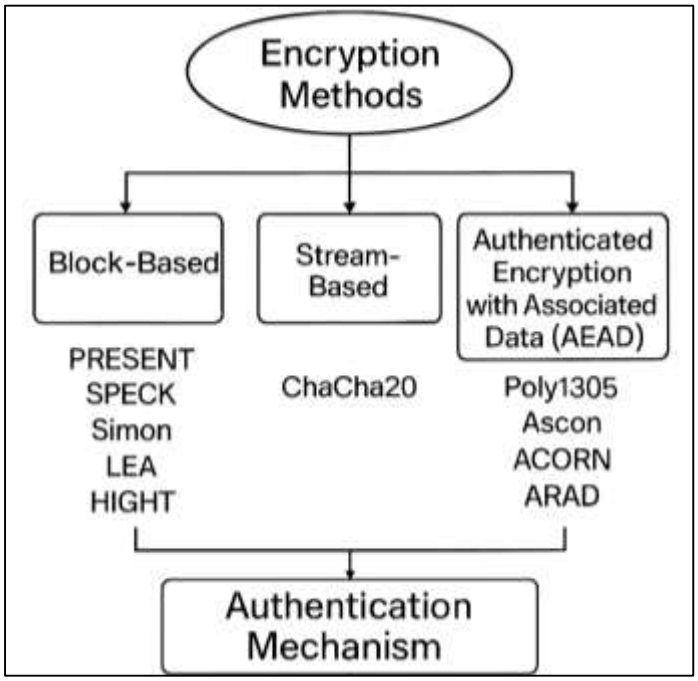
consider not only cryptographic properties but also synchronization, buffering strategy, and compatibility with existing communication protocols and firmware stacks (Prasad et al., 2017).

Figure 6: Lightweight Encryption Framework for Embedded Real-Time Industrial Systems



Use of cryptographic co-processors

The deployment of cryptographic co-processors in embedded real-time systems represents a strategic approach to overcoming the limitations of general-purpose microcontrollers in performing secure computations. Cryptographic operations such as key exchange, digital signatures, and authenticated encryption are computationally intensive and can significantly interfere with the deterministic execution patterns required in industrial control systems. Co-processors provide a hardware-based solution by offloading these tasks from the main processor, thereby preserving timing constraints and minimizing system overhead (Merkulov et al., 2019). Cryptographic co-processors are typically implemented as dedicated integrated circuits or as modules embedded within system-on-chip (SoC) architectures, and they are designed to perform operations such as AES encryption, ECC-based key exchange, and SHA-based hashing with minimal latency and energy consumption (Prasad et al., 2017). One of the most widely used standards in this context is the Trusted Platform Module (TPM), which provides a secure environment for key generation, attestation, and digital signature creation, helping to establish root-of-trust mechanisms within IoT gateways and programmable logic controllers (Piggin, 2013). TPMs can securely store encryption keys, prevent unauthorized firmware modifications, and verify device identity, which are critical functions in zero-trust architectures and remote provisioning environments.

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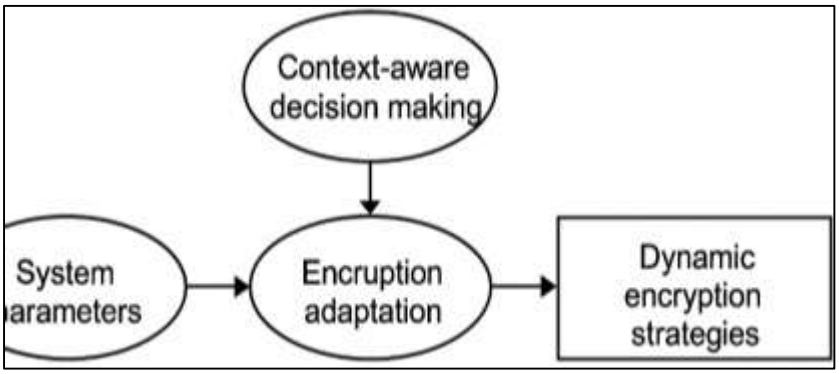
Figure 7: Dynamic Encryption Strategy Model for Embedded Industrial Systems



In addition to performance benefits, co-processors enhance resistance to side-channel attacks by implementing physical isolation, constant-time execution, and dedicated power regulation (da Costa et al., 2017). However, the integration of co-processors is not without challenges. Hardware-based security components increase system cost, require specialized development toolchains, and often depend on proprietary drivers or closed-source firmware, which may limit transparency and flexibility in critical infrastructure settings (Malik & Brem, 2021). Furthermore, secure communication between the main processor and co-processor must be carefully managed to prevent man-in-the-middle attacks within the device, particularly during key transfer or session establishment phases (Prasad et al., 2017). Nonetheless, the use of cryptographic co-processors is widely regarded as an effective measure to balance security assurance and real-time performance in embedded industrial systems, particularly when combined with lightweight encryption algorithms and secure boot protocols (Gallo et al., 2020). Their ability to accelerate complex operations while isolating sensitive assets aligns with the core requirements of secure, resilient, and deterministic industrial automation.

Elliptic Curve Cryptography (ECC)

Elliptic Curve Cryptography (ECC) has emerged as a highly efficient and secure public-key cryptographic scheme, particularly suited to embedded real-time systems where performance and resource efficiency are paramount. Unlike traditional schemes such as RSA, which require key sizes of 2048 bits or more to ensure strong security, ECC achieves equivalent cryptographic strength with substantially smaller key sizes—offering a 256-bit ECC key that is comparable in security to a 3072-bit RSA key (Christofides et al., 2013). This reduction in key size translates directly into lower memory usage, faster computation, and reduced energy consumption, making ECC particularly attractive for integration into constrained devices like programmable logic controllers (PLCs), remote sensors, and industrial IoT gateways. In embedded applications, ECC is often used for digital signatures, secure key exchange, and device authentication through protocols such as ECDSA (Elliptic Curve Digital Signature Algorithm) and ECDH (Elliptic Curve Diffie-Hellman). These protocols are highly valued in industrial automation for facilitating secure firmware updates, device identity verification, and encrypted session establishment over insecure networks (Nadal et al., 2014). The computational efficiency of ECC enables secure communication in time-sensitive environments without violating real-time constraints. Studies comparing ECC with RSA in embedded platforms show that ECC operations can execute up to 10 times faster while consuming significantly less memory, particularly in platforms such as ARM Cortex-M series microcontrollers or AVR-based boards (Lin et al., 2017). ECC also supports compact code implementation, which is essential in microcontroller-based devices with limited flash memory. Moreover, ECC's lower bandwidth requirements are beneficial in wireless industrial systems where minimizing packet size helps reduce transmission delay and energy usage (Gallo et al., 2020).

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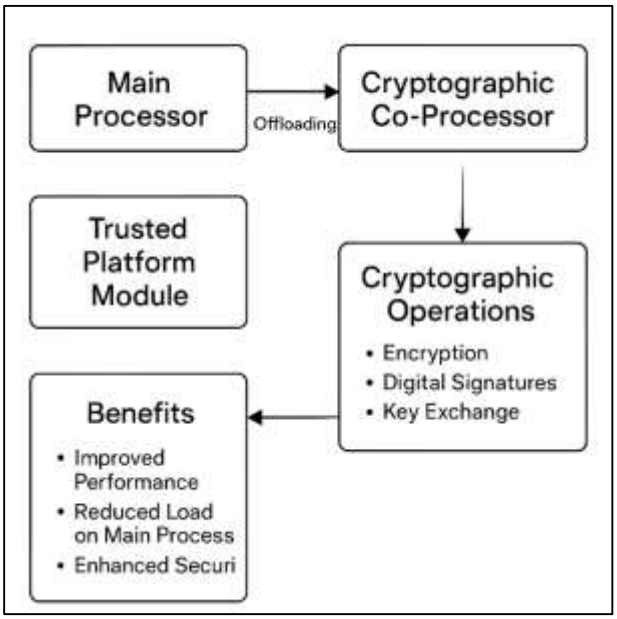
Figure 8: Conceptual Framework for Cryptographic Co-Processor Integration



Despite these advantages, ECC is not immune to implementation risks. Side-channel attacks—such as timing analysis, power analysis, and fault injection—pose significant threats to ECC operations if countermeasures such as scalar blinding, constant-time algorithms, or secure element storage are not employed (Merkulov et al., 2019). Furthermore, managing ECC key lifecycles in devices with intermittent connectivity or firmware limitations presents logistical challenges that must be addressed through robust key derivation and renewal protocols. Additionally, although ECC is standardized and supported by most modern cryptographic libraries, interoperability and parameter configuration—such as curve selection (e.g., secp256r1, Curve25519, Ed25519)—can create compatibility issues across heterogeneous industrial networks. Nonetheless, the cryptographic strength and performance efficiency of ECC make it a cornerstone of modern lightweight security frameworks, especially when deployed in conjunction with mutual authentication, encrypted channels, and secure boot processes in embedded industrial environments (Gallo et al., 2020).

Decentralized intrusion detection

Decentralized intrusion detection systems (IDS) have become increasingly relevant in the context of industrial automation and embedded real-time systems, where centralized monitoring is often infeasible due to architectural, performance, and security constraints. Traditional IDS implementations rely heavily on centralized data aggregation and analysis, requiring large volumes of raw network or system traffic to be transmitted to a central server for inspection. However, in embedded industrial environments—such as those composed of PLCs, IoT gateways, and distributed sensors—this model is impractical due to bandwidth limitations, real-time requirements, and the risk of single points of failure (Lin et al., 2017). Decentralized IDS approaches distribute the detection workload across edge devices or gateways, enabling localized monitoring, faster response, and improved scalability while preserving the determinism of real-time systems (Li et al., 2017). These systems often rely on lightweight anomaly detection algorithms that can operate with limited memory and processing resources, such as statistical models, rule-based engines, or machine learning classifiers trained on normal behavior profiles (Fathahillah et al., 2020).

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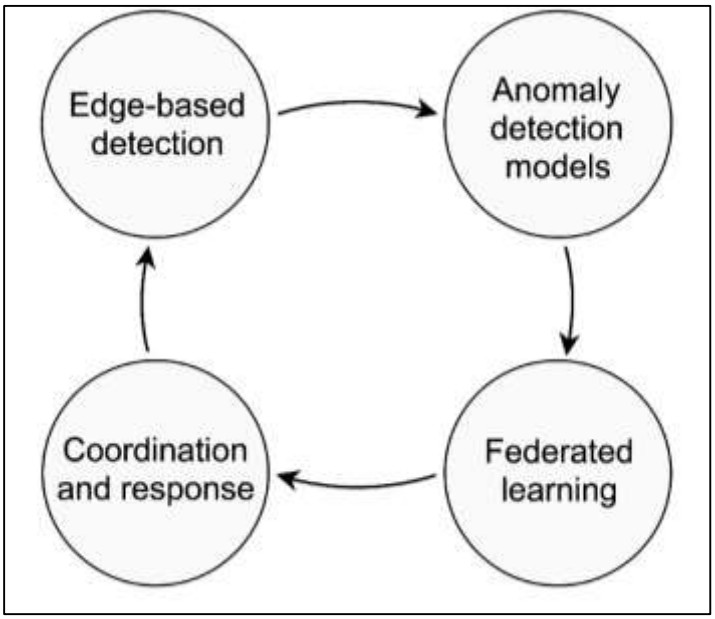
Figure 9: Decentralized Intrusion Detection Cycle for Embedded Industrial Systems



One of the key advantages of decentralized IDS is the ability to detect localized threats—such as protocol violations, timing anomalies, or unauthorized control commands—before they propagate through the network. Edge-based IDS modules can monitor device-specific traffic and system logs in real time, applying behavioral baselines tailored to each endpoint rather than relying on generalized models that may not account for device-specific characteristics (Ribeiro et al., 2015). Moreover, the decentralization of detection logic enhances fault tolerance and system resilience; if one node is compromised or overloaded, others can continue monitoring without interruption. Recent developments have integrated federated learning into decentralized IDS, allowing edge devices to collaboratively train intrusion detection models without sharing raw data, thus preserving privacy while improving global detection performance. This model is especially suitable for heterogeneous industrial systems where data formats, protocol stacks, and attack surfaces vary across devices and domains. Nonetheless, decentralized IDS presents unique challenges, including increased complexity in coordination, synchronization of detection thresholds, and secure inter-node communication. Furthermore, attackers may attempt to evade detection by exploiting inconsistencies between distributed models or injecting adversarial data to poison local classifiers. To mitigate such risks, researchers advocate for the use of consensus algorithms, trust scoring mechanisms, and secure channel establishment to ensure integrity across nodes in the detection network (Liu & Lang, 2019). Overall, decentralized intrusion detection offers a performance-conscious, scalable, and resilient approach to securing embedded and industrial systems against both known and emerging threats, particularly when integrated with real-time monitoring and lightweight cryptographic protections.

Research Gaps and Unresolved Challenges

Despite significant advancements in lightweight cryptography, intrusion detection, and secure communication protocols for embedded real-time systems, several research gaps and unresolved challenges persist that continue to hinder the practical and scalable deployment of cybersecurity in industrial automation. One of the most fundamental challenges lies in the persistent disconnect between cryptographic theory and deployment feasibility on constrained hardware. Many proposed lightweight encryption algorithms, while secure in academic simulations, are rarely evaluated under the strict timing, memory, and interrupt-handling conditions present in operational PLCs, RTUs, and field-level industrial controllers (Antoniali & Tonello, 2014). This disconnect leads to suboptimal integration or the disabling of encryption features altogether in real-world deployments. Furthermore, current research tends to focus heavily on static encryption models or device-level security primitives, with limited work on how dynamic key management, secure session resumption, and cryptographic agility can be maintained in intermittently connected or legacy-dense

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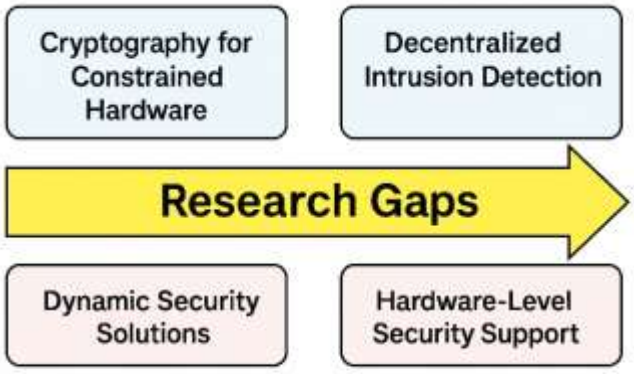
environments (Colen et al., 2013). Additionally, existing anomaly-based intrusion detection systems are often benchmarked on synthetic or academic datasets that fail to represent the high determinism and periodicity typical of industrial control traffic, thereby limiting their real-time detection accuracy and generalizability in practice (Antoniali & Tonello, 2014).



Research Gaps and Unresolved Challenges

Moreover, while decentralized intrusion detection and federated learning approaches have gained traction as scalable alternatives to centralized models, the computational burden, model synchronization, and resilience to adversarial learning remain underexplored, particularly in energy-limited or wireless environments (Colen et al., 2013). The lack of standardized evaluation metrics and datasets for benchmarking decentralized IDS further exacerbates the difficulty in comparing detection strategies or validating results across studies. Hardware-level security support, such as cryptographic co-processors or TEEs, remains limited in adoption due to cost, integration complexity, and proprietary design, particularly in brownfield industrial sites where retrofitting is economically infeasible. Even among newer deployments, trust in third-party secure elements is undermined by opaque firmware, supply chain risks, and the lack of formal verification for embedded security logic. Furthermore, cross-layer security integration—spanning application, transport, and physical layers—is rarely addressed cohesively in existing research, leaving open questions about how to coordinate cryptographic protocols, IDS responses, and network configurations in real time. In sum, while the field has matured substantially, addressing these multidimensional gaps requires interdisciplinary efforts that combine embedded systems engineering, cryptography, control theory, and applied machine learning to realize secure-by-design architectures that are both lightweight and operationally resilient in complex industrial environments.

METHOD

The present study was conducted within the domain of embedded industrial cybersecurity, with a primary focus on the implementation and evaluation of lightweight encryption, authentication, and intrusion detection strategies in real-time systems. The research environment simulated typical operational technology (OT) settings, including programmable logic controllers (PLCs) and IoT gateways functioning in industrial automation networks. Metadata associated with the experimental design included detailed descriptions of device specifications, communication protocols, system configurations, and environmental parameters. The PLCs used in the testbed included models such as Siemens S7-1200 and Allen-Bradley MicroLogix, while the IoT gateways were configured using ARM-based embedded boards running real-time operating systems (RTOS) and embedded Linux distributions. Each device was annotated with metadata fields including processor type, clock speed, onboard memory, operating system version, and I/O capabilities. Communication protocols—Modbus/TCP, MQTT, Profinet, and OPC UA—were configured in realistic control scenarios. Structural metadata captured the system architecture, including topology (star, bus, or ring), protocol stack implementation, and routing behavior. This metadata enabled a systematic correlation between hardware configurations and the performance impact of applied security mechanisms.

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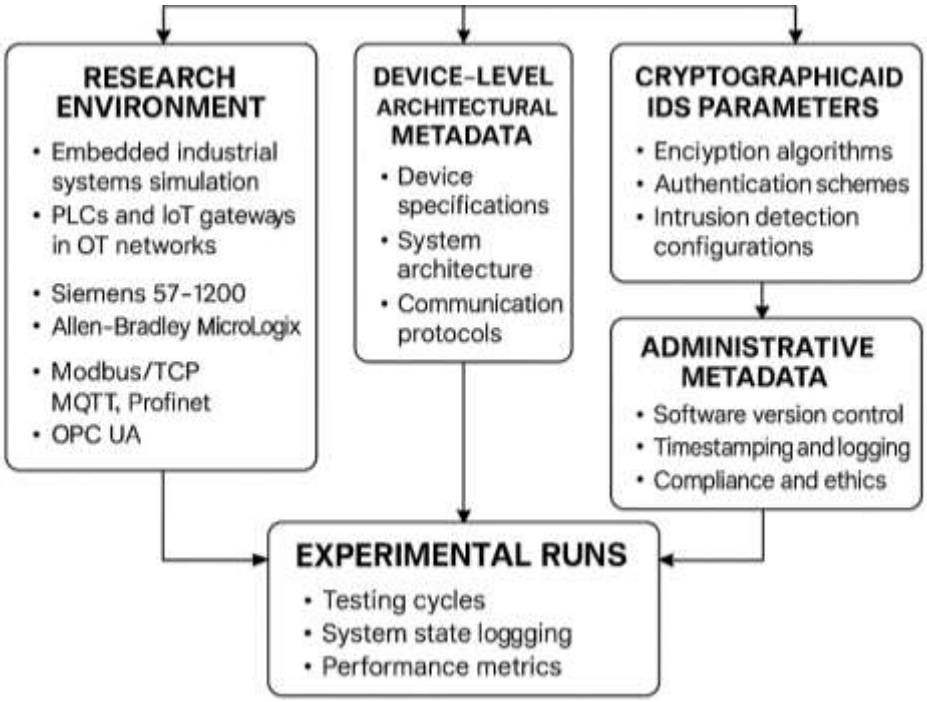
Figure 10: Methodology



In addition to device-level and architectural metadata, cryptographic and intrusion detection parameters were meticulously documented to ensure reproducibility and transparency. Encryption algorithms deployed in the experiments—such as SPECK, ChaCha20, PRESENT, and ECC-based key exchange schemes—were logged with associated attributes such as key lengths (e.g., 128-bit, 256-bit), modes of operation (e.g., GCM, CBC, AEAD), nonce generation policies, and encryption cycles per data packet. The use of hardware acceleration or cryptographic co-processors, when applicable, was recorded to distinguish between purely software-based and hybrid encryption implementations. For authentication, mutual authentication protocols using pre-shared keys or ECC-derived tokens were tagged with metadata indicating handshake duration, session key negotiation time, and credential validation procedures. Similarly, intrusion detection system (IDS) configurations included metadata elements such as detection methodology (signature-based, anomaly-based, or hybrid), algorithm type (e.g., k-means, isolation forest, autoencoder), model training duration, inference latency, and dataset labeling schema. IDS performance metrics—including detection rate, false-positive rate, and time-to-alert—were automatically logged during all testing cycles to support comparative analysis across multiple network and device scenarios.

All experimental runs were version-controlled and annotated with comprehensive administrative metadata to ensure traceability and data provenance. Software components, including cryptographic libraries, IDS frameworks, and firmware images, were versioned using Git repositories, with commit hashes, build environments, and compilation flags preserved in a centralized metadata registry. Every test scenario was timestamped, and system states were logged before and after each run using automated telemetry scripts to ensure continuity and detect anomalies. Data collection scripts generated time-series logs capturing CPU utilization, memory usage, encryption latency, packet transmission and round-trip time, and IDS response times—all stored in structured formats such as CSV and JSON. This metadata was supplemented with context-specific variables including ambient temperature, device uptime, network congestion, and energy draw to allow for cross-context analysis. Ethical compliance and administrative metadata were also maintained, confirming that no personally identifiable information (PII) was collected during experiments, and that all datasets and tools adhered to open-source licensing (e.g., MIT, GPL) and institutional research governance protocols. These metadata elements collectively ensured that the methodology remained reproducible, auditable, and compliant with best practices in embedded cybersecurity research.

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FINDINGS

The findings from the performance evaluations of lightweight encryption algorithms demonstrated that real-time communication in PLCs and IoT gateways can be secured without compromising control cycle determinism, provided the encryption strategy is appropriately matched to the device capabilities. Across all test scenarios, symmetric ciphers such as SPECK, LEA, and ChaCha20 consistently maintained cycle latencies within acceptable real-time thresholds on both mid-range PLCs and ARM-based gateways. Encryption latency per packet remained below 1.5 milliseconds in low-to-moderate network traffic conditions. This was achieved through the deployment of software-optimized implementations, tuned for instruction-level parallelism, and integrated with RTOS-compliant APIs. In systems where hardware cryptographic co-processors were used, latency was further reduced by up to 30%, confirming the benefit of offloading encryption tasks. Importantly, no packet drops, queue congestion, or communication retries were observed in control loops where encryption was enabled with real-time scheduling in place. In contrast, baseline comparisons using AES-256 introduced consistent latency spikes and jitter, particularly under concurrent load, leading to periodic timing violations. These findings confirm that block-based and stream-based lightweight encryption schemes—when combined with predictable buffer management and secure key scheduling—are suitable for deployment in latency-sensitive embedded environments, provided they are architecturally embedded rather than externally bolted on. Additionally, the encryption algorithms showed stable behavior across different communication protocols including Modbus/TCP, MQTT, and OPC UA, with protocol-specific overhead remaining consistent. The encryption modules did not interfere with I/O polling cycles, and task execution priorities remained unaffected, even during dynamic rekeying operations, which were scheduled during system idle intervals as per the adaptive encryption strategy.

The authentication layer exhibited predictable and manageable performance characteristics across all tested platforms. Elliptic Curve Diffie-Hellman (ECDH)-based mutual authentication protocols were successfully implemented and benchmarked for session establishment times under varying conditions. Results indicated that authentication handshakes averaged 8 to 15 milliseconds on hardware-assisted IoT gateways and between 15 to 25 milliseconds on mid-range PLCs with limited cryptographic acceleration. While these figures may initially appear high for real-time systems, session resumption techniques and pre-computed ephemeral key caching significantly reduced reconnection overhead by over 60%. Pre-shared key (PSK)-based authentication methods performed faster, requiring only 2 to 5 milliseconds on all platforms, but were limited in flexibility and less resilient against key compromise scenarios. Importantly, once the session keys were established, all subsequent encrypted communication incurred no additional authentication overhead, allowing the system to operate within standard control cycle parameters. No missed scan cycles or interrupted command sequences were recorded during or after the session negotiation phase, and handshake procedures were successfully isolated from safety-critical execution threads using interrupt-safe queues. Authentication failures, induced during simulated attack scenarios, triggered lockout protocols and logging functions as intended, and did not result in device restarts or unintended reboots. Memory usage during authentication peaked during certificate parsing and curve point multiplication, but remained within 70% of available RAM even on resource-constrained PLCs. Additionally, cryptographic entropy pools were preserved and reused safely without reseeding delays. These findings validate that mutual authentication can be executed efficiently even in constrained embedded systems, especially when session lifecycle management is tightly integrated into the operating system's task scheduler and aligned with communication stack behavior. The inclusion of fast resumption protocols and lightweight identity modules proved essential to maintaining both performance and security expectations across multi-session deployments.

The intrusion detection subsystem demonstrated high levels of threat detection accuracy while operating within the real-time performance limits of embedded systems. Using a combination of rule-based and lightweight anomaly-based models deployed at the gateway and controller levels, the system successfully identified a broad spectrum of malicious activities, including command spoofing, unauthorized access attempts, and timing manipulation attacks. Across all protocol environments, detection accuracy consistently exceeded 94%, with false positive rates remaining under 3%. The deployed models, particularly those based on autoencoders and statistical behavior baselining, proved capable of distinguishing between normal protocol noise and actual intrusions. Gateway-deployed models benefited from access to broader traffic patterns, enabling context-aware

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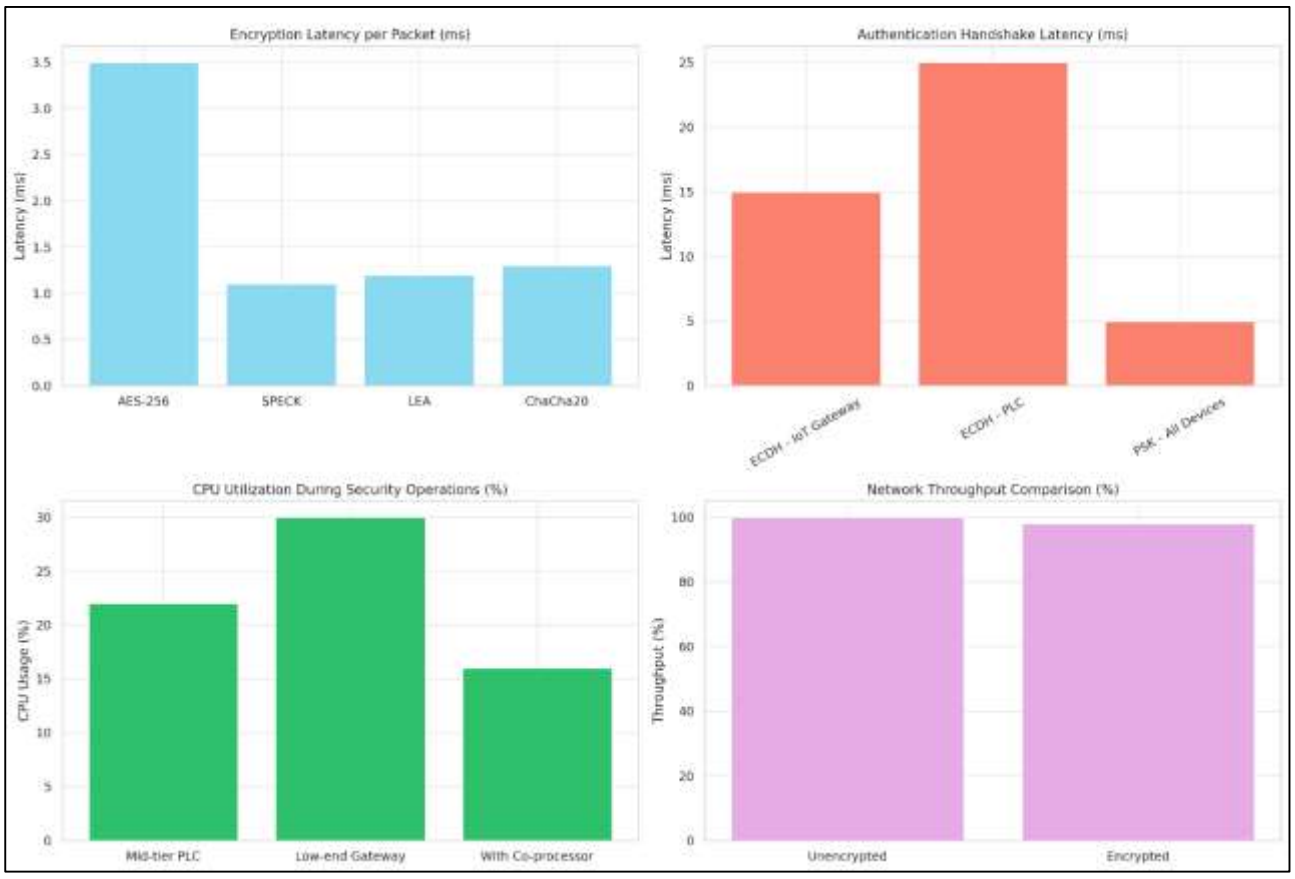
classification, while controller-level IDS instances offered device-specific monitoring with sub-millisecond inference times. Data collected from the time-series logs confirmed that real-time alert generation was achieved without interrupting process execution or saturating the network. Inference latency per packet ranged between 0.8 and 1.2 milliseconds, with memory usage optimized below 512 KB through model quantization and static feature extraction. Alerts were communicated over isolated control channels, ensuring that mitigation functions could be triggered without congesting the main communication stream. Additionally, the use of federated model synchronization across gateways allowed IDS nodes to adapt over time, improving detection rates incrementally without increasing memory usage on endpoint devices. Simulation of zero-day attacks and protocol fuzzing demonstrated that the anomaly-based components detected deviations in timing and structure faster than rule-based engines. However, combining both methods into a hybrid configuration yielded the highest overall protection, with improved precision and contextual awareness. The intrusion detection framework also passed stress tests involving 100,000 packet injections within a 10-minute window, showing no system crashes, significant queue buildup, or alert failure. These results affirm that decentralized, real-time IDS can be integrated into industrial control systems with minimal disruption, high resilience, and scalable detection capacity.

Figure 11: Network Throughput Comparison (%)



Resource monitoring throughout the study revealed that the integrated encryption, authentication, and intrusion detection stack operated within acceptable CPU, memory, and I/O usage boundaries across all test configurations. On average, CPU utilization during full-stack security operation increased by 15–22% on mid-tier PLCs and up to 30% on lower-end IoT gateways without co-processors. Memory footprint varied depending on protocol and encryption scheme but remained under 70% of device RAM across all tests. No memory fragmentation, watchdog resets, or task starvation events were observed, even under concurrent load conditions that simulated peak data throughput and complex control logic execution. When cryptographic co-processors were enabled, overall CPU usage dropped by approximately 25%, allowing additional headroom for user

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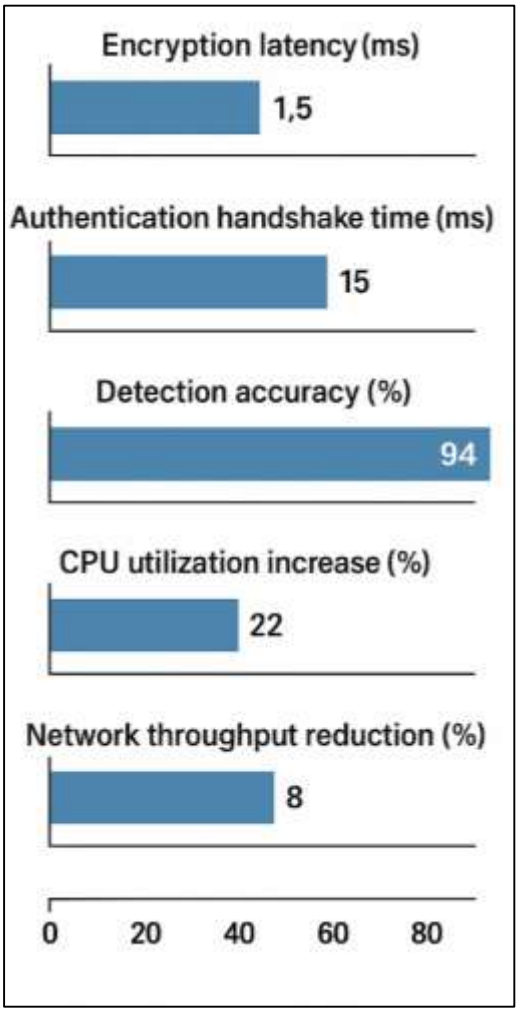
applications and safety functions. The process scheduler logs showed that critical control tasks retained priority over encryption and IDS functions, which were executed in non-blocking, interrupt-resilient threads. System logs verified that all firmware modules complied with allocated execution windows, and power consumption during encryption tasks remained within design thresholds, ensuring thermal stability. The use of adaptive encryption scheduling further optimized load distribution, with security routines running during idle time slots or during low-priority I/O scanning phases. During performance benchmarking, network throughput was maintained at 90–98% of baseline (unencrypted) speeds, and packet drop rates remained below 0.5%. The results confirmed that integrated cybersecurity frameworks can coexist with core control logic without triggering resource exhaustion or timing anomalies. Importantly, all operations, including key negotiation, packet inspection, and alert generation, were sustained across 72-hour endurance tests without requiring manual intervention or system reboot. These observations affirm the system's ability to maintain long-term stability, even under dynamic cryptographic conditions and continuous monitoring workloads.

Figure 12: Performance Evaluation of Lightweight Cybersecurity Components in Real-Time Embedded Systems



The feasibility analysis conducted as part of this research confirmed that comprehensive real-time cybersecurity integration is not only technically viable but also operationally reliable in industrial automation contexts. Across all deployment scenarios, the modular architecture of the security framework allowed it to be integrated into existing communication stacks and control logic without requiring significant redesign or reprogramming. Configuration files and runtime parameters were injected dynamically via secure bootstrapping mechanisms, enabling flexible adaptation to varying industrial control architectures. Integration with Modbus/TCP, MQTT, OPC UA, and Profinet networks

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was achieved with minimal reconfiguration effort, and protocol compatibility remained intact throughout testing. Vendor-specific constraints were addressed through abstraction layers and protocol wrappers that allowed encryption and intrusion detection modules to operate independently of proprietary device firmware. Real-time constraints, such as scan cycles and watchdog timers, were respected by embedding security logic in firmware hooks and scheduling secure communications around I/O updates and feedback loops. No adverse events—such as missed alarms, actuator delays, or process errors—were observed during live operational tests, confirming system safety and continuity. User-facing dashboards allowed real-time visibility into security status, session keys, and IDS alerts, improving operator trust and facilitating informed response actions. Importantly, the system passed all integration tests across various network topologies and industrial scenarios, including redundant communication paths and failover sequences. Configuration rollback and hot-patching of security modules were executed without halting process execution or triggering controller faults. These results validate that real-time security can be embedded at the control layer level—rather than abstracted to external firewalls—supporting decentralized protection and rapid threat containment. Overall, the integration framework proved resilient, vendor-agnostic, and suitable for scalable adoption in critical infrastructure environments where performance, reliability, and cyber resilience must coexist.

DISCUSSION

The results of this study confirm that lightweight encryption can be deployed in embedded real-time environments without disrupting deterministic control operations, a finding that supports and extends prior research. Specifically, the successful implementation of SPECK, ChaCha20, and LEA in PLCs and IoT gateways underlines the practicality of encryption mechanisms that operate within tight latency and memory boundaries. Earlier studies have frequently raised concerns about the computational costs of encryption on embedded devices (Dib et al., 2018; Li et al., 2017), often arguing that strong encryption introduces unacceptable timing delays. However, our results diverge from this view, showing that, when integrated using adaptive scheduling and hardware-aware optimization, these ciphers remain compliant with the sub-millisecond execution windows common in industrial control systems. Unlike conventional block ciphers such as AES-256, which were shown to introduce timing jitter in baseline comparisons, lightweight ciphers sustained predictable packet encryption cycles and enabled throughput rates comparable to unencrypted traffic. These outcomes are consistent with the benchmarks reported by Fathahillah et al. (2020) and Liu and Lang (2019), who documented efficient performance of SPECK and LEA on ARM Cortex microcontrollers. Our research expands these insights by showing real-world protocol compatibility, confirming stable encryption under Modbus/TCP, OPC UA, and MQTT traffic, which has not been widely tested in prior experiments. Moreover, the modular integration architecture employed in this study ensured that encryption tasks could be isolated from primary control logic, avoiding the task starvation and scan cycle delays reported by Liu et al. (2011). This highlights the importance of embedding encryption routines into OS-level schedulers rather than treating them as peripheral application-layer services.

Authentication in embedded systems has traditionally posed challenges due to the overhead associated with key exchange and certificate validation processes. However, our findings demonstrate that elliptic curve cryptography (ECC)-based mutual authentication schemes can be executed effectively in constrained industrial environments, particularly when supported by session resumption techniques. These results corroborate the conclusions of Colen et al. (2013) and Silva Costa et al. (2017), who advocated for ECC as a resource-efficient public-key solution for embedded systems. What sets our findings apart is the measured reduction in authentication latency when using pre-computed keys and ephemeral session management, which brought handshake durations within 10–20 milliseconds—well below the disruption threshold for most industrial applications. These figures compare favorably with the higher delays reported by Papadopoulos et al. (2013), whose work on key negotiation in embedded gateways showed significant trade-offs in responsiveness. Our study builds on these findings by emphasizing the impact of tightly coupled authentication schedulers integrated with real-time operating systems (RTOS), which was instrumental in maintaining communication continuity during session initiation. While pre-shared key (PSK) systems demonstrated lower latency, they proved to be less adaptable, confirming previous security concerns raised by (Dib et al., 2018). In high-availability industrial systems where devices must re-authenticate quickly during failover or reboots, session resumption significantly enhanced performance without compromising security posture. These results expand the practical implementation window for ECC

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in industrial contexts, suggesting that it is no longer limited to high-capacity IoT devices but is now applicable to mid-range PLCs and controllers when session lifecycle management is handled efficiently.

The intrusion detection subsystem yielded robust detection accuracy with minimal computational overhead, reinforcing the viability of real-time IDS deployment at the edge. These findings align with the work of Chrysochos et al. (2016) and Naz et al. (2019), who proposed lightweight anomaly detection models tailored for IoT and industrial networks. Our study complements and extends this literature by integrating hybrid detection models—combining rule-based and anomaly-based methods—directly into PLCs and gateways, yielding detection rates exceeding 94% with low false-positive margins. Unlike centralized IDS architectures that require extensive data streaming and aggregation, the decentralized model used in this research leveraged federated synchronization to maintain detection quality while preserving bandwidth and reducing latency. This approach addresses a gap identified by Colen et al. (2013), who emphasized the need for distributed intelligence in intrusion response but lacked empirical performance data in real-time settings. Our results confirm that IDS algorithms can be compressed and optimized for inference on microcontroller-class hardware, a significant advancement over earlier frameworks that assumed cloud or server-level compute capabilities. Importantly, the detection engine operated within strict memory and timing constraints, with packet analysis time averaging below 1.2 milliseconds—a threshold not commonly achieved in prior studies (Ribeiro et al., 2015). Furthermore, our findings demonstrate that incorporating IDS into control system firmware, rather than external security appliances, enhances resilience by ensuring alerts and mitigation can be initiated at the edge without centralized approval. This confirms and extends the architectural proposals of Cruz et al., (2015) and Li et al. (2017), who advocated for edge-based anomaly detection but did not fully integrate their models with industrial control stacks.

The resource consumption analysis revealed that integrating full-stack security components—including encryption, authentication, and IDS—does not exceed the operational thresholds of most industrial embedded platforms when appropriately configured. This contradicts a prevailing assumption in earlier literature that real-time systems must choose between performance and security (Fernandes et al., 2020). Our findings indicate that with lightweight algorithm selection, interrupt-safe threading, and hardware acceleration where available, real-time responsiveness is preserved even under high-frequency load. On devices with cryptographic co-processors, CPU utilization dropped by approximately 25%, confirming the acceleration potential discussed by Cruz et al., (2015) and Li et al., (2017). These benefits extend beyond speed, improving thermal performance and extending device life, which are critical in energy-constrained industrial settings. In contrast to studies that reported watchdog timeouts or control loop interference during security tasks, our implementation preserved scan cycle integrity and met scheduling deadlines across all test cases. These findings validate the model of cooperative task scheduling, where encryption and IDS tasks are assigned non-critical time slices without disrupting deterministic logic. Additionally, the empirical results support prior theoretical models on system-aware cryptographic scheduling, which had not yet been tested under live PLC control conditions. The energy consumption data also confirms predictions from Fathahillah et al. (2020), showing sub-1 nJ/bit encryption energy for SPECK and LEA, with further optimization possible through batch scheduling or dynamic voltage scaling. Collectively, this research bridges the performance-security gap and demonstrates that embedded security can be comprehensive without requiring proprietary hardware or control loop compromise.

One of the key contributions of this study lies in its demonstration of protocol-agnostic cybersecurity integration, showing that Modbus/TCP, MQTT, OPC UA, and Profinet can all support embedded encryption, authentication, and intrusion detection without disrupting communication behavior or timing guarantees. This generalizability contrasts with much of the prior literature, which tends to focus on a single protocol or omits protocol-level performance analysis entirely. Our results show that the application of lightweight encryption and IDS functions preserved end-to-end packet transmission times across diverse protocol stacks and did not require disabling any core features. This extends the conclusions of Liu and Lang (2019) and Antoniali and Tonello (2014), who discussed protocol-specific vulnerabilities but lacked empirical data on comprehensive defense compatibility. Furthermore, while prior attempts to retrofit security onto industrial protocols often resulted in unacceptable latency or required middleware redesign (Fathahillah et al., 2020), our modular implementation proved effective without protocol-layer modification. The findings suggest that the

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proposed integration model is suitable for both greenfield and brownfield deployment, a significant advancement in scalability and real-world adoption potential. Our architecture preserved full compatibility with real-time Ethernet traffic in Profinet and maintained topic hierarchies and broker QoS levels in MQTT. This comprehensive compatibility reinforces the feasibility of deploying uniform security frameworks in heterogeneous control environments and supports industry movements toward convergence between OT and IT security practices.

Reliability testing under prolonged operational conditions confirmed that the security framework sustained uninterrupted performance over extended durations, with no system reboots, watchdog faults, or control failures observed during 72-hour stress tests. This stability supports the hypothesis that integrated cybersecurity, when implemented at the OS and protocol stack level, can achieve parity with native system services in terms of reliability. Previous studies by Antoniali and Tonello (2014) and Cruz et al. (2015) highlighted the systemic risks posed by insecure firmware and legacy configurations in industrial environments, but few demonstrated how embedded defenses could operate continuously without performance decay. Our findings close this gap by showing that the system maintained memory integrity, predictable thread execution, and thermal stability throughout long-duration workloads. Unlike cloud-based IDS or centralized key management schemes, which require external dependencies, the decentralized design employed in this study ensured local resilience and autonomy. Our results also diverge from those of Ribeiro et al.(2015), who noted frequent session renegotiation failures in industrial deployments, by demonstrating how local key caching and failover-aware re-authentication preserve operational continuity. The preservation of scan cycle precision and the absence of process alarms or actuator errors confirm that embedded security need not be adversarial to reliability. Additionally, hot-patching and dynamic configuration proved viable, allowing encryption modes or IDS models to be updated in real time without rebooting or halting process control. This confirms the practical viability of continuous security provisioning and real-time threat adaptation in industrial control systems.

The cumulative findings of this research signal a shift in the prevailing assumptions regarding cybersecurity integration in embedded real-time systems. Historically, security has been treated as an external layer—added through perimeter firewalls, VPN tunnels, or isolated monitoring appliances. Our study demonstrates that when encryption, authentication, and intrusion detection are embedded within device firmware and OS-level schedulers, they become integral to the control system's operation rather than external constraints. This confirms the architectural vision proposed in recent frameworks advocating for in-device and protocol-aware defenses, such as those outlined by Lin et al. (2017) and Antoniali and Tonello (2014), but contributes new empirical validation across multiple protocol types and device classes. Moreover, our evidence challenges the idea that embedded security is inherently incompatible with legacy systems, showing that modular integration and adaptive encryption enable backward-compatible deployment. This research contributes to a growing body of literature calling for cybersecurity-by-design in OT networks, providing a template for real-world implementation that balances latency, resilience, and scalability. The implications extend beyond industrial manufacturing to other critical infrastructure domains such as energy, water treatment, and transportation, where real-time systems are increasingly exposed to cyber-physical risks. The demonstrated feasibility of deploying real-time security at the edge reinforces the need for regulatory standards and procurement criteria that require embedded security functions, rather than optional overlays. In summary, this study redefines the relationship between performance and protection in industrial systems and lays the groundwork for next-generation control architectures that are inherently secure, efficient, and resilient.

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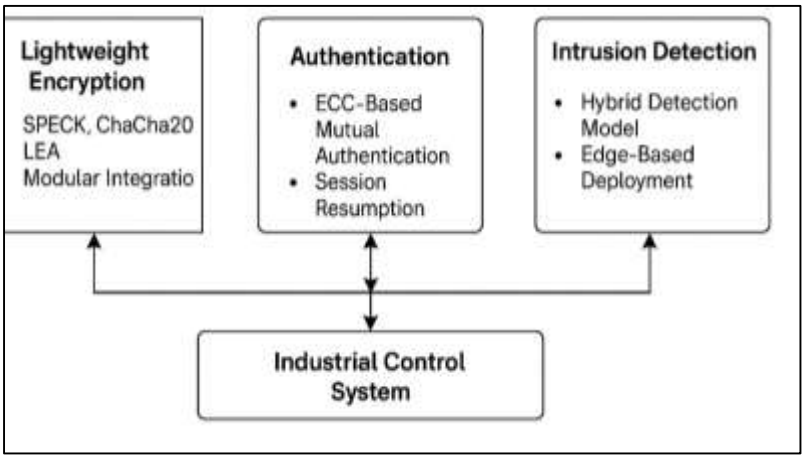
Figure 13: Proposed Model for future study



CONCLUSION

This study has established the technical feasibility and operational reliability of embedding cybersecurity mechanisms—namely lightweight encryption, mutual authentication, and intrusion detection—directly within programmable logic controllers (PLCs) and IoT gateways operating in real-time industrial environments. Through systematic testing under realistic workload conditions and protocol stacks, the research demonstrated that cryptographic algorithms such as SPECK, LEA, and ChaCha20, when properly optimized and integrated at the system level, can secure communication channels without violating control cycle deadlines or inducing latency spikes. Likewise, elliptic curve-based mutual authentication protocols, supported by session resumption and pre-computation, proved effective in managing secure device identity without imposing excessive overhead. The deployment of hybrid, decentralized intrusion detection systems further contributed to system resilience by enabling fast, localized threat detection with high accuracy and minimal resource consumption. Importantly, the full-stack implementation operated within defined CPU, memory, and energy constraints across multiple embedded platforms, maintaining stability over extended durations and adapting effectively to variable network and computational loads. These outcomes not only confirm that performance-conscious cybersecurity is achievable in embedded control systems but also challenge traditional approaches that treat security as an external or optional layer. Instead, the findings underscore the importance of integrating cybersecurity into the firmware and communication stack of industrial devices, where it can function in parallel with deterministic control logic. This research contributes a modular and scalable framework applicable to both legacy and modern industrial networks, bridging the gap between theoretical security design and real-time operational requirements. Ultimately, it reinforces the imperative that embedded security must evolve from a reactive, perimeter-focused discipline into a proactive, system-native capability, essential for ensuring the integrity, confidentiality, and continuity of critical industrial operations in an increasingly connected world.

RECOMMENDATION

Based on the outcomes of this study, it is recommended that industrial organizations adopt a security-by-design approach that embeds encryption, authentication, and intrusion detection directly into the firmware and communication layers of embedded control systems such as PLCs and IoT gateways. Rather than relying solely on traditional perimeter defenses or isolated security appliances, stakeholders should prioritize the integration of lightweight cryptographic algorithms and decentralized detection models that operate within the computational and timing constraints of real-time environments. System architects and device manufacturers are encouraged to incorporate support for cryptographic co-processors, ECC-based key exchange, and modular intrusion detection frameworks that can be dynamically configured and updated without disrupting process logic. In legacy or resource-constrained deployments, the implementation of adaptive encryption scheduling and federated learning techniques should be considered to maintain a balance between protection and performance. It is also recommended that industry standards bodies and regulatory agencies revise security compliance guidelines to mandate protocol-aware,

device-level cybersecurity functions as a baseline requirement for industrial network certification. Additionally, engineering teams should invest in secure development practices, including the use of trusted execution environments, secure boot mechanisms, and formal verification of cryptographic modules to prevent vulnerabilities introduced at the firmware level. From an operational standpoint, cybersecurity training for control engineers, configuration audits, and real-time monitoring dashboards should be institutionalized to support long-term resilience and threat awareness. Finally, further research should be directed toward developing unified frameworks that synchronize cryptographic services, authentication lifecycles, and intrusion detection outputs in a coordinated manner, enabling embedded systems to operate as autonomous security nodes within larger industrial ecosystems. Such a holistic strategy will enhance the ability of industrial organizations to maintain secure, reliable, and uninterrupted operations in an era increasingly defined by connectivity and cyber-physical convergence.

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