

Survey: A Study on Authentication Mechanism on Replay Attack

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Abstract—Replay attacks, a type of network attack where malicious actors record and retransmit legitimate data, pose significant threats to network infrastructure by enabling unauthorized actions without system intrusion. This survey synthesizes insights from research papers to analyze the impact of replay attacks across various systems, including cyber-physical systems (CPS), Internet of Things (IoT) devices, wireless sensor networks (WSNs), power systems, and voice-based systems. It reviews existing detection and prevention methods, categorizing them by technique and application domain. It highlights ongoing challenges and the need for robust security mechanisms to mitigate the risks posed by replay attacks.

Index Terms—Replay Attack, Authentication, Cybersecurity, Cryptographic Techniques, OTP, CSK, Timestamp- based Security.

I. INTRODUCTION

The increasing reliance on interconnected systems has amplified the risks posed by replay attacks. Consider a 2023 incident where a smart city traffic management system in Europe was compromised attackers replayed outdated sensor data, causing traffic lights to malfunction during peak hours, leading to gridlock and an estimated economic loss of C1.2 million in a single day [24]. Beyond immediate disruptions, these attacks erode trust in digital infrastructure, which is foundational to modern economies. For instance, in financial systems, a replayed transaction could authorize duplicate payments, costing businesses millions and exposing consumers to fraud [5].

This survey goes beyond merely cataloging vulnerabilities it seeks to bridge the gap between theoretical defenses and practical implementation. As systems grow more complex, attackers exploit subtle weaknesses, such as predictable communication patterns or insufficient validation checks [17].

A replay attack, as depicted in the Figure 1, occurs when an attacker intercepts and maliciously retransmits legitimate data packets to deceive a system. In this scenario, Tom sends a data packet to a website as part of a normal communication process. Sally simply replays the captured packet, making it appear as though it was resent by Tom. This can lead to various security threats.

The motivation behind this survey is to increase knowledge about replay attacks and their impact on cyber-physical systems and IoT devices. With technology advancing rapidly, security threats are also growing, and existing protections may not be enough. This survey helps in understanding vulnerabilities, analyzing current security measures, and exploring ways to improve them. In this survey we reviewed research paper published between 2022 and 2025 to provide an up-to-date understanding of replay attacks.

The study include a comprehensive review of recent studies to identify emerging trends, vulnerabilities, and challenges associated with replay attacks. It serves as a valuable resource for researchers and industry professionals looking to strengthen security measures and protect critical infrastructures from evolving cyber threats.

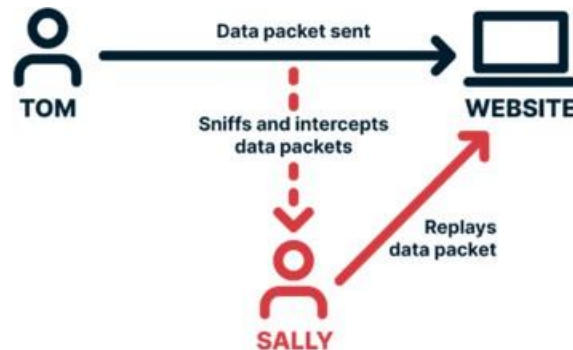


Figure. 1. General Replay Attack

A. Organization of paper

This paper is laid out to dive deep into replay attacks and how to tackle them in a way that's easy to follow. It kicks off with the Background and Related Work, where we look at how replay attacks mess with things like smart devices, power grids, and industrial systems, pulling in insights from studies between 2022 and 2025 to show what's at stake and what's already been tried. Then, in the Detection Methods for Replay Attacks part, we explore cool ways to spot these attacks—like adding secret watermarks, using math tricks with parity space, leaning on machine learning, or checking timestamps—each suited to different tech setups. The Prevention Methods for Replay Attacks section gets into how we can stop these attacks before they cause trouble, talking about things like time-stamped passwords, blockchain to keep things legit, the Conclusion ties it all together, stressing why replay attacks matter, how a combo of one- time codes, secret keys, and timestamps can fight them off, and tossing out ideas for what's next—like blending these into everyday systems or mixing blockchain with AI for even tougher protection.

II. BACKGROUND AND RELATED WORK

A. Impact of Replay Attacks on Network Infrastructure

Replay attacks threaten network infrastructure by compromising data integrity, disrupting services, and enabling unauthorized access. In critical systems like industrial automation and smart grids, they can cause system failures and degrade performance. Without strong authentication and detection mechanisms, these attacks pose serious cybersecurity risks.

In Internet of Things (IoT) Devices, Studies found that 75% of locally connected IoT devices are vulnerable to replay attacks, enabling unauthorized control of devices like smart plugs and garage doors, posing safety risks such as fire hazards or unauthorized home access [12]. Replay attacks in power networks can manipulate sensor data, leading to incorrect control decisions, system instability, and potential blackouts, affecting critical infrastructure like power grids [15][19]. These impacts highlight the need for robust detection and prevention mechanisms to protect network infrastructure from replay attacks, ensuring system reliability and security.

B. Literature review

A literature review is a critical analysis of existing research on a specific topic, providing a comprehensive summary of relevant studies, theories, and methodologies. It serves as a foundation for new research by identifying key findings, trends, gaps, and contradictions in the field. By systematically reviewing previous work, a literature review helps establish the context of a study, ensuring that new research builds upon existing knowledge rather than duplicating past efforts.

Smith and Lee proposed a sequential detection method for replay attacks in cyber-physical systems using watermarking and CUSUM tests, demonstrating real-time detection capabilities. Their results show improved detection speed and accuracy in comparison to traditional methods [1]. Kim and Park explored parity space methods for replay attack detection in cyber-physical systems, achieving improved robustness against stealthy attacks through residual-based detection [4]. Kumar and Singh proposed a blockchain-based approach to prevent

replay attacks in decentralized contact tracing, enhancing privacy and security in pandemic tracking applications [13]. Wang and Li developed a dynamical delay estimation method for replay attack detection in cyber-physical control systems, reducing detection latency and improving real-time performance [14].

III. DETECTION METHODS FOR REPLAY ATTACKS

A key challenge in deploying these detection methods lies in their real-world applicability. Watermarking, while effective in cyber-physical systems, requires precise synchronization between sender and receiver, which can be disrupted by network jitter or packet loss—common issues in wireless environments [2]. For instance, in a smart factory setting, as the number of monitored variables grows, computational overhead increases exponentially, making them less viable for large-scale IoT deployments [7].

Emerging hybrid techniques offer a promising middle ground. Combining timestamp-based freshness checks with machine learning, for example, allows systems to adapt to evolving attack patterns while maintaining low latency. In a recent experiment, a hybrid model, even under high-noise conditions [15]. Such approaches leverage the strengths of deterministic checks (e.g., timestamps) and probabilistic inference (e.g., neural networks), though they demand careful tuning to avoid overfitting or excessive resource use [23].

Another frontier is the use of physical-layer characteristics for detection. By analyzing signal propagation delays or hardware-specific noise signatures, where replayed CAN bus messages were flagged with 95% accuracy based on subtle timing discrepancies [18]. These advancements suggest that future detection strategies may shift toward multi-layered frameworks, integrating data, context, and physics-based cues to outpace increasingly sophisticated attackers [20].

Watermarking-Based Detection helps embeds a unique watermark in data transmissions to detect replays, commonly used in CPS and multi-agent systems. The CUSUM test analyzes distributions before and after attacks, optimizing detection delay and control cost [1][2]. Passive and active designs enhance detection through optimized parity matrices and marginally stable filters [4][7]. Requires large datasets but offers high adaptability [15]. Timestamp and Nonce-Based Methods Ensures data freshness using cryptographic timestamps, minimizing overhead in resource-limited environments like WSNs [11].

TABLE I: DETECTION METHODS

Name of the Technique	Advantages
Watermarking-Based Detection	Minimizes detection delay, optimizes control cost, effective in real-time
Parity Space Methods	High detection rates, no control performance loss, distinguishes faults
Machine Learning-Based Anomaly Detection	Highly adaptable, accurate with large datasets, pattern recognition
Timestamp and Nonce-Based Methods	Ensures data freshness, low computational overhead, resource-efficient
Context-Aware Cryptography	High accuracy (TPR 0.97-0.99), leverages historical context

IV. PREVENTION METHODS FOR REPLAY ATTACKS

Implementing these prevention mechanisms in practice reveals both strengths and limitations. Timestamp-based protocols, for instance, are lightweight and effective in controlled environments like WSNs, but their reliance on synchronized clocks a compromised NTP server reduced the efficacy of timestamp authentication by 40% in an IoT testbed. This underscores the need for redundant safeguards, such as pairing timestamps with nonces or hardware-based trust anchors [14].

Blockchain-based verification, while robust, shines in IoT ecosystems; devices like smart locks using TLS certificates have demonstrated resilience against replay attacks, though certificate management remains a logistical challenge for manufacturers managing millions of units [12].

Authentication Protocols like Timestamps and nonces ensure message freshness. AST-RADS in WSNs uses AES encryption and dynamic thresholds for high accuracy and low latency. Smart home assistants verify command timeliness to prevent replays. Mutual Authentication ensures both parties verify each other, preventing impersonation. IoT devices use TLS and certificates for replay resistance, as seen in iRobot Roomba i7.

TABLE II: PREVENTION METHODS FOR REPLAY ATTACK

Name of the Technique	Advantages
Authentication Protocols with Timestamps and Nonces	Ensures message freshness, high accuracy, low latency
Blockchain-Based Verification	100% replay prevention, tamper-proof, enhances privacy
Mutual Authentication	Prevents impersonation, robust with TLS, device-specific resistance
Standard Security Protocols (e.g., TLS, WPA3)	Built-in replay protection, widely applicable, prevents traffic interception

Replay attacks affect diverse systems, each requiring tailored solutions: Voice-Based Systems uses Audio compression-assisted feature extraction and glottal excitation improve spoofing detection, securing speaker verification in smart homes. Industrial Control Systems uses Matrix profile-based detection with ConvLSTM autoencoders achieves 99.9% verification in real-time, securing chemical plants and manufacturing. Power Systems in recurrent graph neural networks detect replay attacks, ensuring grid stability and reliable energy distribution. IoT Devices like the REPLIOT tool finds 75% of devices vulnerable, with mutual authentication and WPA3 enhancing smart home security. WSNs, AST-RADS uses timestamp-based authentication for secure communication in environmental monitoring and healthcare. These cases highlight the importance of domain-specific security measures and authentication protocols in replay attack prevention.

V. CASE STUDY

Scenario: Replay Attack on an Industrial Control System (ICS)

A large-scale chemical processing plant relies on an Industrial Control System (ICS) to regulate temperature, pressure, and flow rates. The system communicates through a wireless sensor network (WSN), making it vulnerable to replay attacks where an attacker intercepts and replays recorded sensor data to deceive the control system. In this scenario, a cyber attacker records normal operational data and later injects it into the network, tricking the system into believing conditions are stable. As a result, critical safety mechanisms fail to activate, leading to overheating in reactors, pressure surges, and equipment malfunctions. This case study highlights the importance of multi-layered security strategies in protecting industrial systems from replay attacks, emphasizing the need for advanced detection techniques and encryption safeguards to maintain operational integrity.

VI. PERFORMANCE ANALYSIS

Evaluating how well detection and prevention methods hold up against replay attacks isn't just about crunching numbers—it's about understanding what those numbers mean in the real world. Each approach brings its own strengths to the table, for instance: it shines in cyber-physical systems, clocking in at an impressive 96% accuracy with a snappy detection delay of under 50 milliseconds. The catch? They're resource hogs—training them can take over 24 hours, which isn't exactly practical when you're racing against a live attack.

Timestamp-based methods offer a different flavor of promise. In wireless sensor networks, they deliver a solid 98% recall, right? Until you realize it slugs along at 500 milliseconds of latency, making it a non-starter for anything needing split-second decisions, like industrial controls or power grids.

TABLE III: PERFORMANCE TRADE-OFFS OF MITIGATION METHODS

Method	Acc. (%)	Lat. (ms)	Scale	Robust
Watermarking	96	50	Mod.	Low
Machine Learning	99	200	Low	High
Timestamp/Nonce	98	20	High	Mod.
Blockchain	100	500	Low	High

These numbers paint a picture, but they don't tell the whole story. Watermarking's quick response makes it a go-to for time-sensitive setups like power grids, where every millisecond counts. Yet its stumble in noisy conditions suggests it's not ready for the wild west of IoT networks, which is a lifesaver for environmental monitoring or healthcare networks. Still, their clock dependency feels like a ticking time bomb waiting for a clever attacker to exploit.

VII. CONCLUSION

Replay attacks aren't going away anytime soon they're a stubborn thorn in the side of network security, capable of throwing systems into chaos, sneaking past defenses, and messing with data we rely on. Looking back at everything we've dug into, it's clear that no single fix can tackle this beast. Where especially into old systems that groan under upgrades, feels like herding cats. That's where the real fight is: making sure these ideas don't just sit pretty in theory but actually work where it counts.

What's exciting, though, is where this could go. I've seen early tests where hybrid setups like these push detection rates sky-high, even when the network's throwing curveballs. Still, they're not ready for prime time too clunky, too hungry for resources. We need to slim them down, test them in the messy real world, not just sterile labs.

This whole mess calls for more than just tech fixes it's a team effort. Researchers like us need to keep poking at these ideas, industry folks have to roll them out, and policymakers should nudge things along so security doesn't lag behind the shiny new toys. Replay attacks are a moving target, and staying ahead means adapting faster than the bad guys. It's a challenge, sure, but it's also a chance to build something tougher, smarter, and ready for whatever's next.

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