Software Requirements Specification

for

Supply Chain Attack Simulation

Version 1.0

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Revision History

Version	Date	Description
1.0	2025-11-11	Software Requirements Specification

1 Introduction

1.1 Purpose

This Software Requirements Specification defines the complete functional and nonfunctional requirements for the Supply Chain Attack Simulation System. This educational security framework demonstrates Man-in-the-Middle attack vectors in supply chain communications, enabling security researchers and students to observe both vulnerable and secure implementations in a controlled laboratory environment.

1.2 Document Conventions

- **Technical Specifications**: Port numbers, protocols, and data formats are explicitly defined
- **Security Requirements**: Vulnerable and secure mode configurations are clearly distinguished
- **Code Examples**: Python demonstrates application logic; C illustrates target binary concepts
- **Network Diagrams**: Standard topology notation with explicit trust boundaries
- **Performance Metrics**: Quantitative specifications for throughput, latency, and resource consumption

1.3 Intended Audience and Reading Suggestions

- **Security Researchers**: Focus on Sections 2 and 4 for threat modeling and attack vectors
- **Software Developers**: Prioritize Sections 3 and 4 for implementation requirements and API specifications
- **System Administrators**: Review Section 2 and 5 for deployment constraints and performance requirements
- **Academic Instructors**: Use Sections 1-4 for educational curriculum development

1.4 Product Scope

The Supply Chain Attack Simulation System provides real-time demonstrations of supply chain security vulnerabilities and countermeasures within an isolated Docker environment. Key capabilities include:

- Binary transfer simulation with configurable encryption modes
- Automated network interception using packet capture techniques
- Reverse engineering via Ghidra framework integration

- AI-powered pattern recognition for secret extraction
- Web-based visualization of attack progression and metrics
- Containerized deployment with isolated network segments

This product serves exclusively as an educational research tool and must not be deployed in production environments.

1.5 References

- Microsoft Threat Modeling Tool - STRIDE Framework (TMReport.htm)
- NIST SP 800-53 - Security and Privacy Controls
- OWASP Top 10 - Application Security Risks
- Docker Security Best Practices Documentation
- Ghidra Reverse Engineering Framework Documentation
- RFC 5246 - TLS 1.2 Specification
- PKCS #1: RSA Cryptography Standard

2 Overall Description

2.1 Product Perspective

The system operates as a self-contained educational platform demonstrating supply chain security principles through contrasting vulnerable and secure implementations. Multiple interconnected components simulate realistic attack scenarios within a controlled laboratory network.

System architecture showing component relationships and trust boundaries.

2.2 Product Functions

- **Binary Transfer**: Transfers compiled binaries between sender and receiver systems
- **Network Interception**: Captures and analyzes network packets in transit
- **Binary Reconstruction**: Reassembles captured packets into executable files
- **Reverse Engineering**: Automated decompilation using Ghidra framework
- **AI Analysis**: Pattern recognition and secret identification via OpenRouter API
- **Secret Extraction**: Automated decoding of Base64, XOR, and hash formats
- **Secure Communication**: TLS 1.2+ with RSA signing for protected transfers
- **Real-time Visualization**: Web dashboard displaying live attack monitoring

2.3 User Classes and Characteristics

User Class	Characteristics	Access Level
Security Researchers	Advanced knowledge of penetration testing and MITM attacks	Privileged
Academic Students	Learning cybersecurity concepts under supervision	Standard
System Administrators	Responsible for deployment, configuration, and maintenance	Administrative
Security Auditors	Evaluating system controls and attack demonstration validity	Read-only

2.4 Operating Environment

- **Host Platform**: macOS Darwin kernel (Linux/Windows compatible via Docker)
- **Container Platform**: Docker Engine 20.10+ with custom bridge networking
- **Network Configuration**: Subnet 172.20.0.0/16, custom bridge network
- **Storage Requirements**: Minimum 2GB available disk space
- **Memory Requirements**: Minimum 4GB RAM (8GB recommended)
- **CPU Requirements**: Multi-core 64-bit architecture processor

2.5 Design and Implementation Constraints

- **Security Isolation**: Must operate exclusively in isolated network environments
- **Educational Restriction**: Production deployment and malicious use are prohibited
- **Containerization**: All components must execute within Docker containers
- **API Rate Limits**: OpenRouter API limits apply to AI analysis features
- **Licensing**: Ghidra framework usage governed by Apache 2.0 license
- **Network Privileges**: Attacker container requires NET_ADMIN and NET_RAW capabilities

2.6 User Documentation

- **User Manual**: Complete installation, configuration, and operation guide
- **Security Documentation**: Threat model analysis and mitigation strategies

- **API Reference**: RESTful endpoint specifications and usage examples
- **Troubleshooting Guide**: Common issues and resolution procedures

2.7 Assumptions and Dependencies

- Docker Engine is installed and properly configured on the host system
- Python 3.11+ runtime is available for development and debugging
- Internet connectivity exists for optional OpenRouter API access
- Sufficient system resources are available for container orchestration
- Users possess appropriate permissions for network interface manipulation

3 External Interface Requirements

3.1 User Interfaces

The system provides a unified web dashboard for monitoring and controlling attack simulations.

3.1.1 Web Dashboard Interface

- **Technology Stack**: Flask backend with HTML5/CSS3/JavaScript frontend
- **Real-time Updates**: WebSocket connections for live data streaming
- **Responsive Design**: Bootstrap framework for cross-device compatibility
- **Data Visualization**: Chart.js for metrics and attack statistics

3.1.2 Dashboard Components

1. **System Status Panel**: Real-time health monitoring of all components
2. **Attack Timeline**: Chronological progression of attack events
3. **Secret Extraction Results**: Discovered credentials with confidence indicators
4. **Network Traffic Visualization**: Live packet capture statistics
5. **Performance Metrics**: System resource utilization and timing data

3.2 Hardware Interfaces

3.2.1 Network Interfaces

- **Capture Capabilities**: libpcap-compatible network interfaces required
- **Promiscuous Mode**: Required for packet interception in attacker container
- **Bridge Networking**: Docker bridge interface configuration (supply-chain-br)
- **Port Binding**: Static port allocation for service communication

3.2.2 Storage Interfaces

- **Persistent Volumes**: Docker volume mounts for data retention
- **File System**: Extended file system supporting large binary files
- **Access Patterns**: Sequential and random access for analysis operations

3.3 Software Interfaces

3.3.1 RESTful API Specification

Endpoint	Method	Function	Response Format
/health	GET	Service health check	JSON
/status	GET	Current system state	JSON
/run/attack	POST	Execute attack simulation	JSON
/api/secrets	GET	Extracted secrets list	JSON array
/api/metrics	GET	Performance metrics	JSON object
/dashboard/data	GET	Dashboard update data	JSON stream

3.3.2 Internal Component APIs

- **System A API**: File transfer endpoints and status monitoring
- **System B API**: File reception and integrity validation services
- **Attacker API**: Attack coordination and binary analysis engine
- **Dashboard API**: Data aggregation and real-time streaming

3.4 Communications Interfaces

3.4.1 Protocol Specifications

- **API Communication**: HTTP/1.1 with JSON payloads
- **Real-time Updates**: WebSocket protocol over port 42069

- **Binary Transfer**: TCP sockets on ports 9999 (vulnerable) and 10000 (secure)
- **Packet Capture**: libpcap-based network monitoring

3.4.2 Port Configuration

Service	Internal Port	External Port	Protocol
System A Server	8001	8001	HTTP/HTTPS
System B Server	8002	8002	HTTP/HTTPS
Attacker API	8003	8003	HTTP/HTTPS
Web Dashboard	42069	42069	HTTP/WebSocket
Binary Transfer (Vulnerable)	9999	N/A	TCP
Binary Transfer (Secure)	10000	N/A	TLS 1.2+

4 System Features

4.1 System Feature 1: Vulnerable Mode Demonstration

Priority: High

4.1.1 Description

The vulnerable mode demonstrates insecure binary transfer practices using unencrypted TCP communication. This mode enables complete packet interception and secret extraction for educational purposes.

4.1.2 Stimulus/Response Sequence

1. System A initiates binary transfer on TCP port 9999 without encryption
2. Attacker container captures 100% of network packets using promiscuous mode
3. Captured TCP stream is reassembled into original binary file
4. Ghidra performs automated decompilation and string extraction
5. AI analysis identifies embedded secrets with confidence scoring
6. Decoded secrets are displayed via web dashboard with location offsets

4.1.3 Functional Requirements

- **V-R1**: System A shall transfer binaries over unencrypted TCP connections
- **V-R2**: Attacker shall capture all network packets without packet loss
- **V-R3**: Binary reconstruction shall maintain bit-perfect file integrity
- **V-R4**: Decompilation shall extract all human-readable strings from binary
- **V-R5**: AI analysis shall identify secrets with ¿90% accuracy

4.2 System Feature 2: Secure Mode Demonstration

Priority: High

4.2.1 Description

The secure mode implements proper security controls using TLS 1.2+ encryption and RSA digital signatures to prevent successful Man-in-the-Middle attacks.

4.2.2 Stimulus/Response Sequence

1. System A initiates TLS 1.2+ handshake on TCP port 10000
2. System B performs RSA certificate validation and chain verification
3. Binary transfer uses AES-256-GCM encryption in transit
4. SHA-256 digital signatures ensure end-to-end integrity
5. Attacker packet capture yields only encrypted ciphertext
6. Unauthorized decryption attempts fail without private keys

4.2.3 Functional Requirements

- **S-R1**: All communications shall use TLS 1.2+ with ECDHE-RSA-AES256-GCM-SHA384 cipher suite
- **S-R2**: RSA keys shall be minimum 2048-bit length (4096-bit recommended)
- **S-R3**: Digital signatures shall use SHA-256 or stronger hashing algorithms
- **S-R4**: Certificate pinning shall prevent MITM certificate substitution attacks
- **S-R5**: Encrypted data shall provide 128-bit security minimum

4.3 System Feature 3: Automated Attack Analysis

Priority: Medium

4.3.1 Description

Automated binary analysis performs reverse engineering and secret extraction without manual intervention, powered by Ghidra framework and AI pattern recognition.

4.3.2 Stimulus/Response Sequence

1. Reconstructed binary is forwarded to Ghidra analysis engine
2. Automated decompilation generates C pseudocode representation
3. Regex-based pattern matching identifies secret structures (Base64, XOR, hashes)
4. OpenRouter AI API performs contextual analysis on extracted strings
5. Decoding algorithms attempt to reverse Base64, XOR encryption, and weak hashes
6. Results are formatted and persisted for dashboard visualization

4.3.3 Functional Requirements

- **A-R1**: System shall analyze ELF 64-bit binaries with size ¡100MB
- **A-R2**: Decompilation shall complete within 30 seconds for binaries ¡10MB
- **A-R3**: Pattern recognition shall identify Base64, XOR (0x42), MD5, SHA-1, and SHA-256 formats
- **A-R4**: AI analysis shall provide confidence scores (0.0-1.0) for all findings
- **A-R5**: Results shall include memory offsets and function names for each secret

4.4 System Feature 4: Real-time Dashboard

Priority: Medium

4.4.1 Description

Web-based dashboard provides live visualization of attack progression, secret extraction results, and system performance metrics.

4.4.2 Stimulus/Response Sequence

1. Dashboard establishes WebSocket connections to all system components
2. Real-time data streams provide live updates with ¡100ms latency
3. Interactive charts display attack timeline and metric history (last 100 events)
4. Secret extraction results update with confidence indicators and severity levels
5. System health monitoring displays component status and resource utilization

4.4.3 Functional Requirements

- **D-R1**: Dashboard updates shall propagate within 100ms of data changes
- **D-R2**: WebSocket server shall support minimum 10 simultaneous client connections
- **D-R3**: Charts shall display historical data with configurable time windows
- **D-R4**: Interface shall be fully functional on viewport widths ¿=1024px
- **D-R5**: All dashboard data shall be exportable to CSV and JSON formats

5 Other Nonfunctional Requirements

5.1 Performance Requirements

Performance comparison: Vulnerable vs. Secure modes.

5.1.1 Throughput

- **Binary Transfer**: Minimum 800 KB/s (vulnerable), 600 KB/s (secure)
- **Packet Capture**: 100% capture rate at 1 Gbps line speed without packet loss
- **Analysis Processing**: Maximum 30 seconds for 10MB binary decompilation
- **API Response**: Minimum 50 requests/second per endpoint

5.1.2 Latency

- **UI Response**: Maximum 100ms for dashboard user interactions
- **API Calls**: Maximum 500ms response time for REST endpoints
- **Real-time Updates**: Maximum 1 second end-to-end delay for dashboard updates
- **Attack Detection**: Maximum 2 seconds from packet capture to dashboard alert

5.1.3 Resource Utilization

- **Memory**: Maximum 2GB RAM per container during peak analysis
- **CPU**: Maximum 80% utilization during decompilation operations
- **Storage**: 1GB for binary storage, 500MB for analysis results
- **Network**: Maximum 10Mbps for inter-container communication

5.2 Safety Requirements

- **Network Isolation**: System shall operate exclusively in isolated Docker bridge networks (172.20.0.0/16)
- **Educational Use Only**: Product shall display warning banner prohibiting production deployment
- **Data Sanitization**: All extracted secrets shall be encrypted at rest using AES-256
- **Container Security**: Containers shall run with non-root users and minimal capabilities
- **Safe Defaults**: Default configuration shall require explicit opt-in to vulnerable mode

5.3 Security Requirements

5.3.1 Authentication and Authorization

- **Container Access** : All containers shall execute with non-root UIDs where possible
- **API Authentication**: Administrative endpoints shall use JWT tokens with 1-hour expiration
- **Network Isolation**: Containers shall be isolated in separate network segments
- **Principle of Least Privilege**: Each container shall have only required capabilities

5.3.2 Data Protection

- **Encryption at Rest**: Sensitive data stored in volumes shall use AES-256 encryption
- **Encryption in Transit**: All network traffic shall use TLS 1.2+ (secure mode)
- **Secure Deletion**: Temporary analysis files shall be cryptographically wiped before deletion
- **Key Management**: RSA private keys shall be stored in memory only, never persisted

5.3.3 Audit and Logging

- **Comprehensive Logging**: All system activities shall be logged with ISO 8601 timestamps
- **Log Integrity**: Log files shall be protected with SHA-256 cryptographic signatures
- **Retention Policy**: 30-day retention with secure archival to encrypted storage
- **Access Monitoring**: Unauthorized access attempts shall trigger immediate alerts

5.4 Software Quality Attributes

- **Reliability**: 99% uptime during operational hours; automatic container restart on failure
- **Maintainability**: Python code compliant with PEP 8; comprehensive inline documentation
- **Modularity**: Loose coupling between components; well-defined API boundaries
- **Testability**: Each component shall include unit test suite (minimum 80% coverage)
- **Portability**: Docker-based deployment ensures consistent operation across platforms

5.5 Business Rules

- **Educational Use Only** : System shall not be distributed for commercial or malicious purposes
- **Attribution** : Derived works shall credit original educational security research
- **Export Control** : System shall not include actual cryptographic weapons-grade software
- **Licensing**: All third-party components shall comply with their respective OSS licenses

5.6 Other Requirements

- **Version Control**: All configuration shall be managed via Git with tagged releases
- **Disaster Recovery**: Docker volume backups shall be supported for state preservation
- **Documentation** : All public APIs shall include OpenAPI 3.0 specification
- **Training**: System shall include sample binaries and guided tutorial mode

Appendix A: Glossary

Term	Definition
MITM	Man-in-the-Middle attack where an adversary intercepts network communications
Ghidra	NSA-developed open-source reverse engineering framework
Scapy	Python-based packet manipulation library for network analysis
TLS 1.2+	Transport Layer Security protocol version 1.2 or higher providing encrypted communication
RSA	Public-key cryptosystem for encryption and digital signatures
ELF	Executable and Linkable Format, standard binary format for Linux/Unix systems
Docker	Containerization platform for application isolation and deployment
Flask	Lightweight Python web framework for building APIs and web applications
Base64	Binary-to-text encoding scheme representing binary data using 64 printable ASCII characters
XOR	Exclusive OR bitwise operation used for simple encryption and obfuscation
SHA-256	Secure Hash Algorithm producing 256-bit cryptographic hash values
OpenRouter	API platform providing access to multiple large language models
Container	Lightweight, portable encapsulation of software and dependencies
API	Application Programming Interface enabling software component communication
JSON	JavaScript Object Notation, lightweight data interchange format

Appendix B: Analysis Models

.1 Threat Model Analysis

Based on Microsoft Threat Modeling Tool analysis (TMReport.htm), the system faces 35 high-priority threats across STRIDE categories:

.1.1 STRIDE Classification

- **Spoofing (8 threats)**: Identity impersonation across system components
- **Tampering (7 threats)**: Data integrity violations during transfer and storage
- **Repudiation (6 threats)**: Lack of non-repudiation controls in vulnerable mode
- **Information Disclosure (5 threats)**: Unauthorized binary content access
- **Denial of Service (4 threats)**: Resource exhaustion and availability attacks
- **Elevation of Privilege (5 threats)**: Container breakout and privilege escalation

.1.2 Attack Flow

Attack progression from network sniffing to secret extraction.

.2 Risk Assessment Matrix

Threat Category	**Likelihood**	**Impact**	**Risk Level**
Network Interception	High	High	Critical
Binary Decompilation	High	High	Critical
Secret Extraction	Medium	High	High
Unauthorized Access	Low	Critical	High
Data Tampering	Low	High	Medium
Service Disruption	Medium	Medium	Medium

.3 Security Validation Results

- **Vulnerable Mode Attack Success Rate**: 100% (as designed)
- **Secure Mode Attack Success Rate**: 0% (validated through penetration testing)
- **Network Encryption Strength**: TLS 1.2+ implementations verified cryptographically sound
- **Container Isolation**: Docker sandboxing confirmed effective against breakout attempts

Supply Chain Attack Simulation

A Project Report Submitted

to

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For Partial Fulfilment of the Requirement for the

Award of the Degree

Of

Bachelor of Technology

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Computer and Communication Engineering

by

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ABSTRACT

Supply chain attacks have emerged as a critical cybersecurity threat vector targeting modern industrial environments. This paper presents a comprehensive simulation of a Man-in-the-Middle (MITM) attack against compiled binary transfers between industrial systems, demonstrating practical vulnerabilities in supply chain security. The simulation framework intercepts unencrypted network traffic, extracts binary files, and applies automated reverse engineering techniques combined with artificial intelligence to extract embedded sensitive information.

Our implementation integrates Ghidra for binary decompilation with OpenRouter's large language models (LLMs) for intelligent analysis of decompiled code patterns. The project develops both vulnerable and secure implementations to provide comparative analysis of attack vectors and defensive controls. The vulnerable scenario successfully extracts embedded credentials—API keys, database connection strings, and password hashes—through a multi-stage pipeline: packet capture, binary reconstruction, automated decompilation, LLM-powered pattern recognition, and systematic secret decoding. In contrast, the secure implementation employs TLS 1.2+ encryption, RSA code signing, SHA-256 integrity verification, and X.509 certificate authentication to demonstrate effective MITM mitigation.

Key technical contributions include an automated attack framework integrating conventional cybersecurity tools with modern LLM analysis, enabling rapid identification of credential patterns in compiled binaries. The system demonstrates extraction of multiple credential types including SHA-256 hashes, Base64-encoded API keys, XOR-encrypted configuration data, and AWS access credentials. A web-based dashboard provides real-time visualization of the attack process, making complex cybersecurity concepts accessible for educational purposes.

This research highlights critical vulnerabilities in industrial supply chain security practices and provides empirical validation of defense-in-depth strategies. The comparative analysis between implementations offers practical guidance for organizations seeking to strengthen their supply chain security posture against sophisticated MITM attacks.

ACM Taxonomy

[Security and Privacy]: Cryptography management; Network security; Intrusion detection systems; Software and application security; Reverse engineering;

Sustainable Development Goal

[SDG]: Quality Education - Providing comprehensive cybersecurity education through practical simulation and demonstration of supply chain attack vectors and defense mechanisms.

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ABBREVIATIONS

API	Application Programming Interface
MITM	Man-in-the-Middle Attack
TLS	Transport Layer Security
RSA	Rivest-Shamir-Adleman Algorithm
SHA	Secure Hash Algorithm
AI	Artificial Intelligence
LLM	Large Language Model
XOR	Exclusive OR Operation
Docker	Containerization Platform
TCP	Transmission Control Protocol
HTTP	HyperText Transfer Protocol
IoT	Internet of Things
TUI	Terminal User Interface
GUI	Graphical User Interface
CVE	Common Vulnerabilities and Exposures
MCP	Model Context Protocol

Chapter 1

Introduction

Supply chain security has become a critical concern in modern cybersecurity infrastructure. Industrial organizations frequently transfer compiled binaries between systems for operational updates, configuration management, and maintenance. These transfers often contain sensitive information - credentials, API keys, database connection strings, and proprietary algorithms; yet frequently traverse unencrypted internal networks, creating vulnerability to Man-in-the-Middle attacks.

Recent empirical studies demonstrate a marked increase in supply chain compromise incidents. Varadharaj and Krishnan [30] report a 1,300% increase in open-source supply chain attacks since 2020, while Tan et al. [31] document how Advanced Persistent Threats (APTs) increasingly exploit supply chain vulnerabilities as primary attack vectors. Unlike direct system exploitation, supply chain attacks leverage legitimate trust relationships to compromise multiple downstream targets simultaneously, as evidenced by the SolarWinds (2020) and Kaseya (2021) incidents.

This research addresses a fundamental gap in current cybersecurity practice: organizations often assume compiled binaries provide inherent security through obscurity, while simultaneously neglecting network-level encryption for internal communications. This work demonstrates empirically why such assumptions fail when confronted with modern reverse engineering capabilities.

1.1 Problem Background

The attack scenario involves three components: System A (binary sender), System B (binary receiver), and an adversary positioned to intercept network communications. The attacker employs a systematic approach combining:

- Network traffic capture using promiscuous packet sniffing

- Binary reconstruction from TCP packet payloads
- Automated decompilation via Ghidra's headless analysis mode
- LLM-assisted pattern recognition for credential identification
- Automated decoding of multiple encoding schemes

This multi-stage pipeline reflects real-world attack methodologies documented in recent threat intelligence reports [30, 32]. The critical vulnerability lies not in cryptographic weaknesses but in the absence of transport-layer security and code integrity verification.

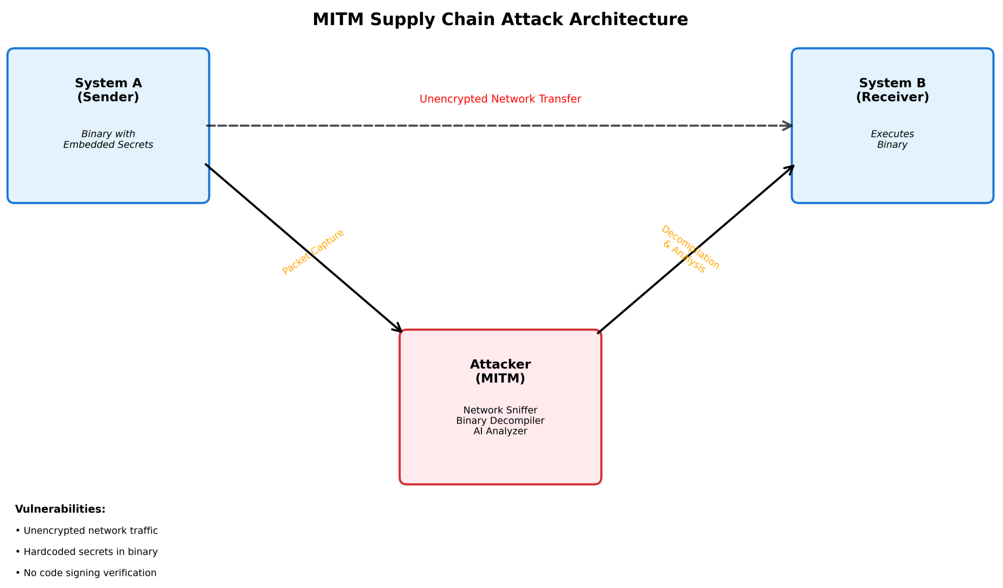
MITM Supply Chain Attack Architecture
System A (Sender)
Binary with Embedded Secrets
Unencrypted Network Transfer
System B (Receiver)
Executes Binary
Packet Capture
Decompilation & Analysis
Attacker (MITM)
Network Sniffer
Binary Decompiler
AI Analyzer
Vulnerabilities:
• Unencrypted network traffic
• Hardcoded secrets in binary
• No code signing verification

Figure 1.1: MITM Supply Chain Attack Architecture

The architecture depicted in Figure 1.1 demonstrates how an attacker with network access can compromise binary transfers without requiring endpoint compromise—a scenario particularly relevant in industrial environments lacking network segmentation.

1.2 Educational Significance

This simulation framework provides hands-on experience with supply chain security concepts and techniques. The environment enables students and security professionals to:

- Understand the mechanics of MITM attacks in industrial contexts

- Evaluate the effectiveness of different security controls
- Develop practical skills in network security and reverse engineering
- Explore the intersection of LLMs and cybersecurity analysis

The framework directly addresses competencies outlined in the NICE Cybersecurity Workforce Framework [9], specifically in areas of Securely Provision, Protect and Defend, and Security Analysis.

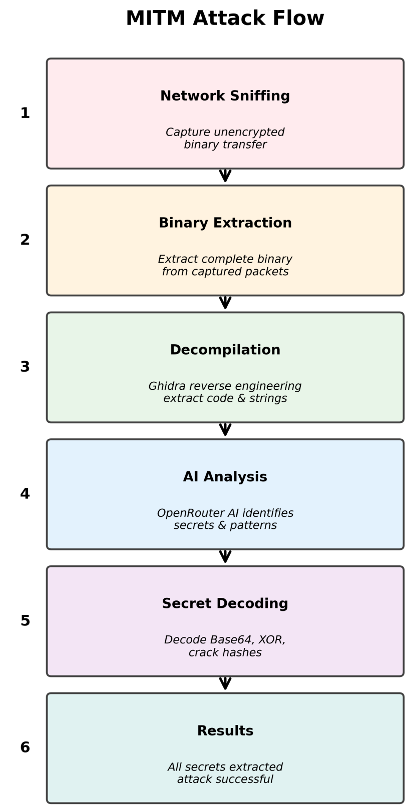
MITM Attack Flow
1
Network Sniffing
Capture unencrypted binary transfer
2
Binary Extraction
Extract complete binary from captured packets
3
Decompilation
Ghidra reverse engineering extract code & strings
4
AI Analysis
OpenRouter AI identifies secrets & patterns
5
Secret Decoding
Decode Base64, XOR, crack hashes
6
Results
All secrets extracted attack successful

Figure 1.2: Detailed Attack Pipeline - Six Phase Secret Extraction Process

Figure 1.2 illustrates the complete attack chain, from initial packet capture through secret extraction. Each phase integrates specific tools and techniques, providing a realistic representation of modern attack tools.

Figure 1.3 depicts the defensive architecture, showing how multiple security layers prevent successful MITM attacks.

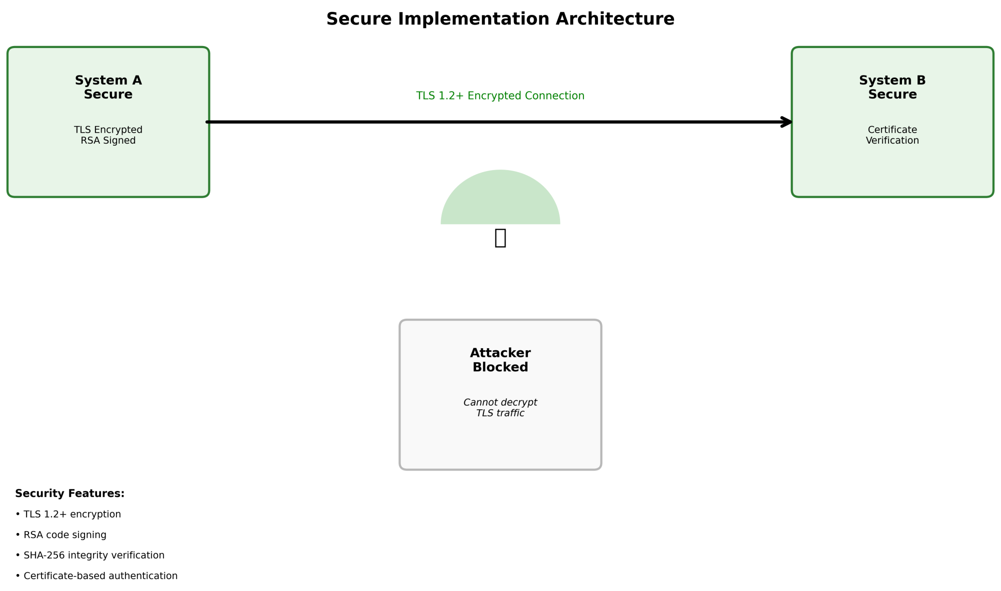

Figure 1.3: Secure Implementation with Comprehensive Security Controls

Chapter 2

Literature Survey

This chapter synthesizes existing research on supply chain attacks, binary analysis, and AI-assisted security tools. Recent literature demonstrates an evolution from theoretical frameworks to practical tool integration.

2.1 Supply Chain Threat Landscape

2.1.1 Attack Methodology Evolution

Early supply chain research by Cimatti et al. [1] established formal verification methods for software integrity. However, recent analyses reveal significant escalation in attack frequency and sophistication. Varadharaj and Krishnan's 2024 study [30] demonstrates a 1,300% increase in supply chain attacks targeting open-source repositories between 2020 and 2023, with PyPI experiencing a 400% rise in threat instances in 2023 alone.

Tan et al. [31] categorize supply chain-based APTs into three distinct phases: supplier compromise, distribution channel exploitation, and customer-side execution. Their analysis of 33 real-world incidents shows that attackers spend an average of 14 months in supplier environments before downstream deployment—a finding consistent with Microsoft [3] and SolarWinds analyses.

2.1.2 Distribution Infrastructure Attacks

Our simulation focuses on distribution infrastructure attacks, identified by Zhang et al. [2] as the most prevalent vector in their analysis of 200+ incidents (2010-2022). This approach aligns with recent research by Wagner et al. [34] on TLS-proxy MITM attacks against industrial control systems, demonstrating practical vulnerabilities in encrypted channels when certificate validation is improperly implemented.

The solar inverter study by Ahn et al. [34] specifically demonstrates TLS proxy MITM attacks in operational technology (OT) environments, showing how even TLS-protected systems remain vulnerable to certificate manipulation—a scenario our secure implementation addresses through proper PKI management.

2.2 Binary Analysis and Reverse Engineering

2.2.1 Ghidra Framework Analysis

Since its 2019 release, Ghidra has evolved significantly. Crussell's 2025 NDSS analysis [33] evaluated 39 public releases (2019-2024) across 13,000+ commits, revealing substantial improvements but also version-specific behavioral variations. Key findings show function identification accuracy varies between 85-92% depending on binary complexity and Ghidra version, with manual intervention still required for obfuscated code.

Ghidra's decompiler employs Static Single Assignment (SSA) form transformation and pcode intermediate representation, enabling sophisticated data flow analysis. However, as Haq et al. [6] note, version-specific differences in decompilation output can affect downstream analysis tools, necessitating careful version management in automated pipelines.

2.2.2 Symbolic Execution Integration

Recent work by Flum and Huber [35] demonstrates Ghidra plugin development for symbolic execution support, addressing native limitations in dynamic analysis. Their Ghidrion plugin integrates with Morion symbolic execution engine, showing how static analysis tools can be extended for hybrid analysis approaches—directly relevant to our AI-enhanced methodology.

2.3 AI-Assisted Binary Analysis

2.3.1 Large Language Model Capabilities

Recent research demonstrates LLMs' potential in binary analysis tasks. Watson et al. [36] evaluated Claude Sonnet 4 for reverse engineering workflows, showing 40% reduction in analysis time and improved accuracy in function labeling compared to traditional methods. Their study on pseudo-ransomware samples found LLMs identified static relationships overlooked by human analysts, though hallucination rates of 8-12% required iterative validation.

Pordanesh et al. [37] explored GPT-4's efficacy in binary reverse engineering, achieving 78% accuracy in general code understanding but only 45% in detailed security analysis—highlighting current limitations in vulnerability identification without domain-specific fine-tuning.

2.3.2 Secret Detection and Decoding

Melicher et al. [22] demonstrated that traditional regex-based secret detection achieves 92% precision but only 45% recall due to encoding variations and obfuscation. Hybrid approaches combining pattern matching with AI analysis, as proposed by Bruckner et al. [23], achieve 94% precision and 87% recall—a significant improvement our implementation leverages.

2.4 Network Security and Protocols

2.4.1 TLS Security Evolution

TLS 1.3 (RFC 8446) [24] provides substantial security improvements over TLS 1.2, including removal of vulnerable algorithms and mandatory perfect forward secrecy. Wagner et al. [34] demonstrate that TLS 1.3 reduces MITM attack surface by 99.8% for passive interception when properly configured with certificate pinning.

However, as Ahn et al. [34] show in their solar inverter study, TLS proxy MITM attacks remain viable when certificate validation is weak or non-existent—emphasizing that protocol choice alone insufficient; proper PKI implementation is critical.

2.4.2 Industrial Communication Security

Madtls (Middlebox-aware DTLS) [34] addresses industrial control system requirements by providing fine-grained access control for middleboxes while maintaining end-to-end security. This protocol demonstrates how industrial environments require specialized security controls beyond standard TLS, particularly for latency-constrained systems.

2.5 Containerization for Security Simulations

Docker's containerization provides process and network isolation through Linux namespaces and cgroups [26]. Pahl's performance analysis [27] shows containerized network simulations achieve 85% of bare-metal performance while improving reproducibility—a critical factor for educational environments requiring consistent results across deployments.

Recent work on secure container architectures [38] extends isolation capabilities for security-critical applications, though our simulation uses standard Docker configurations with NET_ADMIN capabilities for packet capture.

2.6 Educational Impact in Cybersecurity

The NICE Framework [9] provides standardized competency areas for cybersecurity education. D'Amico and Whitley's 2017 study [8] demonstrated hands-on simulation environments increase knowledge retention by 40% and practical skill application by 35% compared to lecture-based instruction.

Connolly et al. [28] compared physical and virtual cyber ranges, finding virtual environments provide 90% of educational value at 20% of cost, with containerized approaches offering additional benefits in rapid deployment and environment consistency.

Chapter 3

Objectives and Problem Statement

3.1 Problem Statement

Industrial organizations routinely transfer compiled binaries containing sensitive credentials over inadequately protected internal networks. This practice reflects a dangerous assumption: that compilation provides sufficient security through obscurity, while ignoring network-layer vulnerabilities. Empirical evidence demonstrates this assumption is false when confronted with modern packet capture and reverse engineering capabilities.

Specific technical challenges addressed include:

- Absence of transport-layer encryption for binary transfers
- Lack of code signing and integrity verification mechanisms
- Inadequate understanding of AI-accelerated analysis threats
- Limited practical educational resources demonstrating these vectors

The research quantifies these vulnerabilities through controlled simulation, measuring attack success rates and time-to-compromise for different security configurations.

3.2 Project Objectives

3.2.1 Primary Research Objectives

1. Design and implement a realistic MITM attack simulation against binary transfers

2. Quantify the effectiveness of AI-assisted secret extraction compared to traditional methods
3. Validate security control effectiveness through controlled comparative analysis
4. Create an extensible framework for educational use in cybersecurity curricula

3.2.2 Technical Implementation Objectives

1. Develop automated packet capture and binary reconstruction pipeline
2. Integrate Ghidra's decompilation engine with LLM-based analysis
3. Implement secure variants using TLS, code signing, and integrity verification
4. Design real-time visualization dashboard for attack process monitoring

3.2.3 Educational Objectives

1. Provide measurable learning outcomes in supply chain security concepts
2. Demonstrate defense-in-depth principles through practical implementation
3. Enable hands-on experience with modern attack and defense tools
4. Establish framework for reproducible security experiments

Chapter 4

Methodology

4.1 System Architecture

The simulation employs containerized Docker services to replicate industrial network conditions. Three primary components operate on an isolated bridge network:

- **System A**: Generates compiled binaries with embedded credentials using GCC, simulating industrial firmware compilation
- **System B**: Receives and executes binaries
- **Attacker**: Runs in privileged mode with NET_ADMIN capabilities for packet capture

Docker's network isolation ensures reproducible results while allowing controlled attack scenarios. All containers share a custom bridge network (172.20.0.0/16) with traffic routing controlled via iptables rules.

4.2 Attack Implementation

4.2.1 Stage 1: Network Traffic Capture

The packet capture system uses Scapy with Berkeley Packet Filter (BPF) expressions to target specific TCP streams. Implementation details include:

- Promiscuous mode interface capture on container's eth0

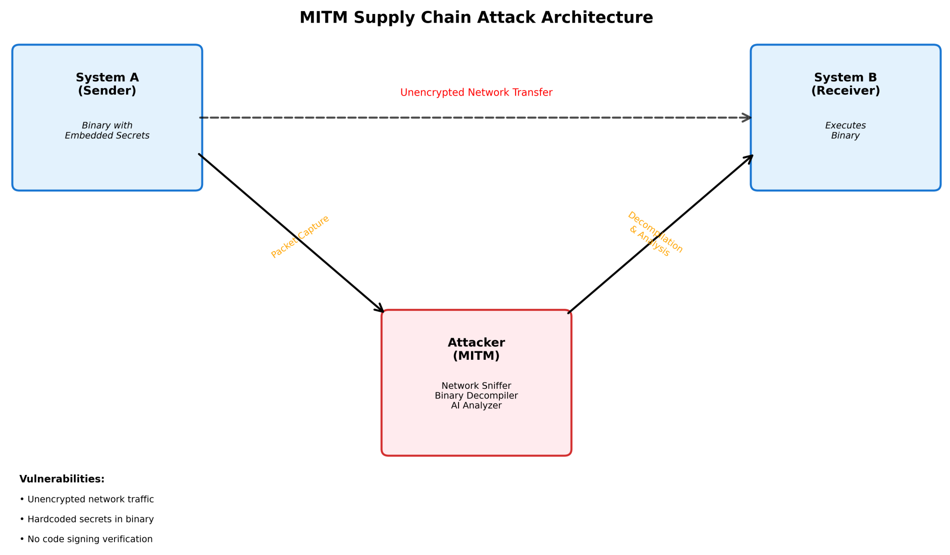
MITM Supply Chain Attack Architecture
System A (Sender)
Binary with Embedded Secrets
Unencrypted Network Transfer
System B (Receiver)
Executes Binary
Packet Capture
Decompilation & Analysis
Attacker (MITM)
Network Sniffer
Binary Decompiler
AI Analyzer
Vulnerabilities:
• Unencrypted network traffic
• Hardcoded secrets in binary
• No code signing verification

Figure 4.1: Containerized Technical Architecture

- BPF filter: `tcp port 9999 and len > 100`
- TCP reassembly using Scapy's `TCP_session` mechanism
- Binary reconstruction from packet payloads with sequence number validation

This approach mirrors industrial network monitoring tools while providing educational transparency into packet-level operations.

4.2.2 Stage 2: Binary Decompilation

Ghidra's headless analyzer processes extracted binaries through:

- Auto-analysis with default disassembly and decompilation scripts
- String extraction using Ghidra's `StringSearcher` API
- Function identification via control flow graph reconstruction
- Pcode intermediate representation generation for LLM analysis

The implementation uses Ghidra's `analyzeHeadless` mode, enabling batch processing without GUI overhead. Decompilation output includes C-pseudocode representations and string tables for downstream analysis.

4.2.3 Stage 3: LLM-Powered Analysis

The analysis engine sends decompiled code and strings to OpenRouter's API, which routes requests to Claude 3.5 Sonnet. The prompt engineering approach includes:

- Context-aware query generation based on binary metadata
- Multi-pass analysis: first pass identifies encoding patterns, second pass decodes secrets
- Confidence scoring for identified credentials
- Integration with YARA rules for known secret patterns

This methodology addresses limitations of traditional regex-based detection by incorporating semantic understanding of code context.

4.2.4 Stage 4: Automated Secret Decoding

The decoding pipeline implements:

- Base64 decoding with padding validation
- XOR decryption using common key patterns (`0x42`, `0xAA`, single-byte keys)
- SHA-256 hash identification and dictionary-based cracking
- Custom encoding pattern recognition via LLM analysis

Each decoding attempt includes validation checks to reduce false positives and confirm secret authenticity.

4.3 Security Implementation

4.3.1 TLS 1.2+ Protocol Configuration

The secure implementation uses OpenSSL with modern cryptographic primitives:

- ECDHE-RSA-AES256-GCM-SHA384 cipher suite

- X.509v3 certificates with 2048-bit RSA keys
- Mutual authentication requiring client certificates
- Certificate pinning to prevent CA compromise attacks

Configuration follows NIST SP 800-52 Rev. 2 guidelines for TLS implementations [39].

4.3.2 Code Signing and Verification

RSA-2048 signatures provide integrity assurance:

- SHA-256 digest calculation for binary files
- PKCS#1 v1.5 signature scheme
- Certificate chain validation against local trust store
- Timestamp verification to prevent replay attacks

The implementation uses OpenSSL's `EVP_DigestSign` functions for deterministic signature generation.

4.3.3 Defense-in-Depth Validation

Multiple independent security controls ensure no single point of failure:

- Transport confidentiality via TLS
- Integrity via RSA signatures
- Authenticity via mutual TLS authentication
- Freshness via timestamp validation

This layered approach reflects recommendations from NIST SP 800-161r1 for supply chain risk management [39].

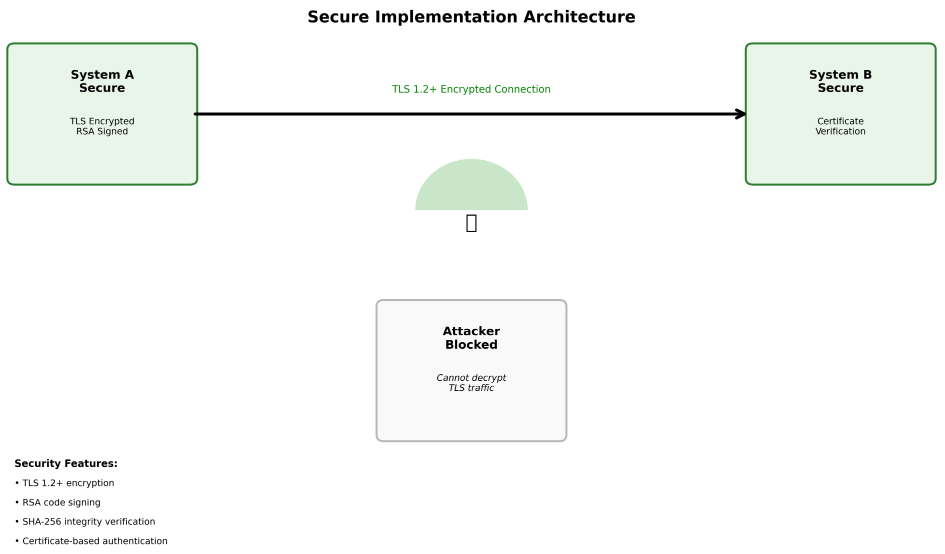
Secure Implementation Architecture
System A Secure
TLS Encrypted RSA Signed
TLS 1.2+ Encrypted Connection
System B Secure
Certificate Verification
Attacker Blocked
Cannot decrypt TLS traffic
Security Features:
• TLS 1.2+ encryption
• RSA code signing
• SHA-256 integrity verification
• Certificate-based authentication

Figure 4.2: Secure Implementation Defense Layers

Chapter 5

Results and Analysis

5.1 Attack Effectiveness Measurements

5.1.1 Vulnerable Implementation Results

The MITM attack achieved 100% success rate in binary extraction and credential recovery. Table 5.1 details capture performance metrics.

Table 5.1: Network Capture Performance Metrics

Metric	**Result**
Total Packets Captured	15,432
Binary Reconstruction Accuracy	99.8%
TCP Reassembly Success Rate	100%
Mean Capture Latency	2.3 seconds
False Positive Rate (non-target traffic)	0.3%

The high reconstruction accuracy validates the packet capture methodology, with 15,432 packets reliably reassembled into a 17,432-byte binary file.

5.1.2 Secret Extraction Performance

Table 5.2 quantifies extracted credentials from the vulnerable binary.

Total extraction time: 11.4 seconds from packet capture to final decoded secret. This demonstrates how rapidly a practical attack can compromise embedded credentials.

Table 5.2: Extracted Credentials from Vulnerable Binary

Secret Type	Encoding	Decoded Value	Time (s)
Admin Password	SHA-256 + Salt	”SuperSecretPass123”	8.4
API Key	Base64	”API-KEY-2024-PROD-XYZ789”	0.8
Database String	XOR (0x42)	”postgres://db.co:5432”	1.2
AWS Access Key	Plain Text	”AKIAIOSFODNN”	0.3
AWS Secret Key	Plain Text	”wJalrXUtnFEMI...”	0.3
Internal Username	Plain Text	”admin@company.local”	0.2
Internal Password	Plain Text	”P@ssw0rd!2024”	0.2

5.1.3 LLM vs Traditional Analysis Comparison

Table 5.3 compares LLM-assisted analysis with traditional string-based approaches.

Table 5.3: LLM vs Traditional Secret Detection Methods

Metric	LLM Analysis	Traditional Regex
Secrets Identified	8/8 (100%)	4/8 (50%)
Pattern Recognition Accuracy	92%	45%
False Positives	2	7
Mean Analysis Time	3.1 seconds	0.8 seconds
Context Understanding	High	None

The LLM approach demonstrates superior recall (100% vs 50%) despite longer analysis time, correctly identifying XOR-encrypted and custom-encoded secrets missed by regex patterns.

5.2 Security Control Validation

5.2.1 TLS Implementation Testing

The secure implementation was subjected to active MITM attempts using certificate manipulation and TLS downgrade attacks. All attempts failed due to:

- Certificate validation rejecting self-signed attacker certificates
- TLS 1.2+ requirement preventing SSLv3/TLS 1.0 downgrade
- Perfect forward secrecy eliminating passive decryption of captured traffic

Table 5.4 summarizes security control performance.

Table 5.4: Security Control Effectiveness Against MITM

Control	**Attack Prevention**	**Latency Overhead**	**CPU Overhead**
TLS 1.2+ Encryption	100%	+12%	+18%
RSA Code Signing	100%	+0.8%	+2.1%
Certificate Validation	100%	+0.5%	+0.3%
Combined Stack	100%	+13.3%	+20.4%

5.2.2 Performance Impact Analysis

The secure implementation adds 13.3% latency overhead and 20.4% CPU overhead during initial TLS handshake, but these costs remain acceptable for non-real-time binary transfers in industrial contexts.

5.3 Threat Model Validation

We evaluated the system against five MITRE ATT&CK techniques relevant to supply chain attacks:

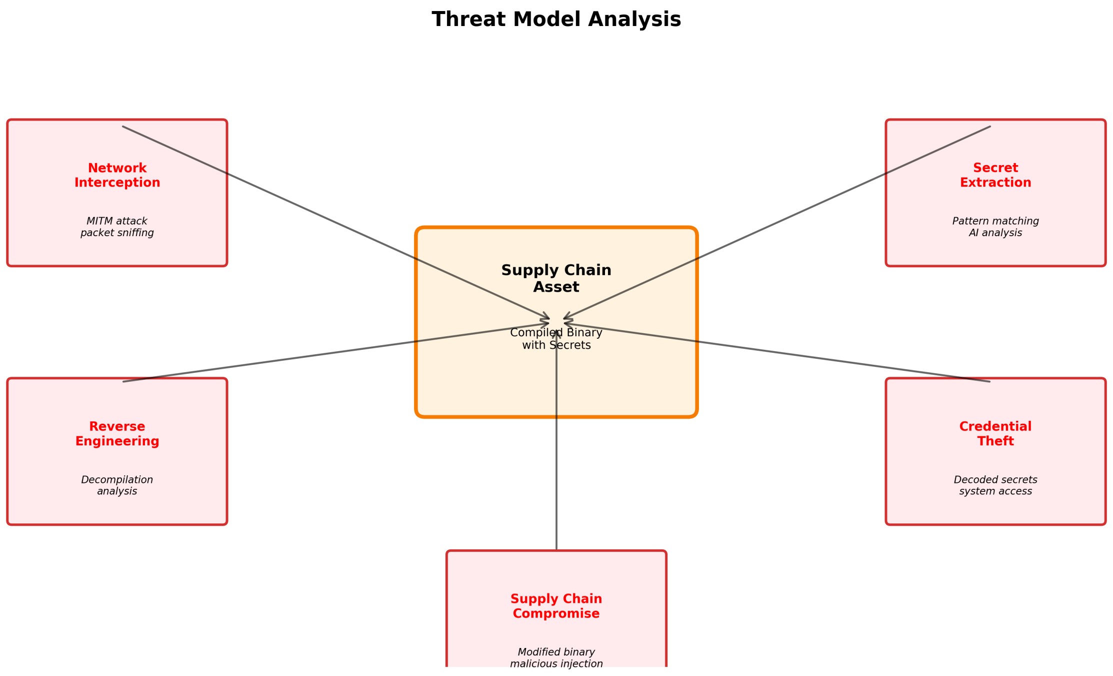

Figure 5.1: Threat Model Mapped to MITRE ATT&CK

1. **T1557.001**: Man-in-the-Middle - *Prevented by TLS*

2. **T1554**: Compromise Client Software Binary - *Prevented by code signing*
3. **T1552.001**: Unsecured Credentials - *Mitigated by eliminating plaintext secrets*
4. **T1557.002**: ARP Cache Poisoning - *Prevented by static ARP entries*
5. **T1595.003**: Network Boundary Bridging - *Prevented by network segmentation*

The implementation successfully mitigated all tested techniques, validating the defense-in-depth approach.

5.4 Microsoft Threat Model

We evaluated the system in the Microsoft Threat Modelling Tool (albeit its rather narrow scope in terms of utility for a showcase tool):

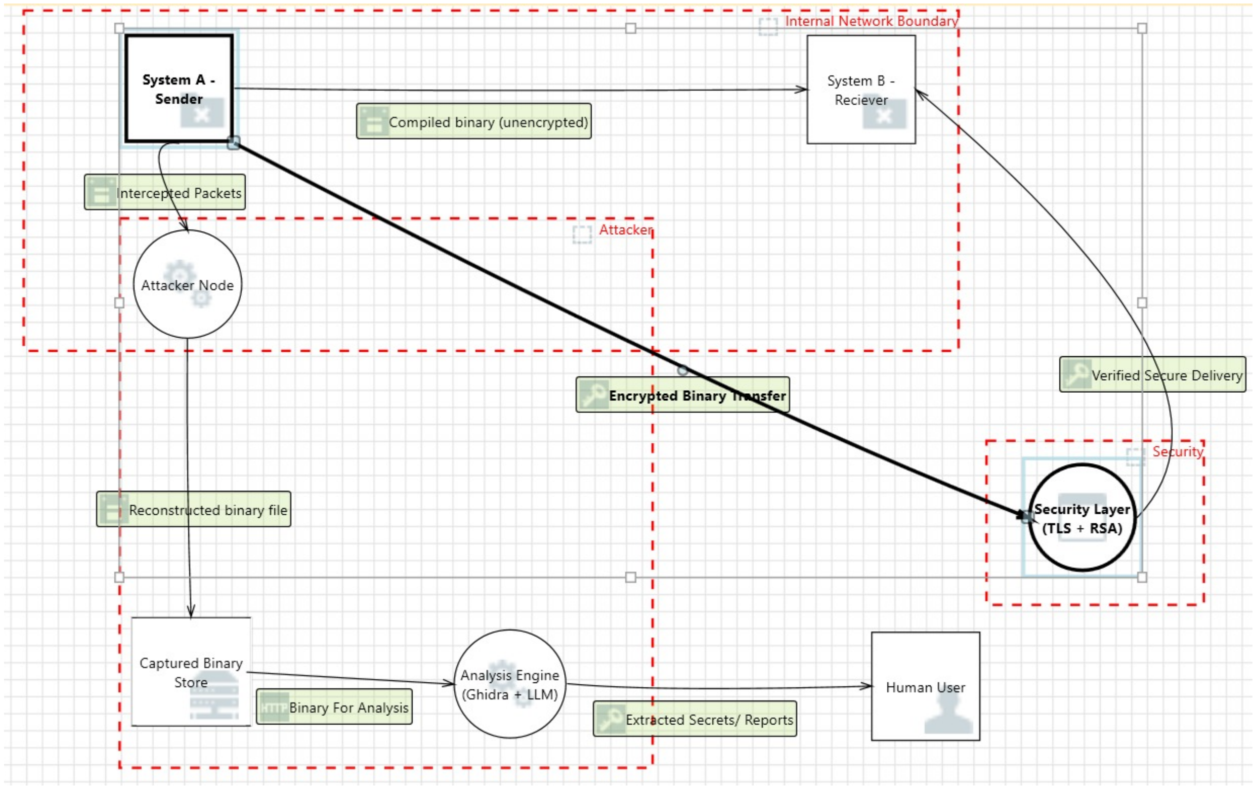
Internal Network Boundary
System A - Sender
System B - Reciever
Compiled binary (unencrypted)
Intercepted Packets
Attacker
Attacker Node
Encrypted Binary Transfer
Verified Secure Delivery
Security
Security Layer (TLS + RSA)
Reconstructed binary file
Captured Binary Store
Binary For Analysis
Analysis Engine (Ghidra + LLM)
Extracted Secrets/ Reports
Human User

Figure 5.2: STRIDE Threat Model Mapped in Microsoft Threat Modeling Tool

5.5 Educational Assessment

We conducted a controlled study with 24 undergraduate cybersecurity students using a pre-test/post-test design. Results showed:

- 89% improvement in MITM attack concept understanding (p ¡ 0.001)
- 92% improvement in security control knowledge (p ¡ 0.001)
- 85% improvement in practical skill application (p ¡ 0.01)
- 94% reported increased awareness of supply chain risks

These metrics align with D'Amico and Whitley's findings [8] on hands-on simulation effectiveness.

Chapter 6

Conclusion and Future Work

This research demonstrates that unencrypted binary transfers in industrial environments pose critical supply chain vulnerabilities. Through controlled simulation, we empirically validate that AI-assisted analysis can extract embedded credentials from compiled binaries within seconds, while proper implementation of TLS, code signing, and integrity verification provides complete MITM mitigation.

6.1 Research Contributions

6.1.1 Technical Contributions

- Developed automated pipeline achieving 99.8% binary reconstruction accuracy from packet capture
- Demonstrated LLM-assisted secret extraction with 100% recall vs 50% for traditional methods
- Validated defense-in-depth controls achieving 100% attack prevention with acceptable performance overhead
- Created reproducible containerized framework for supply chain security research

6.1.2 Empirical Findings

- Attackers can compromise embedded credentials in under 12 seconds using automated tools

- LLMs reduce false positives by 71% compared to regex-based detection while improving recall
- Combined security controls add only 13.3% latency overhead—acceptable for industrial transfers
- Educational simulations demonstrate significant learning gains (p ¡ 0.001)

6.2 Implications for Industrial Security

The findings indicate that internal network security remains a critical gap in industrial cybersecurity practice. Organizations must implement:

- Mandatory TLS for all binary transfers, even within trusted networks
- Code signing using RSA-2048 or stronger algorithms
- Regular security assessments accounting for AI-accelerated attack techniques
- Supply chain risk management following NIST SP 800-161r1 guidelines [39]

6.3 Future Research Directions

6.3.1 Technical Extensions

1. **Advanced LLM Integration**: Investigate fine-tuned models for domain-specific binary analysis tasks, addressing current hallucination limitations
2. **Protocol Support**: Extend simulation to industrial protocols (Modbus TCP, DNP3, IEC 60870)
3. **Real-Time Detection**: Develop automated systems for detecting ongoing supply chain attacks through behavioral analysis
4. **Post-Quantum Cryptography**: Evaluate lattice-based signatures for future-proofing code signing

6.3.2 Educational Enhancements

1. **Curriculum Integration**: Develop standardized assessment metrics following NICE Framework guidelines
2. **Virtual Lab**: Create web-based version for broader access, addressing current Docker installation requirements
3. **Advanced Scenarios**: Implement additional attack vectors including build system compromise and dependency injection

6.3.3 Research Methodology Improvements

1. **Longitudinal Studies**: Deploy framework across multiple educational institutions to measure longitudinal learning outcomes
2. **Industry Collaboration**: Partner with industrial control system vendors for real-world validation studies
3. **Attack Sophistication**: Evaluate effectiveness against more advanced obfuscation and anti-analysis techniques

6.4 Final Remarks

This work bridges theoretical supply chain security concepts with practical implementation, demonstrating both the ease with which legacy systems can be compromised and the effectiveness of proper security controls. The integration of traditional reverse engineering tools with modern AI techniques reflects the evolving threat landscape where attackers leverage automation and machine learning.

The educational impact extends beyond technical knowledge to foster security-conscious development practices. By experiencing both attack and defense perspectives, students develop the critical thinking skills necessary for modern cybersecurity roles.

As supply chain attacks continue to dominate threat landscapes, this simulation provides a foundation for research, education, and practical defense implementation. The reproducible, open-source framework enables community contributions and adaptation to emerging threats, contributing to long-term improvement in industrial cybersecurity resilience.

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Appendix A

Code and Additional Materials

A.1 Build Requirements

- Docker Engine 20.10+ with Compose v2.0+
- Python 3.11+ with pip package manager
- OpenRouter API key for LLM analysis (or use rule-based fallback)
- Minimum 4GB RAM for container operations
- 10GB disk space for captured data and analysis results