SENTINEL-AI: A Multi-Agent AI-Powered Intrusion Detection System for SME Network Security and NIS2 Compliance on Ultra-Low-Resource Edge Devices

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Abstract *— Small and medium-sized enterprises (SMEs) represent over 99% of European businesses yet remain disproportionately vulnerable to cyber threats due to limited budgets and technical expertise. The NIS2 Directive (EU 2022/2555), transposed into Italian law through D.Lgs. 138/2024, mandates robust cybersecurity measures for organizations across 18 critical sectors, imposing significant compliance obligations even on smaller entities within essential supply chains. This paper presents* ***SENTINEL-AI****, a novel multi-agent intrusion detection system (IDS) designed to operate on ultra-low-resource edge hardware (Raspberry Pi Zero 2 W, 512 MB RAM, <5 MB runtime footprint) while providing enterprise-grade threat detection capabilities. The system implements eight specialized detection engines (beaconing analysis, DNS exfiltration, malicious domain identification, lateral movement detection, phishing recognition, brute-force monitoring, suspicious port analysis, and anomalous data volume tracking) coordinated by three AI agents leveraging external APIs (****VirusTotal****,* ***AbuseIPDB****, and* ***Claude AI****) for real-time threat intelligence, reputation scoring, and natural language threat explanation. Experimental evaluation on a simulated SME network environment comprising 17 devices across 7 attack scenarios demonstrated detection of 15 threats with 12 critical alerts, zero false positives on legitimate traffic, and successful identification of Emotet beaconing, Cobalt Strike C2 communications, ransomware lateral movement, DNS tunneling exfiltration, banking phishing, and cryptocurrency mining. Live network capture testing confirmed real-time processing capability of approximately 100 packets per second with 27 devices and 60 flows monitored simultaneously. The system generates automated NIS2/GDPR compliance reports with actionable recommendations in Italian, addressing the language barrier that*

hinders cybersecurity adoption among European SMEs. SENTINEL-AI represents a scalable, cost-effective approach (hardware cost <€25, operational cost <€5/month) to democratize enterprise-grade cybersecurity for the 5.5 million Italian SMEs and 23 million European SMEs currently underserved by existing solutions.

Keywords: Intrusion Detection System, Multi-Agent AI, NIS2 Compliance, Edge Computing, SME Cybersecurity, Threat Intelligence, Network Security, Raspberry Pi.

1. Introduction

The European cybersecurity landscape has undergone a fundamental transformation with the entry into force of the **NIS2 Directive** (Directive (EU) 2022/2555) on 16 January 2023 and its subsequent transposition into Italian national law through Decreto Legislativo 138/2024, published in the Gazzetta Ufficiale on 1 October 2024. This regulatory framework expands cybersecurity obligations to 18 critical sectors and introduces significant penalties — up to €10 million or 2% of annual global turnover — for non-compliance.

Small and medium-sized enterprises face a particularly acute challenge in this new regulatory environment. While large corporations allocate dedicated security operations centers (SOCs) and managed security service providers (MSSPs) at costs ranging from €3,000 to €30,000 per month, the average Italian SME operates with an annual IT budget insufficient to cover even basic commercial security solutions. The result is a dangerous cybersecurity gap: according to Eurostat, over 60% of European SMEs lack any form of advanced network monitoring, leaving them exposed to increasingly sophisticated threats including ransomware, supply chain attacks, and state-sponsored espionage.

This paper introduces **SENTINEL-AI**, a system designed to bridge this gap through three key innovations: (1) a multi-agent AI architecture that combines specialized detection engines with external threat intelligence APIs, (2) deployment on ultra-low-resource edge hardware (Raspberry Pi Zero 2 W) using the ZeroClaw runtime (<5 MB RAM), and (3) automated NIS2/GDPR compliance reporting in the user's native language.

2. Related Work

Existing network intrusion detection systems can be categorized into three classes: signature-based systems (Snort, Suricata), anomaly-based systems (Zeek, OSSEC), and AI-driven systems (Darktrace, Vectra AI). Signature-based systems offer high accuracy for known threats but require continuous signature updates and cannot detect zero-day attacks. Anomaly-based systems provide broader coverage but suffer from high false positive rates, typically requiring dedicated security analysts for triage. Commercial AI-driven solutions such as Darktrace (starting at approximately €30,000/year) offer sophisticated detection but remain economically inaccessible to SMEs.

Consumer-grade network security devices such as Firewalla (€179-€889) provide simplified network monitoring but lack AI-driven analysis, multi-agent threat intelligence integration, and regulatory compliance reporting. No existing solution combines all three capabilities on hardware costing less than €25.

The multi-agent approach to cybersecurity has been explored in academic literature, notably by Sadik et al. (2020) and Alavizadeh et al. (2022), but prior implementations assume cloud infrastructure with significant computational resources. **SENTINEL-AI** extends this paradigm to edge devices through efficient flow-based analysis rather than deep packet inspection, reducing memory requirements by approximately two orders of magnitude.

3. System Architecture

SENTINEL-AI employs a layered architecture comprising four principal components: (a) a real-time packet capture and flow extraction engine, (b) eight specialized threat detection engines, (c) a multi-agent AI coordination layer, and (d) a web-based dashboard with investigative console.

3.1 Packet Capture and Flow Extraction

The capture engine operates at the network interface level using Scapy for packet interception. Raw packets are parsed to extract IP source/destination, transport protocol (TCP/UDP), destination port, packet size, DNS query names, and TLS Server Name Indication (SNI) values. Packets are aggregated into network flows identified by the tuple (source IP, destination IP, destination port). For each flow, the engine computes statistical features including packet count, total bytes, inter-arrival time mean and standard deviation, interval regularity coefficient, DNS query count and average length, and DNS character entropy.

3.2 Threat Detection Engines

Eight specialized detection engines analyze flow features independently:

Beaconing Detection identifies command-and-control (C2) callbacks by measuring inter-packet interval regularity. A flow is flagged when the coefficient of variation (standard deviation / mean) of inter-arrival times falls below 0.3, indicating periodic communication characteristic of malware families including Emotet, Cobalt Strike, and Trickbot. Confidence scoring incorporates interval regularity, packet count, and destination IP reputation.

DNS Exfiltration Detection monitors DNS query characteristics for indicators of data tunneling. Flows exceeding thresholds for query count (>5), average query length (>40 characters), and Shannon entropy (>3.0) are flagged as potential exfiltration channels.

Malicious Domain Identification maintains a curated database of known malicious domains and applies typosquatting detection heuristics to identify domain impersonation attacks.

Lateral Movement Detection monitors internal-to-internal traffic on sensitive ports (SMB/445, RDP/3389, WinRM/5985) for patterns consistent with ransomware propagation, including sequential scanning and large data transfers between workstations.

Phishing Detection identifies DNS queries to domains matching patterns of credential harvesting pages, particularly those mimicking financial institutions.

Brute Force Detection monitors connection frequency to authentication services (SSH/22, RDP/3389) and flags sources exceeding configurable attempt thresholds within time windows.

Suspicious Port Analysis flags traffic on ports commonly associated with malicious activities including cryptocurrency mining (3333, 8333), remote access trojans, and non-standard HTTPS services.

Data Exfiltration Volume Analysis monitors outbound data volumes per flow, flagging transfers exceeding baseline thresholds to external IP addresses.

3.3 Multi-Agent AI Layer

The coordination layer orchestrates three external AI agents:

The **VirusTotal Agent** queries the VirusTotal API v3 for IP address, domain, and file hash reputation, providing detection ratios from 93+ antivirus engines. The agent operates within the free tier (500 queries/day), sufficient for typical SME traffic volumes.

The **AbuseIPDB Agent** retrieves abuse confidence scores, geographic data, ISP information, and historical report counts for suspicious IP addresses, supporting threat contextualization and incident response.

The **Claude AI Agent** receives structured threat data and generates natural language explanations in Italian, including risk assessment, recommended immediate actions, estimated economic impact, and NIS2/GDPR compliance implications. This addresses the critical language barrier that prevents non-English-speaking SME operators from understanding and acting on security alerts.

3.4 Dashboard and Investigative Console

A Flask-based web dashboard provides real-time visualization accessible from any browser, including mobile devices on the same network. The dashboard displays live packet/flow/device/threat counters, a NIS2 compliance status indicator, color-coded alerts organized by severity, a device map with traffic statistics, and an interactive AI console supporting 14+ investigative commands.

4. Experimental Evaluation

4.1 Simulation Environment

A simulated SME network environment was constructed comprising 17 devices: a router/gateway, three workstations (owner, secretary, accounting), a NAS server, a network printer, two smartphones, a guest Wi-Fi access point, and eight external endpoints representing both legitimate services (Google, Microsoft 365, Aruba PEC, Banca Intesa) and malicious infrastructure (C2 servers, scanning nodes, mining pools).

Seven attack scenarios were implemented: (1) Emotet beaconing with 30-second C2 callbacks, (2) Cobalt Strike beaconing on non-standard port 8443, (3) ransomware lateral movement via SMB/445, (4) DNS tunneling exfiltration to evil-command-server.ru, (5) banking phishing via typosquatted domain, (6) cryptocurrency mining from IoT device, and (7) SSH brute force from guest network.

4.2 Detection Results

The system processed 163 packets across 22 flows from 17 devices, detecting 15 threats: 12 critical, 2 high, and 1 medium severity. All seven attack scenarios were successfully identified with zero false positives on legitimate traffic (Google, Microsoft, banking, and email services).

Attack Scenario	Severity	Confidence	Detection Engine
Emotet C2 Beacon	Critical	94%	Beaconing
Cobalt Strike C2	Critical	96%	Beaconing + Suspicious Port
Ransomware Lateral	Critical	88%	Lateral Movement
DNS Exfiltration	Critical	99%	DNS Exfiltration
Banking Phishing	Critical	95%	Malicious Domain + Phishing
Crypto Mining	High	74%	Beaconing + Suspicious Port
SSH Brute Force	High	85%	Brute Force

4.3 Live Network Testing

Live capture testing on a production Wi-Fi network (Intel Wi-Fi 6 AX200) demonstrated real-time processing of 971 packets in 10 seconds (approximately 97 packets/second), with 14 devices identified across the local network. Extended monitoring over 5 minutes captured 2,350+ packets across 60+ flows from 27 devices, with one high-severity alert for anomalous data volume correctly identifying large HTTPS transfers to Cloudflare CDN (confirmed benign via VirusTotal verification).

4.4 Multi-Agent AI Evaluation

The VirusTotal agent correctly classified the Emotet C2 server (185.234.72.100) as suspicious (1/93 detections, ITP-Solutions GmbH, Germany). The AbuseIPDB agent identified a scanning node (45.155.205.10) as a Russian datacenter with prior abuse reports. The Claude AI agent generated comprehensive threat briefings including risk scoring (8-10/10), estimated economic impact (€15,000-500,000), and NIS2 compliance guidance with Garante notification requirements.

5. NIS2 Compliance Framework

SENTINEL-AI addresses specific requirements of the **NIS2 Directive** (Art. 21) and its Italian transposition (D.Lgs. 138/2024):

Art. 21(2)(a) — Risk analysis and information system security policies: Automated risk assessment with severity scoring and compliance status indicators.

Art. 21(2)(b) — Incident handling: Real-time threat detection, alert generation, and recommended response procedures.

Art. 21(2)(d) — Supply chain security: Monitoring of all network communications including third-party connections.

Art. 21(2)(g) — Basic cyber hygiene practices and cybersecurity training: Natural language threat explanations serve as continuous education for non-technical staff.

The system generates monthly compliance reports suitable for audit purposes, documenting monitoring scope, detected threats, response actions, and residual risk assessment.

6. Scalability and Deployment

The system is designed for deployment on Raspberry Pi Zero 2 W (ARM Cortex-A53, 512 MB RAM) using the ZeroClaw runtime, achieving a total memory footprint of approximately 50 MB. The hardware cost of €15-25 and operational cost of €0-5/month (API fees) positions SENTINEL-AI approximately two orders of magnitude below comparable commercial solutions.

Scalability is achieved through horizontal deployment: each network segment receives a dedicated SENTINEL-AI node, with centralized reporting via a cloud aggregation layer (planned for v3.0). The architecture supports multi-site deployment for organizations with distributed offices, a common configuration for European SMEs.

7. Limitations and Future Work

Current limitations include: (1) reliance on flow-based analysis rather than deep packet inspection limits detection of encrypted payload-based threats, (2) the free API tier imposes daily query limits that may be insufficient for high-traffic networks, (3) the system monitors network traffic only and cannot detect host-level threats. Future work will address these limitations through: integration of TLS fingerprinting (JA3/JA4), development of a lightweight on-device machine learning model for anomaly detection without API dependency, and a companion mobile application for remote monitoring and alerting.

8. Conclusion

SENTINEL-AI demonstrates that enterprise-grade network threat detection, multi-agent AI analysis, and regulatory compliance reporting can be achieved on ultra-low-resource edge hardware at a cost accessible to any SME. As the NIS2 Directive reshapes the European cybersecurity landscape, solutions that democratize access to advanced security capabilities will be essential for protecting the millions of small businesses that form the backbone of the EU economy.

Acknowledgments

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Data Availability

Source code available at: https://github.com/TelescaAntonio/SENTINEL-AI (access by request).

Conflict of Interest

The author declares no conflict of interest. IRST is a non-profit Research and Technology Organisation operating under Art. 2(83) of EU Regulation 651/2014.

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IMPRONTE DIGITALI / CRYPTOGRAPHIC FINGERPRINTS

SHA-256:

`c86af21cc114753e00d6997e7333f865356016323d2fc15cd9ceca8c00cc09b1`

SHA-512:

`1444b99d80a3f57b1ed276659e10adfa16677b3e30ab8f14cec9d4b7e0cc81b8821db4`
`89c467bfef6cc4a87700095d9ff557d321350f589939265d27fbad3caa`

SHA-3-256:

`0c6b53318702a076161cb26638968b220c838d778407c25003b1d0473954c194`

ATTESTAZIONI BLOCKCHAIN / BLOCKCHAIN ATTESTATIONS

- **Bitcoin (OpenTimestamps)**

  La registrazione Bitcoin è in corso (~2-4 h). / Bitcoin registration in progress (~2-4 h).

  Verificabile su / Verifiable at: https://opentimestamps.org

- BNB Smart Chain — TX: 0x2a3ad82e...377a17

  Verifica / Verify: https://bscscan.com/tx/0x2a3ad82ecafa239868777cee2a28a2c5819a2368d8b53c2a4ae65a71ed377a17

  BscScan ▸ "Input Data" ▸ "UTF-8" per il certificato on-chain / for on-chain cert

IDENTIFICAZIONE DEL CERTIFICATORE / CERTIFIER IDENTIFICATION

Profilo / Profile: Persona Fisica / Individual

Identità autocertificata ai sensi del DPR 445/2000

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Conforme all'Art. 41 del Regolamento UE 910/2014 (eIDAS). Un timestamp elettronico non può essere rifiutato come prova in sede giudiziaria per il solo motivo della sua forma elettronica.

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