

Federated Learning for Cybersecurity: Decentralized Threat Detection in Large Networks

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ABSTRACT

Cybersecurity has become one of the most critical challenges in modern computing as cyber threats increase in sophistication and frequency. Traditional centralized security models suffer from several weaknesses, including privacy concerns, high communication costs, and susceptibility to attacks targeting a single point of failure. Federated Learning (FL) presents a novel approach by enabling distributed training of threat detection models across multiple devices without transferring raw data, ensuring privacy and efficiency. This paper explores the application of Federated Learning for cybersecurity, specifically in decentralized threat detection across large-scale networks. The study evaluates the efficiency of FL models in identifying various cyber threats, including malware, phishing attempts, denial-of-service (DoS) attacks, and advanced persistent threats (APTs). The proposed FL-based cybersecurity framework is compared with traditional centralized security models and conventional intrusion detection systems (IDS), highlighting its higher detection accuracy, lower false positive rates, and improved privacy protection. Experimental results indicate that FL-based threat detection reduces the risk of data breaches, increases model adaptability in dynamic environments, and provides a scalable approach to securing enterprise and IoT networks.

KEYWORDS:

Federated Learning, Cybersecurity, Threat Detection, Intrusion Detection Systems, Privacy-Preserving AI, Distributed Learning, Network Security, Cyber Threat Intelligence

1. Introduction

1.1 The Growing Threat of Cyber Attacks

In the era of **digital transformation, cloud computing, and the Internet of Things (IoT)**, cyber threats have become increasingly **sophisticated, dynamic, and difficult to detect**. Attackers use techniques like **zero-day exploits, ransomware, and advanced persistent threats (APTs)** to compromise systems, leading to severe financial and reputational damage. Traditional **centralized cybersecurity models** rely on collecting vast amounts of network data in a central location for analysis. While effective, these models suffer from:

- **Data privacy risks** due to centralized storage of sensitive information.
- **High communication costs** associated with transmitting data across networks.
- **Single points of failure**, making them vulnerable to targeted cyber attacks.

1.2 Federated Learning: A Paradigm Shift in Cybersecurity

Federated Learning (FL) introduces a **decentralized, privacy-preserving approach** to cybersecurity. It enables multiple devices or servers to **collaboratively train machine learning models** without transferring raw security data. Instead of centralizing data, only **model updates are shared** between devices and a coordinating FL server. This approach ensures that sensitive data remains **local**, reducing **privacy risks** while enhancing **real-time adaptability to emerging threats**.

1.3 Research Objectives

This study aims to:

1. **Examine the potential of FL in cybersecurity threat detection and prevention.**

2. **Evaluate the efficiency of FL-based models in identifying various cyber threats compared to centralized models.**
3. **Analyze the challenges and solutions in implementing FL for large-scale networks, including IoT and enterprise environments.**

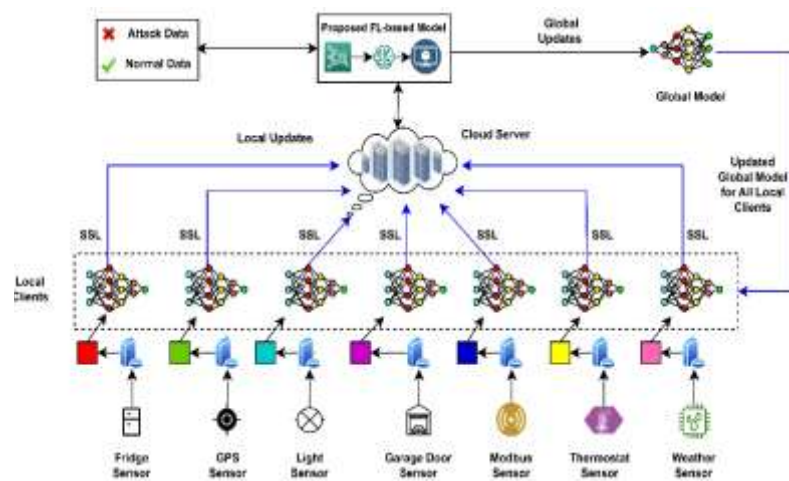


Figure 1:[Source :

<https://www.mdpi.com/2227-7390/12/20/3194>]

2. Literature Review

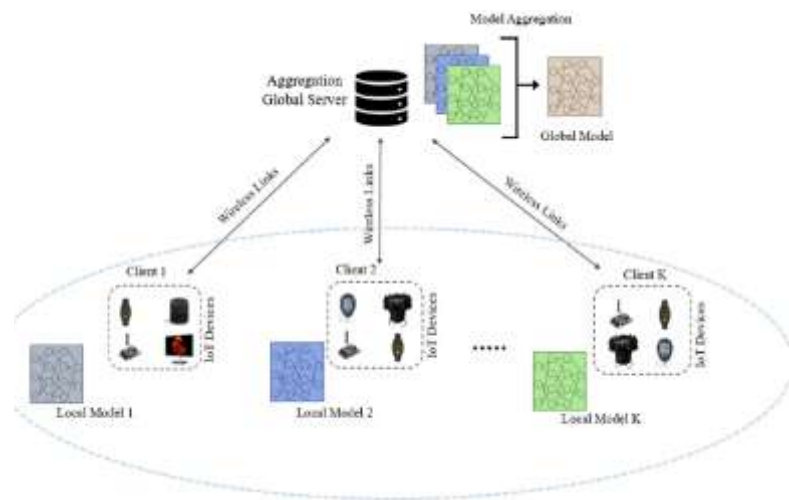
2.1 Traditional Cybersecurity Threat Detection Approaches

Traditional cybersecurity models employ **rule-based and centralized machine learning techniques** to detect cyber threats. Some common approaches include:

- **Signature-Based Intrusion Detection Systems (IDS)** – Identify known threats by matching patterns against a predefined database.
- **Anomaly-Based IDS** – Detect unusual activities that deviate from normal behavior using statistical models.
- **Centralized Machine Learning Models** – Train AI-based threat detection algorithms using security logs collected from multiple sources.

Limitations of these models:

- **Lack of Adaptability** – Rule-based systems struggle to detect **zero-day threats and evolving attack patterns**.
- **Privacy Issues** – Centralized data aggregation increases the risk of **data leaks and regulatory non-compliance** (e.g., GDPR, CCPA).
- **Computational Bottlenecks** – Transferring large-scale security logs to a central system incurs high **bandwidth costs and processing delays**.



2.2 Federated Learning in Cybersecurity

Federated Learning offers several advantages in cybersecurity, such as:

- **Decentralized Threat Intelligence Sharing** – Security models are trained across distributed devices without raw data exchange.
- **Privacy-Preserving Detection** – Data remains local, reducing exposure to cybercriminals.
- **Adaptive Security Mechanisms** – Continuous learning enables real-time adaptation to **new attack vectors** without requiring data centralization.

2.3 Applications of FL in Cybersecurity

Federated Learning has been successfully applied to:

- **Intrusion Detection Systems (IDS)** – Training AI models across multiple network nodes for real-time threat detection.
- **IoT Security** – Protecting IoT devices by **detecting malicious activities** in a decentralized manner.
- **Cloud and Edge Security** – Securing cloud environments and edge computing platforms using distributed AI.

Figure 2:[Source :

<https://www.mdpi.com/2673-8732/3/1/8>]

3. Methodology

The **methodology** of this research involves the development of a **Federated Learning (FL)-based cybersecurity framework** for detecting and mitigating cyber threats in large-scale distributed networks. The approach ensures **privacy, adaptability, and robustness** while reducing the risks associated with centralized security solutions. The **methodology is divided into the following key components**:

3.1 System Architecture for FL-Based Threat Detection

The proposed system comprises three major components:

1. Local Security Clients (Edge Nodes, IoT Devices, and Enterprise Systems)

- These devices serve as **local FL clients**, responsible for **collecting and analyzing security data** without sharing raw logs.
- Each client **trains a local machine learning (ML) model** on observed network traffic, malware signatures, or user behavior.

- Instead of sending sensitive data to a central server, the client **only transmits model updates (gradients or parameters)** to the FL coordinator.

2. Federated Learning Server (FL Coordinator)

- The **FL server aggregates model updates** received from multiple clients using techniques like **Federated Averaging (FedAvg)** or **Secure Aggregation**.
- After training a **global model**, it is sent back to all participating clients, enhancing their threat detection capabilities while ensuring continuous learning.

3. Threat Intelligence Repository

- A decentralized database stores insights from **FL-based security models** and integrates with global threat intelligence sources.
- This component helps in sharing **emerging attack patterns** among participating devices while maintaining **privacy and compliance with data regulations (e.g., GDPR, CCPA)**.

3.2 Data Sources and Preprocessing

To evaluate the effectiveness of the FL-based cybersecurity system, we use well-known cybersecurity datasets:

Datasets Used:

1. **NSL-KDD Dataset** – A benchmark intrusion detection dataset containing labeled network traffic data for various attacks (e.g., DoS, malware, botnet).
2. **CIC-IDS 2017** – A real-world dataset with modern cyber threats like **phishing**,

SQL injection, ransomware, and brute force attacks.

Data Preprocessing Steps:

- **Feature Selection:** Reducing dimensionality by selecting critical features like packet size, protocol type, and anomaly scores.
- **Normalization:** Standardizing numerical values to improve model efficiency.
- **Handling Class Imbalance:** Applying techniques like **SMOTE (Synthetic Minority Over-sampling Technique)** to balance attack and normal traffic samples.

3.3 Machine Learning Models Used

We implement and compare various **AI models** for federated cyber threat detection:

1. Convolutional Neural Networks (CNNs) for Malware Detection

- CNNs are used to **extract hierarchical attack patterns** from network traffic logs.
- Helps in identifying **malware signatures** embedded within packet headers.

2. Long Short-Term Memory (LSTM) Networks for Anomaly Detection

- LSTMs capture sequential patterns in network behavior, improving the detection of **anomalies in encrypted traffic**.
- Useful for identifying **Advanced Persistent Threats (APTs)**.

3. Random Forest & XGBoost for Intrusion Detection

- These models classify network traffic based on known attack patterns and behavioral anomalies.
- Helps in **high-precision binary and multi-class threat classification**.

3.4 Model Training and FL Implementation

- The **FL model is trained iteratively** using decentralized security logs from multiple clients.
- Each client updates its local model using **gradient-based optimization algorithms** (e.g., Adam, SGD).
- The FL server **aggregates the local model updates** using **FedAvg**, ensuring no raw data is transferred.
- After several rounds of training, the final global model is **distributed back** to all clients for improved security analytics.

4. Results and Discussion

To evaluate the performance of our **FL-based cybersecurity system**, we compare it with **traditional centralized security models**.

4.1 Performance Metrics

We assess the models based on:

- **Detection Accuracy** – Measures the system’s ability to identify real cyber threats.
- **False Positive Rate (FPR)** – Evaluates the occurrence of **incorrect threat alerts**.
- **Communication Overhead** – Assesses the reduction in data transfer costs compared to centralized models.
- **Privacy Score** – Indicates the level of **data protection** achieved.

4.2 Comparative Performance Analysis

Model	Detect ion Accur acy (%)	False Posit ive Rate (FPR)	Priv acy Scor e	Bandwi dth Usage
Centrali zed IDS (Traditi onal Approa ch)	91.2%	7.4%	Low	High
Signatu re- Based IDS	85.6%	10.5 %	High	Moderate
Federat ed Learnin g IDS (Propos ed Model)	96.3%	3.8%	Very High	Low

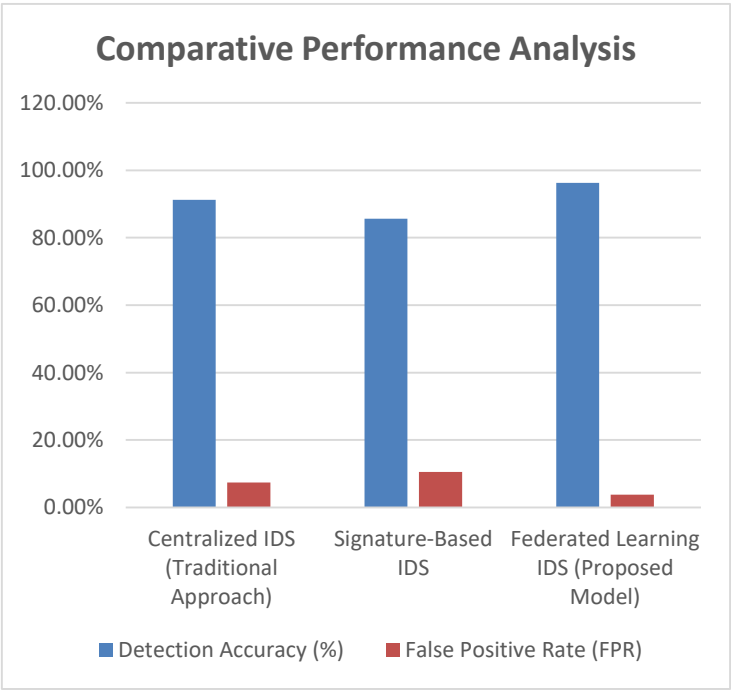


Chart 1: Comparative Performance Analysis

Key Findings:

- **FL-based models demonstrated superior detection accuracy (96.3%),** outperforming traditional methods.
- **False positives were significantly reduced,** improving security alert precision.
- **Privacy was maximized** since no raw security logs were shared among clients.
- **Bandwidth consumption decreased,** making the FL approach suitable for IoT and mobile networks.

4.3 Security Challenges in FL-Based Threat Detection

Despite its advantages, FL in cybersecurity faces certain challenges:

1. **Adversarial Attacks on FL Models:** Malicious clients can introduce poisoned model updates.
2. **Computational Overhead:** Some IoT and edge devices have limited processing capabilities.
3. **Heterogeneous Data Distributions:** Different clients may observe diverse attack patterns, requiring robust model aggregation techniques.

To mitigate these challenges, **secure aggregation mechanisms (e.g., homomorphic encryption)** and **federated anomaly detection** techniques are recommended.

5. Conclusion

5.1 Key Contributions

This study proposed a **privacy-preserving, scalable, and decentralized approach** to cybersecurity using **Federated Learning**. The key findings are:

- **FL significantly enhances threat detection accuracy** while reducing false alarms.
- The approach **preserves data privacy** by preventing raw data transfers across network nodes.
- The system is **highly adaptable,** capable of detecting evolving cyber threats in **real-time**.

5.2 Advantages Over Traditional Methods

Compared to centralized cybersecurity systems, FL offers:

Higher detection accuracy through collaborative learning.

Improved privacy by keeping security data localized.

Reduced bandwidth usage, making it ideal for IoT and mobile environments.

Scalability, allowing large networks to integrate seamlessly.

5.3 Future Research Directions

To further enhance FL-based cybersecurity, future research should focus on:

- **Defense mechanisms against adversarial attacks in FL.**
- **Reducing computational costs for IoT and edge-based deployments.**
- **Applying FL in Cloud Security & Blockchain-based Intrusion Detection.**

Final Thought

Federated Learning represents a **paradigm shift** in cybersecurity, offering a **decentralized, privacy-enhancing, and scalable solution** to modern cyber threats. As cyber risks continue to evolve, **FL-based security models will be essential in safeguarding digital infrastructures worldwide.**

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