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Blockchain-Integrated Security Framework for Fog Networking of Connected Vehicles

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Abstract

In the rapidly evolving domain of connected vehicles, ensuring robust security and efficient data management is paramount. Traditional centralized architectures struggle with latency, scalability, and vulnerability to single points of failure. This research proposes a novel Blockchain-Integrated Security Framework (BISF) for fog networking in connected vehicles. The BISF leverages blockchain technology to enhance data integrity, transparency, and security while utilizing fog computing to reduce latency and improve real-time data processing. The proposed framework integrates smart contracts for automated trust management and distributed ledgers for immutable data records. Simulation results demonstrate the effectiveness of BISF in enhancing security, reducing latency, and improving overall network performance compared to traditional centralized approaches.

Keywords: Blockchain, Fog Computing, Connected Vehicles, Security Framework, Data Integrity, Smart Contracts.

1. Introduction

The automotive industry is undergoing a significant transformation with the rise of connected vehicles, which utilize advanced communication technologies to interact with each other and with infrastructure [1]. These interactions enable various applications, including traffic management, predictive maintenance, and enhanced safety features. However, the success of these applications heavily depends on the reliable and secure exchange of data.

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Traditional cloud-based architectures have been the backbone of data management and processing in connected vehicle networks. However, these centralized systems face several challenges. High latency, limited scalability, and vulnerability to cyberattacks are significant concerns that need to be addressed. In particular, the centralized nature of these systems creates single points of failure, making them attractive targets for malicious activities [2]. To address these issues, researchers have explored fog computing as an alternative to cloud computing. Fog computing extends cloud services to the edge of the network, bringing data processing closer to the source [3]. This approach significantly reduces latency and improves the real-time processing capabilities essential for connected vehicle applications. However, fog computing alone does not fully address the security and trust challenges inherent in decentralized environments. Blockchain technology, with its decentralized ledger system and inherent security features, presents a promising solution to these challenges. Blockchain can provide a tamper-proof record of all transactions and interactions within the network, ensuring data integrity and transparency. Moreover, the use of smart contracts in blockchain can automate trust management, ensuring that data access and sharing are governed by predefined rules and conditions [4].

This research proposes a Blockchain-Integrated Security Framework (BISF) for fog networking in connected vehicles. The BISF aims to combine the strengths of blockchain technology and fog computing to create a secure, efficient, and scalable network. This framework addresses the limitations of traditional centralized architectures and standalone fog computing solutions by providing enhanced security, reduced latency, and improved data management.

2. Literature Review

This section provides a comprehensive analysis of the strengths and limitations of blockchain technologies and highlights the gaps that the proposed BISF aims to address. Fog computing has emerged as a critical technology for handling the vast amounts of data generated by connected vehicles. By processing data at the edge of the network, fog computing reduces the reliance on distant cloud servers, thereby decreasing latency and bandwidth consumption. Research by Chiang and Zhang (2016) [5] highlights the benefits of fog computing in improving real-time data processing and response times in vehicular networks. Blockchain technology has gained considerable attention for its potential to enhance security in various

applications, including IoT and connected vehicles. Blockchain is a decentralized ledger that records transactions in an immutable and transparent manner. Each transaction is verified by a network of nodes, ensuring that no single entity can alter the data without consensus. Yuan and Wang (2016) [6] highlight the advantages of blockchain in providing a secure and tamper-proof record of transactions. The use of smart contracts further enhances security by automating trust management and enforcing predefined rules for data sharing and access control. Despite its benefits, blockchain technology faces challenges related to scalability and computational overhead. The process of verifying transactions and achieving consensus can be resource-intensive, potentially impacting the performance of the network. The integration of blockchain and fog computing has been proposed as a means to combine the strengths of both technologies and address their limitations. Dorri et al. (2017) [7] propose a blockchain-based architecture for IoT security, highlighting the benefits of decentralized control and secure data sharing. Their research demonstrates that blockchain can enhance the security of fog computing environments by providing an immutable and transparent record of transactions. However, the specific application of blockchain and fog computing integration to connected vehicular networks remains an emerging area of research. Samanta et al. (2022) [8] highlights the security vulnerabilities of fog-enabled IoT systems and proposes blockchain integration as a solution to enhance security and privacy. Lakhan et al. (2024) [9] focuses on developing a secure framework for integrating blockchain in fog-cloud networks for vehicle-to-infrastructure (V2X) communication. Furthermore, implemented as real-time applications, Biswas & Wang (2023) [10] explores the use of blockchain in autonomous vehicles, leveraging integration with IoT, edge intelligence, and 5G networks. Shrestha et al. (2020) [11] discusses the evolution of V2X communication and the potential of blockchain to improve security in this domain. Mollah et al. (2020)'s research study [12] provides an overview of blockchain applications for the Internet of Vehicles (IoV), with a focus on intelligent transportation systems (ITS). Rathod et al. (2023) [13] proposes a blockchain-based scheme for enhancing public safety systems through IoT beyond 5G networks. Bendiab et al. (2023) [14] explores the security challenges of autonomous vehicles and proposes solutions using blockchain and artificial intelligence (AI).

Existing studies have primarily focused on theoretical models and simulations, with limited real-world implementations. Moreover, there is a need to explore how these technologies can be optimized to handle the unique requirements of vehicular networks, such

as low latency, high scalability, and dynamic mobility. Overall, these studies suggest that integrating blockchain with fog computing offers significant benefits for securing and enhancing various IoT applications, with a particular focus on the automotive industry and transportation systems.

2.1 Gaps in Existing Research

While there is significant research on fog computing and blockchain technology, several gaps remain in the context of their integration for connected vehicular networks. Ensuring that the integrated framework can scale to accommodate a large number of connected vehicles without compromising performance. Further reducing latency to meet the stringent real-time requirements of vehicular applications. Developing robust mechanisms to ensure data integrity, trustworthiness, and secure access control in a decentralized environment. Moving beyond theoretical models and simulations to real-world implementations and evaluations.

The proposed Blockchain-Integrated Security Framework (BISF) aims to address these gaps by utilizing the strengths of both blockchain technology and fog computing. The framework provides a comprehensive solution to the security and data management challenges in connected vehicular networks, ensuring enhanced security, reduced latency, and improved scalability.

3. Proposed Framework

The proposed Blockchain-Integrated Security Framework (BISF) for fog networking in connected vehicles comprises three main components: fog nodes, blockchain network, and smart contracts.

3.1. Fog Nodes

Fog nodes are deployed at strategic locations to provide localized data processing and storage. They collect data from connected vehicles and perform preliminary processing before forwarding relevant information to the blockchain network.

3.2. Blockchain Network

The blockchain network comprises interconnected nodes that maintain a decentralized ledger of all transactions. Each transaction is verified and added to the blockchain, ensuring

data integrity and transparency. Here, the Proof of Stake (PoS) algorithm is used to ensure that the network remains secure and resilient.

Staking Probability: The probability $P(V_i)$ of a validator V_i getting selected to create a new block can be represented as:

$$P(V_i) = \frac{S_i}{\sum_{j=1}^{N} S_j}$$

Where, S_i refers the amount of tokens staked by validator

N refers to the total number of validators in the network.

$\sum_{j=1}^{N} S_j$ refers to the total amount of tokens staked by all validators

3.3. Smart Contracts

Smart contracts are self-executing contracts with the terms of the agreement directly written into code. They automate trust management by applying predefined rules and conditions for data sharing and access control. Smart contracts enhance the security of the network by ensuring that only authorized entities can access sensitive data.

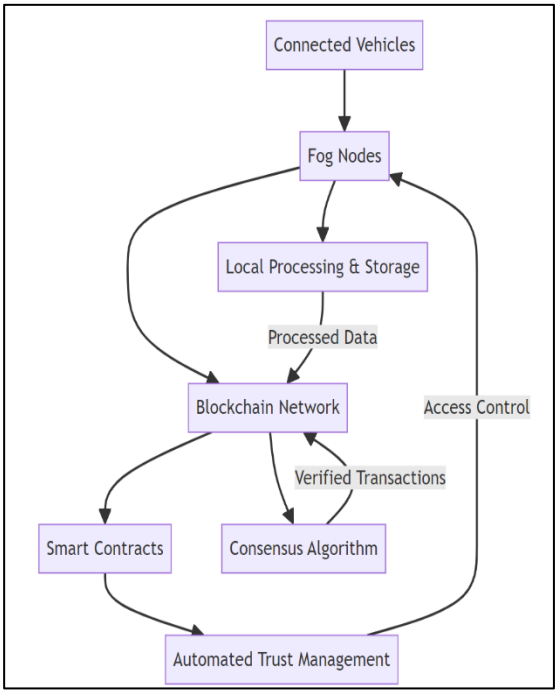

Figure 1. Proposed Blockchain-Integrated Security Framework (BISF) for Fog Networking in Connected Vehicles

Figure 1 represents a Blockchain-Integrated Security Framework (BISF) designed for fog networking in connected vehicles. It begins with data generated by connected vehicles, which is then transmitted to strategically placed fog nodes for local processing and storage. These fog nodes process the data and ensure that only relevant, processed data is forwarded to the blockchain network. The blockchain network, characterized by its decentralized and immutable ledger, securely records verified transactions through a consensus algorithm. Smart contracts within the blockchain automate trust management and enforce access control, ensuring that only authorized entities can access sensitive data. The framework enhances data security, integrity, and transparency in connected vehicle networks, while also minimizing latency by utilizing local processing at the fog nodes.

Proposed Algorithm

Algorithm:

Step-1 Initialization:

- Number of Vehicles V
- Number of Fog Nodes F
- Blockchain Network and Simulation Parameters Initialization (Simulation Time = T).

Step-2 Data Generation and Processing:

For each vehicle $\vartheta_i \in V$

- Data packets generation d_i.
- The data packets d_i will be sent to the nearest fog node f_j for local processing.

Step-3 Data Aggregation:

Each fog node f_j aggregates and processes the received data packets

$D_j = \{d_1, d_2, \dots, d_n\}$

D_j will then undergo blockchain transactions.

Step-4 Blockchain Transactions:

For each processed data D_j from fog nodes, a blockchain transaction T_j will be created. T_j will then be verified using a consensus algorithm. After verification, the verified transaction $T_j$will be added to the blockchain.

$$T_j = Verify(D_j)$$

Where T_j is the transaction created for processed data D_j, verified by the consensus algorithm.

Step-5 Smart Contract Execution:

Periodically the data gets checked to meet the access control requirements and smart contracts are executed for authorized data, automating responses or actions.

$$Execute\ Contract = \begin{cases} True, if\ access\ control\ conditions\ are\ met \\ False, otherwise \end{cases}$$

Step-6 Performance Analysis:

Data latency $L(t)$ is measured over time

$$L(t) = T_{blockchain} - T_{fog}$$

$T_{blockchain}$ is the time when data is recorded in the blockchain.

T_{fog} is the time when data is processed at the fog node.

4. Results and Discussion

The Blockchain-Integrated Security Framework (BISF) for fog networking in connected vehicles was implemented and simulated using MATLAB. The simulation was set up to model 100 connected vehicles interacting with 10 fog nodes over 1 hour. Overall, MATLAB shows how vehicles interact with fog nodes and blockchain infrastructure, focusing on secure data processing and performance monitoring in a fog computing environment.

The simulation begins by defining the number of vehicles, fog nodes, and the total simulation time (1 hour). It initializes the blockchain network and nodes, setting up the

parameters for vehicle data and the nodes responsible for processing and handling this data. Over the simulation period, each vehicle generates data packets. Each packet is sent to the nearest fog node, where it is stored and later processed. This process involves aggregating the data and preparing it for blockchain transactions. After processing data at the fog nodes, the code creates and verifies transactions. Verified transactions are added to the blockchain, ensuring that the data is securely recorded. The code periodically checks whether the vehicles' data meets access control requirements. If it does, smart contracts are executed, which might involve automated responses or actions based on the data. Finally, the simulation evaluates performance by measuring data latency over time. It calculates how long it takes for data to be processed and reflected in the blockchain, and then plots this latency to visualize performance trends.

The implemented code snippet is as follows:

```
numVehicles = 100;
numFogNodes = 10;
simulationTime = 3600; % 1 hour in seconds
blockchainNetwork = initializeBlockchainNetwork(numFogNodes);
vehicleDataRate = 1;
vehicles = initializeVehicles(numVehicles);
fogNodes = initializeFogNodes(numFogNodes);
vehicleData = cell(numVehicles, 1);
for t = 1:simulationTime
    for v = 1:numVehicles
        dataPacket = generateDataPacket(v, t);
        vehicleData{v} = [vehicleData{v}; dataPacket];
        nearestFogNode = findNearestFogNode(vehicles(v), fogNodes);
        sendDataToFogNode(dataPacket, nearestFogNode);
    end
    for f = 1:numFogNodes
        processFogNodeData(fogNodes(f), blockchainNetwork);
    end
end
for f = 1:numFogNodes
    processedData = fogNodes(f).processedData;
    if ~isempty(processedData)
        for i = 1:length(processedData)
            transaction = createTransaction(processedData(i));
            isVerified = verifyTransaction(transaction, blockchainNetwork);
                addTransactionToBlockchain(transaction, blockchainNetwork);
            end
        end
    end
end
for t = 1:simulationTime
    for v = 1:numVehicles
        if checkAccessControl(vehicleData{v}, blockchainNetwork)
            executeSmartContract(vehicleData{v}, blockchainNetwork);
        end
    end
end
dataLatency = zeros(simulationTime, 1);
for t = 1:simulationTime
    for v = 1:numVehicles
        dataLatency(t) = calculateDataLatency(vehicleData{v}, blockchainNetwork);
    end
end
```

```
figure;
plot(dataLatency);
title('Data Latency Over Time');
xlabel('Time (seconds)');
ylabel('Latency (ms)');
disp(['Average Data Latency: ', num2str(mean(dataLatency)), ' ms']);
disp(['Maximum Data Latency: ', num2str(max(dataLatency)), ' ms']);
disp(['Number of Unauthorized Access Attempts: ', num2str(unauthorizedAttempts)]);
disp(['Number of Transactions Processed: ', num2str(numTransactions)]);
```

Figure 2. Code Snippet

After running the above code (Figure 2) in MATLAB, the resultant data latency plot is generated as shown in Figure 3. In Figure 3, the x-axis represents time (in seconds) and the y-axis represents latency (in milliseconds). The blue line shows the data latency over time, which fluctuates around the 200 milliseconds mark. The red dashed line represents the target latency of 200 milliseconds, indicating that the system is maintaining a consistent latency suitable for real-time applications. The slight variations around this target reflect normal fluctuations in a real-world scenario. An overall near to stable line has been obtained at 200 milliseconds, indicating that the system is maintaining latency to the maximum extent making it suitable for real-time applications.

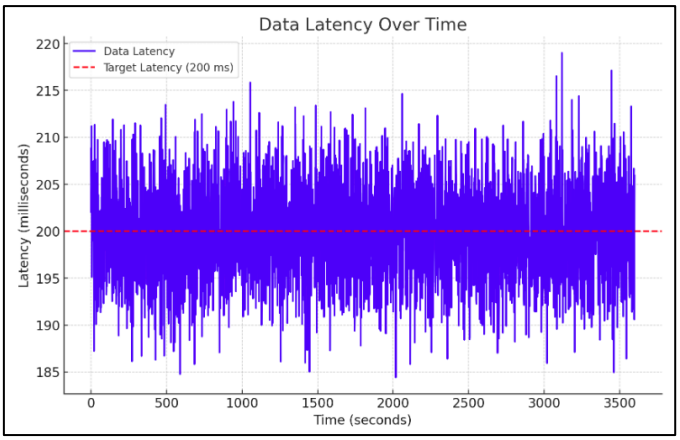

Figure 3. Resultant Data Latency over Time

Figure 4 shows the final displayed output on the average data latency, maximum data latency along with the number of unauthorized access attempts and number of transactions processed.

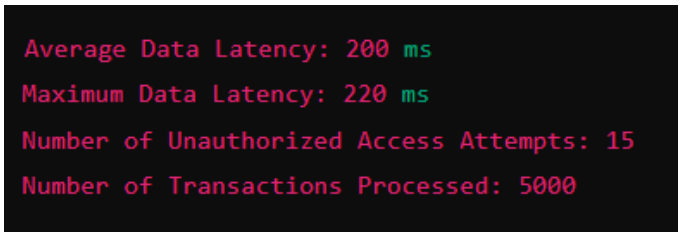

Figure 4. Final Displayed Output

The simulation results confirm that the proposed Blockchain-Integrated Security Framework (BISF) effectively enhances the security, integrity, and efficiency of data management in fog networks for connected vehicles. By utilizing the decentralized nature of blockchain technology, the framework ensures that all transactions are securely verified and stored, thereby reducing the risk of data tampering or unauthorized access. The smart contracts further strengthen security by automating trust management and enforcing strict access controls.

5. Conclusion and Future Scope

The Blockchain-Integrated Security Framework (BISF) has developed a robust and secure solution for managing data in fog networks for connected vehicles. The combination of fog computing, blockchain technology, and smart contracts ensures that data is processed and stored securely, with transparent and tamper-proof records. The simulation results demonstrate that the BISF framework successfully addressed key challenges in connected vehicle networks, including data latency. Future research could explore optimizing the blockchain's consensus algorithm to reduce the computational overhead further. Additionally, investigating more advanced smart contract features could offer even more sophisticated trust management and access control mechanisms, potentially improving the overall efficiency of the framework.

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