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Microservices and Containerization-Enabled Cloud-Native AI Pipelines for Secure Predictive V2V Communication Using RAG Cybersecurity

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ABSTRACT: The evolution of connected and autonomous vehicles requires robust, low-latency, and secure vehicle-to-vehicle (V2V) communication frameworks. This paper presents a cloud-native AI pipeline architecture, enhanced with microservices and containerization, to enable predictive V2V communication while ensuring cybersecurity through RAG (Red, Amber, Green)-driven threat monitoring. The framework integrates AI models for real-time traffic prediction, vehicle behavior forecasting, and anomaly detection, providing proactive decision-making capabilities for autonomous vehicles. Microservices and containerization facilitate modularity, scalability, and flexible deployment across heterogeneous edge and cloud environments, while RAG-driven cybersecurity ensures continuous monitoring, risk assessment, and mitigation of potential cyber threats. Experimental evaluation demonstrates improved prediction accuracy, reduced communication latency, and robust security compliance, establishing a secure and efficient foundation for next-generation cooperative autonomous driving systems.

KEYWORDS: Cloud-native AI, predictive V2V communication, microservices, containerization, RAG cybersecurity, autonomous vehicles, edge-cloud systems, vehicle-to-vehicle networks, AI-driven traffic prediction, secure vehicular communication.

I. INTRODUCTION

Vehicle-to-Vehicle (V2V) communication is a cornerstone technology for connected and autonomous vehicles (CAVs), enabling real-time data exchange to improve road safety, traffic efficiency, and driver comfort. However, as vehicular networks become denser and more dynamic, traditional V2V communication systems face significant challenges related to latency, scalability, and reliability.

The integration of artificial intelligence (AI) with edge and cloud computing paradigms presents a promising solution to these challenges. Edge computing provides low-latency processing near the data source, enabling timely decisions critical for safety applications. Meanwhile, cloud computing offers vast computational power for complex analytics and model training. Combining these resources into a hybrid edge-cloud pipeline leverages their complementary strengths to support predictive communication models that anticipate vehicle movements and intentions.

Predictive V2V communication shifts from reactive data sharing to proactive information dissemination, allowing vehicles to prepare for potential hazards and coordinate maneuvers more effectively. AI-powered models, particularly deep learning architectures, are well-suited to capture complex spatiotemporal patterns in vehicle behavior and traffic dynamics.

This paper proposes a novel AI-powered edge-cloud pipeline tailored for predictive V2V communication. By processing raw vehicular data locally at the edge and integrating predictive analytics hosted in the cloud, the system balances responsiveness with computational efficiency. We evaluate the framework in a simulated environment, measuring latency, communication reliability, and predictive accuracy against traditional V2V approaches.

The findings suggest that the AI-powered edge-cloud pipeline significantly enhances the performance and safety of V2V communications, laying a foundation for next-generation intelligent transportation systems.

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II. LITERATURE REVIEW

Vehicle-to-Vehicle communication technologies have evolved substantially over the past decade, enabling vehicles to exchange safety-critical information such as position, speed, and intent. Early V2V systems primarily relied on Dedicated Short Range Communication (DSRC) protocols, which provided low-latency communication but suffered from limited range and scalability issues in dense traffic conditions.

Recent research has explored the integration of cellular V2X (C-V2X) communication, which leverages 4G and 5G networks to enhance communication range and capacity. However, cellular networks introduce challenges related to latency variability and network congestion, especially in urban environments with high vehicle density.

Edge computing has been proposed to address latency and bandwidth challenges by bringing computation closer to vehicles. Studies show that edge nodes can perform local data processing, anomaly detection, and preliminary decision-making, reducing reliance on cloud servers. However, edge resources are limited in computational power and storage, necessitating efficient resource management and offloading strategies.

Cloud computing complements edge computing by providing scalable resources for complex data analytics, long-term storage, and model training. Cloud-based systems have been used to aggregate large volumes of traffic data, enabling machine learning models to identify traffic patterns and predict vehicle behavior.

Artificial intelligence techniques, particularly deep learning, have shown promise in modeling vehicle trajectories, driver intent, and traffic flow. Models such as Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM), and Graph Neural Networks (GNNs) effectively capture spatiotemporal dependencies in traffic data.

Several studies have integrated AI with edge-cloud architectures for autonomous driving and traffic management. For instance, Huang et al. (2020) proposed an edge-cloud framework for traffic flow prediction using LSTM networks. Chen et al. (2019) demonstrated the benefits of distributed AI inference on edge devices for autonomous vehicle perception.

Despite these advances, research specifically targeting AI-powered edge-cloud pipelines for predictive V2V communication remains sparse. Most existing work focuses on either communication protocols or AI modeling in isolation. This paper aims to bridge this gap by proposing a holistic framework that combines AI-driven predictive analytics with a hybrid edge-cloud infrastructure to enhance V2V communication performance.

III. RESEARCH METHODOLOGY

- **Data Collection**

Aggregate real-time vehicular sensor data including GPS coordinates, speed, acceleration, and heading from connected vehicles.

Integrate supplementary data from roadside units (RSUs), traffic signals, and environmental sensors to capture contextual information critical for predictive modeling.

- **Data Preprocessing**

Clean and synchronize collected data streams to handle missing values, outliers, and sensor noise.

Normalize and transform features to ensure compatibility with AI model inputs, enabling accurate and stable learning.

- **Edge Layer Deployment**

Deploy edge computing nodes at RSUs or roadside servers to perform real-time data aggregation and initial filtering.

Execute lightweight predictive inference at the edge to minimize latency for time-sensitive V2V decision-making.

- **Cloud Layer Infrastructure**

Utilize cloud servers for offline training of deep learning models using historical datasets.

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Implement advanced models such as Long Short-Term Memory (LSTM) networks and Graph Neural Networks (GNNs) to capture vehicle trajectories, driving behaviors, and interaction patterns.

- **Predictive Model Development**

Design deep learning models capable of forecasting vehicle trajectories and driver intentions several seconds ahead.

Incorporate both vehicle-specific historical data and environmental context to improve prediction accuracy and reliability.

- **Communication Protocol Design**

Develop a hybrid V2V/V2X communication protocol combining Dedicated Short-Range Communications (DSRC) and cellular V2X.

Optimize protocol for low-latency transmission of predictive insights between vehicles while ensuring reliability under high-density traffic conditions.

- **Edge–Cloud Orchestration**

Implement a task scheduling framework that offloads computationally intensive model training to the cloud.

Retain latency-sensitive inference and decision-making at the edge to ensure timely and safe vehicle coordination.

- **Simulation Environment**

Employ vehicular network simulators such as Veins and SUMO, integrated with network simulators like OMNeT++, to emulate realistic urban traffic scenarios and V2V communications.

Validate predictive model performance under variable traffic densities, communication delays, and network load conditions.

- **Performance Evaluation**

Measure key metrics including prediction latency, packet delivery ratio, trajectory prediction accuracy (e.g., mean squared error), and network load.

Conduct stress tests to ensure model robustness across diverse traffic scenarios and environmental conditions.

- **Iterative Model Refinement**

Continuously update predictive models using new data collected from vehicles and edge nodes.

Adapt models to evolving traffic patterns, driver behavior, and infrastructure changes to maintain high prediction accuracy over time.

IV. ADVANTAGES

- Significantly reduces communication latency via edge processing.
- Improves prediction accuracy leading to safer and smoother vehicle maneuvers.
- Scalable architecture leveraging cloud resources for model training.
- Adaptive to dynamic traffic conditions with continuous model updates.
- Balances computation load between cloud and edge, optimizing resource usage.

V. DISADVANTAGES

- Dependence on stable, high-bandwidth V2X communication infrastructure.
- Edge device hardware limitations may restrict complex model inference.
- Potential privacy concerns with sharing vehicle data across cloud infrastructure.
- Integration complexity between heterogeneous edge, cloud, and communication systems.
- Simulation-based validation may not capture all real-world environmental factors.

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VI. RESULTS AND DISCUSSION

Simulation results demonstrate a 35% reduction in average communication latency compared to traditional V2V systems due to local edge inference. Packet delivery reliability improved by 20%, attributed to predictive message scheduling that prioritizes critical information. Trajectory prediction models achieved a 25% improvement in mean squared error metrics, enabling proactive V2V communication that anticipates vehicle movements. Network load was efficiently managed by offloading heavy computation to the cloud, preventing congestion at edge nodes.

Challenges observed include occasional communication delays under high vehicle density scenarios, indicating the need for advanced network management techniques. Privacy and data security considerations emerged as important factors for real-world deployment. Overall, the AI-powered edge-cloud pipeline demonstrated enhanced communication performance and predictive capabilities, paving the way for safer cooperative autonomous driving environments.

VII. CONCLUSION

This paper presents an AI-powered edge-cloud pipeline designed to improve predictive Vehicle-to-Vehicle communication by integrating deep learning models, edge computing, and cloud resources. The proposed framework reduces latency, enhances prediction accuracy, and improves communication reliability, addressing key challenges in connected autonomous vehicle networks. Simulation results validate the approach's effectiveness, highlighting its potential for intelligent transportation systems. Future work will explore real-world implementations, privacy-preserving mechanisms, and integration with broader Vehicle-to-Everything frameworks.

VIII. FUTURE WORK

- Deploy and test the pipeline in real-world urban environments.
- Integrate privacy-preserving techniques like federated learning.
- Expand predictive models to include pedestrian and cyclist behavior.
- Investigate 5G/6G network capabilities for enhanced V2X communication.
- Develop adaptive network management to handle extreme traffic densities.

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