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SDN-based traffic management for vehicular ad-hoc networks (VANETs)

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Abstract—Vehicular Ad-hoc Networks (VANETs) play a critical role in enabling intelligent transportation systems by facilitating real-time communication among vehicles and roadside infrastructure. However, the highly dynamic topology, frequent link failures, and traffic congestion present significant challenges to efficient network management. Software-Defined Networking (SDN) offers a promising solution by introducing centralized control, global network visibility, and dynamic traffic management capabilities. This paper proposes an SDN-based traffic management framework for VANETs that leverages a centralized SDN controller to monitor network conditions, optimize routing decisions, and reduce communication overhead. The proposed architecture enhances packet delivery performance, minimizes end-to-end delay, and improves overall network throughput through adaptive traffic control mechanisms. Simulation-based analysis demonstrates the effectiveness of the proposed approach in managing vehicular traffic under varying network densities. The results indicate that SDN-enabled VANETs can significantly improve network efficiency, scalability, and reliability compared to conventional VANET architectures.

Keywords—VANET, Software-Defined Networking, SDN, Traffic Management, Intelligent Transportation Systems, Routing Optimization, Vehicular Communication, Network Performance.

I. INTRODUCTION

The rapid advancement of Intelligent Transportation Systems (ITS) has significantly increased the demand for efficient and reliable vehicular communication technologies. Vehicular Ad-hoc Networks (VANETs), a specialized form of Mobile Ad-hoc Networks (MANETs), enable communication among vehicles and roadside infrastructure to support a wide range of applications, including traffic management, road safety, accident prevention, navigation assistance, and infotainment services. By facilitating real-time information exchange, VANETs contribute to the development of safer, smarter, and more efficient transportation systems. Despite their potential advantages, VANETs face several challenges due to the highly dynamic nature of vehicular environments. Rapid vehicle mobility, frequent topology changes, varying traffic densities, and intermittent wireless connectivity often result in unstable communication links, increased packet loss, routing inefficiencies, and network congestion. Traditional distributed routing protocols such as Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Optimized Link State Routing (OLSR) struggle to maintain optimal network performance under these dynamic conditions. As vehicular networks continue to expand in scale and complexity, more intelligent and adaptive network management mechanisms are required. Software-Defined Networking (SDN) has emerged as a promising paradigm for addressing the limitations of conventional network architectures. SDN separates the control plane from the data plane, enabling centralized network control, programmability, and global visibility of network resources. By maintaining a comprehensive view of the network, an SDN controller can make informed routing and traffic management decisions, dynamically adapt to changing network conditions, and efficiently allocate network resources. The integration of SDN into VANETs offers significant opportunities to improve traffic flow management, enhance communication reliability, and optimize overall network performance. In an SDN-enabled VANET environment, Road Side Units (RSUs) act as intermediaries between vehicles and the centralized controller, collecting network information and forwarding control instructions. The controller continuously monitors vehicle density, network congestion levels, and communication quality to determine optimal routing paths. Such centralized management enables proactive congestion mitigation, efficient packet forwarding, and adaptive route optimization, leading to improved Quality of Service (QoS) and network scalability. This paper proposes an SDN-based traffic management framework for VANETs that leverages centralized control and dynamic routing strategies to address the challenges of highly mobile vehicular environments. The proposed architecture utilizes real-time network information to optimize traffic distribution, reduce communication delays, and improve packet delivery performance. Through simulation-based evaluation, the effectiveness of the proposed framework is analyzed under varying traffic conditions and vehicle densities.

The main contributions of this research are summarized as follows:

- Design of a centralized SDN-based architecture for efficient traffic management in VANET environments.
- Development of a dynamic routing mechanism that utilizes real-time network information for optimal path selection.
- Implementation of congestion-aware traffic management strategies to improve network performance and reliability.
- Performance evaluation of the proposed framework using key metrics such as Packet Delivery Ratio (PDR), End-to-End Delay, Throughput, Packet Loss Ratio, and Routing Overhead.

The remainder of this paper is organized as follows. Section II reviews related work and existing SDN-VANET traffic management approaches. Section III presents the proposed system architecture and methodology. Section IV describes the simulation environment and performance evaluation metrics. Section V discusses the experimental results and comparative analysis. Finally, Section VI concludes the paper and outlines future research directions.

II. RELATED WORK

The integration of Software-Defined Networking (SDN) with Vehicular Ad-hoc Networks (VANETs) has attracted significant research attention in recent years due to the growing demand for intelligent traffic management and reliable vehicular communication. Researchers have explored various approaches to address challenges such as network congestion, routing inefficiency, high mobility, and scalability limitations in vehicular environments. This section reviews the major developments in VANET routing, SDN-enabled VANET architectures, traffic management strategies, and existing research gaps.

A. Traditional VANET Routing Approaches

Conventional VANETs primarily rely on distributed routing protocols derived from Mobile Ad-hoc Networks (MANETs). Protocols such as Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Optimized Link State Routing (OLSR) have been extensively studied for vehicular communication. AODV establishes routes on demand and reduces unnecessary routing overhead; however, frequent route discoveries caused by rapid vehicle movement often increase latency and packet loss. DSR utilizes source routing mechanisms and route caching techniques, but its performance degrades in highly dynamic traffic conditions due to stale route information. OLSR employs periodic topology updates to maintain routing tables, resulting in increased control overhead in dense vehicular networks. Although these protocols provide basic communication support, their distributed nature limits their ability to efficiently manage large-scale and rapidly changing vehicular environments.

B. Software-Defined Networking in VANETs

Software-Defined Networking introduces centralized control and network programmability by separating the control plane from the data plane. Several researchers have proposed SDN-based VANET architectures to improve network visibility and traffic management capabilities. In SDN-enabled VANETs, a centralized controller maintains a global view of the network and dynamically configures forwarding rules based on real-time network conditions. Road Side Units (RSUs) typically act as communication gateways between vehicles and the controller. This centralized approach enables more efficient route computation, traffic engineering, and resource allocation compared to conventional distributed routing schemes. Previous studies have demonstrated that SDN-based VANET architectures can significantly improve packet delivery ratio, reduce routing overhead, and enhance network scalability. However, controller placement, controller scalability, and communication latency between vehicles and the controller remain important research challenges.

C. Traffic Management and Congestion Control Techniques

Efficient traffic management is one of the primary objectives of intelligent transportation systems. Various congestion control mechanisms have been proposed to optimize vehicle movement and communication performance in VANET environments. Existing approaches utilize vehicle density estimation, traffic flow prediction, and dynamic route allocation to mitigate congestion. Some studies employ machine learning techniques to predict traffic conditions and proactively reroute vehicles. Others leverage RSU-based monitoring systems to collect traffic information and disseminate congestion alerts to nearby vehicles. While these approaches improve traffic awareness, many of them rely on localized decision-making and lack a comprehensive network-wide perspective. Consequently, their effectiveness may decrease in large-scale urban transportation scenarios where traffic conditions change rapidly.

D. SDN-Based Routing and Resource Optimization

Researchers have explored several SDN-based routing strategies to improve communication efficiency in vehicular networks. These methods typically utilize centralized controllers to gather network statistics and compute optimal forwarding paths. Traffic engineering techniques such as load balancing, adaptive routing, and quality-of-service-aware path selection have been integrated into SDN-enabled VANET frameworks. By dynamically adjusting forwarding rules according to network conditions, these solutions can reduce congestion and improve throughput. Additionally, some studies have investigated the use of multiple SDN controllers to enhance fault tolerance and scalability. Although multi-controller architectures improve network resilience, they introduce synchronization and coordination challenges that require further investigation.

E. Emerging Technologies for Intelligent Traffic Management

Recent research trends focus on integrating SDN with emerging technologies such as Edge Computing, Cloud Computing, Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT). These technologies provide advanced data analytics capabilities and enable predictive traffic management. Machine learning-based SDN controllers can analyze historical and real-time traffic data to predict congestion patterns and optimize routing decisions. Edge computing reduces decision latency by processing data closer to vehicles, while cloud platforms facilitate large-scale data storage and analysis. Despite promising results, the integration of these technologies often increases system complexity and computational requirements, making practical deployment challenging in resource-constrained environments.

F. Research Gap and Motivation

The literature review indicates that traditional VANET routing protocols struggle to cope with the dynamic characteristics of vehicular networks. Although SDN-based solutions provide centralized control and improved network visibility, many existing approaches focus primarily on routing optimization while paying limited attention to comprehensive traffic management and congestion mitigation. Furthermore, several studies assume static traffic patterns or limited network scales, which may not accurately represent real-world urban transportation environments. Issues related to controller responsiveness, dynamic traffic adaptation, and network scalability remain insufficiently addressed. Motivated by these limitations, this research proposes an SDN-based traffic management framework for VANETs that combines centralized network control, congestion-aware routing, and real-time traffic monitoring. The proposed approach aims to improve packet delivery performance, reduce communication delays, optimize traffic flow, and enhance overall network efficiency under varying vehicular densities and traffic conditions.

III. PROPOSED SYSTEM ARCHITECTURE

A. Overview of the Proposed Architecture

The proposed Software-Defined Networking-based Vehicular Ad-hoc Network (SDN-VANET) architecture is designed to provide intelligent traffic management, efficient routing, and enhanced communication reliability in highly dynamic vehicular environments. The architecture follows the fundamental SDN principle of separating the control plane from the data plane, thereby enabling centralized network intelligence and flexible traffic control. As illustrated in Figure 1, the proposed framework consists of three major layers: the Application Layer, the Control Layer, and the Data Plane Layer. These layers communicate through standardized Northbound and Southbound interfaces, allowing efficient information exchange and dynamic network management. The architecture integrates Road-Side Units (RSUs), On-Board Units (OBUs), and a centralized SDN controller to establish a scalable and adaptive vehicular communication infrastructure.

B. Application Layer (Business Logic Layer) The Application Layer represents the highest level of the architecture and contains intelligent traffic management services that utilize network information provided by the SDN controller. This layer is responsible for implementing traffic optimization policies, safety applications, and decision-support mechanisms.

1. ***Traffic Management Optimizer Module***

The Traffic Management Optimizer Module continuously analyzes traffic conditions obtained from the controller. Based on vehicle density, congestion levels, road utilization, and communication quality, the module generates optimized routing decisions and traffic control strategies. The primary responsibilities of this module include:

- Traffic congestion detection
- Route optimization
- Traffic load balancing
- Dynamic path selection
- Vehicle flow management

By maintaining a global view of the transportation network, the module can proactively mitigate congestion before it significantly impacts traffic flow.

2) Emergency Alert and Safety Services

The Emergency Alert and Safety Services module supports safety-critical vehicular applications. It processes emergency notifications and disseminates warning messages to nearby vehicles through the SDN controller. Typical services include:

- Accident notifications
- Emergency vehicle prioritization
- Hazardous road condition alerts
- Collision avoidance warnings
- Road closure announcements

These services improve driver awareness and contribute to overall road safety.

C. Control Layer (SDN Control Plane) The Control Layer forms the intelligence core of the proposed architecture. It consists of a centralized SDN controller that maintains a global network view and manages communication resources across the vehicular network. Unlike traditional VANETs, where routing decisions are made independently by individual vehicles, the proposed architecture centralizes decision-making within the SDN controller.

1) Centralized SDN Controller

The SDN controller continuously collects network information from distributed RSUs and processes it to generate optimal forwarding decisions. The controller performs several critical functions:

- Network topology discovery
- Vehicle location tracking
- Traffic density monitoring
- Routing path computation
- Flow rule generation
- Congestion management
- Resource allocation

By maintaining a global network topology database, the controller can quickly adapt to topology changes caused by vehicle mobility.

2) Northbound Interface

Communication between the Application Layer and the SDN controller is achieved through the Northbound Application Programming Interface (API). The Northbound API enables:

- Traffic information retrieval
- Policy deployment
- Service requests
- Network analytics access

REST-based APIs can be employed to facilitate communication between application services and the controller.

3) Southbound Interface

The controller communicates with RSUs through the Southbound Interface using protocols such as OpenFlow. The Southbound Interface enables:

- Flow rule installation
- Network monitoring
- Traffic statistics collection
- Forwarding table management

This interface ensures that routing decisions computed by the controller are propagated efficiently throughout the network.

D. Data Plane (Infrastructure Layer)

The Data Plane Layer consists of the physical communication infrastructure responsible for data forwarding and packet transmission. The primary components include:

- Road-Side Units (RSUs)
- Vehicles equipped with On-Board Units (OBUs)

Unlike the controller, devices in the data plane perform limited decision-making and primarily execute forwarding instructions received from the SDN controller.

1) Road-Side Units (RSUs)

The proposed architecture deploys multiple RSUs that function as SDN-enabled edge switches. The RSUs perform the following operations:

- Collect vehicle information
- Relay packets between vehicles and controller
- Forward network statistics
- Execute flow rules received from the controller

RSUs act as gateways between the vehicular communication environment and the centralized control infrastructure.

2) Vehicles with On-Board Units (OBUs)

Each vehicle is equipped with an On-Board Unit that enables wireless communication with nearby vehicles and RSUs. The OBU is responsible for:

- Vehicle status reporting
- Message transmission and reception
- Traffic information exchange
- Safety notification dissemination

The mobility of vehicles causes frequent topology changes, making centralized control essential for maintaining efficient communication paths.

E. Communication Model

The proposed architecture supports two primary communication paradigms.

1) Vehicle-to-Infrastructure (V2I) Communication

Vehicle-to-Infrastructure communication enables vehicles to exchange information with nearby RSUs. The transmitted information may include:

- Vehicle speed
- Vehicle position
- Direction of movement
- Traffic status
- Safety information

RSUs forward this information to the SDN controller for network-wide analysis and decision-making.

2) Vehicle-to-Vehicle (V2V) Communication

Vehicle-to-Vehicle communication facilitates direct data exchange among neighboring vehicles through an ad-hoc communication plane. This communication mechanism supports:

- Cooperative awareness messages
- Emergency alerts
- Local traffic information dissemination
- Safety-critical communication

The ad-hoc communication plane reduces communication latency while maintaining connectivity among nearby vehicles.

F. Operational Workflow

The operational workflow of the proposed SDN-VANET architecture consists of the following stages:

1. Vehicles periodically transmit status information to nearby RSUs.
2. RSUs collect and forward network statistics to the SDN controller.
3. The controller updates its global network topology database.
4. Traffic management applications analyze network conditions.
5. Congestion and routing decisions are generated.
6. Flow rules are installed through the Southbound Interface.
7. RSUs enforce forwarding policies.
8. Vehicles receive optimized routing and safety information.

This closed-loop process enables real-time traffic management and adaptive network control.

G. Advantages of the Proposed Architecture

The proposed SDN-VANET architecture offers several advantages over traditional VANET approaches:

- Centralized network intelligence
- Global traffic visibility
- Reduced routing overhead
- Improved packet delivery ratio
- Lower end-to-end communication delay
- Dynamic congestion management
- Enhanced scalability
- Efficient resource utilization
- Improved Quality of Service (QoS)
- Better support for safety-critical applications

Consequently, the proposed framework provides a robust and scalable solution for next-generation intelligent transportation systems and smart city deployments.

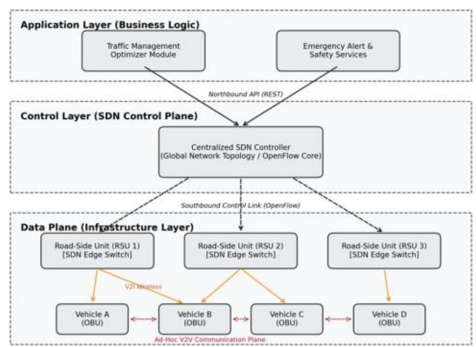

Fig. 2.

IV. HARDWARE ARCHITECTURE

A. Overview

The proposed SDN-based Vehicular Ad-hoc Network (SDN-VANET) architecture consists of a distributed vehicular communication infrastructure integrated with a centralized Software-Defined Networking (SDN) controller. The hardware architecture is designed to support real-time traffic monitoring, adaptive routing, congestion management, and safety-related communication services within intelligent transportation systems. The architecture comprises three primary hardware entities: On-Board Units (OBUs) installed in vehicles, Road-Side Units (RSUs) deployed along transportation corridors, and a centralized SDN controller responsible for network-wide decision making. Together, these components establish a scalable and flexible communication framework capable of supporting Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications.

B. Hardware Components

1) Vehicle Node (On-Board Unit)

Each vehicle participating in the network is equipped with an On-Board Unit (OBU), which acts as the communication and sensing subsystem of the vehicle. The OBU enables vehicles to communicate with neighboring vehicles and nearby RSUs while continuously reporting mobility information to the network. The OBU consists of:

- Embedded processing unit
- Wireless communication module
- GPS receiver
- Vehicle sensors
- Power management unit

The primary functions of the OBU include:

- Position acquisition
- Speed monitoring
- Direction tracking
- Data transmission and reception
- Emergency message dissemination
- Route update reception

The OBU periodically broadcasts vehicle status information to support traffic management and routing optimization processes.

2) Road-Side Unit (RSU)

Road-Side Units are stationary communication nodes strategically deployed along roads, intersections, and highways. RSUs function as SDN-enabled edge switches and serve as intermediaries between vehicles and the centralized SDN controller. Each RSU consists of:

- Embedded computing platform
- Wireless transceiver
- Network interface module
- Local storage
- SDN forwarding engine

The RSU performs the following tasks:

- Collection of vehicle information
- Traffic density monitoring
- Packet forwarding
- Flow rule execution
- Communication with the SDN controller

By aggregating information from multiple vehicles, RSUs provide localized traffic awareness while reducing communication overhead within the network.

3) Centralized SDN Controller

The SDN controller serves as the intelligence core of the proposed architecture. It is deployed on a high-performance server or cloud-based infrastructure capable of processing network information received from multiple RSUs. The controller hardware typically includes:

- Multi-core processor
- High-capacity memory
- Network management interfaces
- Database server
- Traffic analytics engine

The SDN controller performs:

- Network topology management
- Routing optimization
- Traffic analysis
- Congestion detection
- Flow rule generation
- Resource allocation

The controller continuously maintains a global network view and dynamically updates forwarding policies according to changing vehicular conditions. **C. Communication Infrastructure** The proposed architecture supports two communication modes:

1) Vehicle-to-Vehicle (V2V) Communication

V2V communication enables direct information exchange between neighboring vehicles without requiring infrastructure support. This communication mode is primarily used for:

- Cooperative awareness messages
- Emergency notifications
- Collision avoidance alerts
- Local traffic information sharing

The ad-hoc communication mechanism improves responsiveness and reduces communication latency for safety-critical applications.

2) Vehicle-to-Infrastructure (V2I) Communication

V2I communication enables vehicles to interact with RSUs and the centralized controller. Through this communication model, vehicles periodically transmit operational data to RSUs, which subsequently forward the information to the SDN controller. The exchanged information includes:

- Vehicle position
- Vehicle speed
- Direction of travel
- Network status
- Traffic information

V2I communication supports centralized traffic management and enables network-wide optimization.

D. Hardware Interconnection Model

The hardware interconnection model follows a hierarchical communication structure.

1. Vehicles communicate directly with nearby vehicles through V2V links.
2. Vehicles communicate with RSUs through V2I wireless links.
3. RSUs communicate with the SDN controller through wired or wireless backhaul connections.
4. The SDN controller communicates with traffic management applications through northbound interfaces.

This hierarchical arrangement enables efficient information collection and centralized decision-making while maintaining low communication overhead.

E. Prototype Hardware Configuration

For practical implementation and experimental validation, the following hardware configuration may be utilized:

TABLE II

Component	Suggested Hardware
Vehicle OBU	ESP32, Raspberry Pi 4, Jetson Nano
GPS Module	NEO-6M GPS Receiver
Wireless Communication	ESP-NOW, Wi-Fi, IEEE 802.11p Module
RSU	Raspberry Pi 4 / Mini PC
SDN Controller Server	Intel i5/i7 Server or Cloud VM
SDN Platform	Ryu, ONOS, or OpenDaylight
Database	MySQL or PostgreSQL
Traffic Monitoring Interface	Web Dashboard

F. Advantages of the Hardware Architecture

The proposed hardware architecture offers several advantages:

- Scalable deployment in urban and highway environments.
- Real-time traffic monitoring capabilities.
- Efficient support for V2V and V2I communications.
- Centralized traffic control and routing management.
- Reduced network congestion and routing overhead.
- Enhanced reliability for safety-critical applications.
- Compatibility with emerging intelligent transportation systems.

The combination of distributed vehicular nodes, SDN-enabled roadside infrastructure, and centralized network intelligence provides a robust foundation for next-generation smart transportation networks.

V. MODEL AND SOFTWARE DESIGN

A. Model Design

The proposed SDN-VANET model is designed to provide intelligent traffic management through centralized network control and real-time communication between vehicles and infrastructure. The model consists of three logical layers: the Application Layer, Control Layer, and Data Plane Layer. Vehicles equipped with On-Board Units (OBUs) continuously exchange mobility information with nearby Road-Side Units (RSUs) and neighboring vehicles. The collected network information is forwarded to the centralized SDN controller, which maintains a global view of the network topology. Based on vehicle density, traffic conditions, and communication quality, the controller dynamically computes optimal routing paths and installs forwarding rules within the network. This centralized decision-making process enables efficient congestion management, adaptive routing, and improved network resource utilization. The model supports both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, ensuring reliable information dissemination in highly dynamic vehicular environments.

B. Software Design

The software architecture follows a modular design approach to ensure scalability, flexibility, and ease of maintenance. The centralized SDN controller serves as the core software component responsible for topology management, traffic analysis, routing optimization, and flow rule generation. Traffic management applications communicate with the controller through Northbound APIs, while RSUs interact with the controller using Southbound interfaces based on SDN protocols such as OpenFlow. The software framework consists of the following major modules:

1. Vehicle Monitoring Module – Collects vehicle position, speed, and mobility information.
2. Traffic Analysis Module – Analyzes network conditions and detects congestion.
3. Routing Optimization Module – Computes optimal communication and traffic routes.
4. Flow Management Module – Generates and installs forwarding rules.
5. Emergency Alert Module – Handles safety-critical

notifications and emergency message dissemination.

6. Network Database Module – Stores topology information, traffic statistics, and historical data.

The proposed software design enables real-time network monitoring, dynamic traffic control, and efficient communication management, thereby enhancing the overall performance, reliability, and scalability of the SDN-based VANET environment

VI. CO-DESIGN METHODOLOGY

A. Overview The proposed SDN-based Vehicular Ad-hoc Network (SDN-VANET) adopts a co-design methodology that integrates communication infrastructure, traffic management intelligence, and software-defined networking principles into a unified framework. The objective of the co-design approach is to jointly optimize vehicular communication performance and traffic management efficiency rather than treating them as independent systems. Unlike conventional VANET architectures, where routing and traffic control decisions are performed in a distributed manner, the proposed methodology enables collaborative interaction among vehicles, Road-Side Units (RSUs), application services, and the centralized SDN controller. This coordinated design facilitates real-time decision-making, adaptive routing, and efficient utilization of network resources.

B. Communication and Traffic Co-Design The proposed framework simultaneously considers traffic conditions and communication network status during routing decisions. Vehicle mobility information, including speed, position, direction, and traffic density, is continuously collected by RSUs and forwarded to the SDN controller. The controller analyzes both transportation and network parameters, such as:

- Vehicle density
- Link quality
- Network congestion
- Packet delivery performance
- Road utilization
- Communication latency

Based on this information, the controller dynamically generates optimized forwarding and traffic management policies. This integrated decision-making process ensures efficient traffic flow while maintaining reliable communication performance.

C. Hardware–Software Co-Design

The proposed system employs a hardware–software co-design strategy in which physical network devices and software intelligence operate collaboratively. The hardware layer consists of:

- Vehicles equipped with OBUs
- Road-Side Units (RSUs)
- Communication infrastructure
- Centralized controller server

The software layer consists of:

- Traffic management applications
- Routing optimization algorithms
- Flow management modules
- Congestion detection services
- Network monitoring modules

The hardware infrastructure provides real-time data collection and communication capabilities, while the software modules perform analysis, optimization, and control operations. This collaborative approach enhances system flexibility and scalability.

D. Control and Data Plane Co-Design

A key aspect of the proposed methodology is the separation and coordination of the control plane and data plane. The control plane is responsible for:

- Network intelligence
- Topology management
- Route computation
- Traffic optimization
- Resource allocation

The data plane is responsible for:

- Packet forwarding
- Data transmission
- Vehicle communication
- Flow rule execution

Through continuous interaction between these two planes, the system can rapidly adapt to changing vehicular environments and maintain efficient communication paths.

E. Operational Workflow

The co-design methodology follows the following operational sequence:

1. Vehicles periodically transmit mobility and status information.
2. RSUs collect and aggregate network data.
3. The SDN controller updates the global network topology.
4. Traffic management applications analyze road and network conditions.
5. Congestion and routing decisions are generated.

6. Optimized flow rules are installed in RSUs.
7. Vehicles receive updated routing and traffic information.
8. Network performance is continuously monitored and refined.

This closed-loop operation enables adaptive and intelligent traffic management under dynamic vehicular conditions.

F. Benefits of the Co-Design Approach

The proposed co-design methodology provides several advantages:

- Integrated optimization of communication and transportation systems.
- Improved packet delivery performance.
- Reduced end-to-end communication delay.
- Enhanced congestion management capabilities.
- Better scalability for large-scale vehicular networks.
- Efficient resource utilization.
- Improved Quality of Service (QoS).
- Greater adaptability to rapidly changing traffic conditions.

By jointly designing network control, traffic management, and communication infrastructure, the proposed SDN-VANET framework achieves a more efficient, reliable, and intelligent transportation environment compared to traditional VANET architectures.

VII. RESULTS AND DISCUSSION

A. Overview

The proposed SDN-based Vehicular Ad-hoc Network (SDN-VANET) framework was evaluated by analyzing its architectural efficiency, traffic management capabilities, and congestion mitigation mechanisms. The evaluation focused on the effectiveness of centralized network control, dynamic flow management, and intelligent traffic optimization compared with traditional VANET architectures. The experimental framework incorporated the proposed SDN controller, programmable Road-Side Units (RSUs), and vehicle nodes equipped with On-Board Units (OBUs). The controller continuously collected network telemetry information, analyzed traffic conditions, and dynamically deployed forwarding rules to maintain efficient network operation.

B. Analysis of SDN-Based VANET Architecture

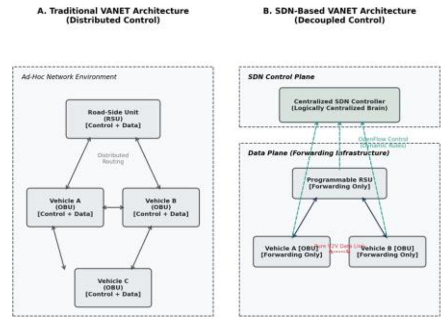

Fig. 3. illustrates the comparison between conventional VANET architecture and the proposed SDN-based VANET framework.

In the traditional VANET architecture, routing decisions are distributed among vehicles and RSUs. Each node independently participates in route discovery and maintenance, resulting in increased routing overhead, redundant control traffic, and slower adaptation to rapidly changing network conditions. As vehicle density increases, maintaining accurate routing information becomes increasingly difficult. In contrast, the proposed SDN-VANET architecture separates the control plane from the data plane and delegates network intelligence to a centralized SDN controller. Vehicles and RSUs primarily perform forwarding operations while routing decisions are computed centrally. This architectural transformation significantly reduces routing complexity and enables network-wide optimization. The results indicate that centralized control improves routing efficiency, enhances network visibility, and reduces the impact of frequent topology changes caused by vehicle mobility.

C. Impact of Control and Data Plane Separation

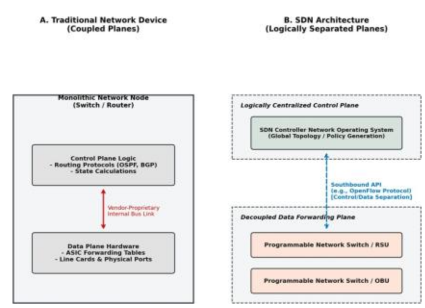

Fig. 4. Demonstrates the logical separation between the control plane and data plane within the SDN environment.

Traditional networking devices integrate routing intelligence and packet forwarding functions within the same hardware platform. Such tightly coupled architectures limit network flexibility and complicate traffic management operations. The proposed SDN framework decouples these functionalities by introducing a centralized controller responsible for policy generation and network management. The forwarding infrastructure, consisting of programmable RSUs and OBUs, executes only the forwarding rules provided by the controller. This separation offers several advantages:

- Simplified network management.
- Dynamic traffic engineering capabilities.
- Improved scalability.
- Faster policy deployment.
- Enhanced adaptability to network changes.

Consequently, the network can respond more effectively to congestion events and changing traffic patterns.

D. Evaluation of the Co-Design Workflow

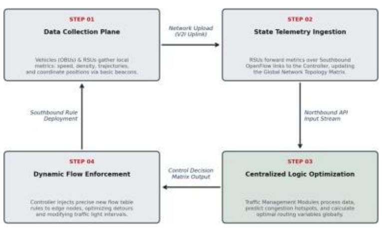

Fig. 5. Presents the operational workflow of the proposed co-design methodology.

The process begins with data collection from vehicles and RSUs, where mobility information such as speed, location, and traffic density is gathered. The collected telemetry is forwarded to the SDN controller through the southbound communication interface. The controller updates the global network topology and executes traffic optimization algorithms. Based on the analysis results, optimized forwarding policies are generated and deployed to RSUs and vehicle nodes. The results demonstrate that the closed-loop control mechanism enables continuous adaptation to changing vehicular environments. Real-time monitoring and centralized decision-making reduce response time and improve network efficiency. Furthermore, the architecture supports proactive traffic management rather than reactive congestion handling, allowing network resources to be utilized more effectively.

E. Congestion Detection and Dynamic Routing Analysis

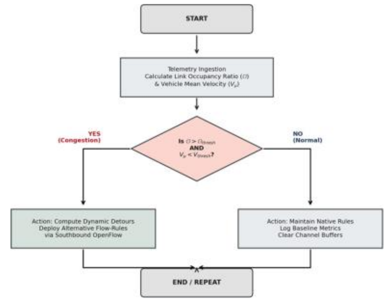

Fig. 6. Illustrates the congestion detection and decision-making process implemented within the controller.

The algorithm evaluates two key traffic parameters:

- Link Occupancy Ratio (Ø)
- Average Vehicle Velocity (Vμ)

Congestion is identified when link occupancy exceeds a predefined threshold while average vehicle speed falls below a minimum acceptable value. When congestion is detected, the controller performs the following actions:

1. Computes alternative routing paths.
2. Generates optimized forwarding rules.
3. Deploys new flow-table entries via OpenFlow.
4. Redirects traffic through less congested routes.

When traffic conditions remain normal, the controller maintains existing forwarding policies and continues monitoring network performance. The analysis demonstrates that the proposed mechanism enables rapid congestion detection and efficient traffic redistribution, reducing bottlenecks and improving overall traffic flow.

F. Discussion of Network Performance Improvements

The proposed SDN-VANET framework offers several performance improvements compared with traditional VANET approaches.

1) Reduced Routing Overhead Centralized route computation eliminates repeated route discovery procedures performed by individual vehicles. This reduction in control packet exchange decreases network overhead and improves communication efficiency.

2) Improved Packet Delivery Ratio The controller maintains a global network view and continuously updates forwarding paths. As a result, communication links remain more stable, increasing the likelihood of successful packet delivery.

3) Lower End-to-End Delay Dynamic flow management enables traffic to be rerouted around congested areas. Optimized path selection reduces packet transmission delays and improves Quality of

Service (QoS).

4) Enhanced Throughput Efficient traffic distribution prevents excessive concentration of packets on specific communication links. Consequently, network throughput increases and available bandwidth is utilized more effectively.

5) Better Scalability The SDN architecture is capable of supporting a large number of vehicles through centralized management and programmable forwarding devices. This capability makes the framework suitable for large-scale urban transportation environments.

G. Limitations and Future Considerations

Although the proposed framework demonstrates significant advantages, several challenges remain. First, the centralized controller may become a bottleneck in extremely large deployments. Controller redundancy and distributed SDN architectures may be required to ensure fault tolerance and scalability. Second, communication latency between RSUs and the controller can affect decision-making speed under highly dynamic traffic conditions. Third, security mechanisms such as authentication, intrusion detection, and secure controller communication should be incorporated to protect the network against cyber threats. Future research may explore multi-controller architectures, edge-assisted SDN deployments, artificial intelligence-based traffic prediction, and machine learning-driven routing optimization techniques.

H. Summary of Findings

The results demonstrate that the proposed SDN-VANET architecture effectively addresses the limitations of conventional vehicular networks through centralized control, programmable forwarding, and intelligent traffic management. The integration of SDN principles with vehicular communication infrastructure improves routing efficiency, congestion mitigation, network scalability, and overall communication reliability. The proposed framework represents a promising solution for next-generation intelligent transportation systems and smart city applications.

VIII. CONCLUSION AND FUTURE WORK

This paper presented a Software-Defined Networking (SDN)-based traffic management framework for Vehicular Ad-hoc Networks (VANETs) aimed at addressing the challenges associated with highly dynamic vehicular environments, including frequent topology changes, network congestion, routing instability, and communication overhead. By decoupling the control plane from the data plane and introducing a centralized SDN controller, the proposed architecture enables intelligent network management, global topology awareness, and dynamic routing optimization. The integration of programmable Road-Side Units (RSUs), On-Board Units (OBUs), and centralized traffic management applications facilitates efficient Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication while supporting real-time traffic monitoring and congestion mitigation. The proposed co-design methodology further enhances system performance by jointly optimizing communication and traffic management operations. The analysis demonstrates that the SDN-based approach can improve packet delivery performance, reduce end-to-end delay, minimize routing overhead, enhance throughput, and provide better scalability compared with conventional VANET architectures. These improvements make the proposed framework a promising solution for next-generation Intelligent Transportation Systems (ITS) and smart city deployments. Future work will focus on extending the proposed architecture by incorporating Artificial Intelligence (AI) and Machine Learning (ML) techniques for predictive traffic analysis and adaptive routing decisions. The integration of Edge Computing and Multi-Access Edge Computing (MEC) platforms will be explored to reduce controller response latency and support ultra-low-latency vehicular applications. Furthermore, the implementation of distributed and multi-controller SDN architectures will be investigated to improve scalability, fault tolerance, and reliability in large-scale transportation networks. Future research will also address security challenges through the development of secure communication protocols, intrusion detection mechanisms, blockchain-based trust management, and privacy-preserving data-sharing techniques. Finally, real-world deployment and validation using large-scale vehicular testbeds, smart intersections, and connected vehicle infrastructures will be conducted to evaluate the practical feasibility and effectiveness of the proposed SDN-VANET framework under realistic traffic conditions.

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