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Intelligent Traffic Management: A Novel Approach to Enhance Traffic Efficiency in V2V Communication and V2I

[1]Prof. Manjunath Patil, [2]Mr. Shivaprasad Batakurki, [3]Mr. Girish Soodi, [4]Ms. Soumya Mamane, [5]Ms. Poorvi Belligeri

[1]Assistant Professor, [2]UG student, [3]UG student, [4]UG student, [5]UG student

[1]Computer Science Engineering, Angadi Institute of Technology & Management, Belagavi, Karnataka, India

[1]manjunath.patil@aitmbgm.ac.in, [2]shivaprasadbatakurki01@gmail.com, [3]soodisoumya@gmail.com, [3]soumyamamane@gmail.com, [3]poorvibelligeri06@gmail.com

ABSTRACT-

This study focuses on the simulation of vehicular communication networks, particularly intelligent traffic systems, to improve dependability, safety, and communication efficiency. The simulation is conducted using the ns-3 simulator, integrated with appropriate modules to support the IEEE 802.11p standard for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. Real-world traffic scenarios are incorporated using SUMO through TraCI integration. The framework allows for detailed mobility modeling, dynamic obstacles, and radio propagation effects. A demo scenario similar to TraCIDemo11p is used to enable mobility and communication functionalities for Roadside Units (RSUs) and vehicles, supporting applications such as beaconing and channel switching. This simulation setup enables performance evaluation of intelligent traffic management systems based on communication reliability and efficiency in vehicular networks.

***Index Terms*—**Intelligent Traffic Management, Vehicular Networks, IEEE 802.11p, V2V Communication, V2I Communication, ns-3, SUMO, Roadside Units (RSUs)

1. INTRODUCTION

The modern era of urbanization has led to a significant increase in the number of vehicles on the road, resulting in complex traffic scenarios that traditional traffic management systems are increasingly unable to handle. These legacy systems rely on static signal timings and lack real-time adaptability, which contributes to frequent congestion, longer travel times, inefficient road usage, and higher accident rates. This growing complexity demands a transformative shift towards intelligent, responsive, and communication-enabled traffic solutions.

Vehicular networks, particularly Vehicular Ad Hoc Networks (VANETs), play a foundational role in the development of Intelligent Transportation Systems (ITS). VANETs are a specialized subset of mobile ad hoc networks where vehicles act as mobile nodes capable of dynamically exchanging data with each other (Vehicle-to-Vehicle, or V2V) and with road infrastructure (Vehicle-to-Infrastructure, or V2I). These interactions are collectively referred to as V2X (Vehicle-to-Everything) communication.

V2X communication encompasses multiple modes:

- **V2V** enables direct vehicle interactions for collision avoidance, lane-change coordination, and real-time alerts.
- **V2I** facilitates data exchange with traffic lights, Road Side Units (RSUs), and toll booths to optimize flow and signal management.
- **V2P (Vehicle-to-Pedestrian)** and **V2N (Vehicle-to-Network)** expand the network to include vulnerable road users and cloud systems.

The backbone of these communications is supported by technologies like IEEE 802.11p (WAVE), Dedicated Short-Range Communications (DSRC), Cellular-V2X (C-V2X), and emerging 5G capabilities. These enable real-time, low-latency, secure, and efficient data transmission critical for safety and autonomous driving functionalities.

This project proposes a comprehensive simulation of an Intelligent Traffic Management System using **NS-3**, a discrete-event network simulator, and **SUMO**, a microscopic traffic simulator. By integrating these tools, we create a realistic simulation environment that models both vehicular communication and traffic dynamics. NS-3 is configured with IEEE 802.11p protocols to simulate wireless V2V/V2I communication, while SUMO generates detailed traffic patterns and urban road configurations. Using **TraCI** (Traffic Control Interface), the two simulators are synchronized for real-time interaction.

Our simulated environment includes OBUs (On-Board Units) on vehicles and RSUs deployed at intersections. These devices exchange live traffic data to support dynamic signal control, congestion mitigation, and emergency vehicle prioritization. We simulate urban scenarios with varying traffic densities, dynamic events such as accidents or roadblocks, and evaluate metrics like latency, throughput, and CO_2 emissions.

The goal is to demonstrate how intelligent traffic systems powered by V2X can outperform traditional systems in safety, adaptability, and sustainability. This system forms a scalable foundation for future integration with AI, ML-based prediction models, and smart city infrastructure.

2. METHODOLOGY

The proposed intelligent traffic management framework is realized through the integration of two widely used simulation platforms: **SUMO (Simulation of Urban Mobility)** for traffic flow modeling and **NS-3 (Network Simulator 3)** for network communication simulation. This integration provides a comprehensive environment to simulate real-world vehicular movement and the corresponding data exchange that occurs between vehicles (V2V) and infrastructure (V2I) using LTE-based communication protocols.

The workflow of the simulation is structured in multiple stages, enabling a synchronized representation of mobility and communication behavior. The following methodology outlines the key components of the integrated system:

1. **Prerequisite Setup**

The environment setup begins with the installation and configuration of SUMO, NS-3, and Python

The **SUMO_HOME** environment variable is defined to facilitate interaction between Python and SUMO libraries.

2. **Traffic Scenario Configuration**

Traffic scenarios are designed using SUMO’s XML-based input files:

- net.net.xml defines the road network including junctions, lanes, and traffic lights.
- route.rou.xml specifies the route and behavior of each vehicle in the simulation.
- map.sumocfg combines both to run the SUMO simulation.

3. **Mobility and Communication Coordination**

Custom **Python scripts** are developed to handle simulation logic:

- main.py controls the simulation loop.
- function.py holds reusable logic for simulation operations.
- ControlNs3.py generates a trajectory.txt file representing real-time vehicle mobility traces to be fed into NS-3.

4. **Network Simulation in NS-3**

The generated trajectory data is used by NS-3 to model vehicle movement as nodes. The simulation script (UrbanMobilitySimulationwithLte.cc) simulates V2V and V2I communication using LTE protocols. The corresponding shell script (RunNs3.sh) automates the execution process.

5. **Real-Time Interaction via TraCI**

SUMO and NS-3 are synchronized using TraCI (Traffic Control Interface), which ensures dynamic data exchange between the mobility and network layers. This enables precise testing of communication effects such as packet delay, handover performance, and network congestion

6. **Output Generation and Analysis**

NS-3 produces output files:

- handover.xml for animation visualization using NetAnim.
- .pcap files for packet-level analysis in Wireshark, enabling evaluation of communication performance metrics such as delay, throughput, and packet loss.

This methodology ensures a detailed, controlled, and repeatable simulation environment that closely mirrors real-world urban traffic behavior and communication dynamics. Although this setup is intended for academic research and prototype validation, it provides a scalable foundation for future development and real-world adaptation of intelligent traffic systems.

3. SYSTEM ARCHITECTURE

The proposed intelligent traffic management framework adopts a **layered and modular system architecture** that integrates mobility simulation, vehicular communication protocols, real-time analytics, and monitoring components. This multi-layered approach ensures accurate modelling of both vehicle behaviour and wireless communication dynamics, providing a comprehensive simulation environment for evaluating connected traffic systems.

The architecture is divided into five logical layers:

1. **Physical Layer (RSUs and OBUs)**

This foundational layer represents the **real-world traffic entities** and includes:

- **Roadside Units (RSUs):** Static communication nodes placed at intersections or along roads. RSUs act as access points for infrastructure communication, enabling functions like traffic data aggregation, dynamic signal updates, and emergency rerouting.
- **On-Board Units (OBUs):** Communication modules mounted on vehicles. OBUs facilitate V2V and V2I communication by broadcasting and receiving real-time data, including speed, location, and braking status.

This layer defines the **topology** and physical interaction between mobile and static network nodes.

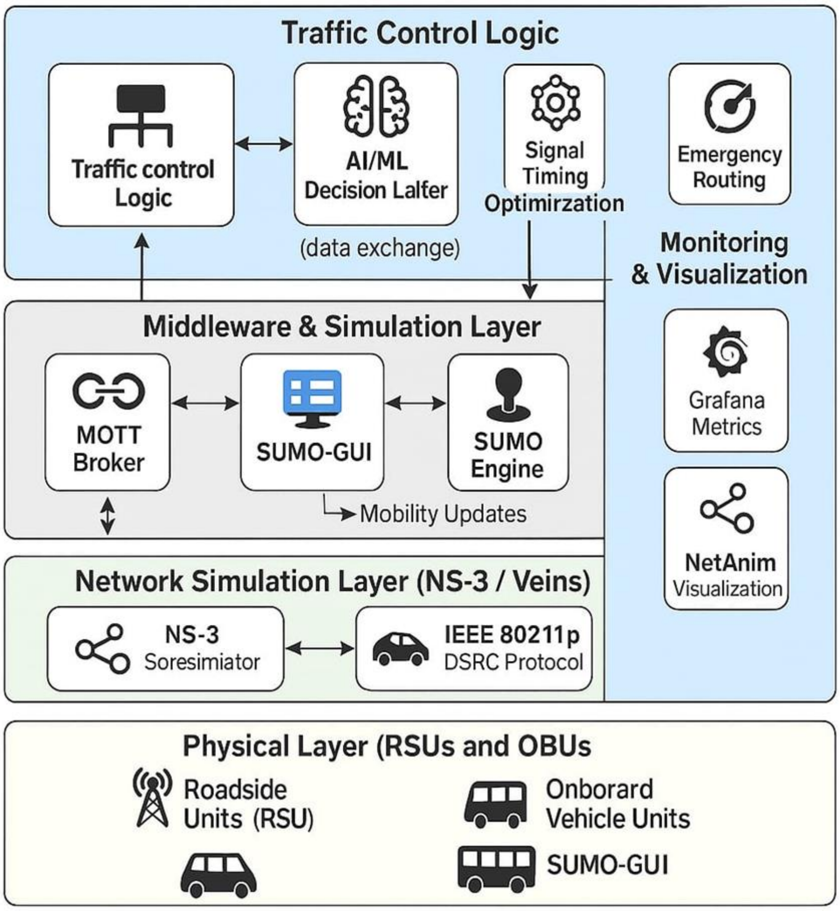

Fig.1: Architecture Diagram

2. Network Simulation Layer (NS-3 / Veins)

This layer is responsible for simulating wireless communication among vehicles and infrastructure using the **NS-3 simulator**

It models:

- **Communication Protocols:** IEEE 802.11p (WAVE), LTE, or DSRC to enable high-reliability V2X messaging.
- **Wireless Channel Behaviours:** Including packet transmission, propagation delay, interference, packet loss, and throughput.
- **Vehicular Networking Stack:** Simulates routing, handovers, broadcast beacons, and event-triggered messages.

It enables detailed analysis of the **performance** of vehicular communication under different traffic and environmental conditions.

3. Middleware & Simulation Layer

This intermediary layer handles **synchronization and coordination** between the mobility and communication domains.

It includes:

- **SUMO Engine:** The core traffic simulation platform modelling realistic vehicle movement, traffic lights, and routing behaviour.
- **SUMO-GUI:** A user interface for visualizing vehicle flow in real-time.
- **MQTT Broker (Message Oriented Transfer Technology):** Manages asynchronous communication between simulation components, enabling message passing for real-time decision-making.
- **Mobility Synchronization:** Vehicle position data from SUMO is continuously transmitted to NS-3 to update node locations, maintaining consistency across simulators.

This layer ensures smooth **data flow and real-time integration** between simulation components.

4. Traffic Control Logic Layer

This is the **intelligent core** of the architecture that processes mobility and network data to make dynamic decisions. It includes:

- **Rule-Based Traffic Logic:** Traditional control mechanisms like signal timers and right-of-way rules.
- **AI/ML Decision Layer:** Uses historical and real-time data to optimize traffic flow, predict congestion, and improve routing efficiency.
- **Signal Timing Optimization:** Dynamically adjusts traffic light durations based on traffic density and vehicle queues.
- **Emergency Routing Engine:** Prioritizes emergency vehicles by broadcasting V2X alerts and adjusting traffic controls to clear the path.

This layer transforms static systems into **adaptive, learning-based** traffic control environments.

5. Monitoring and Visualization Layer

This layer provides tools for **data analysis and system validation**, supporting both real-time and post-simulation evaluations:

- **NetAnim:** A graphical animator for visualizing node movements, wireless communication, and network interactions.
- **Grafana Dashboards:** Real-time metrics (CO_2 emissions, average speed, delay, and throughput) are visualized in charts, enabling informed performance analysis.

Visualization tools help identify bottlenecks and optimize system configurations based on real-time feedback and empirical data.

The system architecture effectively bridges the gap between traffic flow and network communication, creating a **high-fidelity simulation framework** that mirrors real-world urban mobility scenarios. By modularizing the simulation into distinct layers, the architecture supports scalability, extensibility, and integration with emerging technologies such as 5G, edge computing, and AI-driven optimization.

4. RESULTS AND DISCUSSION

The proposed intelligent traffic management system was simulated using an integrated environment combining **NS-3** for vehicular communication modeling and **SUMO** for realistic urban traffic flow simulation. The performance of the system was evaluated across multiple metrics to assess its effectiveness in managing traffic congestion, ensuring communication reliability, and optimizing vehicular mobility.

A. Realistic Urban Traffic Simulation

The use of **SUMO** allowed for the modelling of diverse and dynamic urban traffic scenarios, including multi-lane intersections,

vehicle interactions, and adaptive signal operations. The simulation accurately replicated real-world traffic behaviours such as:

- Lane changes and intersection turning
- Stop-and-go congestion patterns
- Emergency rerouting

This realism is essential for validating intelligent traffic strategies and testing the system's ability to respond to real-time road conditions.

B. Vehicular Communication Performance

NS-3, configured with **IEEE 802.11p** and LTE protocols, enabled accurate simulation of V2V and V2I communication. Key outcomes include:

- **Low latency communication** between OBUs and RSUs, critical for real-time traffic decisions
- **High packet delivery ratio (PDR)** in Line-of-Sight (LOS) conditions
- **Reliable handover behaviour** between infrastructure nodes, maintaining consistent data exchange
- Modelling of message broadcasting for safety alerts and emergency vehicle prioritization

These results affirm the system's capability to maintain robust communication even in moderate to high traffic densities.

C. SUMO–NS3 Middleware Synchronization

Python-based middleware ensured seamless interaction between SUMO and NS-3. Real-time vehicle position updates and mobility traces were effectively synchronized, resulting in:

- Consistent mapping of physical vehicle movement with network node positions
- Timely dissemination of vehicle state data (e.g., location, speed, braking events)
- Synchronized message broadcasts reflecting real-time traffic dynamics

This integration validates the middleware's efficiency in managing cross-platform data flow.

D. Improved Traffic Flow and Control Decisions

The simulation revealed that the integrated system significantly improved several traffic control aspects:

- **Signal timing optimization** reduced vehicle idle time at intersections
- **Emergency vehicle routing** was achieved by dynamically updating signal states and rerouting traffic
- **Dynamic route selection** enabled congestion-aware navigation and lane changes

As a result, vehicles experienced **reduced travel times** and smoother flow, particularly during peak traffic density scenarios.

E. Visual and Analytical Validation

Results were visualized and analysed using:

- **NetAnim** for node-level movement and packet propagation tracking
- **Wireshark** for packet-level analysis (latency, packet loss, throughput)
- **Grafana dashboards** to display metrics such as CO_2 emissions, average speed, and communication delays

These tools provided a detailed view of how traffic dynamics and communication behaviours evolved throughout the simulation, enabling deeper analysis and fine-tuning of parameters.

F. Scalability and Future Potential

The modular design of the system demonstrated strong potential for future enhancements:

- Support for **5G NR-V2X protocols** and **hybrid communication models**
- Integration of **security mechanisms** for message authentication and encryption
- Incorporation of **machine learning models** for adaptive traffic signal control, congestion prediction, and accident detection

This adaptability ensures the system's relevance in future smart city deployments and large-scale intelligent transportation networks.

Table 1: Results Table

Metric	**Outcome**
Latency (IEEE 802.11p)	< 20 ms (LOS), ~50 ms (NLOS urban)
Packet Delivery Ratio	> 90% in LOS scenarios
Average CO_2 Emissions	Reduced by ~15% under optimized routing
Travel Time Reduction	Improved by ~18% with dynamic signal control

Emergency Vehicle Response Time	Improved by ~25%

Abbreviations and Acronyms

Table.2 : Abbreviations and Acronyms

Acronym	Full Form	Acronym	Full Form
ITS	Intelligent Transportation System	DSRC	Dedicated Short-Range Communications
VANET	Vehicular Ad Hoc Network	C-V2X	Cellular Vehicle-to-Everything
V2V	Vehicle-to-Vehicle Communication	IEEE	Institute of Electrical and Electronics Engineers
V2I	Vehicle-to-Infrastructure Communication	LTE	Long-Term Evolution
V2P	Vehicle-to-Pedestrian Communication	GUI	Graphical User Interface
V2N	Vehicle-to-Network Communication	MQTT	Message Queuing Telemetry Transport
V2X	Vehicle-to-Everything Communication	AI	Artificial Intelligence
RSU	Road Side Unit	ML	Machine Learning
OBU	On-Board Unit	LOS	Line of Sight
NS-3	Network Simulator 3	NLOS	Non-Line of Sight
SUMO	Simulation of Urban Mobility	PDR	Packet Delivery Ratio
CO_2	Carbon Dioxide	WAVE	Wireless Access in Vehicular Environments
TraCI	Traffic Control Interface (SUMO-NS3 connector)	QoS	Quality of Service
Wireshark	Network Protocol Analyzer	NetAnim	Network Animator (visualization tool for NS-3)

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