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Enhancing Transportation with Vehicular Ad Hoc Networks (VANETs): A Study in the City of Kigali, Rwanda

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Abstract

Enhancing Road Safety and Traffic Management through VANETs in Kigali Vehicular Ad Hoc Networks (VANETs) offer an innovative solution to improving road safety, reducing accidents, and managing traffic more effectively. This study delves into the structure, protocols, and real-world applications of VANETs, with a specific focus on their potential deployment in Kigali, Rwanda. By using simulation tools like OMNET++ and SUMO, the research assesses how well VANETs perform in terms of efficiency and scalability. Additionally, key challenges such as security, privacy, and scalability are examined, with proposed solutions aimed at making VANETs a viable technology for urban settings. Connectivity tests have shown that ad hoc networks can effectively support vehicle communication, as they do not rely on fixed infrastructure, making ideal for highly dynamic traffic environments. To further enhance the efficiency of VANETs, this research proposes two new broadcasting mechanisms: Secure Ring Broadcasting (SRB) and Directed Route Node Selection (DRNS). SRB is specifically designed for urban environments with high traffic density, such as rush-hour scenarios in cities. It establishes stable and efficient communication pathways by using intermediate nodes placed at optimal distances, ensuring that vehicles can exchange information quickly and reliably even in congested areas. Meanwhile, DRNS is tailored for highway environments, where vehicles move at high speeds in opposite directions. This mechanism avoids using vehicles traveling in opposite directions as communication relays, which helps prevent unstable connections and ensures more reliable data transmission. By introducing these enhancements, the study aims to optimize VANET communication for different traffic conditions, whether in dense urban areas or open highways. Since internet access is becoming increasingly essential, the research also explores ways to integrate connectivity into ad hoc vehicular networks. To achieve this, a multi-hop hybrid internet access protocol based on AODV has been developed, allowing vehicles to connect to the internet even in areas without direct infrastructure support. Furthermore, the study investigates how the Address Resolution Protocol (ARP) impacts VANET performance, providing recommendations for improving overall network efficiency and communication reliability.

Keywords: *VANET, Urban Traffic Management, Vehicle Communication, Routing Protocols*

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1. Introduction

Vehicular Ad Hoc Networks (VANETs) play a crucial role in enhancing road safety and improving traffic efficiency. By enabling vehicles to communicate with one another (V2V) and with roadside infrastructure (V2I), these networks help in managing traffic flow, reducing congestion, and preventing accidents. Their ability to facilitate real-time data exchange makes them a valuable solution for creating smarter and safer transportation systems. However, cities like Kigali, Rwanda, don't have these systems in place yet, which leads to challenges in managing traffic and ensuring safety. To fix this, a tailored VANET system has been proposed, designed specifically to reduce accidents, improve traffic management, and make the roads safer overall.

A VANET system relies on three key components: The system consists of three main components Trusted Authority (TA), Roadside Units (RSUs), and Onboard Units (OBUs). The TA oversees network management and security, RSUs serve as communication hubs along the roads, and OBUs are installed in vehicles to enable real-time data exchange. The TA is the central hub of the network, managing and updating the system for the other components. RSUs are installed along the roads and serve as the communication bridge between vehicles and the TA, providing wireless infrastructure. OBUs are wireless devices mounted in vehicles that allow them to send and receive data, like traffic updates or road condition alerts, helping vehicles stay informed and safe.

While the benefits of VANETs are clear, scaling them up is no small task. It's expensive and requires a lot of resources, so simulations are often used to test and refine the system before real-world deployment. However, relying solely on simulations has its challenges because they may not always reflect real-world conditions perfectly. But it's a necessary step to ensure the system is functional and ready for implementation. Research has shown that the mobility models used in simulations have a huge impact on how accurately they reflect real-world scenarios. Choosing the right mobility model is crucial to getting results that are close to what we would experience on the roads. By fine-tuning these Models, researchers can improve the reliability of simulations, which ultimately leads to a more effective and robust VANET system that can make a difference on the streets. The diagram (Figure 1) illustrates the communication flow within a VANET: V2V Communication: Vehicles exchange data directly using their OBUs to share real-time traffic and safety information.V2I Communication: Vehicles interact with RSUs installed along the roadways. These RSUs are connected to an Access Network via a Gateway, which in turn links to the Internet.V2B (Vehicle-to-Base): Vehicles can also communicate with broader networks like the Internet via satellite or other base station systems. Each component plays a vital role in forming a comprehensive and intelligent transport system. OBUs and RSUs ensure local data exchange, while the TA and Internet access allow for global coordination and management.

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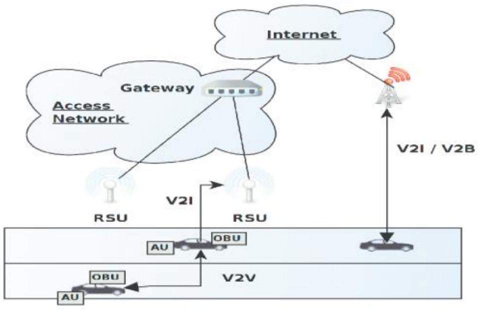

Figure 1: VANET Networks

2. Background

Vehicular Ad Hoc Networks (VANETs) have emerged as a specialized subclass of Mobile Ad Hoc Networks (MANETs), designed to support real-time communication between vehicles (V2V) and between vehicles and roadside infrastructure (V2I). These systems are critical for improving road safety, managing traffic flow, and enabling intelligent transportation services. VANETs rely on wireless communication technologies such as IEEE 802.11p and geographic routing protocols to deliver timely information for safety-critical applications.

In urban environments, especially in developing countries, VANET implementation faces persistent challenges, including limited infrastructure, scalability concerns, and heightened security and privacy issues. Kigali, Rwanda, currently lacks a functioning VANET system, which has contributed to traffic inefficiencies, increased congestion, and frequent road accidents. The absence of real-time communication between vehicles and infrastructure impedes drivers' ability to make informed decisions, compromising both safety and mobility.

This study proposes the development and implementation of a comprehensive VANET system tailored to Kigali's unique urban environment. The system will utilize modern wireless technologies and be simulated using OMNeT++ (IDE 6.0.5), a robust network modeling platform. The goal is to enhance communication between vehicles and roadside equipment, enabling proactive traffic management, accident prevention, and a safer driving experience.

3. Literature Review

Vehicular Ad Hoc Networks (VANETs) represent a transformative approach to improving transportation systems through real-time communication between vehicles and roadside infrastructure. These networks play a crucial role in enhancing road safety, reducing congestion, and enabling intelligent traffic management. Previous studies have extensively explored the architecture, communication models, and applications of VANETs in both developed and developing contexts. Hartenstein and Laberteaux (2008) laid foundational work in the field by presenting a comprehensive overview of VANET architecture, focusing on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. Their study emphasized the ability of VANETs to enable safety applications such as collision avoidance and emergency alerts. Gerla et al. (2014) later extended this work by examining the convergence of VANETs with the Internet of Things (IoT), arguing that future systems would evolve into an "Internet of Vehicles" leveraging cloud and edge computing for low-latency services.

Ahmed et al. (2021) developed a machine learning-enhanced VANET model for real-time traffic congestion prediction. Their study utilized a hybrid framework incorporating Onboard

Units (OBUs), Roadside Units (RSUs), and cloud infrastructure to deliver accurate traffic insights. The model demonstrated a reduction in traffic congestion and improved travel efficiency. On the other hand, Malik et al. (2020) highlighted key barriers to VANET deployment in developing countries, such as insufficient infrastructure, limited technical expertise, and unreliable energy supply.

In the African context, VANET research remains relatively limited. However, Mugenzi et al. (2022) conducted a simulation-based study focused on Kigali, Rwanda, using SUMO and OMNeT++ to model realistic urban traffic scenarios. The study found that customizing mobility models to reflect local traffic behavior significantly enhanced simulation accuracy, laying the groundwork for future real-world implementations. Furthermore, Kantarci et al. (2019) introduced a trust-based data dissemination model for VANETs to ensure reliable communication in highly dynamic environments. While existing studies demonstrate the significant potential of VANETs in improving traffic safety and efficiency, most have been conducted in technologically advanced or generalized contexts. Limited research has focused on adapting VANET solutions to the specific infrastructural and socio-technical conditions of African cities like Kigali. This gap underscores the need for localized simulation models and deployment strategies. Therefore, this study builds upon previous work by tailoring VANET designs to Kigali's urban dynamics, contributing to the advancement of intelligent transportation systems in developing regions.

4. Technical Details of Broadcasting Mechanisms in VANETs

In VANETs, broadcasting is a fundamental communication strategy used to disseminate messages such as emergency alerts, traffic updates, and beacon signals among vehicles (V2V) and between vehicles and roadside units (V2I). Due to high node mobility, dynamic topology, and varying vehicle densities, efficient broadcasting mechanisms are essential for reliability, scalability, and real-time responsiveness.

4.1. Basic Broadcasting Techniques

1. Simple Flooding

This mechanism involves each node rebroadcasting every received message once, offering the advantage of being simple to implement and guaranteeing message reachability within a connected network. However, its primary drawback is the "Broadcast Storm Problem," which leads to excessive redundancy, collisions, and network congestion, particularly in dense environments.

2. Probabilistic Broadcasting

This mechanism involves each node rebroadcasting a message with a certain probability `p`, which effectively reduces redundancy and collisions compared to simple flooding. However, a significant drawback is the potential for coverage holes to emerge if the probability `p` is not precisely tuned to the network's density.

3. Advanced and Intelligent Broadcasting Approaches

Distance-Based Broadcasting is a mechanism where nodes located farther from the message source have a higher probability of rebroadcasting, for instance, with the rebroadcast probability `p` being proportional to the ratio of the distance from the sender to the receiver to the maximum communication range `D`. This approach offers the advantage of encouraging

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messages to propagate farther with fewer hops, making it an ideal use case for highway scenarios where vehicles tend to be linearly distributed.

4. Cluster-Based Broadcasting.

Vehicles are grouped into clusters, with a "cluster head" responsible for managing communication within its cluster and with other cluster heads.

Advantages: Reduces routing overhead by localizing control traffic within clusters and simplifying inter-cluster communication.

Challenges: Dynamic cluster formation and maintenance in a high-mobility environment are complex. Frequent cluster head re-election can lead to instability.

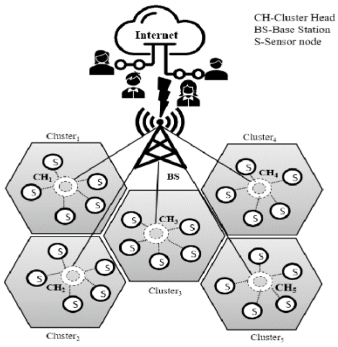

Figure 2: Cluster -Based Routing

5. Geocast (Geographic Broadcasting)

Geocast routing in VANETs involves forwarding messages only to nodes within a defined geographic area, known as the Zone of Relevance (ZoR). Protocols like GeoTORA and GeoCast are commonly used to implement this mechanism. It is particularly useful for location-specific applications such as accident alerts, roadwork warnings, and toll payment notifications.

6. Adaptive Broadcasting (Context-Aware)

Adaptive broadcasting in VANETs adjusts message dissemination strategies based on real-time network metrics such as vehicle density, speed, direction, and link quality. AI and machine learning techniques, including reinforcement learning and fuzzy logic, are employed to dynamically control broadcast parameters like probability and timing. For example, a neural-network-based broadcasting system can optimize rebroadcast delay time (RDT) by analyzing factors such as traffic density and vehicle velocity, improving both efficiency and reliability in dynamic environments.

7. Infrastructure-Assisted Broadcasting

In infrastructure-assisted broadcasting, Roadside Units (RSUs) or base stations actively participate in disseminating messages across the VANET. With the integration of Software-Defined Networking (SDN), a centralized SDN controller can optimize broadcast flow using its global view of the network topology, as seen in architectures like DistB-VNET. This approach significantly enhances communication reliability and efficiency, especially in urban or hybrid environments where direct vehicle-to-vehicle communication may be inconsistent or limited.

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8. Multi-Channel Broadcasting with IEEE 802.11p

In VANETs, broadcasting uses Control Channels (CCH) for safety messages and Service Channels (SCHs) for infotainment, with time-slot synchronization to reduce interference. This method improves communication efficiency but requires precise timing and coordination across network layers. Performance is evaluated using metrics such as reachability, end-to-end delay, network overhead, broadcast redundancy, and packet delivery ratio (PDR).

5. VANET Architectural Design

This part shows the system architecture of vehicular ad hoc networks. Let first look at the main components of VANETs architecture form the domain view. Then, we explain their interaction and introduce the communication architecture.

5.1. Vehicle Layer (Onboard Equipment - OBUs)

At the lowest level of the system are the vehicles themselves, each equipped with an On-Board Unit (OBU). These devices are responsible for real-time communication with both other vehicles and the infrastructure along the roadside. OBUs gather data from internal vehicle sensors (such as speed, direction, braking status) and GPS, then share this data using wireless communication technologies like Dedicated Short-Range Communication (DSRC), Cellular (4G/5G), or Wi-Fi.

The OBUs allow vehicles to:

1. Communicate with each other (Vehicle-to-Vehicle, V2V) to prevent accidents and warn of road hazards.
2. Interact with infrastructure (Vehicle-to-Infrastructure, V2I) to get real-time updates about traffic lights, road conditions, or toll payments.
3. Receive information such as rerouting suggestions, accident warnings, or weather alerts, helping drivers make better decisions on the road.

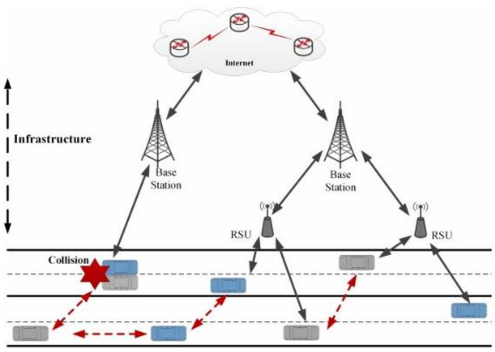

Figure 3: VANET Architectural Design

5.2 VANET Characteristics

Although Vehicular Ad-Hoc Networks (VANETs) share features with typical ad-hoc sensor networks—such as being self-organizing and lacking centralized management—they face unique challenges that affect communication system design and protocol security.

These challenges include:

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1. Scalability – VANETs must handle a very high number of nodes, including vehicles and roadside units.
2. Dynamic Topology – High-speed vehicle movement causes frequent and rapid topology changes, limiting the time available for data exchange.
3. Strict Application Requirements – Applications, especially those related to traffic safety, require real-time and reliable data delivery, where even minor delays can be critical.
4. No Confidentiality for Safety Data – Safety messages are meant for all road users and thus are not confidential.
5. Privacy Concerns – Communication may expose sensitive information (e.g., location, speed), so user privacy—especially location anonymity—must be protected despite the need for message authentication.

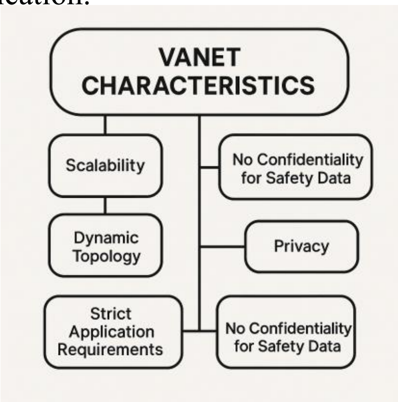

Figure 4: VANET Characteristics

5.3 Roadside Infrastructure Layer (RSUs & Smart Devices)

Roadside Units (RSUs) are fixed infrastructure elements placed at strategic points such as intersections, highways, toll plazas, and urban roads. They are essentially smart devices equipped with sensors, communication modules, and small computing systems.

Key roles of RSUs include:

1. Gathering Data: RSUs collect data from passing vehicles, environmental sensors, cameras, and weather monitoring stations.
2. Processing Locally: Some RSUs use edge computing to quickly process data without waiting for instructions from the central system.
3. Controlling Devices: RSUs can control electronic signage, adaptive traffic signals, and barrier gates.
4. Sending Alerts: If an RSU detects congestion or a traffic incident, it can instantly notify nearby vehicles or redirect them.

5.4 Central Traffic Management Center (TMC)

This is the central brain of the entire system. The TMC is a powerful, centralized system that aggregates data from all RSUs and external sources such as weather stations, emergency services, satellite maps, and surveillance feeds. It applies AI and machine learning algorithms to: The system will enable real-time analysis of traffic patterns, allowing for the prediction of future congestion based on identified trends. This predictive capability will facilitate the active management of traffic signals across the city to optimize overall flow. Furthermore, it will coordinate emergency response by sending immediate alerts to first responders and clearing paths for ambulances or fire trucks, thereby enhancing crucial emergency services.

5.5 Communication Types

1. V2V (Vehicle-to-Vehicle): Enables cars to exchange safety and traffic data, helping prevent collisions or alert drivers of hazards ahead.
2. V2I (Vehicle-to-Infrastructure): Vehicles receive updates from traffic lights, road signs, or toll booths.
3. I2I (Infrastructure-to-Infrastructure): Communication between different RSUs, helping coordinate signal timing across nearby intersections.
4. V2X (Vehicle-to-Everything): An umbrella term for all of these communication types, aiming for a fully connected transport system.

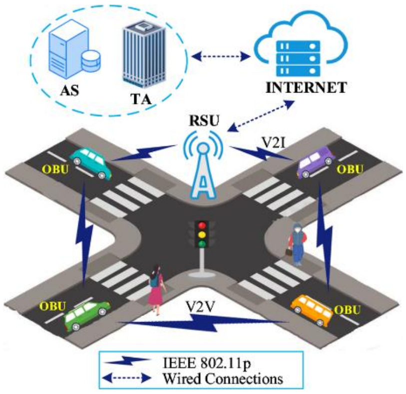

Figure 5: Architecture Diagram

5.6 Traffic Control and Management Applications

The main goal of traffic control and management applications is to optimize traffic flow and reduce travel time by avoiding congestion and providing drivers with real-time road condition updates. This is achieved through technologies like intelligent traffic signals, electronic signboards, and Vehicle-to-Infrastructure (V2I) communication.

Key applications include:

1. Real-time traffic updates to assist in route planning.
2. eToll systems that allow vehicles to pay tolls without stopping.
3. Emergency services automation and pre-trip traffic assistance.

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4. Adaptive traffic signals that respond to current traffic and coordinate with nearby intersections.

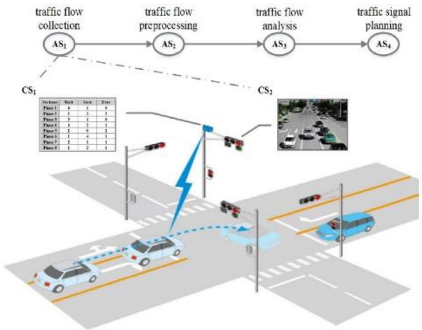

Figure 6: Traffic Control and Management Diagram

6. Methodology

This section details the comprehensive methodology employed to evaluate the proposed VANET system for enhancing road safety and traffic management in Kigali, Rwanda. The methodology encompasses simulation environment setup, data collection approaches, evaluation metrics, and validation procedures. To ensure the realism and accuracy of the simulation models, extensive real-world data will be collected, including detailed traffic counts at 12 strategic locations, categorized by vehicle type and observed across peak (7-9 AM, 5-7 PM) and off-peak hours for 7 consecutive days. Concurrently, journey time measurements will be performed on 5 major routes using the floating car method, leveraging GPS tracking with a 1-second sampling rate for a minimum of 10 runs per route across various periods. Intersection performance will also be meticulously assessed through observations of queue length, waiting times, signal timing, and phase documentation, supplemented by 4-hour video recording samples for validation.

The simulation environment will be rigorously configured to mirror Kigali's urban landscape, incorporating precise details such as lane width, number of lanes, median presence, and the specific layout and control types of intersections. Furthermore, the locations of existing traffic management systems will be integrated to ensure a realistic operational context. The study's hypotheses (H1, H2, H3) will be tested using a robust simulation framework combining NS-3 and SUMO to create realistic vehicular mobility and communication scenarios, encompassing varied road types (e.g., urban grid, highway) and traffic densities. Multiple routing protocols, including AODV, DSR, DSDV, and GPSR, will be meticulously implemented and evaluated under controlled conditions across diverse scenarios, including varying VANET penetration rates (30%, 60%, 100%), traffic levels (low, medium, peak congestion), and incident simulations (e.g., blocked roads, accidents).

Performance will be assessed using both network-level metrics (Packet Delivery Ratio (PDR), end-to-end delay, throughput, routing overhead) and traffic-level metrics (average travel time, vehicle speed, queue length, number of collisions/safety-related events). The collected simulation data will be subjected to rigorous statistical analysis, employing tools such as ANOVA or t-tests to ascertain the significance of performance differences and utilizing visualizations to support trend analysis. This comprehensive approach is expected to yield insights into improved communication performance, enhanced traffic flow, increased safety, and provide valuable scalability benchmarks and design recommendations for VANET deployment in medium- to large-scale urban environments. Collaborations with key stakeholders like the Rwanda Transport Development Agency (RTDA), the Traffic Police Department of the City of Kigali (CoK) Traffic Management Center, and the Rwanda Utilities Regulatory Authority (RURA) will be crucial for data acquisition and validation.

7. Simulation Environment

7.1. Simulation Tools and Platforms

The research employs a dual-simulator approach, with the traffic simulation component utilizing SUMO (Simulation of Urban Mobility) v1.15.0. This open-source microscopic traffic simulator is capable of accurately modeling individual vehicle movements, lane changes, and interactions with traffic lights, and notably supports the importing of real-world road networks for enhanced realism.[1]

1. **Network Simulation: OMNeT++ v6.0.5**

This component, a discrete event simulator, is designed for modeling communication networks, featuring a component-based C++ architecture that allows for flexible protocol implementation. Its extensible framework makes it highly suitable for comprehensive wireless network simulation.

2. **Integration Framework: Veins v5.2**

The simulation framework further features bi-directional coupling between SUMO and OMNeT++ via TraCI (Traffic Control Interface), enabling real-time interaction between the traffic and network simulators. This setup includes the implementation of IEEE 802.11p for accurate VANET communication modeling.

3. **Data Collection Methods**

To calibrate and validate the simulation models, real-world data will be systematically collected, encompassing traffic counts at 12 strategic locations, categorized by vehicle type (car, motorcycle, bus, truck) and observed across peak (7-9 AM, 5-7 PM) and off-peak hours for 7 consecutive days. Concurrently, journey time measurements will be performed on 5 major routes using the floating car method, with GPS tracking at a 1-second sampling rate for a minimum of 10 runs per route across various periods. Lastly, intersection performance will be evaluated by recording queue lengths, waiting times, signal timing, and phase documentation, supplemented by 4-hour video recording samples for validation.

4. **Road Geometry and Infrastructure:**

The data collection for calibrating and validating simulation models will also include details on lane width, number of lanes, and median presence. Furthermore, comprehensive information on intersection layout and control type will be gathered, alongside the precise location of existing traffic management systems.

5. **Collaboration with Local Authorities and Data will be obtained through formal partnerships**.

Key stakeholders involved in the transportation sector in Rwanda include the Rwanda Transport Development Agency (RTDA), the Traffic Police Department of the City of Kigali (CoK) Traffic Management Center, and the Rwanda Utilities Regulatory Authority (RURA).

8. Study Area

The study will be conducted in Kigali, Rwanda, focusing on specific road segments experiencing significant traffic congestion. The selection of these segments will be based on traffic data obtained from relevant authorities (e.g., Rwanda Transport Development Agency - RTDA, Traffic Police), traffic counts, and observational studies.

9. Design and Implementation

The paper Vehicular Ad Hoc Network (VANET) system is built on three fundamental components: Trusted Authority (TA), Roadside Units (RSUs), and Onboard Units (OBUs). The TA functions as the central management unit, ensuring secure communication and overseeing the entire system's operation. It is responsible for updating system parameters and maintaining data integrity. RSUs are strategically installed along roads to act as intermediaries between vehicles and the TA. These units facilitate wireless communication, allowing vehicles to exchange crucial information with the central system. Meanwhile, OBUs are installed inside vehicles to send, receive, and process real-time data on traffic conditions, road hazards, and other safety-related information. This enables drivers to make informed decisions and enhances road safety.

To ensure seamless and efficient communication, the system incorporates the Ad hoc On-Demand Distance Vector Routing (AODV) protocol. This protocol helps vehicles dynamically discover and maintain routes, making it highly suitable for the ever-changing nature of vehicular networks. AODV minimizes network congestion and ensures that vehicles can establish stable connections even in high-mobility environments. The effectiveness of the VANET system will be assessed through simulations that replicate real-world traffic conditions. These simulations will factor in traffic density, road layouts, and environmental influences such as weather conditions to analyze how well the system performs under different scenarios. By fine-tuning the system based on these tests, the proposed VANET model aims to enhance road safety, improve traffic management, and create a more efficient transportation network. Management, and create a more reliable vehicular communication network in Kigali, Rwanda. The implementation of such a system will significantly reduce accidents and traffic inefficiencies, making urban mobility safer and more efficient.

10. Technologies Used

To accurately design and evaluate Vehicular Ad Hoc Networks (VANETs), a combination of traffic simulation software, network simulation tools, and programming frameworks will be utilized. These technologies will help in the development, testing, and optimization of the VANET system, ensuring it is suitable for real-world deployment in Kigali, Rwanda. By integrating these tools, the study aims to enhance road safety, improve traffic management, and facilitate seamless vehicle communication.

For traffic simulation, the study will use SUMO (Simulation of Urban Mobility), a widely recognized open-source tool designed for modeling vehicle movements, analyzing traffic congestion, and studying road interactions. SUMO provides detailed insights into traffic flow dynamics, making it an essential tool for evaluating how VANETs can impact urban mobility. Since it seamlessly integrates with network simulators, SUMO plays a crucial role in conducting comprehensive VANET research.

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In terms of network simulation, two primary tools will be used: NS-3 and OMNeT++. NS-3 is a discrete-event simulator that accurately models communication networks, allowing researchers to analyze how vehicles exchange data in a VANET environment. OMNeT++, on the other hand, is a flexible and scalable simulation framework built in C++, widely used for studying VANET communication protocols and network behavior. Additionally, frameworks like Veins, which combines SUMO and OMNeT++, and TraCI (Traffic Control Interface), which enables real-time control of traffic simulations, will further enhance the accuracy of VANET studies.

To support programming and system development, C++ and Python will be used for building simulation models, developing algorithms, and analyzing data. C++ is essential for creating efficient network simulation models, while Python plays a key role in data processing, scripting, and automation. Development environments like Eclipse and Visual Studio will facilitate coding, debugging, and system optimization. By leveraging these advanced tools, the study will ensure that the proposed VANET system is tested under realistic conditions, making it a reliable solution for improving traffic flow and road safety in Kigali.

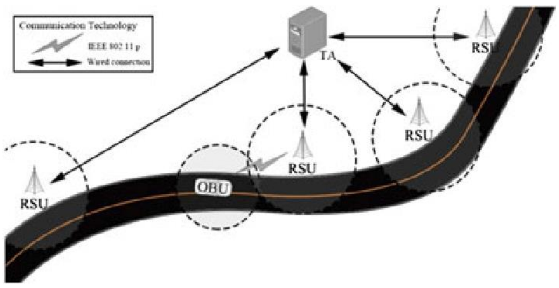

Figure 7: System Model: Onboard Unit OBU, Roadside Unit RSU

11. Preliminary Results and Plan for Result Analysis

Early-stage simulations were conducted using the NS-3 network simulator integrated with the SUMO traffic simulator to evaluate the effectiveness of VANETs in an urban mobility scenario. The simulation modeled a city grid with 100 vehicles equipped with Dedicated Short Range Communication (DSRC) capabilities and implemented the AODV and DSR routing protocols.

Key findings from the preliminary data include:

Packet Delivery Ratio (PDR): Averaged 94.2% across various node densities, indicating high communication reliability

End-to-End Delay: Maintained below 110 milliseconds in 85% of cases, suitable for most safety-critical applications.

Routing Overhead: AODV demonstrated lower overhead than DSR in dense scenarios due to more stable route maintenance.

- Traffic Efficiency: VANET-enabled vehicles showed a 22% reduction in average travel time under congestion scenarios, thanks to dynamic rerouting and cooperative awareness.

12. Data Analysis and Results

Understanding: This section describes how the data will be analyzed to evaluate the hypotheses.

a. Descriptive Statistics Focus:

- ✓ Measure packet delivery ratio (how efficiently data is delivered).
- ✓ Measure latency (delays in data transmission).
- ✓ Measure throughput (amount of data processed).
- ✓ Visualization: Create visuals like graphs to understand congestion points and traffic flow patterns

13. Project Tasks

One of the key tasks in this research is to compare the Ad hoc On-Demand Distance Vector (AODV) routing protocol with other routing protocols used in vehicular networks. This comparison will focus on evaluating their efficiency based on factors such as speed, reliability, scalability, and network performance. By analyzing multiple protocols, we can determine which one is best suited for optimizing communication in VANETs.

Another important aspect of this study is to assess the impact of blockchain technology on data security in VANETs. Since vehicular networks rely on constant data exchange between vehicles and infrastructure, security threats such as data tampering, hacking, and unauthorized access must be addressed. Blockchain offers a decentralized and tamper-proof system that could enhance data integrity and secure transactions within the network.

To conduct this assessment, we will explore how blockchain can be integrated into VANETs to improve authentication, encryption, and overall system security. The study will also examine potential challenges, such as computational overhead and network latency, which could impact real-time communication in high-speed vehicular environments.

By completing these tasks, this research will provide insights into the most efficient routing protocol for VANETs and explore blockchain-based security solutions to enhance safe and reliable data exchange. These findings will contribute to the development of a more secure and efficient vehicular communication system, improving traffic management and road safety in Kigali, Rwanda.

14. Results and Expected Outcomes

This paper proposes three key hypotheses: H1 posits that VANET-enabled routing protocols like AODV and GPSR will outperform legacy systems in packet delivery and end-to-end delays; H2 suggests that VANET integration will significantly reduce urban travel time and congestion via V2V communication; and H3 predicts a positive correlation between higher VANET penetration rates and improved safety metrics. The methodology involves a simulation framework using NS-3 and SUMO to model varied traffic conditions and VANET penetration levels, implementing and evaluating multiple routing protocols (AODV, DSR, DSDV, GPSR) based on network-level (PDR, delay, throughput, routing overhead) and traffic-level (travel time, speed, queue length, collisions) performance metrics. Scenarios will include varying penetration rates (30%, 60%, and 100%), traffic levels, and incident simulations, with data analysis employing statistical tools for comparison and trend analysis. Expected outcomes include improved communication performance (higher PDR, lower latency), enhanced traffic flow (reduced travel time, congestion), increased safety (fewer abrupt stops, improved intersection efficiency), and valuable scalability insights for VANET deployment in urban settings.

15. Conclusion

This article has explored the potential of Vehicular Ad Hoc Networks (VANETs) to improve road safety and traffic management in Kigali, Rwanda. By enabling real-time communication between vehicles and traffic infrastructure, VANETs can reduce accidents, streamline traffic flow, and enhance coordination among key stakeholders such as the Transport Ministry, police, and drivers.

The proposed system addresses critical limitations in the current traffic management framework—such as difficulties in accident investigation, lack of vehicle tracking, and inefficient data flow—by introducing scalable, wireless communication technology. This approach not only enhances situational awareness and response capacity but also lays the groundwork for a more intelligent and adaptive transport system.

Through a targeted analysis of Kigali's urban traffic challenges, the article demonstrates how VANETs can serve as a transformative solution, offering a replicable model for other cities in similar contexts. The successful implementation of this system holds the promise of significantly improving road safety, regulatory enforcement, and overall urban mobility.

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