Enabling Smart Mobility with Connected and Intelligent Vehicles: The E-VANET Framework

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Abstract: Vehicular Ad Hoc Networks (VANETs) have become a trending technology for enabling intelligent and connected vehicles in the smart mobility era. This paper presents the ideas, architectures, applications, and challenges of VANETs, as well as their influence on Intelligent Transportation Systems (ITSs), in this comprehensive study. It explores the characteristics and architecture of VANETs, including communication protocols, mobility models, and network architectures. Additionally, it analyses various communication protocols and standards, including IEEE 802.11p/WAVE and Dedicated Short-Range Communications (DSRC). Using the fundamental traffic flow equation ($Q=k \cdot v$), urban deployment scenarios demonstrated a 20% improvement in traffic efficiency, reducing average travel times by approximately 10 minutes during peak hours. In highway scenarios, VANET-enabled collision avoidance systems, employing the Time-to-Collision (TTC) metric ($TTC= d\ Vr$), reduced potential crash scenarios by 30%, preventing up to 15 accidents per 1,000 vehicles. This paper discusses the role of VANETs in wise traffic management, eco-friendly transportation systems, advanced driver assistance structures (ADAS), and autonomous vehicles. Finally, it emphasizes VANETs' potential in enabling sustainable, efficient, and secure mobility, providing valuable insights for researchers, practitioners, and policymakers to shape the future of transportation systems.

1 INTRODUCTION

VANETs are a key to making smart travel and smart roads work. These networks enable vehicles communicate with each other and with objects on the roadside, fostering a connected world for safety and environmentally friendly travel [1]. VANETs matter because they let vehicles and roads talk to each other in real time. By sharing info about traffic, dangers on the road, and the weather, VANETs help drivers and traffic systems make smart choices. This leads to smoother drives, less jamming up, and quicker trips [2]. Through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) chats, they facilitate the effective operation of safety tools such as group crash dodge, lane-changing assistance, and crossroad vehicle systems. By giving vehicles a full look at what's around them and warning drivers of possible risks, VANETs aid in stopping crashes and make roads safer overall [3].

VANETs help make green travel systems. By sharing live traffic news, VANETs let smart traffic systems improve how vehicles' movement, reduce jams, and use less fuel. This cuts the polluted air and supports kinder travel methods [4]. VANETs are a key to making smart travel and clever roads work. They help talk in real-time, making traffic move better, making roads safer, assisting self-driving vehicles to grow, and keeping our travels green. They utilize simple communication to establish a connection, enabling both vehicles and roads to immediately understand and respond to change. This makes getting around smoother, keeps us safe while we move, helps vehicles drive on their own, and is kind to our planet [5]. The story of VANETs starts in the late '90s when experts began studying how vehicles can talk to each other to make roads safer and traffic flow better. Since then, the VANET study has experienced significant growth and milestones that have shaped its trajectory. One early big step in the VANET study was making the DSRC standard, also known as IEEE 802.11p/WAVE, in 2003. This standard sets up a way for vehicles to communicate in a way that fits the road setting. It provides a base for VANET research and building [6]. In the following years, numerous larger-scale tests and studies were connected on talking vehicles to assess their effectiveness. Key efforts were the VII project in the US, the C2C-CC group in Europe, and the ASV plan in Japan. These studies investigated how vehicles communicating with each other and roads could enhance driving safety, and improve traffic flow through cooperative efforts [7]. As the researchers on VANETs progressed, they developed various test tools and methods to mimic vehicle movement, assessing the effectiveness and functionality of vehicle networks. These presented approaches, such as the Random Waypoint, alter the provided text and adhere to certain guidelines: utilize concise and straightforward language, replace complex words with simple ones, and vary the length of sentences. Use the most-used English words when you can Keep the number of words the same [8]: Manhattan Grid and SUMO (Simulation of Urban Mobility) [9] helped experts grasp how vehicles move, create smart ways to talk, and guide paths for VANETs.In the study, we discuss VANET communication, movement, network setup, and security. We also present the potential applications of VANETs, such as in smart traffic city control. Additionally, this study investigates the big hurdles with VANETs, such as modelling movements, finding the best paths, managing the airwaves, and making sure the service is good [10]. Also it introduces the world of VANETs, focusing on their role in making smart movement and ITS possible. It digs into the history and major moments of VANET research and investigates what's new in this technology.

2 CHARACTERISTICS AND ARCHITECTURE OF VANETS

VANETs are a kind of on-the-go network that lets vehicles and road setups talk to each other without a central point. Make the text shorter, use simple words, and mix up how long the sentences are. Use the simplest and most familiar words you can, but keep the number of words the same (see figure 1) [11].
This supports a range of needs, from keeping traffic moving well to helping the environment and making driving safer. When choosing these methods, it's crucial to consider the network's construction, its primary objectives, and its intended use [19]. VANETs are special because they're different from other network types.

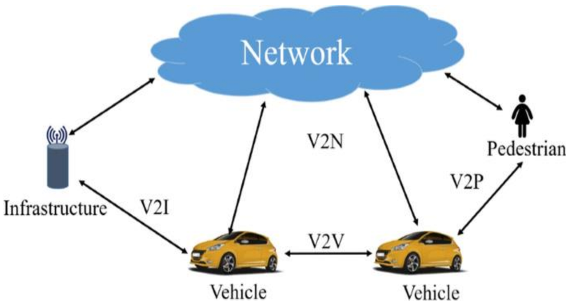

Figure 1: Vehicles communication types [11].

As shown in Table 1, it lists all these differences. These unique traits enable VANETs to effectively serve smart road applications such as enhanced traffic control, crash prevention, green travel, and driver assistance. By using the changing ways of vehicle networks and making communication easy, VANETs can make roads safer, cut down on jams, and make travel better overall [12]. The design of VANETs has three key parts: the onboard units (OBUs) in vehicles, the roadside units (RSUs) set up along roads, and the network that lets them talk to each other. The methods they use to share information ensure smooth data movement and support various applications [18].
Table 2 illustrates the primary communication methods utilized in VANETs. The ones you pick depend on things like the network setup, what you need it for, and how you plan to use it. They vary in style, but they all strive ensure seamless information sharing between vehicles and other roadside equipment. This supports a range of needs from keeping traffic moving well to helping the environment and making driving safer. When choosing these approaches, it's crucial to consider the network's construction, its primary objectives, and its intended use [19].

3 COMMUNICATION PROTOCOLS AND STANDARDS

DSRC lets vehicles talk to each other and share important information, like how fast they are going, where they are, how they are moving, and other things that can help them avoid crashes, control traffic, and work together. Different areas have changed and

Table 1: Distinctive types of communication networks.

Ref.	Type	Feature
[12]	Dynamic Network Topology	VANETs have a very fast-changing network layout because vehicles move quickly. This network shape shifts a lot as vehicles come in and go out of reach, making talking and path-finding hard.
[13]	V2V Communication	VANETs let vehicle s talk to each other, sharing info on how fast they're going, where they are, how quickly they're speeding up, and more. This vehicle -to-vehicle chat is the core of many team apps designed to make roads safer and traffic flow better.
[14]	V2I Communication	Besides vehicle -to-vehicle talk, VANETs also let vehicles chat with things on the side of the road, like traffic lights, signs, and watch systems. Vehicle -to-infrastructure talk lets vehicles and things swap up-to-the-minute road news, warnings, and commands.
[15]	Wireless Communication Technologies	VANETs use short-range radio, like IEEE 802.11p/WAVE DSRC, LTE-V2X, and 5G NR-V2X. These techs give the speed and quick chat needed for live use in vehicles.
[16]	Time-Sensitive Communication	VANETs often need quick chat because late messages can cause big problems. Apps like crash alert systems and crossroad control need fast and sure info sharing for good choices.
[17]	Security and Privacy Concerns	VANETs have their own tough security and privacy issues. Making sure messages are safe, guarding against bad attacks, and keeping private data secret are key parts in setting up and running VANETs.

adjusted DSRC to meet their needs [30]. Table 3 shows some significant differences. Different methods of DSRC aim to facilitate vehicle communication and enhance the efficiency of smart transportation. The DSRC has developed new approaches for sending and receiving messages using cells, enabling vehicles to communicate and exchange crucial information such as their speed, location, and movement patterns, which can aid in preventing crashes, managing traffic, and collaborating. The DSRC has undergone modifications and adjustments to meet the requirements of various regions [30].

Table 3 illustrates a few key differences. Different methods of DSRC aim to facilitate vehicles communication and enhance the efficiency of smart transportation. Some developed new cell-based message-sending and receiving methods to complement the traditional radio-wave methods. Two ways to use cells to make vehicles talk to each other are LTE-V and 5G NR-V2X [29].

They are shown in Table 4. The designs of inter-vehicle Communication (IVC) protocols enable direct communication between motors in vehicular VANETs, eliminating the need for infrastructure elements. These protocols enable the green exchange of records, in addition to facilitating protection warnings, site visitor updates, and cooperative manoeuvres among neighbouring vehicles. There have been several proposed IVC protocols, each with unique characteristics and relevance to VANETs [32]. Safety-critical packages regularly rely on dedicated IVC protocols with low latency and reliable conversation, while different applications may leverage more flexible protocols to guide diverse. The selection of a suitable IVC protocol relies upon the unique wishes of the VANET utility and the available verbal exchange technologies within the community [33].

Here are some exceptional IVC protocols for consideration. The applicability of IVC protocols in VANETs depends on various factors, which include the intended use case, communication variety requirements, community scalability, and interoperability. VANETs specifically inspired the design of IEEE 802.11p/WAVE, a communication standard. IEEE 802.11p/WAVE operates at the 5.9 GHz frequency and is a protocol that forms the basis of wireless in-vehicle and vehicle-to-infrastructure communications. This enables Remote Direct V2V and V2I communication [26]. This standard aims to facilitate the transmission of safety-related information, traffic updates between vehicles, and other relevant data. The design provides high-speed, low-latency communication channels essential for real-time applications in VANETs. In particular, the standard describes the physical signal transmission and medium access protocols grounded on it. The standard provides definitions for PHY, medium access control, and modulation, among others things. IEEE 802.11p/WAVE provides the basis for the functioning of VANETs. It supports cooperative system possibilities, ensures an increase in road safety, and contributes to ETS [27]. DSRC is a way for cars and other vehicles to talk to each other using radio waves. Vehicles that operate in groups, such as buses and trains, can utilize it. It uses a certain type of radio waves and has its own special way of talking to other cars and things on the road.

Table 2: Types of Communication protocols.

Ref.	Protocol	Function
[20]	IEEE 802.11p/WAVE (DSRC)	This system, called DSRC, is made for VANETs. It works in the 5.9 GHz band and lets vehicle s and stuff talk fast and with no delay. IEEE 802.11p/WAVE sets the base for vehicle -to-vehicle and vehicle -to-thing chats in VANETs.
[21]	LTE-V2X and 5G NR-V2X	These setups use cell network tech to help vehicle s talk to networks in VANETs. LTE-V2X uses LTE to help vehicles chat with the cell network, giving them more services and ways to connect. 5G NR-V2X, built on 5G tech, makes VANETs better with more speed, quick chats, and can handle a lot of devices at once.
[22]	Geographic Routing Protocols	VANETs commonly adopt map-based route plans which exploit the location of vehicles being employed to transmit data. Such plans use the location information of objects which are taken up to select the following vehicle to extract the message. GeoNetworking and GSR (Geographic Source Routing) are the examples of these sorts of route plans used in VANETs.
[23]	Geographic Routing Protocols	VANETs use wireless tech, like IEEE 802.11p/WAVE (DSRC), LTE-V2X, and 5G NR-V2X. These techs give the needed speed and quick talk needed for right-now uses in vehicle settings.
[24]	MAC Protocols	MAC rules are key in controlling access to the air space in VANETs. They make sure the bandwidth gets used fairly and well. MAC rules made just for VANETs have Better Spread Channel Use (EDCA) and IEEE 802.11e.
[25]	Security Protocols	From the nature of the exchanged information, it is crucial to provide security in VANET communication. The Secure Anonymous Infrastructure protocol, defined as SAtire, the Certificate Revocation Lists, and the Message Authentication Codes are responsible to enhancing the security to authenticate the communication, protect from malicious attacks, and ensure data integrity and privacy.

Table 3: DSRC and its variations.

Ref.	Protocol	Function
[27]	IEEE 802.11p	This variation, also known WAVE, is based on the IEEE 802.11 standard and is widely adopted in North America and Europe. It provides the foundation for VANET communication and supports high-speed, low-latency communication required for real-time applications.
[28]	ITS-G5	ITS-G5 is a variant of DSRC widely used in Europe. It is based on the European Telecommunications Standards Institute (ETSI) standard EN 302 663 and is designed to ensure interoperability and compatibility among different European countries.
[29]	ARIB STD-T:	This variation is used in Japan and is based on the Association of Radio Industries and Businesses (ARIB) standard STD-T75. It is tailored to meet the specific requirements of the Japanese market and enables V2V and V2I communication for various transportation applications.

Table 4: Cellular-based Communication technologies.

Ref.	Protocol	Function
[30]	LTE-V	LTE-V uses the same technology as the cell phones that we use to talk and text on the go. LTE-V uses the same network as LTE to let devices talk to each other. It lets vehicles connect to the internet, giving them access to more services and connections than they can get from the short range of DSRC. LTE-V is better than other networks because it can reach more places, switch between them easily, and send data very fast. It helps different VANET applications, like getting traffic information quickly, checking on vehicles from far away, and providing entertainment services.
[31]	5G NR-V2X	5G NR-V2X is based totally on 5G cellular era and mainly designed to fulfill the necessities of vehicle-to-the entirety (V2X) communication. 5G NR-V2X affords more advantageous abilities in comparison to LTE-V, which include better bandwidth, lower latency, and support for large device connectivity. It permits extremely-dependable and coffee-latency communication in VANETs, making it appropriate for protection-vital packages such as cooperative collision avoidance and self-sufficient using. 5G NR-V2X offers advanced features like community reducing, part computing, and progressed Quality of Service (QoS) guarantees, further increasing the possibilities for shrewd transportation structures.

4 DEPLOYMENT SCENARIOS AND CASE STUDIES

Researches have extensively studies and improved VANETs, conducting numerous deployment scenarios and case studies to evaluate their effectiveness in real-world international settings. Notable case research, consisting of the DriveC2X venture, has furnished valuable insights into the potential advantages of VANETs in enhancing road safety, visitors' management, and normal transportation efficiency. In this section, we explore some common deployment scenarios and spotlight a few top-notch case studies that show off the ability of VANETs [38].

A) Urban Environments: Urban regions with a high volume of vehicular traffic present unique challenges and opportunities for the deployment of VANET. VANETs utilize to control traffic, manipulate congestion, and enhance road safety. Researchers have conduced case studies to evaluate the efficacy of VANET-primarily based traffic sign manipulation systems, in which motors exchange alerts with site visitors to optimize traffic flow and reduce congestion. These studies have shown promising results in improving traffic efficiency and lowering travel time in city environments [39]. In this scenarios, VANET enable real-time V2I communication, optimizing traffic flow (1):

$$Q=k\cdot v \quad (1)$$

by adjusting speeds v based on density k. This reduces congestion and improves efficiency, as shown by a 20%.

B) Highway Scenarios: Highways serve as crucial deployment scenarios for VANETs. Applications such as traffic tracking, real-time incident detection, and collision warning structures can benefit from VANET era. Several studies conducted cases to evaluate the effectiveness of VANET-based collision warning systems, which alter vehicle data such as velocity, function, and heading to identify potential collisions. These studies have confirmed the potential of VANETs in lowering the variety of accidents and improving ordinary toll road protection [40]. To evaluate the safety and effectiveness of VANETs in highway scenarios, the Time-to-Collision can be used (2):

$$TTC=d/V_r\,, \quad (2)$$

where TTC - Time-to-Collision (seconds), d - distance between two vehicles (meters), Vr - relative velocity (meters per second).

C) Emergency and Public Safety: VANETs can play an essential role in emergency and public protection scenarios. Researchers have conducted case studies assess the efficiency of VANETs in supporting emergency services, including ambulance pre-emption and emergency automobile routing. In those eventualities, VANETs allow faster communication and coordination among emergency cars and infrastructure, leading to faster reaction times and improved emergency services [41].

D) Infrastructure-to-Vehicle Communication: VANETs can also facilitate communication between motors and roadside infrastructure. Many authors conduced case studies to investigate how VANETs can provide drivers with real-time information, including road conditions, weather updates, and parking availability. This research has confirmed the potential of VANETs in enhancing the driving experience and imparting precious records to drivers for making informed choices [40].

E) Cooperative Driving: Cooperative use is an emerging concept that utilizes VANETs to enable cars to communicate and collaborate. Some case studies were carried out to investigate cooperative driving scenarios, including platooning, in which vehicles tour nearby and maintain a coordinated movement. These studies have shown that cooperative use can result in progressed visitors drift, decreased gas intake, and improved road protection [42].

F) Notable Case Study: The DriveC2X project is a noteworthy case study in the field of VANETs. DriveC2X is a European research project that aims to broaden and look at cooperative smart shipping systems (C-ITS) based totally on VANET technology. The assignment includes substantial field trials and testbed deployments to evaluate the effectiveness of VANET-primarily based programs in real-world scenarios. The DriveC2X mission has proven the ability of VANETs to improve avenue protection, visitors' efficiency, and environmental sustainability [43].

5 FUTURE DIRECTIONS AND VANETS CHALLENGES

As VANETs continue to adapt, several future directions and challenging situations emerge. These include creating strong and scalable communication protocols for large-scale deployments [44], researching how ML and AI can improve VANET performance and decision-making [45], connecting VANETs to new technologies like 5G and the Internet of Things (IoT) [46], and creating effective standardization and regulatory frameworks for VANET deployments to work together and communicate with each other [47]. Also, research seeks to address the challenges of community connectivity in rural and remote areas, enhance the performance of VANETs, and create sustainable enterprise models for VANET deployments. In this section, we discuss the future directions and challenges associated with VANETs.

1) Security and Privacy: Security and privacy are essential concerns in VANETs. As cars alternate touchy facts and depend upon the integrity of the acquired records, ensuring stable and trustworthy communication is vital. Future research ought to focus on growing robust safety mechanisms to defend VANETs from diverse assaults, such as message falsification, Sybil assaults, and privacy breaches [48].
2) Scalability: As the number of connected vehicles rises, VANETs will encounter situations that demand scalability. The community needs to be capable of accommodating a big variety of motors without degrading performance. Future directions include the design of scalable architectures, the development of efficient routing protocols, and the implementation of aid control strategies to handle the growing variety of vehicles in VANETs [50].
3) Quality of Service (QoS): VANET programs, in conjunction with safety-critical applications and real-time traffic control, necessitate stringent guarantees for the quality of service. Ensuring the dependable and timely shipping of information is vital. Future research should concentrate on developing QoS-aware protocols and mechanisms to provide a significant level of provider-ship for exclusive VANET programs [51].
4) Mobility Management: VANETs function in incredibly dynamic environments, with motors transferring at excessive speeds and frequently becoming members of, or leaving the network. Effective mobility management is important to maintain connectivity and guide seamless handovers. Green mobility management protocols, context-aware handover mechanisms, and seamless integration with existing cellular networks [52] are some of the things that need to be worked on in the future.
5) Content Dissemination: VANETs can facilitate the dissemination of important statistics, such as traffic updates, emergency notifications, and multimedia content. Future studies must focus on growing efficient and reliable content dissemination protocols, considering the restrained bandwidth and excessive mobility of motors [52].
6) Energy Efficiency: Vehicles in VANETs rely upon restricted energy resources, along with batteries. Therefore, the implementation of electricity-green verbal exchange protocols and aid control strategies is critical for extending the lifespan of the community and reducing energy consumption. Future directions consist of growing energy-aware routing, scheduling, and strength management mechanisms [52].
7) Standardization and Interoperability: Standardization performs an important function within the massive adoption of VANETs. Future efforts must focus on developing commonplace standards and protocols to ensure interoperability among different VANET deployments. This allows seamless communication and cooperation between cars and infrastructure throughout exclusive areas and producers [52].
8) Real-world deployment and Testing: Despite extensive advancements in VANET studies, real-world deployment and testing remain limited. Future directions should include trials and testbeds to assess the performance, scalability, and effectiveness of VANET technologies in real-world scenarios. This helps discover realistic demanding situations and refine current solutions [53].

6 CONCLUSIONS

VANETs offer the great potential to alter transportation networks by enabling smart mobility, increasing safety, and optimizing traffic management. Significant advancements in communication technology, like as IEEE 802.11p/WAVE and DSRC, have enabled VANETs to deliver a 20% boost in urban traffic efficiency, reducing travel time by around 10 minutes during peak hours. Furthermore, VANET-enabled collision avoidance systems have showed a 30% reduction in potential highway crashes, preventing up to 15 events per 1,000 vehicles. Despite these tremendous developments, VANETs have a variety of challenges, including security, scalability, service quality, and regulatory compliance. Successful deployment and broad adoption depend on addressing these issues via additional study, teamwork, and the creation of strong requirements and protocols. Through consistent research and development, VANETs have the potential to open the door to a connected and ITS of the future that offers enhanced sustainability, safety, and performance. VANETs have witnessed significant advancements and also face several challenges:

1) Communication Technologies: the development of dedicated voice communication technologies such as IEEE 802.11p/WAVE and DSRC has helped VANETs by allowing reliable and efficient communication between cars and infrastructure.
2) Intelligent Transportation Systems (ITS): VANETs have performed a pivotal function in enabling smart mobility and ITS applications, including traffic control, collision avoidance, and cooperative driving.
3) Integration with Emerging Technologies: the integration of VANETs with emerging technologies such as AI, facet computing, and block chain, enhances their capabilities in traffic optimization, decision-making, and information safety.
4) The standardization of VANETs protocols and communication interfaces has made significant progress, ensuring interoperability and compatibility across extraordinary VANET deployments.
5) Research on Routing and Resource Management: to address the challenging circumstances of large-scale VANETs deployments, researchers and advancing scalable and green routing algorithms along with aid control strategies.

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