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Analysis of Reduction Schemes for Network Congestion in Vehicular AD-HOC Networks

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Abstract

Vehicular Ad-hoc Networks (VANETs) have garnered considerable attention due to their potential to improve road safety, traffic efficiency, and passenger comfort. However, VANETs face challenges due to their dynamic nature, which includes fast-moving vehicles and changing network topologies. One of the major challenges is network congestion, which can significantly impact communication performance and hinder the delivery of critical safety messages. Therefore, it is crucial to have effective congestion reduction schemes in place to ensure reliable and efficient communication in VANETs. This research paper presents a comprehensive analysis of various congestion reduction schemes designed specifically for VANETs. These schemes are categorized into three main classes: traffic management, routing optimization, and congestion control. For each class, the paper reviews and evaluates state-of-the-art techniques, highlighting their strengths, weaknesses, and applicability in different VANET scenarios. Additionally, the paper identifies open research challenges and opportunities for future work in the field of congestion reduction in VANETs. By addressing these challenges and exploring the opportunities, we can further enhance the performance and reliability of VANET communication systems.

Keywords: Vehicular Ad-hoc Networks, Network Congestion, Reduction Schemes, Traffic Management, Routing Optimization, Congestion Control.

Introduction

Vehicular Ad-hoc Networks (VANETs) are a type of network that allows vehicles to communicate with each other and with roadside infrastructure. Imagine cars talking to each other and to traffic lights – that's the basic idea behind VANETs. Vehicular ad hoc network (VANET) is one of the specialized segments of Mobile ad hoc network (MANET) VANET contends to improve the vehicle networking by emphasizing on different facilities to be offered to the vehicles on the go. The vehicles moving on road ask for services like less congestion on road, safety related information, prediction of best path on the way (Karagiannis et al., 2011).

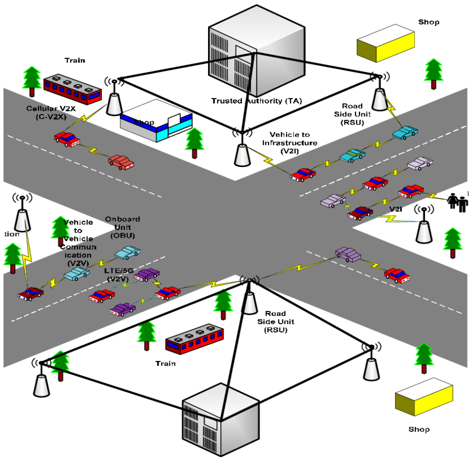

Fig. 1 Vehicular Ad-hoc Networks (VANETs) Here's a breakdown of the key concepts

Network Type

VANETs are a subcategory of Mobile Ad-hoc Networks (MANETs). This means the network is formed "on-the-fly" as vehicles come into range of each other, without relying on a central access point like a cell tower.

Components

VANETs consist of two main parts:

Vehicles

Equipped with On-Board Units (OBUs) for communication. OBUs typically include a transceiver for sending and receiving messages, along with GPS and other sensors.

Roadside Units (RSUs)

These are fixed infrastructure elements placed along roadsides. They can act as relays and information hubs for vehicles.

Communication

VANETs facilitate two types of communication:

Vehicle-to-Vehicle (V2V)

Direct communication between vehicles within transmission range. This allows for real-time exchange of information like accidents, traffic jams, or road conditions. It enhances the current crash avoidance systems that use cameras and radars to detect collisions (Willis et al., 2014).

Vehicle-to-Infrastructure (V2I)

Communication between vehicles and RSUs. RSUs can collect data from vehicles and transmit it to a central traffic management system or provide localized information like upcoming stop signs. The communication is bidirectional. Infrastructures like traffic lights, road signs, and lane markings send data to the cars wirelessly and vice versa (Willis et al., 2014).

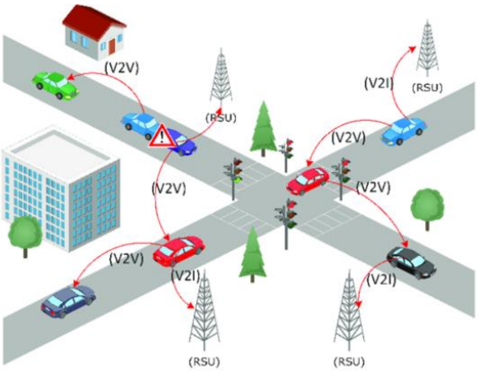

Fig. 3 VANET Components

Difficulties in Vehicular AD-HOC Networks

VANETs have the potential to revolutionize our roadways, making them safer and more efficient.

Nevertheless, there are various obstacles that must be overcome before this technology can be widely implemented. Here are some of the main challenges to consider.

Network Dynamics

Unlike traditional networks, VANETs are highly dynamic due to the constant movement of vehicles. This rapid change in network topology makes it difficult to maintain stable connections and ensure reliable message delivery.

Limited Range

Vehicles have a limited communication range due to factors like signal strength, terrain, and weather. This necessitates routing messages through other vehicles or relying on roadside infrastructure (RSUs) to extend their reach. However, sparse RSU deployment or uneven vehicle distribution can create communication gaps.

Congestion Control

With increasing vehicle density, especially in urban areas, the shared wireless medium in VANETs can become congested. This can lead to data packet collisions and delays in critical safety messages. Efficient congestion control mechanisms are needed to prioritize messages and ensure timely information flow.

Security and Privacy

VANETs exchange sensitive data like location and speed. Ensuring secure communication is paramount to prevent malicious attacks that could disrupt traffic flow or compromise driver privacy. Robust authentication and encryption techniques are crucial.

Standardization

The lack of standardized protocols and communication interfaces across different manufacturers can hinder seamless communication between vehicles and RSUs. Establishing common standards is essential for widespread interoperability.

Cost and Infrastructure

Equipping vehicles with On-Board Units (OBUs) and deploying RSUs involve significant costs. Additionally, integrating VANETs with existing transportation infrastructure requires substantial investment.

Importance of Reduction in VANET

Considering the challenges of real-world including time and safety, one of the critical research areas in VANET is congestion control (Zeadally et al., 2012). In the context of Vehicular Ad-hoc Networks (VANETs), congestion reduction holds even greater significance compared to general traffic flow. The major reason behind congestion is the dynamic topology and the varying speed and number of vehicles in VANET (Sepulcre et al., 2016). Here's why:

Enhanced Safety Applications

Reliable Message Delivery

Vehicular ad hoc networks (VANETs) depend on the exchange of real-time information to support safety applications such as accident warnings and emergency vehicle notifications. The presence of congestion within the network can result in delays or even loss of data packets, which can significantly impact the efficiency of these crucial messages. By minimizing congestion, we can guarantee the prompt and dependable delivery of safety-related information, ultimately playing a vital role in accident prevention and the preservation of human lives.

Improved Traffic Management

Accurate Traffic Data

VANETs have the capability to gather and exchange up-to-the-minute traffic information in order to enhance the efficiency of traffic flow. Nevertheless, the presence of congestion can distort this data, posing challenges in accurately evaluating the prevailing traffic conditions. By reducing congestion, the collection of precise data becomes feasible, thereby facilitating the implementation of improved traffic management strategies such as dynamic route guidance and signal timing adjustments.

Efficient Resource Utilization

Network Bandwidth

Congestion strains the limited bandwidth available in VANETs. This can lead to competition for resources, potentially delaying or even dropping non-critical messages. Reducing congestion frees up bandwidth, allowing for efficient communication and ensuring critical safety messages have priority.

Scalability and Network Performance

Network Stability

High congestion can destabilize the VANET itself. With frequent connection drops and message delays, the network becomes less reliable and effective. Reduced congestion fosters a more stable network environment, enabling VANETs to function optimally even with increasing traffic density.

Congestion Control Techniques in VANET

Congestion control techniques play a vital role in managing and mitigating congestion in Vehicular Ad-hoc Networks (VANETs). Resources in this context refer to either introducing an entirely new path to some vehicles or to alert the upcoming vehicles on the congested road segment about the congestion (Darus et al., 2011; Sepulcre et al., 2010; Liang et al., 2014).

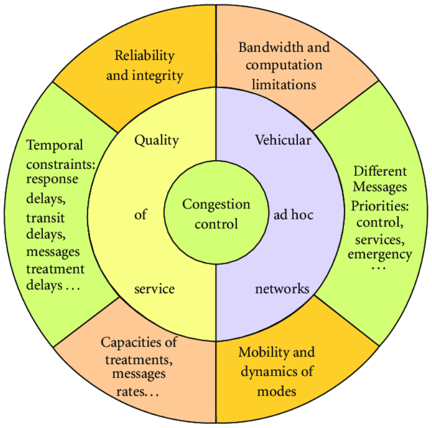

Fig. 2 Traffic Control Parameters

These techniques aim to regulate traffic flow, optimize resource utilization, and ensure reliable communication under varying network conditions. VANET congestion control is an important and active area of research, and has received significant attention in recent years, for both safety and comfort applications (Rahim et al., 2021). Here are some common congestion control techniques used in VANETs:

Rate Control Techniques

Adjusting Transmission Power

Vehicles can dynamically adjust their transmission power based on network density. In congested areas, lowering power reduces signal overlap and improves channel access.

Adaptive Packet Transmission Rates

Similar to power control, vehicles can adjust their packet transmission rates. Lower rates in congested areas can help prevent collisions and improve overall network throughput.

Queue Management

Vehicles can employ queueing mechanisms to buffer outgoing messages during congestion. This prevents overwhelming the network and allows for controlled transmission when channel availability improves.

Media Access Control (MAC) Techniques

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

This is a common MAC protocol used in VANETs. It involves checking for channel availability before transmission to avoid collisions. Enhanced versions of CSMA/CA can incorporate congestion information into the access procedure (Aslam et al., 2013).

Priority Scheduling

Different message types in VANETs have varying importance. Safety messages, for instance, require immediate attention. Priority scheduling ensures these critical messages are prioritized for transmission even during congestion.

Trajectory-Based Forwarding Schemes

Exploiting Mobility Patterns

Vehicles can predict their movement and that of nearby vehicles. By forwarding messages only to vehicles on a similar trajectory towards the destination, unnecessary transmissions and congestion can be reduced (Aslam et al., 2013).

Clustering: Vehicles can form temporary clusters to share information and manage communication within the cluster. This can help localize congestion and improve overall network efficiency.

Cooperative Techniques

Information Exchange

Vehicles can exchange information about network congestion levels with each other and with RSUs. This allows for coordinated congestion control strategies and resource allocation.

Content Caching

RSUs or designated vehicles can act as caches to store frequently transmitted messages. Vehicles can then retrieve these messages from the cache instead of flooding the network with redundant transmissions.

Rate Control Techniques in Techniques in VANET

Rate control techniques in Vehicular Ad-hoc Networks (VANETs) are crucial for managing the transmission rates of vehicles and optimizing network resources to mitigate congestion and ensure efficient communication. Here are some rate control techniques commonly used in VANETs:

Adaptive Rate Control:

Adaptive rate control adjusts the data transmission rates of vehicles dynamically based on network conditions, such as congestion levels, channel quality, and available bandwidth.
In VANETs, adaptive rate control algorithms continuously monitor the network environment and adapt the transmission rates of vehicles accordingly.

These algorithms aim to maximize throughput while minimizing packet loss and delay by dynamically adjusting the transmission rates to match the current network capacity.

Rate Adaptation Based on Channel Conditions

Rate adaptation techniques in VANETs consider the quality of the communication channel to adjust the transmission rates of vehicles.

Vehicles measure channel conditions, such as signal strength, interference, and fading, to determine the optimal transmission rate.

Rate adaptation algorithms increase the transmission rate when channel conditions are favorable and decrease it when the channel quality deteriorates, ensuring reliable communication under varying channel conditions.

Congestion-Aware Rate Control

Congestion-aware rate control mechanisms adjust the transmission rates of vehicles based on the level of network congestion.

In VANETs, vehicles monitor congestion levels by observing packet delays, collisions, and channel utilization.

When congestion is detected, congestion-aware rate control algorithms reduce the transmission rates to alleviate congestion and prevent network overload.

These algorithms dynamically adjust the transmission rates of vehicles to maintain network stability and optimize resource utilization.

Priority-Based Rate Control

Priority-based rate control assigns different transmission priorities to vehicles based on application requirements, traffic conditions, and network policies.

In VANETs, safety-critical applications may be assigned higher transmission priorities to ensure timely delivery of critical messages, while non-safety applications may have lower priorities.

Priority-based rate control mechanisms allocate transmission resources based on the priority levels of different applications, optimizing resource utilization and ensuring fair access to the communication channel.

Rate Control with QoS Guarantees

Rate control techniques in VANETs may incorporate Quality of Service (QoS) guarantees to ensure that certain performance metrics, such as packet loss, delay, and throughput, meet predefined requirements.

QoS-aware rate control algorithms dynamically adjust the transmission rates of vehicles to meet QoS targets while minimizing network congestion and resource contention.

These algorithms prioritize traffic streams based on their QoS requirements and dynamically allocate transmission resources to satisfy the desired performance levels for each application.

Example of Rate Control Techniques in VANET

One example of a rate control technique in Vehicular Ad-hoc Networks (VANETs) is the Adaptive Rate Control (ARC) algorithm. ARC dynamically adjusts the data transmission rates of vehicles based on the current network conditions to optimize throughput and minimize congestion. Here's how ARC works:

Network Monitoring

Vehicles continuously monitor the network environment, including congestion levels, channel conditions, and available bandwidth. This information is collected through periodic beacon messages exchanged between neighboring vehicles and infrastructure nodes.

Rate Adaptation

Based on the network monitoring data, each vehicle autonomously adjusts its transmission rate to match the current network capacity and channel conditions. If the network is congested or the channel quality deteriorates, vehicles reduce their transmission rates to avoid packet loss and mitigate congestion. Conversely, if the network is underutilized or the channel conditions improve, vehicles increase their transmission rates to maximize throughput.

Feedback Mechanism

ARC incorporates a feedback mechanism to assess the effectiveness of rate adaptation and adjust transmission rates accordingly. Vehicles exchange feedback messages to share information about successful packet delivery, packet loss, and channel conditions. Based on this feedback, vehicles fine-tune their transmission rates to maintain optimal performance and adapt to changing network conditions over time.

Congestion Avoidance

ARC aims to prevent network congestion by dynamically regulating the data transmission rates of vehicles. By reducing transmission rates in congested areas or during periods of high network load, ARC helps alleviate congestion and maintain network stability. Vehicles adjust their transmission rates based on congestion indicators such as packet delays, collisions, and channel utilization, ensuring efficient resource utilization and reliable communication in VANETs.

Algorithm on Rate Control Techniques in VANET

Step 1: Initialize
- Set the initial transmission rate for each vehicle.
- Define thresholds for congestion detection and channel quality assessment.
- Configure parameters for feedback exchange and rate adaptation.

Step 2: Repeat

a. Monitor Network Conditions:
- Vehicles periodically monitor the network environment, including congestion levels and channel conditions.
- Measure metrics such as packet delay, collision rate, channel utilization, and signal strength.

b. Congestion Detection:
-If the measured congestion metrics exceed predefined thresholds:
- Set a flag indicating network congestion.

c. Channel Quality Assessment:
- Evaluate the quality of the communication channel based on signal strength, interference, and fading.
- Determine the channel conditions (e.g., good, fair, poor).

d. Rate Adaptation:
- If congestion is detected or channel conditions deteriorate:
- Reduce the transmission rate of the vehicle to alleviate congestion and prevent packet loss.
- Adjust the transmission power and modulation scheme to improve signal quality and reliability.
- If congestion is not detected and channel conditions are favorable:
- Increase the transmission rate of the vehicle to maximize throughput and exploit available bandwidth.
- Consider feedback from neighboring vehicles and infrastructure nodes to fine-tune the transmission parameters.

e. Feedback Exchange:
- Vehicles exchange feedback messages with neighboring vehicles and infrastructure nodes.
- Share information about successful packet delivery, packet loss, channel conditions, and congestion levels.
- Use feedback to update transmission rates, adapt transmission parameters, and optimize resource utilization.

Step 3: Until Termination Condition

- Continue monitoring network conditions and adjusting transmission rates based on real-time feedback.

- Terminate the algorithm based on predefined criteria (e.g., elapsed time, number of iterations, convergence).

Step 4: End

Conclusion

VANETs, characterized by rapidly changing network conditions and varying traffic densities, necessitate adaptive strategies to regulate transmission rates and mitigate congestion effectively. By implementing rate control algorithms such as Adaptive Rate Control (ARC), VANETs can dynamically adjust transmission rates based on real-time network monitoring and feedback exchange. These algorithms enable vehicles to adapt their transmission rates in response to congestion detection, channel quality assessment, and feedback from neighboring nodes.

By optimizing transmission rates based on network conditions, rate control techniques help enhance network performance, improve throughput, and ensure reliable communication in VANETs. These techniques contribute to mitigating congestion, minimizing packet loss, and optimizing resource utilization, thereby facilitating efficient and seamless communication among vehicles and infrastructure elements.

The future direction of research and development in Vehicular Ad-hoc Networks (VANETs) will focus on addressing emerging challenges and leveraging advanced technologies to enhance the performance, reliability, and efficiency of VANETs. Here are some key future directions for VANETs:

5G and Beyond

Continued research into leveraging 5G and beyond-5G (B5G) technologies to enhance VANETs' capabilities, including higher data rates, lower latency, and improved reliability. Exploring how VANETs can benefit from network slicing, edge computing, and massive MIMO to support diverse applications and services.

Autonomous and Connected Vehicle

Advancing communication and coordination mechanisms for autonomous and connected vehicles, enabling seamless vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communication. Developing efficient protocols and algorithms for autonomous vehicle platooning, cooperative perception, and intersection management.

Edge Computing and Fog Computing

Researching edge computing and fog computing architectures tailored for VANETs to improve data processing, decision-making, and response times. Investigating distributed computing models, edge caching techniques, and decentralized data management solutions to support latency-sensitive applications and reduce reliance on centralized cloud infrastructure.

Security and Privacy

Addressing security and privacy challenges in VANETs through advanced cryptographic techniques, secure communication protocols, and intrusion detection systems. Developing robust solutions for secure message authentication, privacy-preserving data aggregation, and trust management to protect against cyber threats and ensure user privacy.

Machine Learning and Artificial Intelligence

Integrating machine learning and artificial intelligence techniques into VANETs for traffic prediction, congestion management, and anomaly detection. Exploring how AI-driven algorithms can optimize resource allocation, improve network efficiency, and enhance the adaptability of VANETs to dynamic and unpredictable environments.

Blockchain Technology

Investigating the potential of blockchain technology to enhance the security, transparency, and trustworthiness of VANETs. Exploring blockchain-based solutions for secure data sharing, decentralized authentication, and tamper-proof event logging to mitigate security risks and build trust among network participants.

Standardization and Interoperability

Promoting standardization efforts and interoperability among different VANET technologies, protocols, and communication standards. Collaborating with industry stakeholders, standards organizations, and regulatory bodies to develop unified frameworks, interoperability guidelines, and certification processes for VANET deployments.

Real-World Deployment and Testing

Conducting large-scale field trials and real-world deployments of VANETs to validate research findings, assess performance under diverse scenarios, and identify practical challenges. Collaborating with transportation authorities, urban planners, and industry partners to deploy VANET infrastructure and integrate VANETs into existing transportation systems.

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