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Congestion Avoidance in Vehicular Networks: A Contemporary Survey

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ABSTRACT Congestion in vehicular ad hoc networks affects the performance of delay-sensitive applications when exchanging emergency or general information sharing messages. In particular, during emergencies on roads like road accidents and security warnings demand high reliability and low latency. However, in traditional solutions, such messages use the same control channel for transmission leading up to a saturated or congested channel. Furthermore, the highly dynamic nature of vehicular networks leading up to unpredictable routing patterns, subsequently degrading the network performance. An uneven deliverance of these critical messages can be catastrophic for the delay-sensitive applications. Thus, congestion control remains one of the most challenging problems within the domain of vehicular networks. This paper provides a comprehensive overview of the working of vehicular networks, the recent research advances to cater for congestion in such networks, and open problems and challenges relevant to congestion avoidance.

INDEX TERMS Ad hoc vehicular network, congestion avoidance, power-based, rate-based, priority-based, clustering-based, CSMA/CA-based, hybrid, vehicular simulation.

NOMENCLATURE

ACRONYMS

BEB	binary exponential back-off
BPR	Bayesian prediction ranking
C-ITS	cooperative intelligent transport system
CAM	cooperative awareness messages
CBR	channel busy ratio
CBT	channel busy time
CCW	cooperative collision warning
CPB	clustering-based probabilistic broadcasting
CPRC	combined power and rate control
CRN	congestion road notification
CSMA/CA	carrier-sense multiple access with collision avoidance
DBSMA	dynamic broadcast storm mitigation approach
DCF	distribution coordination function
DSRC	dedicated short range communication
DCP-ABE	Distributed cipher policy attribute based encryption
ECPR	environmental and context-aware combined power and rate distributed congestion control
EDF	earliest deadline first
EEADP	effective and efficient adaptive probabilistic data dissemination protocol
GloMoSim	global mobile information system simulator
IDP	inter packet delay
IRT	inter-reception time
JiST	Java in simulation time
LCA	lane change assistance
LIMERIC	linear message rate integrated control
MoNoTrac	mobile node trace generator
MOVE	mobility model generator for vehicular networks
MPC	multi-metric tx-power control protocol
OTCL	object-oriented tool command language
OMNeT++	objective modular network test-bed in C++
OPNET	optimized network engineering tools
PCW	predictive contention window
PDR	packet delivery ratio
PE-MAC	power efficient media access control
PLE	path loss exponent
SBAPC	speed-based adaptive power control

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SDSCC	static and dynamic scheduling for congestion control
SIR	signal-to-interference ratio
SR-CSMA	safety range-carrier sense multiple access
SFIR	SDN and fog-based intersection routing
SESAC	SDN-Enabled Social-Aware Clustering
STRAW	street random waypoint
SUMO	simulation of urban mobility
TMS	traffic management system
TPM	trajectory predicted mechanism
TPRC	joint transmission power rate control
TTC	time to collision
U-EDF	uni-priority safety messages message dissemination using earliest deadline first
UFC	unified framework of clustering
VDBPC	vehicle density-based power control
VENTOS	vehicular network open simulator
VMaSC-LTE	vehicular multihop algorithm for stable clustering - Long term evolution
VSIMRTI	V2X simulation runtime infrastructure
XML	extensible markup language

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are an active research area since it offers a wide variety of services and applications. The essential services and features include enhanced traffic efficiency, infotainment, and passenger safety. VANETs make the journey comfortable for passengers and drivers by performing efficient traffic management and road safety. VANETs primarily have two modes of operations, i.e. vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). In V2V, vehicles directly communicate in a distributed fashion whereas in V2I mode vehicles communicate through the roadside unit (RSU) as illustrated in Figure 1. The vehicles in VANET architecture usually send and share two types of messages: safety general and safety-critical messages [1]. The non-safety or safety general messages include infotainment services which are usually delayed tolerant, whereas, safety general messages are delay-insensitive. A dedicated short-range communication (DSRC) at 5.9GHZ is provided by a standardized IEEE 802.11p WAVE (wireless access in vehicular environments) protocol.

Network congestion is a severe issue in VANETs. Congestion occurs when the communication channel or medium becomes overloaded, which results in degrading the network performance [2]. Network congestion is directly proportional to the vehicular density in a specific area. There is high mobility of nodes or vehicles, which is continuously changing the network topology and vehicular density. These dynamic topology changes create connectivity issues between V2V and V2I communication. In a dense network environment, significant numbers of nodes trying to send the packets cause congestion in the network. The delay and packet loss increase many folds when vehicular density increases resulting in network congestion [2], [3]. This consequently decreases the network throughput. Thus, congestion control becomes the point of interest to enhance the efficiency, reliability, and safety of the network.

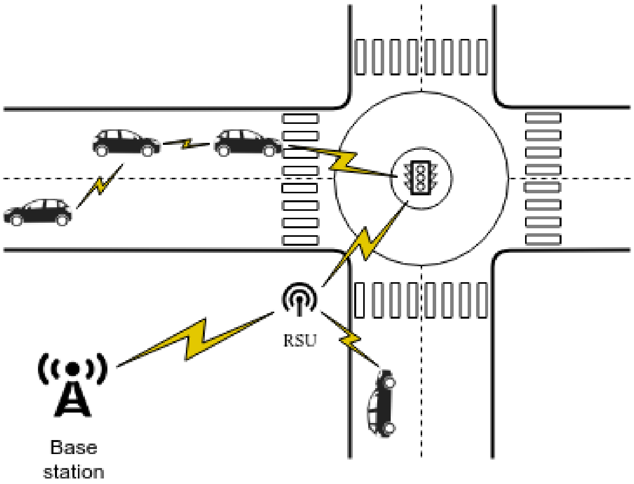

FIGURE 1. VANET environment.

Another important concern in VANETs is how to minimize communication delay achieving a low latency path.This is one of the crucial issues for the future deployment of VANETs. It is a point of concern that how to perform efficient computations with effective resource sharing that in turn decreases latency and enhances the quality of service (QoS) of connection [4], [5]. Since safety-critical messages require low latency so network congestion can have an impact on the latency of the transmitted packets. The critical messages face delays due to MAC contention and with the poor channel utilization, which is not suitable or desirable in VANETs [6]. Similarly, distribution coordination function (DCF) is a technique used to access medium in conventional 802.11 wireless local area networks, and analytical models are proposed to compute the throughput for DCF [7]. The contention-based carrier-sense multiple access with collision avoidance (CSMA/CA) scheme and a limited transmission range of DSRC make the dissemination of critical messages a challenge in VANETs [8]. The frequent delay in the dissemination of crucial messages can cause a severe threat to network performance and neighboring vehicles as well. Packet loss is another factor that affects the performance of the VANETs [9]. Packet loss occurs due to several different factors including packet transmission rate, transmission power, traffic flow, and communication distance.

In VANETs the key challenges are intermittent connectivity, high mobility, heterogeneous vehicle management, security, and support of network intelligence. Therefore, based on the above-mentioned concerns, designing optimized network protocols needs further exploration. This work is organized as Section II present important features of VANETs. Section III reviews different congestion controls strategies for VANETs. Section IV summarizes existing simulators used to simulate congestion scenarios. Section V concludes the work with the future perspectives.

II. IMPORTANT FEATURES OF VANETS

In this section, we have discussed the main features of VANETs, which includes its characteristics, applications, and challenges. We have also discussed different performance metrics for congestion control at the end of this section.

A. CHARACTERISTICS OF VANETS

VANETs itself is an application of mobile ad hoc networks (MANETs). Its highly mobile and dynamic nature makes it different from other mobile networks. The VANET characteristics include high mobility, dynamic topology, predictable mobility patterns, energy constraints, unbounded network size, wireless communication, etc.

1) ***Dynamic topology*** – Vehicles move at high speed, and their direction and speed are continuously changing; this makes it difficult to predict vehicular position at the next instance. These abruptly changes the vehicular density in a particular region. With the increase in vehicular density, congestion control becomes a point of concern. With the varying speed, the geographical location of vehicular nodes also changes with time. This is the major difference between VANETs and fixed size network [10].
2) ***Time criticality*** – One of the important features of information or messages in VANETs is its time criticality. The data and information should be delivered in time to take adequate actions. Let's say if medical emergency messages are delivered in time, it can save precious lives. That's why timely dissemination of safety-critical messages becomes crucial for network efficiency and reliability. The data or packets should be transmitted in a way that the congestion should be avoided increasing the throughput and decreasing the network latency [11], [12].
3) ***Mobility patterns*** – Mobility patterns in VANETs are usually predictable as vehicles follow specific predefined pathways and roads. By analyzing the mobility patterns and information communicated among vehicular nodes, traffic jams, and other network scenarios can be predicted. This can help to predict the traffic condition in a region at a particular time. Similarly, by managing the mobility can help to effectively deliver the services to the vehicles [13], [14].
4) ***No energy constraints*** – Fortunately VANETs do not have any power constraint like MANETs. The vehicle battery is sufficient to provide power for a variety of computations. It is viable to implement those schemes and solutions which are computationally intensive; however, the time-critical nature of information makes it challenging to come up with a reasonable solution that guarantees a tradeoff between efficiency and complexity. Secondly, the reliability of communication is an important concern to provide due assistance to drivers. The continuous acknowledgment of these messages can cause congestion [15].
5) ***Unbounded network size*** – Unbounded network size means that VANET is not limited to a specific area, city or region but it can be implemented having variant sizes for a town, multiple cities, and even countries. It means you can develop a scalable version of VANET but high vehicular density along with higher mobility makes scalability a challenging issue. Bandwidth limitation makes it necessary to use the effective use of it. It is encouraged to design routing protocols that negate the principle of simple flooding preventing the broadcasting storm problem. This enhances the scalability to some extent [16].
6) ***Wireless communication and frequent information exchange*** – VANET is a wireless environment and Vehicles and nodes are continuously sharing the information. Vehicles receive periodic messages from other nodes as each vehicle wants to make other vehicles aware of the surroundings. Due to the wireless nature of VANETs, there are a lot of security concerns that need to consider for efficient communication. Another essential use-case and relatively new idea after the emergence of the internet of things (IoT) and VANETs is the smart cities or vehicles-to-everything (V2X) communication that will undoubtedly revolutionize the ways of interaction between machines. Secondly, handover also becomes the point of concern in these highly dynamic scenarios [17], [18].
7) ***Better nodes protection*** – Nodes in VANETs are better physically protected so this provides better physical security and is usually difficult to compromise. The on-board unit (OBU) provides sensors, resources, and read/write storage for data and user interface. This is responsible for communication between different OBUs and RSUs [19].

B. VANETS APPLICATIONS

VANET applications can be classified based on two essential requirements, named as efficiency and safety. Usually, VANET applications sense different types of data from the surrounding environment and take decisions by exchanging the relevant information with the other nodes. VANET application can be divided into safety applications, efficiency applications, comfort applications, interactive, entertainment, and urban sensing, etc. Multiple applications can be used by specifying their requirements. These applications are supported and used in a dynamic and multihop topology. Safety and non-safety applications are the most common ones while others are usually variations of it [20], [21].

1) ***Safety applications*** – Safety application reduces the chances of an accident and is delay-sensitive. These applications provide early warnings to the vehicles to proactively preventing any event like an accident. More than 60 percent of the accidents can be avoided when a driver receives an early warning. This can reduce the accidents and congestion at the intersections by providing the drivers with the best route to

the destination. Flow control at the intersection is challenging as many different flows are intersecting at that point. Safety messages are sent as cooperative awareness messages (CAM) which is a consequence of an emerging technology named cooperative intelligent transport system (C-ITS) [21], [22].

2) ***Efficiency applications*** – These types of application make other vehicles aware of its location to enhance interaction between vehicles. It improves the vehicle's mobility-based on the information received from the neighboring vehicles. These types of applications enhance the perception of road traffic by predicting traffic. It uses different features like velocity, position, acceleration and other parameters of the neighboring vehicles to increase the cooperative awareness [23].
3) ***Comfort or customization applications*** –These applications make the driver's journey more comfortable and enjoyable. These applications usually include information about nearby restaurants, gas stations, weather information, etc. Suppose a driver's health condition becomes upset and wants to go to some hospital then the message can be sent to a vehicular cloud that replies with the location of the nearby health center. Similarly, in case of accidents, these types of applications can assist the driver. The vehicles can find the site of a bar or any friend meetup based on these applications. It can provide a crowdsourcing feature to enhance the interaction of applications for collective benefit [24].
4) ***Interactive applications*** – These applications provide entertainment related services to passengers. Examples of this type of application include music, chats, web browsing, internet services, distributed games, etc. Let's say if a vehicle enters a new city, then different picnic spots and advertisements are downloaded automatically from the internet for passengers and drivers. Different multimedia files and entertainment services are attractive features of these applications. [25]–[27].
5) ***Urban sensing*** – Sensing and communications can enhance the interactions and management in a traffic management system (TMS) [26]. The vehicles equipped with different kinds of sensors use their sensing capability to sense traffic conditions, video/audio surveillance, and environmental parameters. These applications sense the urban environment and their environmental conditions using OBU's sensors. This data of common interest is further shared among vehicles. The sensing of social activities play an important role in urban sensing [28], [29]. Similarly, application in VANETs can be divided into congestion road notification (CRN), cooperative collision warning (CCW), lane change assistance (LCA), post-crash notification, etc. [30].

C. PERFORMANCE METRICS

Due to abrupt topology changes, the vehicular ad hoc network can exist for a short period. In this time, the data must be transmitted efficiently, and low latency paths must be established. Small changes in operational parameters lead to considerable effects on the efficiency of the network [31]. There are numerous parameters to judge the efficiency of a congestion control algorithm. Some of the commonly used metrics for performance measurements are discussed below [30].

1) ***Average delay and average throughput*** – Average delay is the inter-packet delay (IDP) between successive packets. It is also called inter-reception time (IRT) which is reception time between two subsequent or consecutive sender recipient pair [32]. It is one of the most important parameters to determine the efficiency and effectiveness of the congestion control algorithm. The reason for this is the time criticality of the event-driven safety messages, as discussed earlier. The optimal flow of the network is based on the timely availability of these messages as actions are solely dependent on this critical information. Less inter packet or average delay is usually the indication of less congestion in the network. Similarly, vehicular density plays a vital role in latency and delays in transmitting packets [33]. It means more packets can reach the destination and fewer packets are wasted, dropped or delayed due to collisions or buffering. Throughput is the number of packets received which are sent from the source to destination. If throughput is low, it is an indication that the network is congested. Throughput and average delay are inversely proportional to each other if one is higher another one automatically becomes lower. Due to the unique nature of the vehicular network, the device discovery process time also needs to minimize, reducing the overall latency and delay [34].
2) ***Packet delivery ratio (PDR)*** – is related to the number of packet send over the number of packets received [35]. PDR is an important parameter to determine the level of congestion in the network. The value of PDR lies between 0 to 1. A higher value of PDR means more packets can reach the destination. If the value of PDR is one, it means all sent packets have reached the destination. Low delay and high packet delivery are requirements for optimal VANET behavior. However, due to frequent changes in vehicular density and network topology, these parameters are drastically affected. By giving close attention to the time-varying behavior of VANETs can enhance the performance [36], [37].
3) ***Channel busy ratio (CBR)*** – is an important parameter to enhance the packet delivery ratio which in turn will increase the packet delivery performance [38]. It is also referred to as channel busy time (CBT), which is the ratio of the time during which the channel is sensed busy and the total observation time. CBR is the measure of perceived congestion or channel load, which depends upon the number of vehicles in the transmission range and individual message generation rates. Usually, power and rate control strategies depend upon the channel busy ratio which is the feedback of the network against network traffic. These approaches try to maintain the busy

channel ration to an optimal level so that the network may not get congested [3].

4) ***Parameters affecting performances matrices*** – Different parameters affect the performance of the above parameters directly or indirectly. Similarly, vehicular speed, Vehicular density, area, and track length also affect the network congestion that is usually handled by varying the transmission range of vehicles [39]. The high speed makes the topology change more vibrant. Intersections are challenging to handle as compared to highway lanes.

D. CHALLENGES FOR VANETS

In the previous section, we have discussed the application and characteristics of VANETs. In this section, we will see what the challenges associated with VANETs are. As previously discussed, the unique nature of VANETs has made it quite different from the traditional networks, and there are a lot of serious issues and challenges that need to be addressed in this type of network [40]. The associated challenges are:

1) ***Delay constraints*** – A challenge in VANETs is to design a protocol that provides a low latency path with varying topology, speed, and connectivity. The network should provide adequate quality of service with fewer retransmissions, more extended connectivity, and little delay. By handling delay constraints effectively, the accidents can be reduced to a greater extent by enhancing the early decision making [41]. In an area where there are multiple vehicles transmitting beacons at the same time, it will create uneven delays causing network congestion. The speed of the vehicle is also one of the critical factors that can be adapted according to the situation to enhance network performance. [39].
2) ***Packets congestion control and prioritization*** – Emergency packets have significant impact over the network performance. The network should not drop, delay or waste those packets. There is a significant amount of research done to find out how to give different priorities to these event-driven messages to enhance network performance. By giving priority to different packets based on their importance, the congestion and uneven delays in the network can be greatly reduced. It becomes the point of interest on how to give priority and develop priority queues based on the message types e.g. safety general, safety-critical, video etc [42].
3) ***Cross-layering and reliability*** – VANETs use wireless medium to communicate. Due to wireless communication medium and high mobility, these connections and routes break frequently. It is challenging to design a protocol that effectively handles routing phenomena in these networks. In most of the reliable transmissions, a particular vehicle uses some scheduling discipline to transmit messages. Devising a concurrent transmission protocol is a challenge that can enhance network performance and reduces delays [43].
4) ***Geo addressing*** – Some application requires the physical site of the vehicle to offer a different kind of services. Because of the high mobility and dynamic environment, the geo addressing is quite hard in VANETs. Most of the protocols support topology-based routing, but due to abrupt topology changes, these protocols are unsuitable for VANETs [44]. Position-based protocol is a solution to these problems but developing an efficient routing protocol in VANETs is a challenging task [45]. Often the protocols support unicast data forwarding in highly volatile ad hoc network.
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6) ***Data trust and verification*** – Trust and privacy are crucial concerns for the deployment for vehicular networks. VANETs communication broadly supports broadcast scenarios were verifying the authenticity of a particular message is very important [46]. Insecurity perspective usually, confidentiality is not an issue of prime importance as messages are broadcasted. But data verification is an essential aspect of data security. It is necessary to propose some solutions that ensure the integrity of data to predict better the future state of the network enhancing the decision making the process.

E. MOTIVATION BEHIND THIS WORK

Congestion control is one of the most important concerns for VANETs. When traffic increases in a particular region, then the packet drop takes place, which is the result of the traffic congestion [47]. Every time a vehicle receives a message from the nearby cars, it updates its information and takes decisions based on that information. The collected data is crucial because the network state depends upon the availability and validity of these messages.

Every vehicle repeatedly sends CAMs that describe the current state of the network environment. These messages are sent using control channels. As CAMs messages are sent periodically so control channels are occupied by these messages for a significant amount of the time which can lead to congestion in the network [48]. These messages are crucial as they contain information regarding some accidents and congestion information at some intersection. Accidents and traffic congestion can be avoided by decreasing the delays of these crucial messages. If by any means network is congested, then these crucial messages will get wasted and remain unavailable to other vehicles at the right and desired instance. It can cause an uncertain future

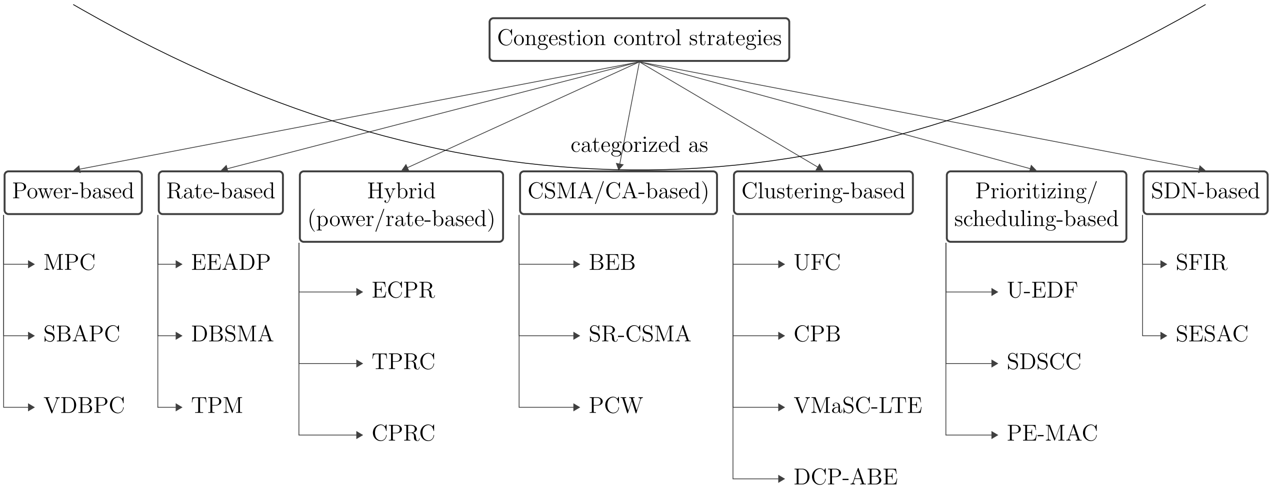

FIGURE 2. **Taxonomy of congestion control protocols.**

state of the network with frequent accidents and uneven delays.

This work describes the approaches and strategies used to avoid network congestion so that efficient congestion control protocols may be designed by getting a broader familiarity with these schemes.

III. CONGESTION CONTROL STRATEGIES FOR VANETS

In VANETs messages are broadcasted in the network. A vehicle creates a copy of a message and sends it to all other vehicles in a network. VANETs use three different approaches to address congestion in the network. [49], [50]. These approaches include proactive, reactive, and hybrid congestion control. Based on functional mechanisms and techniques, congestion control strategies using the approaches mentioned above in VANETs are mainly categorized into six types. The different types include rate-based, power-based, hybrid strategies, CSMA/CA-based, prioritizing and clustering-based strategies [51], [52].

Power-based approaches try to prevent congestion by limiting the transmission power of nodes. When there are a large number of nodes sending and receiving packets at the same time, it will also increase the collision probability of packets causing the congestion and packet loss. This approach decreases the transmission power by a factor allowing less number of nodes transmitting or receiving the packets [3], [53]. Rate-based strategies shift the transmission or data rate based on the condition of the network. When the network is congested, and packet loss takes place, this type of protocol shifts the data rate of the medium to a lower rate to avoid collision of packets. That will eventually reduce the packet loss and congestion in the network [52], [54]. Hybrid approaches combine rate based and power-based methods and simultaneously change them to address congestion in the vehicular network. MAC-based strategies are default strategies to address congestion in VANETs. In CSMA/CA environment, a node detects the channel before sending a packet in the medium. If the medium is found free and no other node is transmitting the packet, it starts transmitting its packets. These types of protocols control channel access through adjustment of channel access parameters, e.g. contention window size [55]. In priority-based approaches, different priorities are assigned to messages based on their type [56]. Emergency or safety-critical messages are given high priority to get delivered to the destination as compared to general safety messages. In VANETs emergency or safety-critical information include accidental or congestion information that is crucial for the optimal performance of the network.

In this section, we will describe different strategies to overcome congestion in the network. The summarised taxonomy and related works are illustrated in 2.

A. POWER-BASED STRATEGIES

Power-based strategies control congestion in the network by changing the transmission power based on the network behavior. If a vehicle sees the congestion in the network, it adjusts its transmission power accordingly to handle congestion [2], [57], [58].

1) ***Multi-metric tx-power control protocol (MPC)*** [59] – maintains an acceptable level of channel saturation and transmission power with the different coverage ranges. Control channel quality and application requirements are two factors to adapt the transmission power of each node according to its needs by effective use of control channels. It is important to know the channel quality for current and future transmissions to avoid channel saturation along with the collision. The current channel quality is calculated by measuring the CBT for the last 100ms. The protocol uses a beaconing load metric to calculate channel quality for future beacons. Denda et al. [60] explained the beaconing load is expected load determining how much load is there on the control channel for transmission power that covers the estimated vehicular density. Beacon load

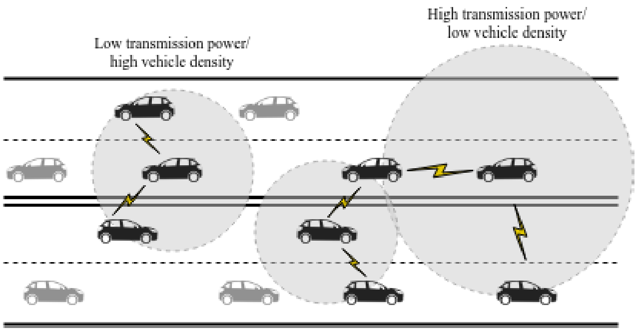

FIGURE 3. Transmission power change based on vehicular densities.

for all vehicles is calculated by assuming a constant frequency and packet size. As far as the application requirement is concerned, transmission power is adapted based on the desired transmission range and priority for different types of messages (Figure 3). A higher priority level of 1 is assigned to event-driven messages, whereas a lower priority level of 0 is assigned to the safety general messages. The highest transmission power is used to send event-specific messages when there is no congestion in the network, whereas general purpose messages are sent with the lowest transmission power in case of congestion. In all other cases, transmission power is adapted to avoid congestion in the network. ***Drawbacks:*** On vehicular advertisement vehicular density is calculated. What is the threshold for congestion detection and how vehicles will receive beacons if there is already congestion in the network?

2) ***Speed-based adaptive power control (SBAPC)*** [60] – reduces network congestion by adapting transmission power for basic safety messages (BSM) based on vehicle's speed. The protocol is based on the fact that increasing the speed of a vehicle decreases time to collision TTC) with neighboring vehicles. This means distant vehicles should have an awareness of a vehicle to receive BSMs. The protocol has initialization and power control phase. Maximum transmission power and cycle length are two metrics that are assigned with suitable values during the initialization phase. The value of 10mW is selected for maximum transmission power which corresponds to maximum distance for BSM to reach, i.e. 360m. Cycle length determines the number of BSM packets sent by a vehicle which is 7 in this case. The power control phase is invoked on each new cycle startup. Power factor is calculated based on maximum power level, cycle length and vehicle speed which eventually controls transmission power. After every BSM transmission, Vehicle's transmission power is increased by a factor based upon the power factor. The last BSM in the cycle is always sent with maximum transmission power irrespective of vehicle speed. The approach tries to expand the awareness circle for a vehicle increasing the transmission power. A quick increase in power level is observed in case of a higher speed. ***Drawbacks:*** A high vehicular density in a region will decrease the transmission power to a smaller value which will decrease the awareness of the surrounding vehicles.

3) ***Vehicle density-based power control (VDBPC)*** [61] – controls the transmission power on MAC layer based on the number of vehicles in a region. Initially in this maximum transmission range is selected, which is 1000m in this range and packets are set to transmit at the constant maximum rate of 10HZ. It means on average, 10 packets are transmitted for every second. Scheme counts the number of vehicles in a region and determines the state of vehicular density based on the count. If vehicle count is greater than 100, the state is considered dense. In moderately dense state vehicle count is between 50 to 100. On the other hand, if the vehicle count is less than 50, the scheme classifies it as a sparse topology. In dense environment transmission speed is shifted to a lower level because higher proximity will increase the collision rate causing congestion. In a moderate state, transmission power is shifted to a medium state such that it is just able to accommodate vehicles that are far apart. In the sparse state, transmission power is set to maximum as vehicles are far apart causing less congestion. ***Drawbacks:*** Congestion consequences for event-driven messages remained unaddressed. Vehicular count or density is randomly assumed.

4) ***Discussion*** – The goal of the congestion control techniques is to make awareness of distant vehicles. Power-based approaches serve this purpose to increase the transmission range. It will make the remote vehicle better aware of the environment. The issue with the power-based approach is that in the case of higher transmission power scenarios, the hidden node, and channel fading phenomena become more prevalent. It reduces the channel sensing range as well. So power control approaches sacrifice the awareness of distant vehicles but can make the nearby vehicles better aware of its surroundings [62].

B. RATE-BASED STRATEGIES

Rate-based strategies rely on changing the transmission rate or packet generation rate to control congestion in VANETs. Increasing the transmission rate has a significant effect on the performance of VANETs as it will increase the transmission rate of safety messages making vehicles more aware of their surrounding environment. There is also some cost attached to the increase in transmission rate leading to the congestion in the network. In the high-density scenario, there are large numbers of vehicles transmitting a large amount of data that increases the channel load and causes collision and channel saturation [1], [63], [64].

1) ***Effective and efficient adaptive probabilistic data dissemination protocol (EEADP)*** [51] – incorporates distance from source node and number of road segments

based on delay and probability to control congestion. This approach decreases the broadcast storm problem and increases the data delivery rate. The waiting period is calculated by using the distance variable, and the suitability of rebroadcasting is determined for each node based on its probability in the least waiting time. If there are large numbers of nodes on a road segment then increasing the number of road segments will eventually decrease vehicle density. Vehicle farthest from the source node is given the minimum wait time before transmitting. The broadcast problem can be resolved by giving different wait times to different segments with the last slot chosen as the unique forwarder node. If the number of vehicles in a region is increased, then the issue of rebroadcasting can be addressed by calculating the present and preceding redundancy which is the number of delivered messages to the total number of new messages. The slot with the lowest number of vehicles and redundancy ratio will be given the highest probability to rebroadcast based on the redundancy ratio. The approach is only suitable for safety messages with no periodic safety message exchange. ***Drawbacks:*** The proposed solution is cost-efficient. The author suggests that if vehicular density crosses a certain threshold, then the issue of network congestion can be addressed by introducing enough road segments. This will be quite inefficient in a particular scenario. There are numerous solutions like adjusting the transmission power, giving priority to event-driven safety messages that can be adopted to reduce the network congestion effectively.

2) ***Dynamic broadcast storm mitigation approach (DBSMA)*** [65] – senses any hazard efficiently and take immediate action accordingly. Perception time is 1/4 to 1/2, whereas reaction time is usually 1/4 to 3/4 of a second. A minimum safety distance of 200m is defined based on some safety rules at a speed of 120 km/h. Usually, 3s rule is observed if the vehicle is showing normal behavior in the network along with the minimum safety distance. The maximum communication range for the vehicle to vehicle communication is 1000m based on WAVE standard. A faulty vehicle parked on the roadside transmits messages to make other vehicles aware of the situation but transmits at the lower rate. A fast-moving vehicle moving at the speed of 120km/h transmits at a higher rate as compared to slow-moving vehicles. Tolerance range is 20% which is 800m in the specific scenario, and a parked vehicle or vehicles with speed less than 6km/h transmit at least two messages for the traveling distance of 800m. So fast-moving vehicles approaching the faulty or parked vehicle will slow down after receiving the messages, and it will start transmitting at a lower rate. This approach reduces congestion by varying the transmission rate according to the situation Drawbacks: The issue of unreachability of sensitive information can arise. The event-driven safety messages, i.e. accident information or traffic congestion information, are critical. These messages should be propagated to the approaching vehicles in a particular time frame. Lowering the data rate can make the information unavailable at specific instances.

3) ***Trajectory predicted mechanism (TPM)*** [66] – is introduced to avoid congestion in V2I communication by reducing the beaconing rate. Congestion is avoided by reducing the messages that create vehicle awareness in the network. Each vehicle builds its future trajectory model based on its sensed information and previous predicted information. Rather than sending data at a constant rate, now, each car sends messages based on its predicted future trajectory. After some time, this model expires because of continuous topology change and the position becomes inaccurate. Now a new model is transmitted that provides updated predicted positions. TPM uses a linear model, and a new model is sent when a vehicle makes a turn, applies brakes or accelerates. A threshold for new model transmission is calculated based on the error position vector. Every vehicle has two position vectors: one received or gathered from the vehicle's GPS and the second is the predicted one. The difference between these two positions vector determines the error that is used as a threshold for a new updated model. TPM also forces vehicles to send a new model after a specific time even though estimated error remains within the threshold limit. ***Drawbacks:*** What if predicted trajectory is inaccurate due to the malicious behavior of some vehicles?

4) ***Discussion*** – Data rate approaches can reduce the congestion to some extent by adopting the data rate according to the network behavior. When significant collisions are detected in the network, these schemes reduce the data rate that effectively controls the congestion. Data rate adjustments are usually tricky in the case of VANETs. The traditional network sends broadcast with least supported data rate, but the unbounded nature of VANETs makes it challenging to address the interference level with efficient usage of channels [67]. The hidden node terminal effect is amplified with the increase in vehicular density, and efficient channel utilization becomes quite challenging to allow a minimum level of interference. Similarly increasing the data rate decreases the transmission power for constant target loads and vice versa [68].

C. HYBRID STRATEGIES

These approaches use the hybrid strategy to control power and rate at the same time. Rather than individually changing the power or rate, it uses an improved way to handle congestion. It adjusts the transmission rate based on the range of the transmission [69], [70].

1) ***Environmental and context-aware combined power and rate distributed congestion control (ECPR)*** [69] – improves cooperative awareness at the target distance by changing both transmission and data rate. The purpose

of the congestion control is to improve awareness and make the other vehicles informed about the periodic or event-driven safety messages so that vehicles may prevent any hazardous action. Power is changed to address the awareness issue of neighboring vehicles and also reduces the channel load, whereas data rate control adjusts the data rate to make the efficient use of the resources by achieving the target load. If the data rate is increased, then the data rate is reduced and vice versa. Power is adapted based on the transmit power level of the sending vehicles which is piggybacked in the transmitted packets. Based on that, channel path loss for all vehicles is estimated by calculating the path loss exponent (PLE). To adjust the data rate, channel busy ratio and current beacon rate are used as an input to the linear message rate integrated control (LIMERIC), rate adaptation algorithm. The beacon data rate is adjusted to keep the channel busy ratio under the threshold. ***Drawbacks:*** As nodes are dynamic and mobile. Vehicles which piggyback the messages are not tracked so at the next instance topology will be changed, which can degrade the quality of awareness. Tracking error should be considered while implementing the congestion control [71].

2) ***Joint transmission power rate control (TPRC)*** [72] – is a joint power/rate control that optimizes the performance of the reception for the vehicular safety communication by calculating the kth percentile of IRT at the target distance preventing the channel over-saturation. This is based on the fact that there is an optimal value of transmission power that independent of vehicular density, unlike the corresponding transmission rate. For this purpose, Spatio-temporal characteristics in terms of packet reception are analyzed for safety applications. The spatial aspect is related to this fact that sending vehicles should make sure that its beacons have listened at a target distance. The temporal element is related to IRT which is the maximum tolerable time for consecutive or sequential packets for particular sender and receiver. Performance is optimized by selecting the transmission power concerning the target distance, whereas channel load is used as a metric to choose the data rate reducing the unnecessary interference. The algorithm first checks if channel load is less than the maximum allowed load it will look for the maximum value of the transmission power for the maximum load in a lookup table and increases transmission power accordingly or increases the transmission rate is lower than the maximum tolerable limit. In the second scenario data rate or transmission power is decreased to optimize the reception performance. ***Drawbacks:*** Scheme only considers beacons and does not consider event-driven safety messages that are crucial for the safety of VANETs.
3) ***Combined power and rate control (CPRC)*** [70] – addresses the congestion in the network in the single loop instead adjusting power and rate in two different phases. When a node comes across a dangerous situation, which is turning left or right at the intersection, these nodes decrease their transmission power and allow other nodes to become aware of this dangerous situation. On the other hand, the transmission rate is increased required by some contextual factors like higher collision probability and speed such that it may remain below a predefined reliability-based threshold. In these schemes, two algorithms run such that after running the first algorithm second can intervene anytime providing a certain degree of flexibility. In the first step, the transmission rate is calculated based on vehicular density, and data rates are also determined for each transmits power level. Every node in a particular transmission range uses the same transmission rate to achieve fairness. In the second phase, each node calculates the inter-packet arrival time for its neighbors and also calculates its packet generation rate as well. So transmission rate is selected according to the transmission power such that overall traffic load is kept below a specific threshold. ***Drawbacks:*** Scheme uses the same data rate to achieve fairness. In practical scenarios fairness is not met with the same data rate. There are a variety of other factors like the vehicular speed that determine different data rates for different vehicles.
4) ***Discussion*** – These approaches mainly consider the power and data rate to address congestion in the network but ignore traffic dynamics and the status of vehicular movement, e.g. speed, etc. These approaches also do not take into account the position error computed by neighboring vehicles as the vehicular network requires the high accuracy of vehicles which can help to park vehicles at the specified place. Similarly, it also requires a better navigation facility to route the packets from source to destination.

D. CSMA/CA-BASED STRATEGIES

CSMA/CA-based strategies are the default congestion control strategies in VANETs. These approaches try to address the congestion by changing the channel access parameters, e.g. congestion window (Figure 4). To provide services, each vehicle should be able to access the medium efficiently. MAC strategies describe how vehicles can efficiently access channel to reliably and effectively use safety and non-safety applications. Based on different types of media access MAC-based protocols can be divided into three types: contention-based, contention-free, and hybrid MAC protocols [73]–[76].

1) ***Binary exponential back-off (BEB)*** [77] – is a decrement exponential back-off strategy to find equilibrium between collisions and expired beacons while addressing the issue of ghost nodes. It reduces the contention window for the consecutive messages if the message is expired, improving the quality of communication on the control channel. The scheme discovers that RTS/CTS and BEB strategies are unsuitable for a broadcast environment like VANETs as CAM messages have limited lifetime and should be available at the right time to

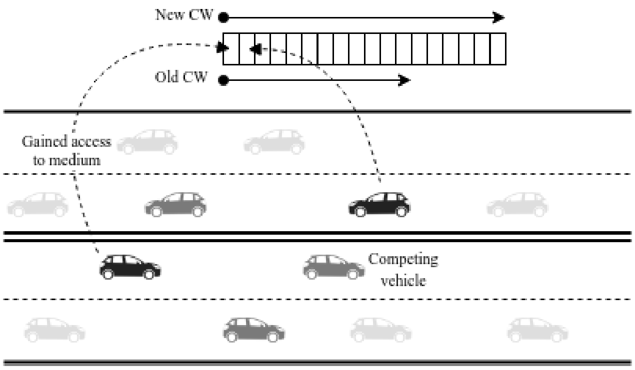

FIGURE 4. CSMA/CA-based Strategies.

neighbors. If based on the contention window a vehicle has to wait for some time before sending any crucial message then that information becomes outdated after some time, it will be useless to the network and becomes hazardous. It develops the notion that for VANETs while considering CAM the achievement is not to send a large amount of data or increase the throughput, but the real objective is to make its neighboring vehicles more aware of its environment. Approach says that In case of optimal contention window in a crowded environment, the risk of losing some critical information always exists that cannot be tolerated. So genuine problem is how to achieve a tradeoff between collision and expired beacons? The tradeoff is achieved such that initially contention window (CW) is introduced with large value and then on each message expire window is reduced to half. By doing so, event-based crucial messages are given higher priorities with less collision and the issue of ghost nodes is tried to be controlled as well. ***Drawbacks:*** Reducing congestion window to half is not a good idea as the vehicle may be able to send packets more than the half without causing the collision.

2) ***Safety range-carrier sense multiple access (SR-CSMA)*** [78] – increases the reception probability of messages within the safety range by proposing a channel access technique. The safety range is larger than the transmission range of the vehicles. Congestion is avoided using carrier sense, contention window, and location of the transmitting vehicle. It uses the same concept of conventional CSMA. If no other node is transmitting and the channel is empty, it sends the beacon. If the channel is not empty, conventional CSMA starts an exponential backoff timer and waits for a specific time before transmitting the message again. SR-CSMA introduces an intermediary step before setting the waiting period. If the safety range of two transmitting nodes is nonempty and messages are crucial, then the channel is considered busy. If the channel is busy, this calculates the signal-to-interference ratio (SIR) to determine what level of interference of a node transmission in a channel at the border of the safety range of the already transmitting station can still make the transmission possible increasing the reception probability. If SIR is greater than a threshold, then the channel is considered idle, and nodes can transmit its message. Drawbacks: If there are safety messages to send and the channel is busy, the random back-off timer makes it inefficient.

3) ***Predictive contention window (PCW)*** [79] – determines the CW to mitigate broadcast collision in VANETs. It first classifies the vehicular information and then uses Bayesian prediction ranking (BPR) to find expected contention window for each attribute set using stochastic gradient and sigmoid function. After that hidden Markov model is used to find contention for the future by determining future vehicle state. Vehicular states are classified into attribute sets using classification strategy. The classification strategy uses a fuzzy nearness approach based on fuzzy mathematics to find a similarity degree between states of objective vehicles and attribute sets to determine window size. The window is selected based on multiple factors that represent vehicular density including neighboring vehicles, velocity and stop time, etc. BPR uses stochastic gradient descent (SGD) to find the expected value of each contention window corresponding to each attribute set. PCW Optimizes broadcast performance and reduces collision probability by implementing an estimation mechanism using a hidden Markov model (HMM). A vehicle sends traffic information on the control channel, and other vehicles adjust their window based on this information. HMM improves real-time ability by predicting vehicular state for future movement based on attribute sets and PCW adjusts window size supported via the MAC layer. ***Drawbacks:*** The predictive contention window predicts window size but does not address how it handles the safety messages.

4) ***Discussion*** – These approaches try to sense medium before initiating their transmission. Because of the multi-access wireless medium, many factors can affect the transmission. If the vehicular density is increased in a region, then it can cause a delay in the transmission of safety messages because of the limited channel bandwidth. In the lower-density environment, CSMA/CA-based approaches perform better as they save the transmissions from wastage. It can make efficient use of bandwidth with fewer transmissions in a low-density environment.

E. CLUSTER-BASED STRATEGIES

Clustering in VANETs is usually used to enhance the reliability and scalability of the network. In these techniques, vehicles are grouped into different clusters that in turn, make the vehicles to communicate in a distributed fashion (Figure 5). Each group is autonomously efficiently handling the responsibilities. These groups can better disseminate information and detect accidents or congestion in the network. The most important benefit is the scalability

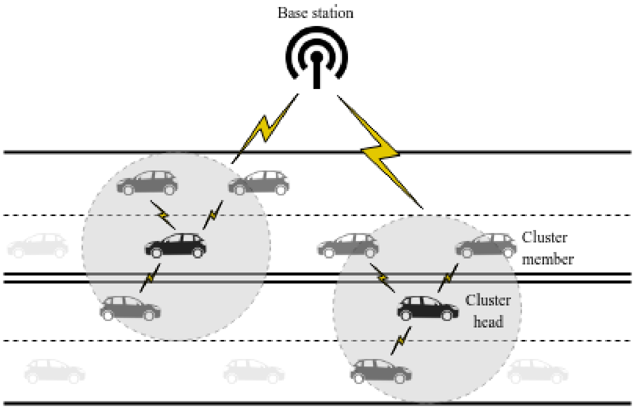

FIGURE 5. Clustering-based approaches.

while going for cluster-based routing, where the network is converted from flat to hierarchical [80], [81]. Different clustering-based techniques include:

1) ***Unified framework of clustering (UFC)*** [82] – uses mobility-based metrics to enhance the efficiency of the cluster. First of all, it separates stable neighbors that can build a connection with the cluster head (CH). A vehicle clears the criteria of a potential stable neighbor based on the similarity in the mobility pattern that includes the same direction and the speed difference smaller than a threshold. The overhead in clustering management is reduced through calculating the random backoff timer by each vehicle that makes a cluster head decision for that vehicle. A smaller backoff timer is selected by the vehicle that has a higher chance of being selected as a cluster head. Three parameters are considered For CH selection and computation of random backoff timer. These three parameters are average relative speed, average relative distance, and average link lifetime. The first vehicle sending the first cluster head broadcast announcement message is chosen as the first cluster head. Each vehicle communication with the cluster head maintains a cache of the list of cluster heads as it's back up, in case any connection to the cluster head fails then the vehicle can connect with the cluster head from the created list that is ordered based on their priorities. Backup cluster head with the longer link lifetime is given the highest priority. UFC is analyzed under the highly dynamic and stable traffic scenarios. ***Drawbacks:*** Random back-off timer-based schemes become inefficient for low latency networks like VANETs.
2) ***Clustering-based probabilistic broadcasting (CPB)*** [83] – is clustering-based probabilistic broadcasting to efficiently disseminate safety messages for v2v communication in VANETs while reducing the collisions. A cluster head is selected based on the direction of the vehicle and its geographic location at a particular instance. Driving directions of vehicles make it easier to communicate effectively for the longer amount of time between vehicles before discontinuity starts. After CH selection, each CH calculates its capacity of broadcast based on a locally generated counter to guarantee the transmission coverage and packet delivery ratio. For broadcasting the data, first, a probability assignment function is intelligently designed based on the vehicular density or the current condition of the network. A probabilistic forwarding algorithm is developed based on the probability assignment function that decides for data forwarding based on the calculated probability. If the packet receiver is the CH and is in the message dissemination range, it will broadcast the packet. On the other hand, if any other node has received the packets and CH does not reside in the transmission range of that node it will broadcast that packet probabilistically. In case CH is in transmission range, the vehicle drops the packet. It will, in turn, decrease the latency and the packet loss. ***Drawbacks:*** How to efficiently determine density threshold that can be used to forward packets on a probabilistic basis?
3) ***Vehicular multihop algorithm for stable clustering - Long term evolution (VMaSC-LTE)*** [84] – decreases end-to-end delay and increases packet delivery ratio by combining LTE with IEEE 802.11p based multi-hop clustering and minimizing the inter-cluster interference. Vehicles use average speed as a metric concerning other vehicles to select a CH. There are two interfaces defined: 802.11p operates between V2V communications, whereas LTE allows the CH to communicate with vehicles and infrastructure. The network creates a strong interference when clusters overlap in the space, which increases contention and collisions degrading network performance badly. This issue is resolved by keeping the size of the cluster and count to an optimal level. Each vehicle always tries to connect with the already present clusters and does not advertise itself a new CH unless necessary. Secondly, clusters in the transmission range of each other try to merge each other to form a single cluster with the numbers of vehicles smaller than the threshold. Initially, a vehicle connects with the cluster and tries to include it as cluster member, if cluster members are less than a maximum threshold. On the other side, vehicles send a multi-hop request to join the cluster if the cluster head is directly unreachable for that vehicle. If CH is indirectly unreachable as well than the vehicle can also advertise it as a CH. VMaSC-LTE proposes that neighboring cluster in the same direction can also be merged and slow-moving CH in previously clusters is selected as a new CH: ***Drawbacks:*** Does not explain the threshold or vehicular count for a cluster and its effects on the contention.
4) ***A Cluster of CP-ABE Microservices for VANET*** [85] – Deals with the computational delays about data encryption. It represents a clustering technique based on Kubernetes to efficiently encrypt the data with cipher policy attribute-based encryption (CP-ABE).

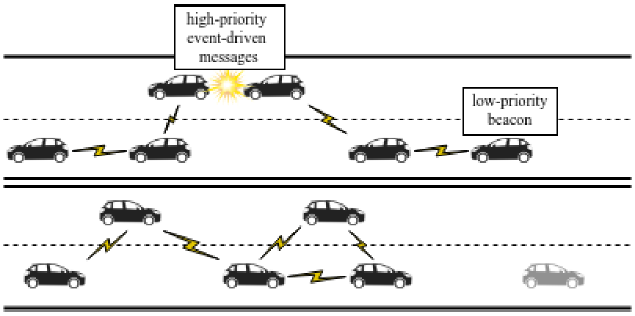

FIGURE 6. Priority and scheduling based strategy.

This, in turn, reduces the computational delays by distributing the encryption tasks to the vehicle cluster created with the help of Kubernetes. The encryption task is distributed based on the computational capabilities and resource information of the individual vehicles that Kubernetes collect to reduce the time of CP-ABE process. The encryption task is distributed in a V2V connection without using the infrastructure component, i.e. RSU. This decreases the computational cost of the operation reducing the delays. ***Drawbacks:*** If the number of clusters is increased, it also increases the inter-cluster interference. The scheme does not describe how to keep an optimal interference level when the number of clusters increases.

5) ***Discussion*** – clustering-based approaches enhanced the idea of access points in infrastructure-based networks where a node or CH just like an access point (AP) tries to share the network resources effectively with optimal scheduling of channel access [80]. In this way in which a large network is divided into smaller sub-network achieving better network management. The issues with clustering-based approaches are their cluster head management. All the information in the cluster depends on the expected behavior of the CH. If CH is failed then every function in the cluster will not perform as expected.

F. PRIORITY-BASED STRATEGIES

Event-driven safety messages play a crucial role in vehicular networks. Crucial messages should be available to the destination at the right instant so that other vehicles and networks can adapt itself according to the network behavior (Figure 6). Some messages have higher priorities as they carry crucial information, e.g., accidental or congestion information. The network gives preference to these messages and loss, or late delivery of these packets can create havoc due to congestion. Below discussed are some protocols that try to handle congestion giving some messages priority over the other's [86], [87].

1) ***Uni-priority safety messages dissemination using earliest deadline first (U-EDF)*** [88] – proposes a congestion control strategy to reliably deliver uni-priority or same priority event-driven messages on control channels. This protocol is divided into two parts. The first part is related to congestion detection and control, whereas the second part is the scheduling of safety messages. Congestion detection uses an event-driven and measurement-based detection method to measure traffic on control channels. In measurement-based detection, scheme packets are measured in a queue. If some packets are greater than a threshold that is five in this case, new incoming messages are dropped. Event-driven congestion detection is based on the fact that event-driven message is given higher priority as compared to ordinary packets. When these event-driven or crucial messages are detected, then all MAC transmission is free-zed, and these messages are provided with enough resources for their efficient dissemination in the network. The protocol uses the earliest deadline first (EDF) scheduling algorithm that is suited for real-time application. EDF handles messages based on their priority and deadlines that correspond to maximum latency. In VANETs each packet has attached deadline and priority, and packet with the smallest deadline is transmitted first by EDF. ***Drawbacks:*** This scheme only addresses uni-priority messages. Uni-priority messages are the messages that are generated from the traffic having the same priority level i.e emergency messages in this case. The scheme does describes to handle messages with different priorities.

2) ***Static and dynamic scheduling for congestion control (SDSCC)*** – decreases congestion in the network by prioritizing packets [84].It improves the IEEE 1609.2 multi-channel MAC on a prior basis by rescheduling the message queues before sending messages on control and service channels. In a static scheduling scheme, this approach makes a packet sending decision either to control or service channel based on the different static parameters and factors defined in the priority assignment unit. Messages of different types including beacons, safety low, and highest priority messages are sent to control channels, whereas lower priority messages are sent to service channels. In case the priority channel is congested traffic is diverted to the service channel. Dynamic scheduling further uses two methods. In the first method, initial priorities calculated by the priority transmission unit are rescheduled and packets in each queue are reordered when a new packet enters the queue. On the other hand, dynamic topology constraints make message scheduling an NP-hard problem. So, the second method uses a meta-heuristic algorithmic approach called tabu search algorithm that gives a near-optimal solution to schedule the control and service queues which reduces delay and jitter at the end of the day. ***Drawbacks:*** In normal circumstances the traffic on service channels is usually high as it carries the low priority or safety general messages. In case of congestion, the packets are directed to these channels. If service

channel is congested, where to send the event-driven safety messages.

3) ***Power efficient media access control (PE-MAC)*** [89] – modifies the original 801.11p protocol with PE-MAC protocol to set the congestion window and select a random back-off timer reducing delays for emergency messages. Data is divided into different types that include ambulance data, fire engine data, police car data, and normal data. Here ambulance data is the most crucial and sensitive one. When any data is transmitted, the data type is also appended with the data. The emergency data has a smaller back-off period as compared to other kinds of data. First, three types of data have normal distributions whereas normal data has a uniform distribution. Normal distribution picks the lower mean value that tends to have a smaller back-off timer with higher probabilities. Mean values are selected in order such that mean1>mean2>mean3, which ends up choosing the back-off timer in increasing order. If the average difference of packet sent to the MAC and passed to the link is less than the maximum delay for an emergency message transmission on the link than the contention window is divided into intervals. Otherwise means the value is reduced further and a smaller back-off timer is selected. ***Drawbacks:*** Retransmission is not a good option for low latency networks like VANETs. The delay and packet loss increases by the change in vehicular density which is the indication of network congestion.

G. SDN-BASED STRATEGIES

1) ***SDN and fog-based intersection routing (SFIR)*** [90] Discusses an SDN and fog-based intersection routing (SFIR) approach that makes V2V communication possible in communication coverage holes. These communication coverage holes are the regions in the VANET environment where RSUs are not located, and vehicles take the responsibility to forward the data packets covering these holes. Intersection based routing tries to find the optimal path from the source to destination. Due to the lack of a global overview of the system, some times optimal routing paths are not generated. This issue is resolved here by using the software defined networking (SDN). Vehicles density, street length and Euclid distance among vehicular nodes are calculated by the fog nodes in coverage zones and coverage holes aswell. The gathered information is used by the SDN controller to find the optimal and appropriate transmission paths. Data is forwarded on the V2V channel using the computed paths. ***Drawbacks:*** There can be numerous available metrics to consider in these kinds of scenarios. How many parameters or features can give an optimal solution is still an open problem.

2) ***SDN-Enabled Social-Aware Clustering algorithm (SESAC)*** [91]– Proposes clustering techniques based on software-defined networking (SDN) using 5G VANETs to decrease packet loss and congestion. Due to the flexibility and programmability of the SDN, it enhances the stability of the cluster in the highly dynamic VANET environment. The stability of the cluster is enhanced by exploiting the future route predictions or social patterns in VANET. Social patterns are defined as the corresponding sojourn period on each road segment along with the number of those road segments in which a vehicle is going to travel. Sojourn time probability distribution and state transition probability are passed as an input to the discrete time-homogeneous semi-Markov model which gives the social pattern of each vehicle as an output. These predicted outputs are used to develop clusters such that all vehicles in a cluster share the same route. Cluster heads(CH) are chosen based on different metrics which include relative speed, vehicle distance and other attributes of the vehicle. ***Drawbacks:*** The optimal behavior of the cluster depends upon many other factors as well. As the number of cluster increases, it also increases the inter-cluster interference. So what should be an optimal number for the cluster is an important aspect to deal with.

A summary table with all the congestion control approaches and their common attributes is shown in Table 1.

IV. VEHICULAR NETWORK SIMULATION

Simulations provide a cost-effective solution to model or simulate the performance of objects or activities in a real-time environment. Sometimes due to nature and design constraints, practical experiments cannot be performed, so it is better to simulate the environment that imitates the physical nature of your environment. There are a variety of simulation tools available to simulate vehicular networks, including open source and commercially available simulation tools [70], [92]. Simulation in VANETs is mainly performed with two different types of simulators, namely mobility generator or traffic simulators and network simulators. Network simulators are used to design and simulate protocols for VANETs whereas traffic simulators are usually used to manage and simulate traffic or road behavior for these protocols. Mobility generator specifically addresses the mobility aspect of the vehicles which depends upon the track length, vehicular speed, vehicular density and number of lanes, etc. These simulators can be used individually but to model and simulate a real VANET environment both of these simulation tools are used collaboratively. VANETs use different types of VANETs simulators to make mobility generators and network simulators work in a collaboration, which we will discuss shortly. In the following section, we will discuss these three different types of simulation tools, their characteristics along with advantages and disadvantages.

A. TRAFFIC SIMULATORS/MOBILITY GENERATORS

As discussed earlier, that mobility generators primarily focus on the mobility aspect. Several simulators perform traffic engineering of vehicles in large geographical areas and cities. There are numerous traffic simulators available and

TABLE 1. Summary table of congestion strategies with relevant attributes.

	Simulator	Dataset	Density	Delay	Throughput	Loss	Coverage	Nodes/ devices	Internode commun.	Commun. protocol
Power-based strategies										
Shah et al. (2016)	OMNeT++/ Veins	U/L	✓	✓	✓	×	750m	×	✓	DSRC
Joseph et al. (2018)	OMNeT++/ Veins/SUMO	D/U/M	✓	✓	✓	×	1000m	×	✓	DSRC/Wave
Akinlade (2018)	OMNeT++/ Veins/SUMO	D/U/M	✓	✓	✓	✓	1000m	×	✓	DSRC/Wave
Rate-based strategies										
Sospeter et al. (2018)	NS2/SUMO	U/ML	✓	✓	✓	×	700m	×	✓	IEE802.11p
Feukeu et al. (2018)	MATLAB	D/U/ML	✓	✓	✓	×	1000m	×	✓	IEEE802.11p/IEEE1609
Boquet et al. (2017)	NS3/SUMO	D/U/ML	✓	✓	✓	×	20 mW	✓	✓	IEEE802.11p
CSMA/CA-based strategies										
Stanica et al. (2011)	JiST/ SWANS/STRAW	D/HW	✓	✓	✓	✓	200m	×	✓	IEEE802.11p
Stanica et al. (2012)	NA	U	✓	✓	✓	×	100m	×	✓	IEEE802.11p
Y.LU et al. (2016)	NA	D/U	✓	✓	✓	×	NA	×	✓	IEEE802.11p
Clustering-based strategies										
Ren et al. (2018)	NS2/SUMO	HW/M	×	✓	✓	×	300m	×	✓	IEEE802.11p
Liu et al. (2018)	NS2/ VanetMobiSim	HW/H	✓	✓	✓	×	250m	×	✓	IEEE802.11DCF
Ucar et al. (2016)	NS3/SUMO	U/H	✓	✓	✓	×	200m	×	✓	IEEE802.11p-LTE
Taha et al.(2019)	NA	NA	×	✓	×	×	NA	✓	✓	NA
Priority-based strategies										
Darus et al. (2013)	OMNeT++/ SWANS/STRAW	H	✓	✓	✓	×	400m	×	✓	IEEE802.11p
Taherkhani et al. (2016)	NS2/SUMO/ MOVE	U/H	✓	✓	✓	×	10 packet/s	×	✓	IEEE802.11p
Nellore et al. (2016)	NS2/MATLAB	NA	✓	✓	✓	×	NA	×	✓	IEEE802.11p
SDN-based strategies										
Noorani et al. (2018)	NS2/SUMO	U/M	×	✓	✓	×	200m	×	✓	IEEE802.11p
Qi et al. (2018)	NA	U/M	✓	✓	×	×	350m	×	✓	IEEE802.11p
Hybrid strategies										
Aygun et al. (2016)	NS2/GEMv2 V2V/SUMO	U	✓	✓	✓	×	500m	×	✓	DCC/IEEE802.11p
Tielert et al. (2013)	NS3	U	✓	✓	✓	×	600m	×	✓	NA
Baldessari et al. (2019)	NS2	HW/H	✓	✓	✓	×	500m	✓	✓	IEEE802.11MAC

D: Dense, U: Urban, HW: Highway, ML: Multilane, L: Low Speed, M: Medium speed, H: High speed, NA: Not available

most commonly used are SUMO, MOVE, STRAW, vanet-MobiSim, PARAMICS, VISSIM, and MoNoTrac.

1) ***Simulation of urban mobility (SUMO)*** [93] – is open source and one of the widely used traffic simulator which can handle significant traffic. SUMO supports vehicle collision avoidance, multiple vehicle categories, traffic portability, and speed control, etc. It can import as well as edit different mobility maps. SUMO uses GUI to route traffic through single and multiple vehicles. It can be used with NS2 NS3 and OMNeT++.
2) ***Mobility model generator for vehicular networks (MOVE)*** [94] – is GUI-based build on the top and an extension of SUMO. It saves one's time to write simulation scripts to simulate the environment. MOVE edits maps, and it can be used with other simulators like NS2 and global mobile information system simulator (GloMoSim).
3) ***Street random waypoint (STRAW)*** [95] – is only used with SWANS. Modifications are usually performed to use it with NS2 or some other simulators. It can parse the TIGER map, but its management is complex, due to this reason it is not widely used.
4) ***vanet-MobiSim*** [96] – is Java-based mobility generator which is used with NS2, GloMoSim, and QualNet. It supports different intelligent mobility models like lane changing and intersection management. It can also

use pre-compiled intelligent mobility models as well. This simulator simulates a realistic mobility model, and besides generating those models, it can also import different US mobility models.

5) ***PARAMICS*** [97] – is commercially available and can be used by adding plugins for macroscopic or microscopic models. It provides enhanced features like 3D visualization and large traffic generation.
6) ***VISSIM***[1] – simulates different types of traffic scenarios like vehicles, pedestrians, public transport etc. Inherently it addresses microscopic traffic flow, but it can support multi traffic flows which include microscopic and macroscopic traffic flow levels. That's why it is also called a hybrid simulator. Its output can be exported to some 3D graphics platforms, e.g. AutoCAD.
7) ***Mobile node trace generator (MoNoTrac)*** [98] – is a Java-based traffic simulator which can create a simulation environment based on real geographic data. The user can define different simulation parameters like vehicle position and simulation time on its own. It can also be used with NS2, NS3, and OMNeT++ with extensible markup language (XML) formats.

B. NETWORK SIMULATORS

Network Simulators are used to analyze the performance of different protocols under different scenarios in a controlled environment. We are specifically interested in network simulators that support DSRC 802.11 standard for vehicular communication. Most of the popular commonly used vehicular network simulators are NS2, NS3, OMNeT++, Mininet, and OPNET.

1) ***Network simulator 2 (NS2)*** [99] – is an open-source easy to implement discrete-event network simulator. NS2 uses object-oriented tool command language (OTCL) for simulation modeling with a simulation kernel written in C++. The initial version of NS2 has no support for IEEE802.11p but in later versions, e.g. NS2.33 the support was included. NS2 is extended to include radio propagation model and node mobility. It uses an event log that is supported by an event scheduler. Pros: It is open-source, and its setup is easy. Cons: NS2 scalability aspect is poor; it does not support scalable architecture. Initial versions of NS2 do not support VANETs default IEEE802.11p wireless standard but later version support this, does not support parallel processing as well.
2) ***Network simulator 3 (NS3)*** [100] – is an enhancement on NS2 and still under development. It is purely written in C++ which removes the OTCL for simulation modeling from NS2. It has significantly reduced the code length to a smaller value. It also enables the python script support. Pros: It supports multiple programming languages like C++ and python, including the default IEEE802.11p standard. NS3 also supports parallel processing and distributed simulations. Its throughput is high. Cons: NS3 has a higher network delay with different routing protocols like AODV and DSDV because many packets cannot be delivered to the destination at once.
3) ***Objective modular network test-bed in C++ (OMNeT++)*** [101] – Is C++ based, free and open-source discrete-time event simulator which can be used for the simulation of different communication networks using a GUI. The simulation system in OMNeT++ is developed by integrating different modules. There are two major frameworks currently used in OMNeT++ including INIT and mobility framework [104]. The mobility framework describes different layers of the internet protocol stack, whereas, on the other hand, the INIT framework describes different mobile and wireless protocols. INIT supports different MAC models like IEEE802.11a, but it does not support the IEEE802.11p model. OMNeT++ output, which is a text file, can also be processed with MATLAB and other simulation tools. Its open-source version is only available for nonprofit, and academics use, other versions are available for commercial use. Pros: Computation time or simulation runtime is faster. OMNeT++ has quite less network delay, and it has improved performance as per the network delay is concerned. As a simulation tool, it is memory efficient. Cons: Does not support scalability and throughput decreases as the number of nodes increases.
4) ***Mininet***[2] [102] – is an open-source network emulator that can emulate an environment with the help of an extensible python APIs. It makes each networking switch and node to work as a real-time machine by enabling virtualization. Mininet can also simulate a wireless network by adding Mininet wi-fi add-ons. It supports the IEEE802.11p protocol and can simulate wireless networks with SDN. Pros: It is an emulator that offers virtualization and effective resource sharing. Cons: Scalability of Mininnet lies in the middle. It lacks the performance fidelity as due to the emulated environment data forwarding rate of open flow switches is unpredictable. Due to this reason, it only helps to analyze the network behavior, not network performance [105].
5) ***Optimized network engineering tools (OPNET)*** [103] – is discrete-time event simulator that uses GUI to configure parameters for different layers and defines topologies. GUI inputs are mapped to simulate the real systems using an objected-oriented paradigm. It can make use of external libraries with its open interface and also supports custom packet formats. Pros: Supports custom packet formats and deal with external libraries. OPNET supports different programming languages like C++ and Java. Its GUI support is excellent. It also supports

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[1] http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/

[2] http://www.mininet.org

TABLE 2. Comparison of simulation software.

	Written in	Language support	Multi-language support	802.11p support	Scalability	Network delay	Availability	Learning curve	Virtualization support	Parallel support
NS2 [103]	C++	OTCL/C++	✓	✓	Low	High	✓	Easy	×	×
NS3 [104]	Python/C++	C++	✓	✓	Limited	Low	✓	Hard	✓	✓
OMNeT++ [105]	C++	C++	×	✓	Medium	Medium	✓	Easy	×	✓
Mininet [106]	Python	Python	×	✓	Medium	NA	✓	Hard	✓	✓
OPNET [107]	C++	C++/OTCL	✓	✓	large	Low	×	Easy	×	✓
JiST/SWANS [106]	Java	Java	×	×	High	Low	✓	Hard	✓	✓

TABLE 3. Evaluation measures used.

Author (Year)	Delay	Throughput	Loss	Contention	Energy	Clustering overhead	Coverage
Shah et al. (2016)	✓	✓	×	×	×	×	×
Joseph et al. (2018)	✓	✓	×	✓	×	×	×
Akinlade (2019)	✓	✓	✓	✓	×	×	×
Sospeter et al. (2018)	✓	✓	×	✓	×	×	×
Feukeu et al. (2018)	✓	✓	×	×	×	×	×
Boquet et al. (2017)	✓	✓	×	✓	×	×	×
Stanica et al. (2011)	✓	✓	✓	✓	×	×	×
Stanica et al. (2012)	✓	✓	×	×	×	×	×
Y.LU et al. (2016)	✓	✓	×	×	×	×	×
Ren et al. (2018)	✓	✓	×	×	×	×	×
Liu et al. (2018)	✓	✓	×	×	×	×	×
Ucar et al. (2016)	✓	✓	×	×	×	✓	×
M.B.Taha et al.(2019)	✓	×	×	×	✓	×	×
Darus et al. (2013)	✓	✓	×	✓	×	×	✓
Taherkhani et al. (2016)	✓	✓	✓	×	×	×	×
Nellore et al. (2013)	✓	✓	×	×	✓	×	✓
N.Noorani et al. (2018)	✓	✓	×	×	×	×	✓
W.Qi et al. (2018)	✓	×	×	×	×	×	✓
Aygun et al. (2016)	✓	✓	×	✓	×	×	×
Tielert et al. (2013)	✓	✓	×	×	×	×	×
Baldessari et al. (2019)	✓	✓	×	✓	×	×	×

communication with other protocols. Cons: It is complex and takes time to master. OPNET is commercially available, so it is expensive.

6) ***Java in simulation time (JiST)*** [102] – Is built on the top of Java virtual machine and can simulate larger scale wireless sensor networks with less memory and computational resources as compared to NS2. It is a discrete-time event simulator that uses SWANS wireless network simulation engine built on the JiSt platform to simulate network. Pros: Benefit scalability. Cons: Does not have 802.11p support which is the default standard.

C. VANET SIMULATORS AND FRAMEWORKS

In this section, we will discuss different frameworks that integrate mobility generators and simulators to simulate an environment. So it forms an integrated environment that resolves the issues of interdependencies. Famous VANET frameworks are Veins, VSIMRTI, VENTOS, etc.

1) ***Veins*** [106] – is a popular integrator framework that integrates SUMO mobility generator with INIT framework in OMNeT++ simulator. Veins allow network simulator to communicate with mobility generator. Mobility generator slows down or controls the flow of traffic based on warning messages generated by the network simulator to control the network congestion. Messages are transmitted on TCP. There is also an integrated application that controls the emission of carbon dioxide.
2) ***V2X simulation runtime infrastructure (VSIM-RTI)*** [64] – supports a layered architecture and can be used to simulate latest ITS application using VSIM-RTI AppNT module. It has a flexible framework and easy integration that's why it can get integrated with a variety of network simulators like NS3, JiST/SWANS, and OMNeT++. VSIMRTI also supports a couple of mobility generators, e.g. SUMO and VISSIM, etc.
3) ***Vehicular network open simulator (VENTOS)*** [107] – is cooperative platoon management simulator that

uses OMNeT++ and SUMO as network simulator and mobility generator respectively. It uses the DSRC standard to enable V2I communication. Bidirectional communication is made possible by using the SNMP protocol. Other supported features include dynamic routing of traffic and the adversary models for security attacks.

D. SUMMARY AND PERFORMANCE ANALYSIS

This section mainly discusses the performance aspects of discussed congestion control strategies. As previously discussed congestion control is a crucial concern in VANETs. There are varieties of parameters that can become the point of interest while addressing congestion in the vehicular network. The two most important parameters are latency and throughput. Latency discusses how much time a message takes moving from source to destination. Whereas throughput addresses how much data is transmitted from source to destination in a unit time. If latency is reduced and throughput is increased, then this is the desired network behavior. If resources are optimally distributed and congestion control is addressed efficiently, it can significantly enhance the performance of VANETs. In-fact highly dynamic nature of VANETs makes it a very challenging task to set these two parameters at an optimal level. We have considered six prominent congestion control strategies and discussed different kinds of protocols using these strategies.

Proactive congestion control or open-loop approaches are best suited for low latency networks. These types of routing approaches take action priorly before the occurrence of congestion in the network taking preventive measures against congestion. Reactive congestion control or closed-loop methods try to detect congestion after it has occurred. These approaches introduce delays and take action after the network has become congested. So on the one hand, delay and throughput are drastically affected, and secondly, high dynamic topology quickly makes network condition, even worse, at every new instance degrading the network performance severely. Proactive approaches, on the other side, try to address congestion before it's happening and give the network enough time not to go into a deadlock state.

Out of six discussed protocols, power-based and rate-based approaches take feedback from the network to adjust their transmission power or data rate accordingly. It means if congestion increases more than a threshold, preventive measures are taken to overcome congestion by adjusting transmission power and data rate. Hybrid approaches deal with the transmission power and rate at the same time to address congestion phenomena. Albeit 802.11P uses CSMA/CA-based approach but increase in the vehicular density degrades the VANETs performance badly. It just behaves like a random transmission technique rather than properly sending the data at higher densities. On the other hand, priority-based and clustering-based congestion control protocols show better performance compared to previously discussed approaches. These techniques tend to have increased throughput and decreased latency, providing better congestion control. The clustering-based method uses a distributed approach to make the network into smaller subgroup which causes a better strategy to handle packet collisions and congestion in the network. Priority-based techniques give individual packets higher priority as compared to others increasing their chances to reach destinations. A summary of the evaluation measures used by the different approaches is shown in Table 3.

V. CONCLUSION AND FUTURE WORK

This paper is a survey of different congestion avoidance protocols and techniques for VANETs. We discussed different congestion control strategies and analyzed different important network performance parameters, including throughput and latency. We also discussed prominent simulators support used to simulate network environment along with their pros and cons. We have seen that proactive approaches are best suited for congestion control in VANETs. Due to their proactive congestion handling nature, priority-based and clustering-based approaches show enhanced performance as compared to other congestion avoidance approaches if hybrid strategies are Incorporated along with priority-based strategy, it can even produce better results.

As per the future work is concerned, cloud-based approaches with artificial intelligence techniques can be a promising research area for efficiently handling network congestion. Fog computing is an active research area that is a suitable choice for low latency networks like VANETs. Rather than sending the data for processing to cloud it can be processed by sending to fog servers that are placed near vehicles. Using AI with fog computing will have a couple of benefits.

First AI-based techniques can predict physically congested areas in the future so that based on the prior future predictions; it can effectively divert the traffic to other directions or tracks. Less vehicular density in a region will decrease the congestion in the network. Secondly, most of the discussed approaches have emphasized more on congestion control by controlling network traffic. In-fact low latency for crucial or event-driven safety messages is the core issue as compared to merely managing the traffic flow. AI along with fog computing can separate those event-driven or crucial messages from the ordinary traffic that can be processed in a better way for their efficient dissemination in the network. An interesting concern is if any malicious entity in the network individually or a group tries to consume network resources to create network congestion, e.g. DOS attack, AI can efficiently handle all these concerns by analyzing the vehicle or node behavior.

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