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|---|---|
| **Titre:** Title: | Congestion Control in Vehicular Ad Hoc Networks |
| **Auteur:** Author: | Nasrin Taherkhani |
| **Date:** | 2015 |
| **Type:** | Mémoire ou thèse / Dissertation or Thesis |
| **Référence:** Citation: | Taherkhani, N. (2015). Congestion Control in Vehicular Ad Hoc Networks [Thèse de doctorat, École Polytechnique de Montréal]. PolyPublie. https://publications.polymtl.ca/1971/ |



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|---|---|
| **URL de PolyPublie:** PolyPublie URL: | https://publications.polymtl.ca/1971/ |
| **Directeurs de recherche:** Advisors: | Samuel Pierre |
| **Programme:** Program: | Génie informatique |

UNIVERSITÉ DE MONTRÉAL

# CONGESTION CONTROL IN VEHICULAR AD HOC NETWORKS

NASRIN TAHERKHANI

DÉPARTEMENT DE GÉNIE INFORMATIQUE ET GÉNIE LOGICIEL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

THÈSE PRÉSENTÉE EN VUE DE L'OBTENTION

DU DIPLÔME DE PHILOSOPHIAE DOCTOR

(GÉNIE INFORMATIQUE)

NOVEMBRE 2015

UNIVERSITÉ DE MONTRÉAL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

Cette thèse intitulée :

# CONGESTION CONTROL IN VEHICULAR AD HOC NETWORKS

présentée par : TAHERKHANI Nasrin

en vue de l'obtention du diplôme de : Philosophiae Doctor

a été dûment acceptée par le jury d'examen constitué de :

M. DAGENAIS Michel, Ph. D., président

M. PIERRE Samuel, Ph. D., membre et directeur de recherche

M. QUINTERO Alejandro, Doctorat, membre

Mme CHERKAOUI Soumaya, Ph. D., membre externe

# DEDICATION

*I would like to dedicate this thesis to my husband, Saheb, for all of his constant love, support and inspiration.*

*Also, I dedicate this thesis to my parents and my family for all their permanent love, encouragement and support.*

# ACKNOWLEDGEMENTS

I would like to thank my supervisor, Professor Samuel Pierre. His endless supports, friendliness, inspiration, kind guidance, and patience are a key basis for my PhD. Thank you for everything you have done for me.

I would like to express my sincere gratitude to my committee members M.  Alejandro Quintero, M. Michel Dagenais, and Mme Soumaya Cherkaoui for sparing their precious time in order to review and evaluate my research work.

I would also like to show my appreciation to all my friends and colleagues in LAboratoire de recherche en Réseautique et Informatique Mobile (LARIM).

I would also like to gratefully acknowledge National Sciences and Engineering Research Council of Canada (NSERC) and Developing next generation Intelligent Vehicular networks and Applications (DIVA) for funding my research.

I wish to give special heartfelt thanks to my parents, Fatemeh and Hossein, to whom I am greatly indebted for their moral support and unwavering love throughout my life. I would like to thank my brothers Mohammad Reza and Hamid Reza, my sister Samira, my nephews Parsa and Arian, and my sister-in-law Shiva. Without their support and encouragement, my efforts to complete this dissertation would not have been possible.

Most importantly, my deepest gratitude goes to my spouse, Saheb, who has been very supportive and understanding, and for his unconditional love and always being a continuous source of inspiration.

# RÉSUMÉ

Les réseaux Véhiculaires ad hoc (VANets) sont conçus pour permettre des communications sans fil fiables entre les nœuds mobiles à haute vitesse. Afin d'améliorer la performance des applications dans ce type de réseaux et garantir un environnement sûr et confortable pour ses utilisateurs, la Qualité de Service (QoS) doit être supportée dans ces réseaux. Le délai ainsi que les pertes de paquets sont deux principaux indicateurs de QoS qui augmentent de manière significative en raison de la congestion dans les réseaux. En effet, la congestion du réseau entraîne une saturation des canaux ainsi qu'une augmentation des collisions de paquets dans les canaux. Par conséquent, elle doit être contrôlée pour réduire les pertes de paquets ainsi que le délai, et améliorer les performances des réseaux véhiculaires.

Le contrôle de congestion dans les réseaux VANets est une tâche difficile en raison des caractéristiques spécifiques des VANets, telles que la grande mobilité des nœuds à haute vitesse, le taux élevé de changement de topologie, etc. Le contrôle de congestion dans les réseaux VANets peut être effectué en ayant recours à une stratégie qui utilise l'un des paramètres suivants : le taux de transmission, la puissance de transmission, la priorisation et l'ordonnancement, ainsi que les stratégies hybrides. Les stratégies de contrôle de congestion dans les réseaux VANets doivent faire face à quelques défis tels que l'utilisation inéquitable des ressources, la surcharge de communication, le délai de transmission élevé, et l'utilisation inefficace de la bande passante, etc. Par conséquent, il est nécessaire de développer de nouvelles approches pour faire face à ces défis et améliorer la performance des réseaux VANets.

Dans cette thèse, dans un premier temps, une stratégie de contrôle de congestion en boucle fermée est développée. Cette stratégie est une méthode de contrôle de congestion dynamique et distribuée qui détecte la congestion en mesurant le niveau d'utilisation du canal. Ensuite, la congestion est contrôlée en ajustant la portée et le taux de transmission qui ont un impact considérable sur la saturation du canal. Ajuster la portée et le taux de transmission au sein des VANets est un problème NP-difficile en raison de la grande complexité de la détermination des valeurs appropriées pour ces paramètres. Considérant les avantages de la méthode de recherche Tabou et son adaptabilité au problème, une méthode de recherche multi-objective est utilisée pour trouver une portée et un taux de transmission dans un délai raisonnable. Le délai et la gigue, fonctions multi-objectifs de l'algorithme Tabou, sont minimisés dans l'algorithme proposé.

Par la suite, deux stratégies de contrôle de congestion en boucle ouverte sont proposées afin de réduire la congestion dans les canaux en utilisant la priorisation et l'ordonnancement des messages. Ces stratégies définissent la priorité pour chaque message en considérant son type de contenu (par exemple les messages d'urgence, de beacon, et de service), la taille des messages, et l’état du réseau (par exemple, les métriques de la vélocité, la direction, l'utilité, la distance, et la validité). L'ordonnancement des messages est effectué sur la base des priorités définies. De plus, comme seconde technique d'ordonnancement, une méthode de recherche Tabou est employée pour planifier les files d'attente de contrôle et de service des canaux de transmission dans un délai raisonnable. A cet effet, le délai et la gigue lors de l'acheminement des messages sont minimisés.

Enfin, une stratégie localisée et centralisée qui utilise les ensembles RSU fixés aux intersections pour détecter et contrôler de la congestion est proposée. Cette stratégie regroupe tous les messages transférés entre les véhicules qui se sont arrêtés à une lumière de signalisation en utilisant les algorithmes de Machine Learning. Dans cette stratégie, un algorithme de k-means est utilisé pour regrouper les messages en fonction de leurs caractéristiques (par exemple la taille des messages, la validité des messages, et le type de messages, etc.). Les paramètres de communication, y compris le portée et le taux de transmission, la taille de la fenêtre de contention, et le paramètre AIFS (Arbitration Inter-Frame Spacing) sont déterminés pour chaque grappe de messages en vue de minimiser le délai de livraison. Ensuite, les paramètres de communication déterminés sont envoyés aux véhicules par les RSUs, et les véhicules opèrent en fonction de ces paramètres pour le transfert des messages.

Les performances des trois stratégies proposées ont été évaluées en simulant des scénarios dans les autoroutes et la circulation urbaine avec les simulateurs NS2 et SUMO. Des comparaisons ont aussi été faites entre les résultats obtenus à partir des stratégies proposées et les stratégies de contrôle de congestion communément utilisées. Les résultats révèlent qu’avec les stratégies de contrôle de congestion proposées, le débit du réseau augmente et le taux de perte de paquets ainsi que de délai diminuent de manière significative en comparaison aux autres stratégies. Par conséquent, l'application des méthodes proposées aide à améliorer la performance, la sureté et la fiabilité des VANets.

# ABSTRACT

Vehicular Ad hoc Networks (VANets) are designed to provide reliable wireless communications between high-speed mobile nodes. In order to improve the performance of VANets' applications, and make a safe and comfort environment for VANets' users, Quality of Service (QoS) should be supported in these networks. The delay and packet losses are two main indicators of QoS that dramatically increase due to the congestion occurrence in the networks. Indeed, due to congestion occurrence, the channels are saturated and the packet collisions increase in the channels. Therefore, the congestion should be controlled to decrease the packet losses and delay, and to increase the performance of VANets.

Congestion control in VANets is a challenging task due to the specific characteristics of VANets such as high mobility of the nodes with high speed, and high rate of topology changes, and so on. Congestion control in VANets can be carried out using the strategies that can be classified into rate-based, power-based, CSMA/CA-based, prioritizing and scheduling-based, and hybrid strategies. The congestion control strategies in VANets face to some challenges such as unfair resources usage, communication overhead, high transmission delay, and inefficient bandwidth utilization, and so on. Therefore, it is required to develop new strategies to cope with these challenges and improve the performance of VANets.

In this dissertation, first, a closed-loop congestion control strategy is developed. This strategy is a dynamic and distributed congestion control strategy that detects the congestion by measuring the channel usage level. Then, the congestion is controlled by tuning the transmission range and rate that considerably impact on the channel saturation. Tuning the transmission range and rate in VANets is an NP-hard problem due to the high complexity of determining the proper values for these parameters in vehicular networks. Considering the benefits of Tabu search algorithm and its adaptability with the problem, a multi-objective Tabu search algorithm is used for tuning transmission range and rate in reasonable time. In the proposed algorithm, the delay and jitter are minimized as the objective functions of multi-objective Tabu Search algorithm.

Second, two open-loop congestion control strategies are proposed that prevent the congestion occurrence in the channels using the prioritizing and scheduling the messages. These strategies define the priority for each message by considering the content of messages (i.e. types of the messages for example emergency, beacon, and service messages), size of messages, and state of

the networks (e.g. velocity, direction, usefulness, distance and validity metrics). The scheduling of the messages is conducted based on the defined priorities. In addition, as the second scheduling technique, a Tabu Search algorithm is employed to schedule the control and service channel queues in a reasonable time. For this purpose, the delay and jitter of messages delivery are minimized.

Finally, a localized and centralized strategy is proposed that uses RSUs set at intersections for detecting and controlling the congestion. These strategy clusters all the messages that transferred between the vehicles stopped before the red traffic light using Machine Learning algorithms. In this strategy, a K-means learning algorithm is used for clustering the messages based on their features (e.g. size of messages, validity of messages, and type of messages, and so on). The communication parameters including the transmission range and rate, contention window size, and Arbitration Inter-Frame Spacing (AIFS) are determined for each messages cluter based on the minimized delivery delay. Then, the determined communication parameters are sent to the vehicles by RSUs, and the vehicles operate based on these parameters for transferring the messages.

The performances of three proposed strategies were evaluated by simulating the highway and urban scenarios in NS2 and SUMO simulators. Comparisons were also made between the results obtained from the proposed strategies and the common used congestion control strategies. The results reveal that using the proposed congestion control strategies, the throughput, packet loss ratio and delay are significantly improved as compared to the other strategies. Therefore, applications of the proposed strategies help improve the performance, safety, and reliability of VANets.

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# LIST OF SYMBOLS AND ABBREVIATIONS

The list of symbols and abbreviations presents the symbols and abbreviations used in the thesis or dissertation in alphabetical order, along with their meanings. Examples:

| | |
|---|---|
| AC | Access Categories |
| AIC | Akiake Information Criterion |
| AIFS | Arbitration Inter-Frame Spacing |
| AMRC | Adaptive Message Rate Control |
| AOS | Adaptable Offset Slot |
| ATB | Adaptive Traffic Beacon |
| AVOCA | A Vehicle Oriented Congestion Control Algorithm |
| AWT | Average Waiting Time |
| BIC | Bayes Information Criterion |
| BIRCH | Balanced Iterative Reducing and Clustering using Hierarchies |
| BRR | Beacon Reception Rate |
| C2C-CC | Car-to-Car Communication Consortium |
| CABS | Context Aware Beacon Scheduling |
| CBR | Channel Busy Ratio |
| CC | Congestion Control |
| CCH | Control CHannel |
| CMDI | Channel Monitoring and Decision Interval |
| CR | Collision Rate |
| CSMA/CA | Carrier Sense Multiple Access with Collision Avoidance |
| CW | Contention Window |
| DITRAC | Dynamic Integrated TRAnsmission Control |
| D-FPAV | Distributed Fair Power Adjustments for Vehicular environment |
| DSDV | Destination-Sequenced Distance-Vector |
| DSRC | Dedicated Short Range Communication |

| | |
|---|---|
| EDCA | Enhanced Distributed Channel Access |
| EM | Expectation-maximization |
| ESA | Event-driven Safety Applications |
| FCC | Federal Communication Commission |
| FDF | First Deadline First |
| FIFO | First-In-Firs-Out |
| FPAV | Fair Power Adjustment for Vehicular environment |
| GMM | Gaussian Mixture Model |
| GNSS | Global Navigation Satellite System |
| GPRS | General packet radio service |
| GPS | Global Positioning System |
| GPU | Graphics Processor Unit |
| GSM | Global System for Mobile communications |
| HS | HotSpot |
| HVC | Hybrid Vehicle Communication |
| IEEE | Institute of Electrical and Electronics Engineers |
| IETF | Internet Engineering Task Force |
| IPCS | Incremental Power Carrier Sensing |
| ISO | International Organization for Standardization |
| ITS | Intelligent Transport System |
| IVC | Inter-Vehicle Communication |
| LSF | Least Selected First |
| LTE | Long-Term Evolution |
| LTSF | Longest Total Stretch First |
| LWT | Longest Wait Time |
| MAC | Media Access Control |
| MANet | Mobile Ad hoc Network |

| | |
|---|---|
| MDL | Minimum Description Length |
| MIVC | Multi-hop IVC |
| ML-CC | Machine Learning Congestion Control |
| MOTabu | Multi-Objective Tabu Search |
| MOVE | MObility model generator for VEhicular networks |
| MQIF | Maximum Quality Increment First |
| MRF | Maximum Request First |
| NC-CC | Network Coding Congestion Control |
| NS | Network Simulator |
| OBU | On-Board Unit |
| ODRC | On-Demand Rate Control |
| PHY | PHYsical |
| PSA | Periodic Safety Applications |
| PULSAR | Periodically Updated Load Sensitive Adaptive Rate |
| QoD | Quality of Data |
| QoS | Quality of Service |
| RSU | Road-Side Unit |
| RTT | Round Trip Time |
| RVC | Roadside-Vehicle Communication |
| SCH | Service CHannel |
| SDF | Smallest Data-size First |
| SIVC | Single-hop IVC |
| SNR | Signal-to-Noise Ratio |
| SR-CSMA | Safety Rang-CSMA |
| SRV | Sparse RVC |
| SUMO | Simulation of Urban MObility |
| SVM | Support Vector Machine |

| | |
|---|---|
| TCP | Transmission Control Protocol |
| TDMA | Time Division Multiple Access |
| TRANSIMS | TRansportation ANalysis SIMulation System |
| TTL | Time-To-Live |
| UBPFCC | Utility-Based Packet Forwarding and Congestion Control |
| UMTS | Universal Mobile Telecommunications System |
| UOTabu | Uni-Objective Tabu |
| URVC | Ubiquitous RVC |
| UTC | Coordinated Universal Time |
| V2I | Vehicle-to-Infrastructure |
| V2V | Vehicle-to-Vehicle |
| VANet | Vehicular Ad hoc Network |
| VC | Vehicular Communication |
| WAVE | Wireless Access in a Vehicular Environment |
| WSD | WAVE-enhanced Safety message Delivery |

# LIST OF APPENDICES

# CHAPTER 1 INTRODUCTION

Vehicular Ad hoc Networks (VANets) are employed by Intelligent Transport Systems (ITSs) to operate wireless communications in the vehicular environments. VANets are designed to provide a reliable and safe environment for users by reducing the road accidents, traffic jams, and fuel consumptions, and so on. The VANets' users can be informed of hazardous situations by vehicular communications and exchanging the information about surrounding environments [1], [2]. VANets are a type of Mobile Ad hoc Networks (MANets). The vehicles in VANets are similar to the mobile nodes in the MANets. Although VANets inherit most of the characteristics of MANets, VANets have some unique characteristics such as high mobility, high rate of topology changes, and high density of the network, and so on. Thus, VANets have different characteristics in comparison with MANets [1], [3]-[7].

Congestion occurs in the channels when these channels are saturated by the nodes competing to acquire the channels. Indeed, by increasing the vehicle density, the number of channel collisions increases occurrence of congestion in the network. The occurrence of congestion increases the delay and packet loss (especially for safety messages) leading to mitigation of the VANets' performance [8]-[11]. To guarantee the reliability and safety of the vehicular communications, and to improve the performance of VANets, Quality of Service (QoS) should be supported. Controlling congestion is an effective way that should be employed to support the QoS [2], [4]. By controlling the congestion, the delay and packet loss and consequently the performance of VANet can be improved that help have a safer and more reliable environment for VANets' users [8]-[12].

Due to the special characteristics of VANets, the congestion control strategies are different compared to the congestion control strategies proposed for MANets [12]. The congestion can be controlled in VANets in different ways such as by tuning the transmission rate, tuning the transmission power, determining the contention window size and Arbitration Inter-Frame Spacing (AIFS), and prioritizing and scheduling the messages [13]-[22]. However, congestion control strategies in VANets face some problems including high transmission delay, unfair resource usage, inefficient bandwidth usage, communication overhead, and computing overheads, and so on [10], [13]-[22]. Therefore, new strategies, considering these problems, should be developed to control the congestion in VANets, especially in critical situations where the safety messages should be transferred without any significant delay and packet loss.

The rest of this chapter is organized as follows. In Section 1.1, some definitions and basic concepts of VANets are introduced to help understanding the addressed subjects. In Section 1.2, the congestion control in wired and wireless networks and VANets are discussed. In Section 1.3, the open problems of congestion control in VANets are explained. Then, the research objectives, global research methodology, and research contributions are presented in Section 1.4 to 1.6. Finally, in Section 1.7, the outline of the dissertation is presented.

## 1.1 Definitions and Basic Concepts of VANets

VANets are designed to improve the road safety and traffic efficiency in the vehicular environments. These networks, thus, offer some important issue for research in academia and industries. In this section, the definitions and basic concepts of VANets are presented.

### 1.1.1 Characteristics of VANets

Since VANets are a subset of MANets, they inherit most of the characteristics of MANets. However, VANets possess some special characteristics including high mobility of nodes, high density of nodes, high rate of topology change, road pattern restrictions, infinite energy supply, no restriction on network size, and so on [4], [23]. Using the rechargeable batteries in VANet environments, users do not have any energy constraint [2], [24]. In VANets, the mobile nodes are the vehicles that can move with very high velocities (e.g. 120 -140 Km/s in highways). Therefore, one of the most significant characteristics of VANets is high mobility. Also, in VANets, the topology can change very frequently because the vehicle can move rapidly, the drivers can randomly choose the paths, and so on [23].

Due to the dynamic nature of the traffic in roads, some gaps may be created between the vehicles and consequently isolated node clusters can be created in the roads [2], [25]. Also, due to the high topology change in VANets, the connection duration of the link is very short. The nodes need to frequently choose the new route for transferring data. Also, when the density of network decreases, the rate of disconnections increases. The high rate of link disconnections makes some issues in the performance of VANets. This issue can be solved using roadside units and relay nodes. These issues of VANets lead to carry out new researches to maintain the seamless connectivity and decrease the effects of fading in VANets [24].

VANets mobility model is limited to the plan of highways, roads, and streets. However, it is necessary to know the position of nodes and their movement direction to better predict the future driver decision and prevent the link disconnection. In addition, changing the mobility model (i.e. highways or urban environments) influences the design of the control algorithms in VANets. The highway mobility model is simple due to one-dimension movements of vehicles, whereas, in urban model, some features like street pattern, high node density, two-dimension movements of vehicles, obstacles and interferences via tall buildings and trees must be considered. These features make the design of VANets in urban environments different and more complex [4], [23], [25].

### 1.1.2 Requirements of VANets

The requirements of VANets rely on the requirements of VANets' applications. The requirements of VANets can be classified into device, strategic, economic, system capabilities, system performance, and standardization requirements [2], [26]. The device requirements that the EANets should be equippedfor communicating between the vehicles and between the vehicles and infrastructures. In VANets, the vehicles are equipped with On-Board Units (OBUs). In additions, Road-Side Units (RSUs) are installed on the roadsides in highway and urban environments. The strategic requirements are related to the strategies defined by the commissions and governments, and the level of deployment of VANets (e.g. minimum threshold of penetration). In the economical requirements, some factors are considered such as the required cost and time for returning the investigated financial resources [2], [26], .

The system capabilities requirements are the requirements to provide the capabilities for the radio communication, network communication, and vehicle positioning, and so on. The radio communication capabilities include the available bandwidth, one-hop radio communication range, used radio frequency channels, bit rate, and level of compensation for radio signal propagation difficulties by RSUs and OBUs, and so on. The capabilities of network communication include dissemination mode (e.g. unicast, multicast, geocast, broadcast), congestion control, prioritizing and scheduling the messages, data collection, IPv4 and IPv6 addressing, and mobility managements. The capabilities of vehicle positioning can be provided by the Global Navigation Satellite System (GNSS) such as Global Positioning System (GPS) [2], [26].

The requirements of system performance are the requirements related to the performance of vehicle communications (e.g. maximum delay time, updating information frequency, and retransmitting information), accuracy of vehicle positioning, and network reliability, and so on. In standardization requirements, the standards and norms are defined to provide VANets in the vehicular environments [2], [26].

### 1.1.3 Communication Patterns in VANets

In VANets, each vehicle may have different roles including sender, receiver and router to conduct vehicular communications in the network. Vehicular Communication (VC) is divided to three major groups: 1) Inter-Vehicle Communication (IVC), 2) Roadside-Vehicle Communication (RVC), and 3) Hybrid Vehicle Communication (HVC) [23], [27].

IVCs are the communications between vehicles that are completely free of infrastructures. This group of communications needs OBUs for carrying out the communications. IVCs are classified into Single-hop IVCs (SIVCs) and Multi-hop IVCs (MIVCs) communications. SIVCs support the applications requiring the short range communications like the lane merging application. In the other hand, the MIVCs are used by the applications requiring the long range communications like the traffic monitoring applications [23], [27].

RVCs develop the communication between OBUs and RSUs. RVCs are composed of Sparse RVC (SRVC) and Ubiquitous RVC (URVC). SRVCs provide communication services in hotspots, while URVCs provide the high speed communications for all the nodes. For full coverage in all roads (in large countries), the URVCs may require extra equipment [23], [27].

Finally, HVCs are used for making communication between vehicles and roadside infrastructures for extending the coverage area of RVCs. Also, when the vehicles do not resident in the range of roadside infrastructure, HVCs can use other intermediate vehicles as the mobile relay nodes. Therefore, HVCs increase the transmission range of RVCs. In the other hand, HVCs cannot guarantee the connectivity in low vehicle density environments. Figure 1.1 demonstrates the communication patterns in VANets [23], [27].

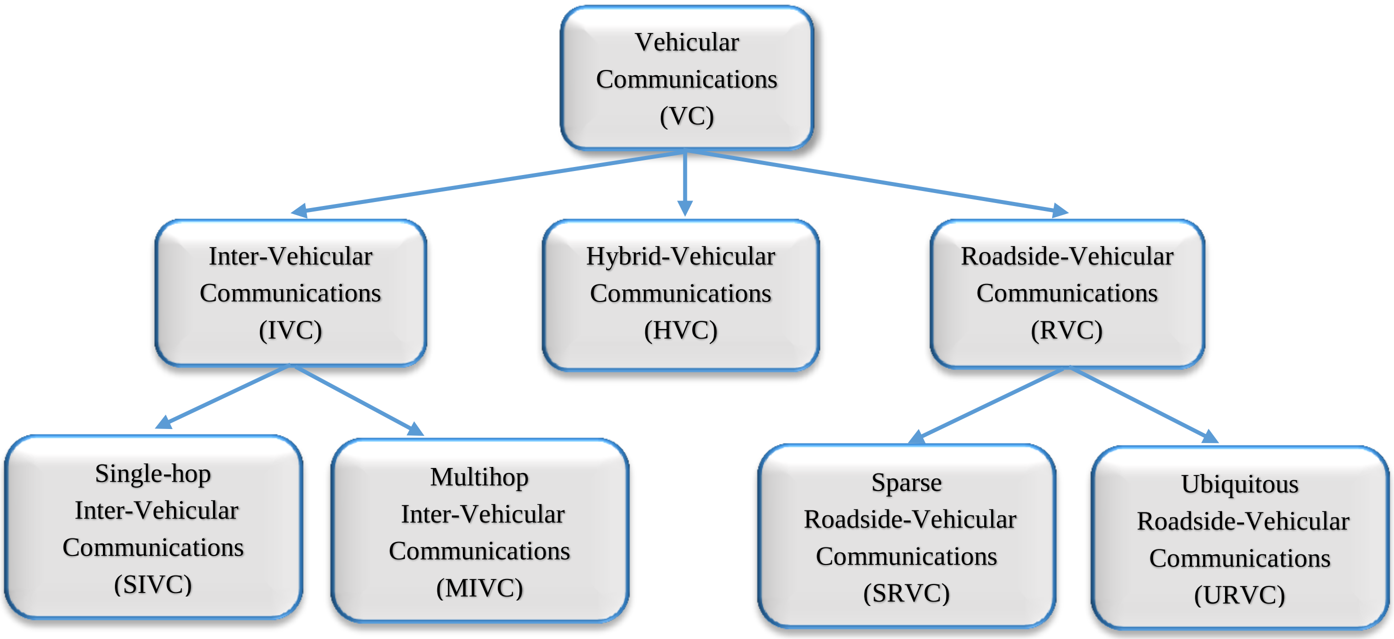



Figure 1.1: Communication patterns in VANet [27].

### 1.1.4 Architecture of VANets

Figure 1.2 depicts three district domains of VANets including In-vehicle domain, Ad hoc domain, and infrastructure domain. In-vehicle domain is formed of OBUs. Each vehicle is considered to be equipped with OBU. Short range wireless communication is generated by OBUs for safety and non-safety communications. The second domain is Ad hoc domain which is composed of OBUs and RSUs. One mobile ad hoc network can be considered between OBUs that makes inter-vehicle communications. OBUs communications can be conducted by one-hop communication or multi-hop communications that depend on the applications generating these communications [24], [28]. e third domain is Infrastructure domain that is composed by RSUs and Hotspots (HS). Infrastructure domain is employed to access the safety and non-safety applications. RSUs provide internet access, and HS is considered for low controlled environments. In the case that RSUs or HSs cannot provide internet access, OBUs can employ integrated cellular networks including General packet radio service (GPRS), Global System for

Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), 4G, and WiMAX [24], [28].

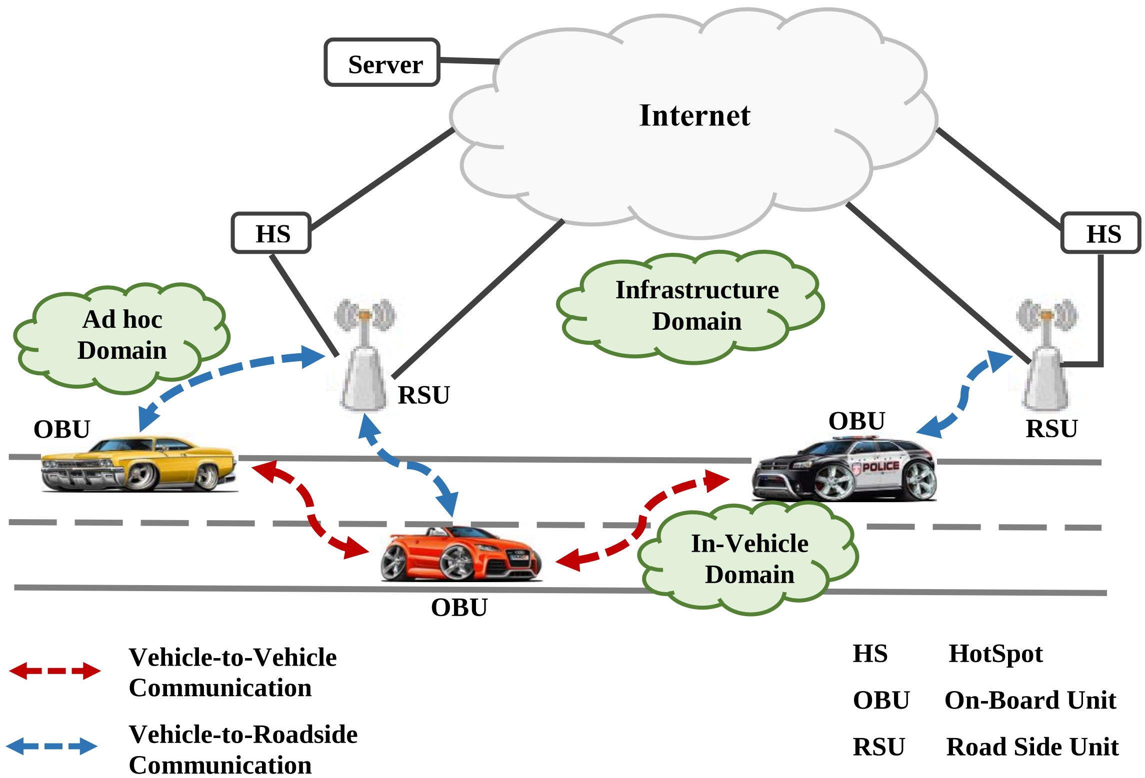



Figure 1.2: VANet system architecture [28].

### 1.1.5 Applications of VANets

Various applications are developed for VANets to provide a safe and comfortable vehicular environment for the users. VANets applications can be classified into two main groups including safety and non-safety (service) applications [2], [4]. The safety applications are used to decrease the road accident and traffic collisions that eventually enhance the safety of vehicular environments. Due to the high speed of vehicles on the roads, drivers may not react promptly and correctly in the hazard situations. The safety applications can be used to warn the drivers about the hazardous situations (e.g. a road accident). When the safety applications send emergency messages to the vehicles, the drivers can reduce their speeds before approaching to the site of the accident; thus, another accident can be prevented. Moreover, the likelihood of accident occurring and traffic jams at the intersection is high. The drivers can use safety application to inform each other about an emergency situation occurred at the intersection. Safety applications can be also used for saving the time and reducing the fuel consumption by suggesting the nearest and/or uncrowded paths. Therefore, the safety applications help improve the safety and efficiency of the vehicular environment [3], [6], [9].

Safety applications use safety messages that can be classified into beacon (periodic) messages and emergency (event-driven) messages. The beacon messages are broadcasted periodically between the vehicles to transfer the information about the neighboring vehicles. However, the emergency messages are broadcasted when a hazardous event (e.g. car accidents) occurs in the VANets. The safety applications using the emergency messages are the crash warning, and emergency election break lights applications. The beacon messages include some information about the vehicles situations such as position, speed, and direction of the vehicle and so on. The intersection collision warning, low bridge warning, and cooperative collision warning are some of the applications that employ the beacon messages to provide their services for VANets' users. Table 1.1 shows some safety applications and the type of their communication and data transmitted [19], [23]-[25].

The second group of VANets' applications is non-safety (service) applications. This group of applications is used for providing information about the traffic jam, comfort driving and route optimizing. Due to the increasing daily needs of people traveling with vehicles to the internet, non-safety applications of VANet should provide seamless internet connectivity for users in roads. These applications should also provide file sharing or game playing between vehicular users. Some of non-safety applications are shown in Table 1.2 [19], [23]-[25].

### 1.1.6 Standards of VANets

Major standardization groups (e.g. IEEE, IETF, and ISO) and consortia (e.g. car-to-car communication consortium (C2C-CC)) define standards for vehicular communications. In North America, the Federal Communication Commission (FCC) defined a new standard for VANets that called Dedicated Short Range Communication (DSRC) [3], [4]. This standard allocates a 75 MHz of spectrum in 5.9GHz bandwidth for carrying out the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. In DSRC, the defined transmission range and rate are 10-1000 m and 3-27 Mbps, respectively. Wireless Access in a Vehicular Environment (WAVE) is employed in DSRC standard to generate a norm for the performance of communications of VANets in PHY and MAC layers. WAVE is composed by two protocols of IEEE standard including IEEE 802.11p and IEEE 1609 protocols that are defined to manage the network services, resources, security services, and multi-channel operations, and so on [1]-[4], [6].

Table 1.1: Safety applications in VANets [19].

| **Application** | **Communication Pattern** | **Data transmitted** |
|---|---|---|
| Traffic Signal Violation | V2I | Signal phase, timing, position, direction, road geometry |
| Curve speed warning | V2I | Curve location, curvature, slope, speed limit, surface |
| Emergency brake lights | V2V | Position, heading, velocity, acceleration |
| Pre-crash sensing | V2V | Vehicle type, position, heading, velocity, acceleration, yaw rate |
| Forward collision | V2V | Vehicle type, position, heading, velocity, acceleration, yaw rate |
| Left turn assist | V2I or V2V | Signal phase, timing, position, direction, road geometry |
| Lane change warning | V2V | Position, heading, velocity, acceleration, turn signal status, |
| Stop sign assist | V2I or V2V | Position, velocity, heading, warning |

Table 1.2: Service applications in VANets [19].

| **Application** | **Examples** |
|---|---|
| Traffic optimization | Traffic information and recommendations, enhanced route guidance |
| Infotainment | Internet access, media downloading, instant messaging |
| Payment services | Electronic toll collection, parking management |
| Roadside service finder | Finding nearest fuel station, restaurants |

IEEE 802.11p is a protocol that specifies the features of IEEE 802.11 protocol in PHY and lower part of MAC layers to transfer data in vehicular environments. This protocol employs an MAC layer protocol based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for

disseminating data in VANets. IEEE 1609 protocol handles the operational functions and complexities of the performance of DSRC. IEEE 1609.1 is defined in application layers for managing the activities of applications to make interactions between the OBUs and other network resources. Indeed, IEEE 1609.1 normalizes the operation of VANets' applications based on WAVE standard. IEEE 1609.2 provides the security in WAVE by defining secure formats for messages and carrying out the secure processing on the messages. IEEE 1609.2 also provides the security of message exchange. IEEE1609.3 is defined in the network layer for routing and addressing the messages. Finally, IEEE1609.4 resides in the upper part of the MAC layer that provides the multi-channel operations in VANets and handles the operations of higher layers without considering the physical channel parameters in lower layers. The architecture of the WAVE standard is demonstrated in [2], [4].

DSRC considers eight channels for transferring the various messages generated by safety and non-safety applications. These channels consist of six service channels (SCH) for non-safety applications, one control channel (CCH) for safety communications, and one reserved channel for future uses. The control channel is used for transferring high priority safety messages including emergency (event-driven) and beacon messages. The service channels are used for transferring the low priority non-safety messages. The bandwidth of each control and service channel is 10MHz while the bandwidth of the reserved channel is 5MHz [4]-[6], [29]. Figure 1.4 demonstrates the bandwidth allocated to each channel based on DSRC standard [5].

Coordinated Universal Time (UTC) is employed to synchronize the vehicles to be able to operate in multi-channel single-transceiver in VANets environments. UTC operates based on the information obtained from GPS or other surrounding vehicles. The time of each vehicle is adjusted based on UTC for switching synchronously between the control and service channels. However, the delay of switching periodically between control and service channels is high [30], [31].

C2C-CC, which is a research project for vehicular communication in Europe, aims to establish an open European standard for V2V and V2I communications. C2C-CC defines prototypes to provide harmonized vehicular communication standards for all around the world. According to C2C-CC, the IEEE 802.11p protocol was modified to operate based on European conditions.

Non-safety applications employ TCP/UDP layers and 802.11a/b/g (GPRS/UMTS). Figure 1.5 depicts the frequency allocations based on C2C-CC [2], [4], [32].

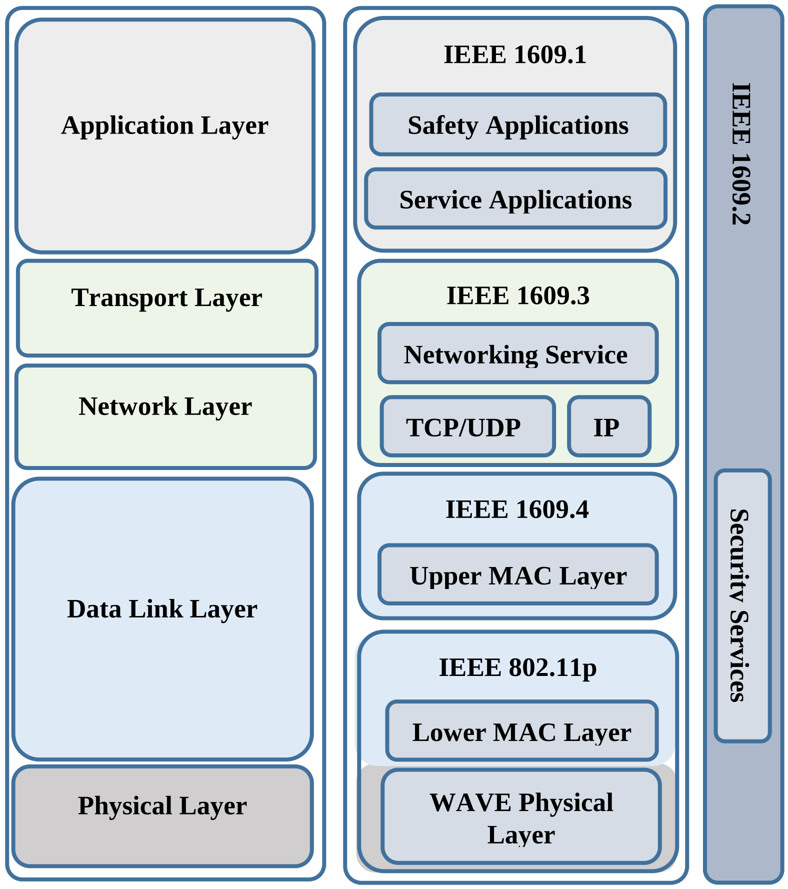


Figure 1.3: WAVE protocols and their operations in layers of network [4].

### 1.1.7 Challenges in VANets

VANets are a subset of MANets; thus, VANets inherit the most of the characteristics of MANets as well as their challenges. VANets also face some new challenges related to the unique characteristics of VANets such as the data routing, scalability, data dissemination, security, and QoS [1]-[3], [12]. In VANets, it is assumed that the velocity of RSUs is zero, while the velocity of vehicles, which are considered as mobile nodes in VANets, can be between zero in traffic jam situations to over 140 km per hour on highways. These variations of velocities lead to some challenges for data routing, data dissemination, and QoS. For example, the high velocities of vehicles lead to the high rate of topology changes in VANets, while the low velocity of vehicles may lead to high vehicles density resulting in high collisions rate and congestion. In the other hand, different road patterns influence the mobility of vehicles. The nature of movement is different on highways and urban environment lead to some challenges for data routing, data dissemination, QoS, scalability, and so on. The position of vehicles also needs to be determined for some VANets' applications. Due to the unique characteristics of VANet (e.g. high mobility), the positioning of the vehicles is also a challenging task in VANets [2], [3], [33].

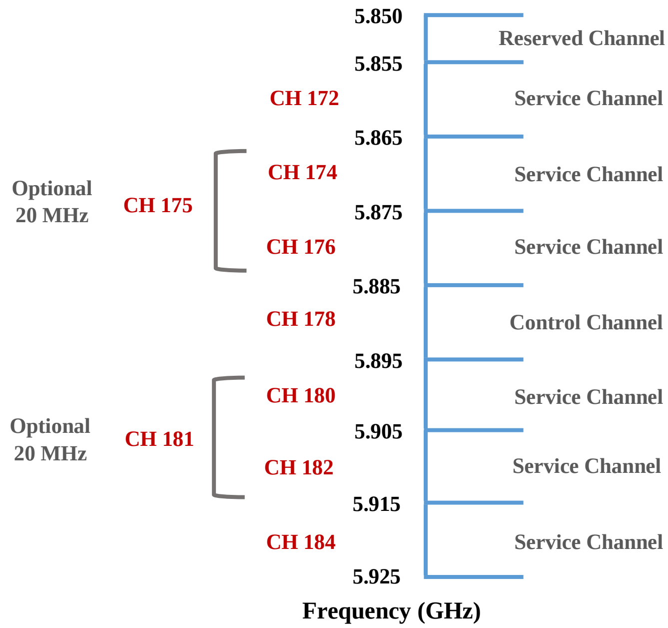



Figure 1.4: North American DSRC channel allocation [5].

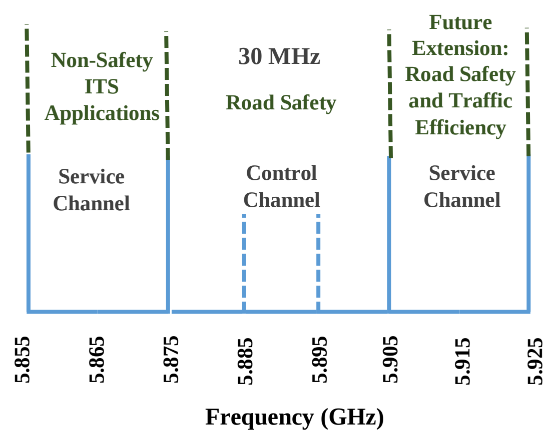



Figure 1.5: Frequency allocation in Europe [32].

## 1.2 Congestion Control

Generally, in each network, there are some resources that are shared between the users of the network competing to acquire those resources. Adjusting the data rate used by each user is essential to control the network load and prevent the channel overload. When the packets arrive to a router node and the router cannot forward them, the router drops the new packets, whereas these packets consumed a significant amount of resources for arriving to this node. One of the main reasons, which results in dropping the packets by the router nodes, is the congestion. Indeed, when the capacity of the network is less than the networks load, the packets are dropped due to the congestion occurrence in the networks. The throughput of the network significantly reduces due to the network congestion. Therefore, congestion control should be performed to prevent the congestion occurrence and increase the successful delivery of data in the networks. In addition, controlling the congestion enhance the bandwidth utilization, responsiveness, and fairness usage of network resources [34]-[36].

Transmission Control Protocol (TCP) employs the slow-start algorithm as the main part of the congestion control process in the networks. In the slow-start algorithm, the congestion window size is initially set to 1, 2, or 10. When an acknowledgment is received, the congestion window size is doubled. Once a packet is lost or the congestion window size exceeds the predefined slow-start threshold, TCP considers that the congestion occurred in the network. In this situation, TCP increases the congestion window size by one unit in each Round Trip Time (RTT) to reduce the channel loads and control the congestion [34]-[36].

Various congestion control strategies accomplish based on TCP to avoid the congestion occurrence in the networks. TCP-Tahoe is a congestion control strategy referred by many congestion control strategies. Using the TCP-Tahoe strategy, the congestion is detected by determining the timer for acknowledgments. In the TCP-Tahoe strategy, when congestion occurs in the network, the slow-start threshold is set to half of the current congestion window size and the slow-start algorithm is reset to the initial state. In TCP-Reno strategy, however, when three duplicate acknowledgements are received, the congestion window size is set to the half of the current value, and the slow-start threshold is set to the current value of congestion window size [35]-[37].

The packet losses are considered to detect the channel overloading in the traditional TCP congestion control strategies. However, when the bandwidth is available, the packets losses may still occur due to the random bit corruption, channel error, and route failure. Also, using the packet losses is not a sufficient for determining the level of contention in the channels. Therefore, in addition to packet losses, other parameters of network conditions should be considered for controlling the congestion in the networks. For example, the TCP-Vegas congestion control algorithm uses the queuing delay parameter. In the TCP-Vegas algorithm, the congestion window is linearly increased and decreased such that a constant number of packets stay in the queues. The TCP-Westwood (TCPW) algorithm, however, resets the congestion window to the predefined threshold based on the estimation of the bandwidth-delay product path [35], [38], [39].

Although TCP congestion control strategies efficiently carry out on the Internet, these strategies are not efficient for MANets due to the unique characteristics of these networks. Indeed, the standard TCP faces many issues in MANets due to unique characteristics of these networks, different environments, different protocols, and different architecture. The unique characteristics of MANets include the shared wireless channels, node mobility, and multi-hop wireless communications and so on. Due to the node mobility in MANets, the frequently routes break or change lead to increasing the packet loss or delay for delivering the packets. In the Internet, congestion occurs in a single router node, while, in MANets, the congestion occurs in an area because of employing the shared medium in these networks. Moreover, TCP congestion control strategies consider that all packet losses are caused by congestion, while, in wireless mobile networks, the packet can be lost due to the congestion occurrence, channel errors, and route failures. Therefore, TCP congestion control strategies are not efficient in mobile ad hoc networks and result in a performance reduction [40].

In VANets, it is necessary to propose new strategies for controlling the congestion due to their special characteristics such as high mobility, high rate of topology change, high density, and no energy constraints. The IEEE 802.11p protocol employs CSMA/CA MAC protocol and Enhanced Distributed Channel Access (EDCA) mechanisms for controlling the congestion in VANets [10]. Based on CSMA/CA protocol, the vehicles start to listen to the channel. If the channel is free for an AIFS time period, the sender vehicle transmits the packets into the channel. However, if the channel is busy (i.e. the channel is occupied by other vehicles during AIFS) the sender vehicle should wait a random period of time and then performs the back-off procedure.

The back-off procedure determines a random integer value between zero and contention window size. Then, this procedure multiplies this integer value with the time slot, which is determined in PHY layer, to calculate the back-off value. When the channel is free, the back-off value decreases, until the back-off value reaches zero, then the packets are immediately sent to the channel [34], [41].

The EDCA mechanism is used in the IEEE 1609 WAVE protocol for determining the priorities for different types of messages generated in VANets. In EDCA, the high priorities are assigned to the safety messages to occupy the channel and transfer with less delay compared to the other low priority messages. Indeed, EDCA determines a smaller contention window size and AIFS for high priority safety messages to acquire the channels quickly [17]-[19]. The determined value for the contention window size and AIFS in EDCA are shown in Table 1.3 [17], [19].

Table 1.3: EDCA parameters for each Access Categories [17], [19].

| **Access Categories (AC)** | **Minimum Contention Window ($CW_{min}$)** | **Maximum Contention Window ($CW_{max}$)** | **AIFS** |
|---|---|---|---|
| Background (AC_BK) | $CW_{min} = 15$ | $CW_{max} = 1023$ | 7 |
| Best Effort (AC_BE) | $CW_{min} = 15$ | $CW_{max} = 1023$ | 3 |
| Video (AC_VI) | $(CW_{min} +1)/2-1 = 7$ | $CW_{min} = 15$ | 2 |
| Voice (AC_VO) | $(CW_{min} +1)/4-1 = 3$ | $(CW_{min} +1)/2-1 = 7$ | 2 |

Figure 1.6 shows a schematic view of a cross-layer congestion control architecture in VANets. In this figure, a management entity is considered for detecting and controlling the congestion. The congestion detection part employs some information from the application layer to detect the congestion occurrence in the network. In addition, the congestion can be detected by sensing the channel in the physical layer and measuring some parameters like channel usage level. The congestion control can be conducted in different ways in different network layers. The application layer can contribute to congestion control by tuning the message generation rates of different applications, and reducing the traffic loads as well as congestion in the networks. The network layer can control the congestion by smart routing algorithms that efficiently rebroadcast

the messages and mitigate the congestion. The prioritizing and scheduling messages at MAC layer can significantly help control the congestion in VANets. Moreover, the control and service channels can employ to transfer the prioritized safety and non-safety messages, respectively [42], [43].

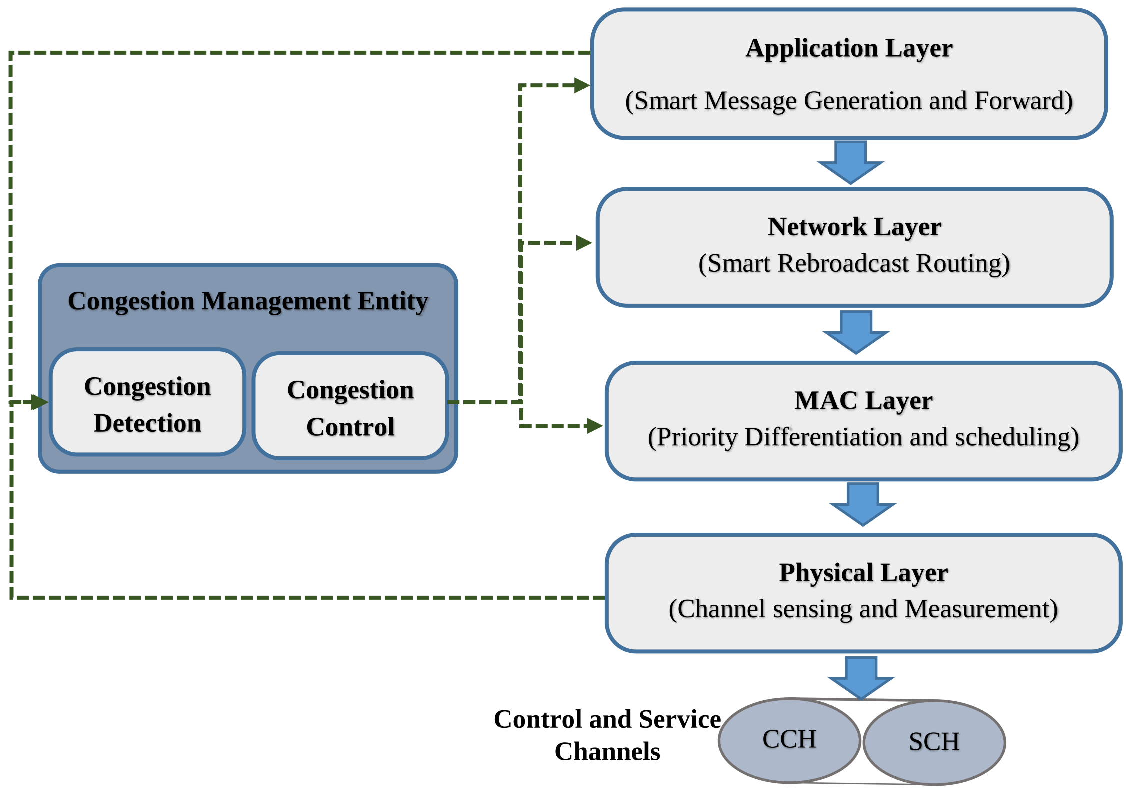



Figure 1.6: Cross-layer congestion control architecture [42].

In VANets, congestion control strategies can be classified based on the means and parameters employed for controlling the congestion. Thus, the congestion control strategies can be classified into the rate-based, power-based, CSMA/CA-based, prioritizing and scheduling-based, and hybrid strategies. The rate-based strategies adjust the transmission rate based on the channels conditions to reduce the collisions in the channels. The power-based strategies dynamically tune the transmission power (range) to control the channels loads. The CSMA/CA-based strategies control the congestion by adjusting parameters of CSMA/CA protocol such as the contention window size and/or AIFS. In prioritizing and scheduling-based strategies, the priorities are defined for the message, and then the prioritized messages are scheduled to transfer in the control and service channels. Finally, in the hybrid strategies, all or some of the means or parameters used in previous categories are employed to avoid or control congestion occurrence in the netwconnectork [13].

## 1.3 Open Problems

Practically, TCP congestion control strategies were proposed for wired networks where the congestion is the only reason leading to packet loss in the network. However, in MANets the packets losses can occur due to the congestion, route breaks, and channel errors. Indeed, MANets face the contention problems because of sharing the wireless medium between all mobile nodes that leads to increasing the number of packet loss in the networks. The mobility is a major problem that causes route breakages, and consequently leads to packet losses in the networks. Moreover, there are many challenges related to the wireless links that cause packet loss in the wireless networks, such as multipath fading, attacks, link failures, and channel errors [40], [44].

The existing congestion control strategies in MANets are not efficient in VANets due to the special characteristics of VANets in comparison with MANets. These special characteristics are included but not limited to high mobility of nodes with high speed, high rate of topology change, high density, and no energy constraints of nodes [12], [15]. Therefore, new congestion control strategies are required to propos in the vehicular environments.

Some of the congestion control problems are discussed in the following. The packet losses can result from the congestion occurrence in the channels. However, the estimation of packet losses due to the congestion occurrence is a challenging task in VANets. As it was mentioned before, the packet losses in VANets may occur due to the disconnections resulting from transmitting special media in physical layer, failure in data link layer, dynamic route changing in network layer, error transporting protocol, and fading connections due to handover. TCP congestion control protocols are triggered by all types of packet losses and reduce the channel loads that cause to reduction of the throughput and fairness in the channels. Therefore, differentiating between various types of packet losses can be very efficient for improving the performance of VANets [34], [36], [44], [45].

CSMA/CA protocol is used to access to the communication channel in IEEE 802.11p WAVE standard [16]. This protocol is employed to control congestion in VANets using the exponential back-off mechanism that is not efficient for broadcasting the beacon messages [46]. This mechanism does not work properly for the high transmission rate of messages in high vehicle density, especially when these messages have time-out that may lead to dropping the packets before their transmission [46]-[48].

In VANets, congestion detection can be conducted by retransmitting some packets; however, it is not an efficient approach in VANets due to the high mobility of nodes and high rate of topology changes. In addition, it results in extra loads in the channels and intensifying the congestion. In VANets, the congestion detection can be also conducted by extra interaction between the vehicles which leads to increase the channel load and collisions in the networks [13], [48]-[51]. Some of the congestion control strategies piggyback some extra bytes to the packets, or generate extra packets for informing vehicles about the congestion situation. These extra bytes or packets increase the channel loads and lead to the congestion occurrence. Thus, despite these congestion control strategies trying to reduce and control the congestion in the network, they generate the communication overhead, broadcasting storm and consequently increase the congestion in the networks [52]. The threshold-based strategies may also face some challenges for controlling congestion because the performance of these strategies is influenced by the initial value of the thresholds [53].

### 1.3.1 Problems Considered in This Dissertation

According to the general goal of VANets (i.e. making a safe and reliable environment for VANets' users), the emergency messages should be broadcasted without delay and lost [2]. However, the congestion control strategies do not differentiate between the emergency and the other types of messages in critical situations. This issue is more important in the real-time safety applications [54].

In VANets, the safety messages are usually sent with high transmission range (power) to immediately broadcast the safety messages in a larger area and increase the number of receivers. However, when the transmission range is high, the probability of collision increases in the channels due to the increasing number of nodes that compete to acquire the channel. The transmission rate also has a significant impact on the channel saturation. When the transmission rate increases, the applications of VANets can perform more efficiently due to updating the information. However, the channel can be saturated frequently by increasing the transmission rate [10], [14].

Beacon messages are a kind of safety messages that periodically broadcast some information about the vehicles, including position, velocity, and direction. These messages are transferred in the control channel. Due to the high beaconing rate in high vehicle density, the control channel may face overloading as well as congestion. On the other hand, by decreasing the beaconing rate, the operation of safety applications encounters many challenges due to failure in receiving the beacon message and updated information[48], [55].

Therefore, tuning the transmission range and transmission rate has an important effect on the situation of the channels and can help control the congestion in the channels. However, tuning transmission range and rate are challenging in VANets due to high vehicle density, high rate of topology changes, and high mobility of nodes. Various factors (e.g. vehicle velocity, vehicle density, message size, distance between senders and receivers, and number of lanes) can impact obtaining the proper values for transmission range and rate. In addition, transmission rate and range should be tuned in reasonable time to satisfy the reliability requirements of the safety applications [12], [50], [56].

Moreover, prioritizing and scheduling various messages in control and service channel is another challenging task in VANets due to increasing the number of parameters in large-scale networks [20], [57]. The priority of each message is usually defined independently in each vehicle. This may result in congestion because the vehicles are not aware of the priority of messages in the other vehicles. For example, a vehicle having an emergency message, which should be transferred immediately, must compete with other vehicles, which want to transfer the low priority messages. Therefore, the vehicles with low priority messages may acquire the channel postponing immediate transferring of the emergency messages and consequently some hazardous situation may happen [58].

In summary, controlling congestion in VANets faces many challenges due to their unique characteristics. Some of these challenges are high transmission delay, unfair use of resources, inefficient bandwidth utilization, and communication overhead. Therefore, new strategies need to be designed to solve these problems, especially in emergency situations of VANet.

## 1.4 Research Objectives

Congestion is an important mechanism that may result in degradation of QoS in VANets. Congestion occurs when the networks load exceeds the capacity of the networks. The congestion increases the packet loss and delay, and decreases the throughput by saturating the channels in the high-density networks. Congestion control is a most effective approach to improve the performance of VANets. Indeed, congestion control helps providing a safer and more reliable environment for VANets' users.

The main objective of this dissertation is to enhance the performance of VANets by controlling congestion. This will be achieved through proposing novel strategies to control congestion. Such strategies help controlling the traffic communications, decreasing the channel saturation, and reducing the likelihood of congestion, whereas the requirements of VANets' applications are satisfied. The main objective of this dissertation is fulfilled through three sub-objectives including:

1. Closed-loop congestion control: A dynamic and distributed congestion control strategy is proposed for tuning the transmission range and rate for all kind of messages in a reasonable time.

2. Open-loop congestion control: A congestion control strategy is proposed for prioritizing various types of messages and scheduling them into the control and service channels such that the channel access is controlled and safety messages is transferred with less delay.

3. Localized congestion control: A centralized congestion control strategy is proposed for adjusting the communication parameters in RSUs for the vehicles before red traffic lights at the intersections.

## 1.5 Global Research Methodology

The transmission rate has a significant impact on the condition of channels such that by increasing the transmission rate, the channels overload and the congestion occurs. However, by decreasing the transmission rate, the VANets' applications face a lack of fresh information. By increasing the broadcasting rate of the beacon messages, the control channel, which is used to transfer the safety messages (i.e. emergency and beacon messages), is saturated. In VANets, the transmission range is increased to increase the number of vehicles receiving the messages in the communication range. In the other hand, high transmission range increases the rate of channel collisions. Therefore, tuning the transmission range and rate seems to be an effective mean for controlling the condition of channels and consequently the congestion in VANets [14], [15].

Due to the high complexity of tuning the transmission range and rate in VANets, this problem is considered as an NP-hard optimization problem. NP-hard problems can be solved using Meta-heuristic algorithms that find a near-optimal solution in reasonable time. Among Meta-heuristic algorithms, the Tabu Search algorithm is more adaptable and flexible for solving the considered NP-hard problem. Therefore, using Tabu Search algorithm, the near-optimal values can be obtained for transmission range and rate that controls the congestion in VANets.

The message prioritizing can be conducted to enhance safety and reliability of VANets. The safety messages should have the higher chance to access the channels. Thus, a higher priority should be assigned to the safety messages in comparison with the other messages. Prioritizing of the messages can be conducted based on different factors including messages content (e.g. size of messages, type of messages, and so on), and the state of networks (e.g. vehicles velocity, and utility of messages, and so on). In addition, the message scheduling can be carried out based on the defined priorities. For optimizing the message scheduling in control and service channel queues, message scheduling can be conducted using Meta-heuristic techniques. The Tabu Search algorithm can schedule the messages for being transferred with low delay and jitter.

Moreover, the transmission range and rate, contention window size, and AIFS parameters are the effective communication parameters for congestion occurrence. Thus, the congestion can be controlled by adjusting the communication parameters for the messages. Adjusting the communication parameters for different class of messages rather than all the messages increases the efficiency of the process. To classify different messages based on their features, message clustering is required. Machine learning algorithms are useful tools for clustering the messages.

## 1.6 Research Contributions

This dissertation develops novel strategies for controlling the congestion in VANets. Moreover, the principal contributions of this dissertation are:

- Proposing a new closed-loop congestion control strategy that uses a Meta-heuristic techniques to tune the transmission range and rate. After detecting the congestion occurrence in the network, this strategy employs a multi-objective Tabu Search algorithm for obtaining the proper values for transmission range and rate such that the delay and jitter are minimized.
- Designing open-loop congestion control strategies that use the message prioritizing and scheduling. These strategies first define the priority for each message based on the size of messages, the message content and the network states. Then, the prioritized messages are scheduled in two ways: 1) based on the defined priority for the messages, and 2) employing Tabu Search algorithm to reschedule the control and service channel queues by considering the minimum delay and jitter.
- Developing a localized congestion control strategy by clustering the messages using machine learning algorithms and adjusting centrally the communication parameters in RSUs set at intersections. K-means algorithm is used to cluster the messages based on their features including message size, validity of messages, distance between vehicles and RSUs, type of message, and direction of message sender. The communication parameters are determined for each messages cluster such that the transfer delay is minimized.

## 1.7 Outline of Dissertation

This dissertation is organized in eight chapters with the core three chapters based on published or submitted journal papers. Chapter 2 reviews the available literature related to the congestion control strategies in VANets. In this chapter, different classifications of the congestion control strategies are presented and discussed in detail. Chapter 3 describes the relation between the submitted/published articles obtained from this research and the objectives of the dissertation.

Chapter 4 presents the full text of a published article entitled “Improving Dynamic and Distributed Congestion Control in Vehicular Ad Hoc Networks”. In this article, a closed-loop congestion control strategy is proposed. This strategy controls congestion by tuning the transmission rate and range after detecting the congestion occurrence in the channels. A Meta-heuristic algorithm is used to obtain the proper values of transmission range and rate.

Chapter 5 presents a full text of a submitted article entitled “Prioritizing and Scheduling Messages for Congestion Control in Vehicular Ad Hoc Networks”. This article proposes an open-loop congestion control strategy that avoids the congestion before it happens in the network using prioritizing and scheduling all types of messages. The message prioritizing is conducted based on the content of messages and the network state. The prioritized messages are scheduled in control and service queues to control the messages transferred in the control or service channels. In addition, the Meta-heuristic techniques are used to schedule the messages in different queues such that the packet loss and delay decrease.

Chapter 6 presents the full text of a submitted article entitled “Centralized and Localized Congestion Control Strategy for Vehicular Ad-hoc Networks Using a Machine Learning Clustering Algorithm”. In this chapter, a localized congestion control is presented to control the congestion at intersections using RSUs. This strategy classifies the messages centrally in RSUs and determines the proper values for communication parameters including the transmission range and rate, contention window size and AIFS.

In Chapter 7, a general discussion is provided on all aspects of the proposed strategies in this dissertation for controlling congestion. Finally, Chapter 8 concludes the contributions of this dissertation and practical limitations for implementing the proposed strategies in VANets. Some recommendations for future work are also suggested in this chapter.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Congestion Control Strategies

Congestion control strategies can improve the performance of wired/wireless networks and provide more reliable communications by controlling the channels loads. The congestion should be controlled in the networks to attain higher responsiveness, bandwidth utilization, scalability, efficiency, and stability. Congestion also needs to be controlled to reduce the packet loss, and increase fairness and compatibility of networks with various protocols and standards. The efficiency of the congestion control strategies should be improved by increasing the convergence speed, smoothness, and responsiveness of the strategies. The convergence speed is estimated based on the duration of time required to reach the stable state in the network. The smoothness depends on the fluctuation size that is measured based on reflection of fluctuation intensity. The responsiveness is calculated based on Round Trip Time (RTT) required for reaching stability in the network [12], [35].

Generally, the congestion control solutions are categorized into two groups of open-loop, and closed-loop solutions. The open-loop solutions prevent congestion before its occurrence in the network while the closed-loop solutions control the congestion after it is detected in the network [34]. The open-loop strategies employ some policies such as retransmission, window, admission, out-of-order caching, flow control, discarding, and acknowledgement policies to avoid the congestion occurrence. In the other hands, close-loop strategies are back pressure, choke packet, implicit signalling, and explicit signalling [34].

The congestion control strategies in wireless networks can be also classified into two general groups including end-to-end and hop-by-hop strategies. In the end-to-end strategies, only the communication flows between senders and receivers are considered. The end-to-end strategies are not suitable for controlling congestion in VANets because, in these strategies, the intermediate node context (e.g. the collisions, interferences, and transmission problems) are not taken into account. In the hop-by-hop strategies, however, the capacity of intermediate nodes is considered [20].

The hop-by-hop strategies are suitable for controlling congestion in VANets due to the dynamic nature of these networks and the limitations related to the storage and computation capacities of the vehicles. The hop-by-hop strategies can locally control the congestion for a specific subset of nodes in the VANets. However, the application of these strategies in VANets present some disadvantages. These strategies generate communication and computation overheads. These strategies are also not scalable when the number of transmissions increases in the networks. Therefore, it is necessary to propose new strategies considering the especial characteristics of VANets such as high mobility, high rate of topology change, high density. In the following, congestion control strategies in VANets and some of their classifications are discussed [20].

## 2.2 Congestion Control Strategies in VANets

### 2.2.1 Proactive, Reactive, and Hybrid Strategies

Congestion control strategies in VANets can be classified based on various criteria. Based on how the strategies decide to prevent or control the congestion, the congestion control strategies in VANets can be classified into three classes including proactive, reactive, and hybrid strategies [10], [42], [59]. In the proactive strategies, based on some information such as the number of neighboring vehicles, and data generation patterns, the transmission parameters are tuned such that the congestion occurrence will be prevented. In the other words, the proactive strategies can be considered as open-loop congestion control solutions that adjust the transmission parameters before the channels become congested. The proactive strategies estimate the channel load by employing a system model. Then, to provide the desired performance for application level, the optimization mechanism is used for obtaining the proper values for transmission parameters to avoid congestion occurrence in the channels. The proactive strategies are efficient for congestion control in vehicular environments because these environments are where the safety messages primarily sent to the radio communication channels that are seriously threated by congesting the channel. Briefly, the proactive strategies reduce the channel loads to avoid the occurrence of congestion in the channels by adjusting the transmission parameters [10], [59].

To estimate the channel loads generated by neighboring vehicle, the proactive strategies employ a communication model for mapping the transmission power level to the carrier sense range. The propagation conditions should be considered for reasonable mapping. However, it is very difficult to estimate the propagation conditions in the practical scenarios where the vehicles move dynamically. In addition, in proactive strategies, the delay for estimating the channel generation load should be considered. Although, this delay is acceptable (e.g. in the case that the applications employ the beacon messages), the accurate estimation of channel generation rates is a challenging task in general [10], [59].

The reactive strategies employ the information of channel congestion conditions to decide how they should conduct the congestion control by tuning the transmission parameters. Indeed, the reactive strategies can be considered as the closed-loop congestion control solutions that control the congestion after it happens in the networks. Therefore, these strategies sense the channels periodically, measure some channel parameters (e.g. channel usage level, number of messages in queues, and channel occupancy time), and compare the value of these parameters with a predefined threshold to detect the congestion occurrence in the networks. If the congestion occurrence is detected in the channels, the transmission parameters are tuned to decrease the load of channels and control the congestion. Briefly, the reactive strategies reduce the load of channels by locally obtaining the feedback from the vehicular networks. Since these strategies control the channels loads after detecting the congestion occurrence, it is required to recover the network from this critical situation. However, the network recovery leads to decrease the performance of safety applications in these critical situations [10], [59].

The third class of congestion control strategies is the hybrid strategies that use the advantages of proactive and reactive strategies. For example, these strategies adjust the transmission power proactively and transmission rate reactively to control the congestion in the channels [10], [59].

### 2.2.2 Congestion Detection Methods

In VANets, congestion detection can be conducted using two kinds of methods including event-driven and measurement-based methods [42], [49]. Event-driven methods detect the congestion based on event-driven safety messages. In these methods, when a safety application generates and broadcasts an event-driven safety message in the network, it is assumed that the congestion occurred in the network. Indeed, by detecting the event-driven safety message in the network, the MAC transmission queues are frozen except the control channel queue to guarantee the delivery of the high priority event-driven safety messages. For example, when a safety application (e.g. cooperative lane change warning and Emergency Electronic Brake Light with Forwarding (EEBL-F) applications) generates an event-driven message, the nodes assume that the congestion occurred in the network when they generate or receive these messages. Thus, to improve the performance of safety applications, the congestion is controlled immediately by freezing the transmissions of other messages except the event-driven safety messages [42], [49].

The measurement-based methods detect congestion by periodically sensing the channel and measuring some parameters such as the number of messages in queues [20], channel occupancy time [60], and channel usage level [42]. The values of these parameters are compared with predefined thresholds to make the decision about congestion occurrence in the network. The predefined thresholds have a significant impact on the performance of networks for monitoring the communication channels and detecting the congestion. In [20], if the length of SCHs queue exceeds a threshold, it is considered that the congestion occurs in the network. Then, the detected node controls the congestion by decreasing the transmission rate. However, in [60], each node independently measures the channel occupancy time of its CCH. Since the channel occupancy time of CCH exceeds the threshold, the node blocks the transmissions of the beacon messages for controlling the congestion. In [42], congestion is detected since the channel usage level exceeds a predefined threshold that is estimated based on the packet transmission process in MAC layer of WAVE standard (Figure 2.1).

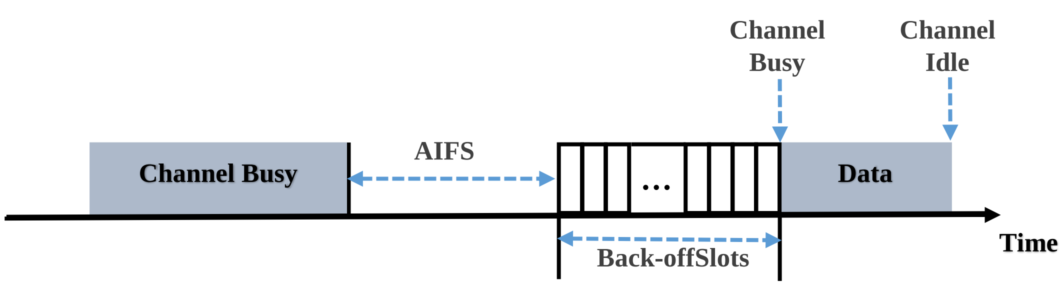



Figure 2.1: Packet transmission process in MAC layer of WAVE standard [42].

The channel usage level of n messages sent by a vehicle in each CCH interval is estimated by Equation (2.1) [42].

$$\boldsymbol{Channel_{Usage}} = \frac{\sum_n (D_{BUSY}+D_{AIFS}+D_{Backoff})}{D_{CCH}} \times \mathbf{100}\% \tag{2.1}$$

### 2.2.3 Classification Congestion Control Strategies based on Parameters and Means

Based on the parameters and means to control congestion in VANets, the congestion control strategies can be classified into five classes including rate-based, power-based, CSMA/CA-based, prioritizing and scheduling-based, and hybrid strategies. Rate-based strategies tune the transmission rate based on the channel condition to control the congestion. Power-based strategies dynamically adjust transmission power (range) to control the load of channels. CSMA/CA-based strategies control congestion by determining the proper values for the contention window size and AIFS to control the channel access. The prioritizing and scheduling-based strategies control the congestion by defining a priority for each message and then scheduling them in the control or service queues according to the CCH and SCH, respectively. In these strategies, the high priority safety messages get the higher chance to transfer in the channels. Finally, the hybrid strategies employ all or some of the parameters and means of previous strategies to control congestion in VANets [13]. In the following, these strategies are discussed in more details.

#### 2.2.3.1 Rate-based strategies

Due to the significant impact of transmission rate on the performance of networks, the rate-based strategies dynamically adjust the transmission rate or packet generation rate to control the channel loads and congestion in the networks. The performance of VANets improves by increasing the transmission rate because safety applications can receive fresh information about the status of neighboring vehicles, send their own status to the neighboring vehicles, and update their information to operate efficiently. In addition, high beaconing rate in the network, especially when the density of the network is high, leads to high bandwidth utilization and consequently congestion into the control channel. Therefore, the performance of safety applications is reduced due to disorder in the delivery of safety messages. It should be also noted that when the transmission rate increases, the channel may saturate due to increasing the channel loads [10], [13], [14], [55].

Ye et al. [61] modified the WAVE standard to add a new layer which communicates with MAC layer for controlling congestion in the vehicular networks. The authors considered two parameters including reliability and efficiency to measure the performance of broadcasting of the beacon messages in VANets. In this work, the efficiency is defined as the rate of delivery of the broadcasted packets to the neighboring nodes; and the reliability is defined as the average number of nodes that successfully receive the specific broadcasted packet. Indeed, this work addressed the efficiency and reliability of the beacon messages broadcasting by obtaining the optimal packet transmission rate and based on the vehicle density. However, the constrains related to the strict transmission rate of safety messages, which need to be considered to avoid the collisions in channels and transfer these messages without delay, are not taken into account. Although, in this work, the channel fading is considered as the only source of the packet failures, the collision occurrences by concurrent transmissions is not considered. Also, the hidden terminal problem is not taken into account. In addition, the communication scenario investigated in this work is a single lane scenario, thus the vehicles just can conduct one-dimension broadcasting that is not common in VANets.

He et al. [60] introduced a cross-layer congestion control strategy that increases the transmissions rate of event-driven safety messages compared to beacon messages. In this strategy, all nodes use the MAC blocking method for detection of the congestion in the control channel. Indeed, if the channel occupancy time exceeds a predefined threshold, congestion is considered to occur in the control channel. Then, the MAC layer sent a signal to the application layer to block all beacon messages. Thus, the channel load is reduced and the control channel is reserved for only event-driven safety messages. In this strategy, an initial value is considered for the transmission rate of beacon messages. The transmission rate is increased with a time step until the channel occupancy time exceeds the threshold. After detecting the congestion in the control channel, half of the current transmission rate is considered to be the new threshold. When the MAC layer is unblocked, the transmission of beacon messages is set to the initial value. Then, this value increases until it reaches to the new threshold. Figure 2.2 shows the transmission rate adaption using this strategy. Moreover, in this strategy, the blocking node sends a message to the neighboring nodes to notify them about MAC blocking. Then, the neighboring nodes collaborate to control the transmission rate of beacon messages. Although, this strategy improves the fairness of message generation, the requirements of safety applications are not taken into account in this strategy. In addition, there is some difficulty to measure and analyze the channel occupancy time in the MAC layer.

Huang et al. [50] proposed the On-Demand Rate Control (ODRC) algorithm that controls the transmission rate of safety applications based on the network conditions such as the congestion occurrence and unexpected vehicles movements. In the ODRC algorithm, a transmission probability is calculated by tracking errors in neighboring vehicles based on the position of vehicles (unexpected vehicles movements). This algorithm increases the transmission rate when the vehicles have unexpected behaviors. In the other hand, the transmission rate is diminished to decrease the packet loss when the channel collision occurs. ODRC is a decentralized algorithm that improves the performance of VANets. However, the priority of packets is not taken into account in this algorithm.

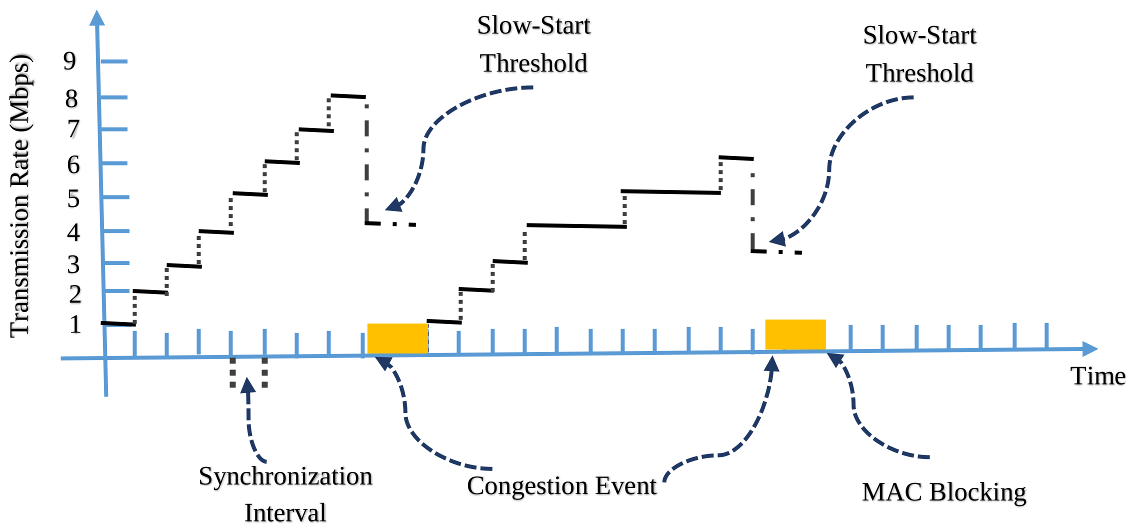



Figure 2.2: Transmission rate adaption [50].

Wischhof et al. [62] introduced the Utility-Based Packet Forwarding and Congestion Control (UBPFCC) strategy to control congestion for non-safety applications. This strategy adjusts the transmission rate based on the utility and size of packets. The UBPFCC strategy dynamically assigns the available bandwidth to the vehicles in a hop-by-hop manner based on the average utility calculated for each vehicle. Indeed, in this strategy, the vehicles with high average utility can consume the larger part of available bandwidth, whereas the packets with the low utility are dropped in congestion conditions. The average utility is calculated independently at the application layer of each node without considering the density and movements of vehicles. Then, an appropriate transmission rate is determined for the vehicle based on the calculated average utility. Due to exchanging the available bandwidth between the neighboring vehicles regardless of the capacity and congestion situation of the vehicles the channels are significantly overloaded, especially in high-density networks. UBPFCC needs to carry out the road segmentation to calculate the utility metric. This strategy employs the GPS information for segmenting the roads. Due to road segmentation, this strategy cannot be used by safety applications. In addition, GPS signals may not be received in some situations (e.g. in tunnels) which reduces the accuracy of the information for segmenting the roads. This strategy does not work for transaction-based applications of VANets. Moreover, tuning the transmission rate based on packet utility and size leads to decreased performance of event-driven safety messages.

Tielert et al. [63] presented a rate adaption based strategy to control the congestion in VANets which was called Periodically Updated Load Sensitive Adaptive Rate (PULSAR) control. In this strategy, the transmission range is selected based on the channel load that depends on the driving environment. The transmission range is also considered to be fixed based on the applications requirements. The PULSAR strategy controls the congestion in three main steps. In the first step, the channel load assessment is conducted using the Channel Busy Ratio (CBR) to detect congestion. In the second step, when a new CBR is measured, the transmission rate is tuned at the end of each Channel Monitoring and Decision Interval (CMDI). If the measured CBR exceeds a predefined threshold, the transmission rate decreases. However, if the measured CBR is smaller than the threshold, the transmission rate increases linearly. Finally, in the last step, the selected transmission rate is shared between the neighboring vehicles located in the communication range. Therefore, in this strategy, the neighboring vehicles contribute to the congestion control process. The PULSAR strategy disseminates fairly the congestion information between the neighboring vehicles over multi-hops such that the hidden nodes are considered. However, in this strategy, the safety application requirements are not taken into account. Moreover, sharing the congestion information lead in extra load to the channels.

Seo et al. [64] designed a congestion control strategy to solve the problem of safety messages in dense networks based on the application level acknowledgments. In this strategy, the acknowledgments of successfully delivering of the messages are piggybacked on beacon messages. When a vehicle receives a piggybacked acknowledgment, the vehicle increases the interval between two beacon messages automatically reducing the beaconing rate and consequently the channel load. However, in dense networks, these extra piggybacked acknowledgment bytes in beacon messages lead to extra load in the channels. Moreover, this strategy is not practical for VANets because the delay resulting from controlling all safety messages in surrounding vehicles increases due to the processing of the extra piggybacked acknowledgment bytes.

In [65], Sommer et al. proposed the Adaptive Traffic Beacon (ATB) approach to increase the message sending in the network and avoid overloading the channel. ATB is a fully distributed approach that adjusts dynamically the beaconing rate based on the channel quality and the message utility. In this approach, the channel quality is estimated by measuring the Signal-to-Noise Ratio (SNR), the number of neighboring vehicles, and the last evaluated status of the network. Also, the message utility is calculated based on the age of messages, the distance between vehicles, and the event occurrence positions. The ATB approach can prevent channel collisions in the non-congested channel during the messages broadcasting. Moreover, using the ATB approach, the message dissemination can be conducted in much broader areas in comparison with the flooding-based approaches. The ATB can reduce the channel loads in the congested conditions only by transmitting the important messages. However, this approach does not consider the MAC layer setting since it calculates the beacon reception probability and delay. In addition, in ATB approach, some safety applications are not satisfy due to the reduction of beaconing rate that leads to the lack of required information to operate efficiently.

Schmidt et al. [66] proposed an adaptive beaconing rate strategy to guarantee the position information accuracy. The authors adjust the beaconing rate to make a trade-off between information accuracy and bandwidth usage. Tuning the beaconing rate is a powerful solution to control the channel load and congestion. In this strategy, the beaconing rate is adjusted based on the mobility property of each vehicle, mobility property of neighboring vehicles, and situation of the network. Indeed, this strategy employs the different information such as the direction of vehicles, vehicles density, and velocity of vehicles that exist in the beacon messages to determine the beaconing rate. However, according to the requirements of some safety applications, reducing beaconing rate have some constraints for these applications.

#### 2.2.3.2 Power-based strategies

In power-based strategies, the transmission power (range) is tuned to decrease the channel collisions. To provide fairness to VANets, all nodes should have a similar opportunity to communicate with other neighboring vehicles. The safety applications usually send their safety messages with the high transmission range to cover a larger area such that a greater number of nodes can receive these safety messages. However, if the congestion occurs in the networks, some vehicles should reduce their transmission power to reduce the channel collisions. Thus, the chance of communicating with neighboring vehicles is reduced and the fairness goal in VANets is violated. In addition, a high transmission power leads to increase the channel collision and the channel saturation [10], [13], [14], [55].

Sepulcre et al. [10] introduced a decentralized strategy to avoid the congestion occurrence in the communication channels. The authors employ an awareness control strategy to control the transmission power. The introduced strategy decreases the transmission power in the network with high density that causes reducing the packet reception probability at further distance, while keeping a high packet reception ratio at close distance. This characteristic is very useful for safety applications that must have more effects on the surrounding vehicles instead of farther vehicles. However, tuning transmission power in VANets is not a scalable solution for controlling congestion in the channels.

Torrent-Moreno et al. [67] presented a new algorithm for sharing the bandwidth fairly between the vehicles. This algorithm is named Fair Power Adjustment for Vehicular environment (FPAV). The authors proposed a congestion control strategy that increases the packet reception probability at the neighboring vehicles, such that fairness is provided in the system. In FPAV, the algorithm controls the congestion only for the safety messages including the beacons and emergency messages. FPAV algorithm limits the beaconing loads and provides an appropriate transmission power based on the vehicles density. Indeed, for ensuring fair utilization of the medium, when the number of active vehicles increases, the transmission power is reduced to a predefined threshold. In addition, this algorithm reserves a part of bandwidth for the emergency messages. However, reserving the bandwidth may waste the bandwidth in the normal conditions of VANet.

Torrent-Moreno et al. [68] proposed the Distributed Fair Power Adjustments for Vehicular environments (D-FPAV) strategy that is a fully distributed and localized transmission power adjustment strategy. D-FPAV provides an efficient transmission power for the event-driven messages by decreasing the beaconing loads in the control channel. Using D-FPAV, the event-driven messages have higher priority compare to the beacon messages to transfer in the control channel. This strategy considers that the beaconing reception rates do not diminish at neighboring nodes. This strategy controls the congestion by adjusting fairly the range of beacon messages based on vehicle density. In D-FPAV, each vehicle requires the overall information about the status of the neighboring vehicles located in the carrier-sense range. Based on this knowledge, the vehicles adjust the maximum transmission range for beacon messages such that the beaconing load does not exceed a fixed predefined threshold. Then, the adjusted transmission range is broadcasted to the neighboring vehicles located in the carrier-sense range. Figure 2.3 shows the pseudocode for the D-FPAV strategy. A fair channel busy time is achieved using D-FPAV. However, the reduction of the beaconing transmission range reduces the delivery of beacon messages in farther distances. Therefore, the applications of VANets that used the information of beacon messages may face the lack of essential information to operate efficiently and effectively. Moreover, gathering the overall information about surrounding vehicles is a difficult task in VANets, and exchanging the adjusted transmission power between neighboring vehicles causes extra load in the channels.

Fallah et al. [69] presented a strategy to monitor and control congestion based on the channel occupancy. This strategy controls congestion by adapting the transmission range for obtaining optimal channel occupancy, such that the high rate of density changes in VANets is considered. The authors introduced a mathematic model that estimates the channel occupancy based on the transmission rate, transmission range, contention window size, and network density. In this strategy, the knowledge of the propagation model, vehicle density, and transmission rate of the neighboring vehicles is not required. However, if the transmission rate is changed, the transmission range should be adapted with new transmission rate due to the modification in the mathematical model. In addition, this strategy does not consider the delay that is a critical factor for safety messages.

Wei et al. [70] proposed a forward broadcasting strategy for data dissemination by controlling the transmission power for the emergency messages. This strategy mitigates the broadcast storm phenomena using the relay vehicles that retransmit the broadcasted packets. In this strategy, the relay vehicles are selected based on a predefined transmission power threshold. Indeed, if the received transmission power by the vehicles exceeds the threshold, the vehicles should retransmit the received packets. However, the vehicles that receive transmission with less powers than the threshold do not retransmit the packets. This strategy provides the reliability of one-hop broadcasting messages. Indeed, using this strategy, the one-hop broadcasting collisions and redundancy are decreased. In addition, this strategy avoids congestion occurrence. Therefore, the packet delivery ratio increases and the dissemination delay for safety messages decreases.

Algorithm D-FPAV: (algorithm for node $u_i$)

$CS_{MAX}$ : maximum carrier sense
Tx: Transmission
*BMMTxP*: Beaconing Max-Min Tx Power
*MBL:* Maximum Beaconing Load

INPUT: status of all the nodes in $CS_{MAX}$ *(i)*

OUTPUT: a power setting *PA(i)* for node $u_i$, such that the resulting power assignment is an optimal solution to *BMMTxP*

1. Based on the status of the nodes in $CS_{MAX}$ *(i)*, compute the maximum common Tx power level $P_i$ the *MBL* threshold is not violated at any node in $CS_{MAX}$ *(i)*

2a. Broadcast $P_i$ to all nodes in $CS_{MAX}$ *(i)*

2b. Receive the messages with the power level from nodes $u_j$ such that $u_i$ *Є CSMAX (i)*; store the received values in $P_j$

3. Compute the final power level :
$PA(i) = \min [\, P_i , \min_{j:ui \in CSMAX (i)} [P_j]\, ]$

Figure 2.3: Pseudocode of D-FPAV strategy [68].

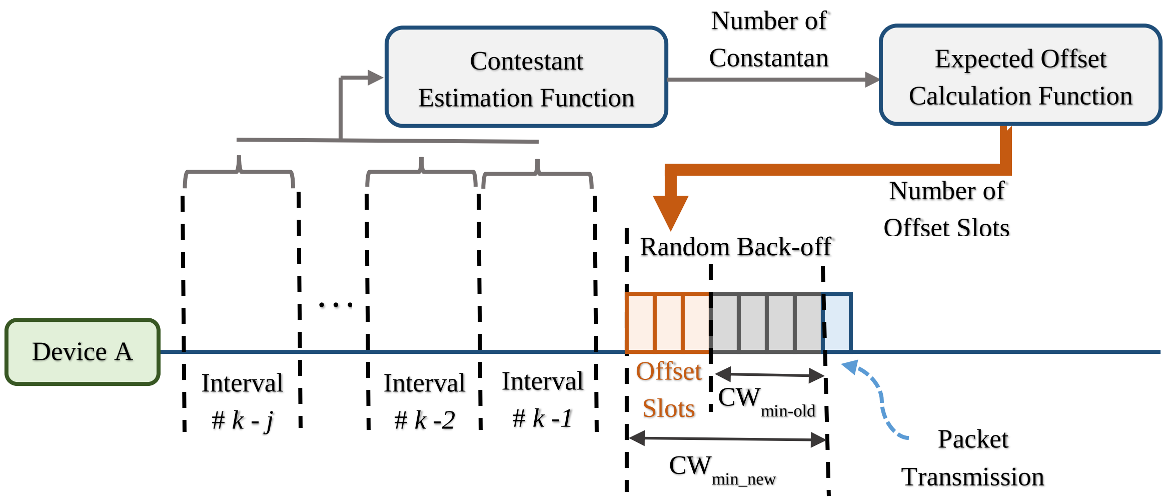
Sahu et al. [71] presented a strategy that controls the congestion by tuning the transmission range of beacon messages and network coding in the packets level. In this strategy, the transmission range of beacon messages is reduced in each vehicle to reduce the number of beacon messages in the VANet. This strategy provides the transmission range required for safety application using the network coding in the packet level to forward the beacon messages for only two-hop. Indeed, in this strategy, a forwarder is selected within a forwarding zone that is determined within the transmission range. The vehicles located in this zone communicate with each other to select a proper forwarder. Therefore, by reducing the beaconing range, the channel collisions are reduced and consequently the congestion is controlled. However, in this strategy the value of contention window size is assumed to be fixed, while for prioritizing the messages, the different value of contention window size is required due to the different types of messages.

#### 2.2.3.3 CSMA/CA-based Strategies

The CSMA/CA strategy is a collision avoidance strategy that is employed as a default congestion control strategy in IEEE 802.11p. This strategy determines the channel access ability of each node in the MAC layer by adjusting the contention window size and AIFS. The contention window size and AIFS play important roles to reduce the channel collisions and avoid the congestion occurrence in the channels. In addition, in the CSMA/CA strategy, the exponential back-off mechanism is used to control the congestion. However, when the message generation rate is high and the beacon messages have the timeout, the exponential back-off mechanism is not efficiently performed in VANets due to dropping the messages before transmission [10], [13], [16].

Fu et al. [72] proposed the Incremental Power Carrier Sensing (IPCS) mechanism that provides a safe carrier sensing range in VANets. This mechanism is an appropriate mechanism to prevent the collisions caused by the hidden nodes. The IPCS mechanism guarantees interference-safe transmissions in CSMA-based networks according to the physical interference model. This mechanism monitors each power level increase in the network and then, compares it with a predefined threshold. Indeed, this mechanism is able to detect and separate transmission powers of vehicles transmitted concurrently in the network. Then, based on the level of received transmission power, this mechanism detects the idle status of the channels and determines the carrier sensing range. Although, using this mechanism, the throughput is improved, the background noises are not considered in this mechanism. Thus, this mechanism cannot operate efficiently in the real environments.

Hsu et al. [47] introduced an Adaptable Offset Slot (AOS) strategy to control congestion in the MAC layer. The AOS strategy reduces the packet collisions in the dense network by dynamically adjusting the minimum contention window size based on the local information about the vehicles density. In other words, using the AOS strategy, an optimal back-off time is determined based on the number of neighboring vehicles. In this strategy, the vehicle density is calculated by broadcasting the hello messages to the neighboring vehicles and listening to the control channel




for the responses. In the next step, a new minimum contention window size is determined based on the calculated vehicle density and is linearly increased by increasing the vehicles. Figure 2.4 shows how the AOS strategy performs. This strategy significantly improves the throughput and packet loss ratio. However, by increasing the contention window size in the high vehicle density, the delay of safety messages increases. Therefore, information required by VANets applications are staled.

Figure 2.4: The performance of AOS strategy [47].

Jang et al. [73] proposed a closed-loop congestion control strategy performed in the MAC layer. This strategy detects the congestion by exchanging the RTS/CTS messages. Then, the contention window size is dynamically adjusted to reduce the number of collisions. In other words, this strategy increases the contention window size to reduce the channel overload caused by competing nodes. Using this strategy, the standard deviation of delay and the number of collisions are decreased, and the throughput is increased. However, this strategy is not efficient for real-time messages broadcasting. Also, the congestion detection is conducted by the RTS/CTS messages that are transferred unicast in the VANets.

Stanica et al. [46] modified the physical carrier sensing method and proposed the Safety Rang-CSMA (SR-CSMA) strategy. In this strategy, the probability of beaconing reception is investigated based on the physical carrier sense. SR-CSMA controls congestion by adjusting the contention window size and physical carrier sense and using some network characteristics (e.g. location of vehicles that occupied the channel). A safety range is defined in SR-CSMA that is smaller than the transmission range of vehicles. Then, SR-CSMA increases the reception probability of the safety messages for this range. This strategy improved the performance of VANets by reducing the collisions in the channels. However, SR-CSMA was proposed for one-dimension networks that neglects many complexities associated with the real in VANets.

Barradi et al. [74] presented a MAC layer congestion control strategy to solve the problem of the EDCA algorithm that guarantees the transfer of high priority safety message on the control channel without delay. This strategy adjusts the ranges of back-off window size and AIFS for various types of messages in VANets, in order to implement the strict priorities for the safety messages. In addition, this strategy provides the acknowledgements for safety messages broadcasting in the control channel to ensure the safety message delivery and prevent the messages retransmitting. However, these acknowledgments cause more collisions in the dense networks due to adding the extra loads on the congested channels. Using this strategy, the delay, jitter, and packet loss reduces for safety messages in high dense conditions. However, for the low priority messages, the performance of VANets decreases.

#### 2.2.3.4 Prioritizing and Scheduling-based Strategies

Prioritizing and scheduling strategies control the congestion by assigning the priority to the messages and scheduling them to transfer in control and service channels. In these strategies, the priorities are defined such that the high priority safety messages have more chance to acquire the channels and transfer with less delay. Using these strategies, the channel access is controlled such that the channel collisions are decreased. In this class of congestion control strategies, a strict prioritization is required for different types of messages generated in VANet. Then, the prioritized messages are scheduled to transfer into control or service channels. Therefore, the prioritizing and scheduling-based strategies can prevent the channel saturation and consequently the congestion occurrence in the networks. Generally, the prioritizing and scheduling-based strategies are very common proactive congestion control strategies which are employed to prevent the congestion occurrence in the networks [22], [29], [57].

Some prioritizing and scheduling algorithms that can be employed in VANets are First-in-First-out (FIFO), Longest Wait Time (LWT), and Maximum Request First (MRF), First Deadline First (FDF), Smallest Data-size First (SDF), Longest Total Stretch First (LTSF), Maximum Quality Increment First (MQIF), Least Selected First (LSF), and D*S algorithms. The FIFO algorithm, which is the one of the simplest scheduling algorithms, first serves the earliest arrival request. Indeed, the first packets coming to the queues are first transferred to the channels. The LWT algorithm gives higher priority to the messages that wait longer in the queues to be transferred in the channels. The MRF algorithm assigns a higher priority to the messages that were requested more by various services. In the FDF algorithm, the messages are scheduled based on the remaining time to their deadlines. The SDF algorithm determined the higher priority for the messages with lower size [57].

In LTSF, a stretch metric is employed to reduce the waiting time in the queues. This metric is defined as the ratio of the request response time to the request service time. LTSF algorithm aims to optimize the value of the stretch metric. However, this scheduling algorithm cannot perform efficiently when the system size is large (especially when the messages are broadcasted) due to increasing the computing time for calculating the stretch metric for each data item [75]. In the MQIF algorithm, the messages are scheduled based on the Quality of Service (QoS) and Quality of Data (QoD) metrics. The QoS and QoD metrics are defined for considering the responsiveness and staleness of data messages, respectively. Finally, D*S algorithm determines the priorities based on Deadline (D) and Size (S) of messages [57], [76], [77].

Bai et al. [21] proposed the Context Aware Beacon Scheduling (CABS) strategy to control the congestion for the safety applications. Indeed, this strategy is used to address the high beaconing rate problem in dense networks that leads to the overloading and congesting the channels. The CABS is a distributed strategy that dynamically schedules beacon messages using a channel access method (e.g. Time Division Multiple Access (TDMA)) for allocating a time slot for sending the beacon messages. This time slot is determined based on the channel status and the context aware information (e.g. speed, position, and direction of vehicles) piggybacked to the beacon messages. In CABS, the packet reception rate and channel access delay are reduced due to decreasing the beaconing rate in the congestion conditions. However, in this strategy, the MAC layer inter-networking is not considered to allocate the proper time slot to different transmissions.

Bouassida et al. [22] presented a new strategy that controls congestion in VANets by dynamically scheduling messages based on their priorities. In this strategy, the priorities of messages are defined using static and dynamic factors and the size of the messages. The static factor is defined based on the message context, and the dynamic factor is defined based on the condition of the network. For calculating the dynamic factor, some metrics such as the speed of vehicle, utility of sender, and validity of message are considered. After prioritizing the messages, they are scheduled in the control and service channels. The control channel can be used for transferring the service messages when it is free. This strategy transfers the high priority messages without delay, and reschedule the mid and low priority messages for transferring in the channels. Using the proposed strategy, the network loads are decreased and the network resources are efficiently employed. Moreover, this strategy improves the delay of safety messages. In this strategy, however, the communication overhead increases due to exchanging the context of messages between the neighboring vehicles. Also, in this strategy, the broadcast storm problem is not considered.

Felice et al. [54] developed the WAVE-enhanced Safety message Delivery (WSD) strategy to reduce the delivery delay of safety messages. WSD was developed to address the switching between the channels in multi-channel VANets. In multi-channel and single transceivers VANet, the synchronized channel switching increases the delay of the safety messages that should be delivered with less delay. WSD employs the heuristics to schedule all safety and non-safety messages in the parallel multi-channel machines. Using WSD, the high priority safety messages are transferred during service channel intervals such that the reception rate of the safety messages in all neighboring vehicles is considered. Indeed, when an emergency message is generated during the service channel interval, the vehicle generated emergency message notifies all neighboring vehicles to acquire the channel for transferring the emergency message immediately. Using WSD, the delivery delay is reduced for safety messages. However, the multi-hop communications of VANets are not considered in this strategy.

Suthaputchakun et al. [78] proposed a priority-based congestion control strategy that uses inter-vehicle communications to increase the reliability of broadcasting the messages between vehicles. In the proposed strategy, each message, which was transferred in inter-vehicle communications, is prioritized based on the urgency and average delay. In this strategy, high priority safety messages are retransmitted more than lower priority messages to increase the chance of delivery, and enhance the reliability of the safety messages. In this strategy, as Figure 2.5 shows, four internal queues are assumed for each vehicle, according to four different priorities of messages. This strategy is fully compatible with IEEE 802.11 and IEEE 802.11e standards. Using the proposed strategy, the delay and successful transmission ratio are improved in high-density networks.

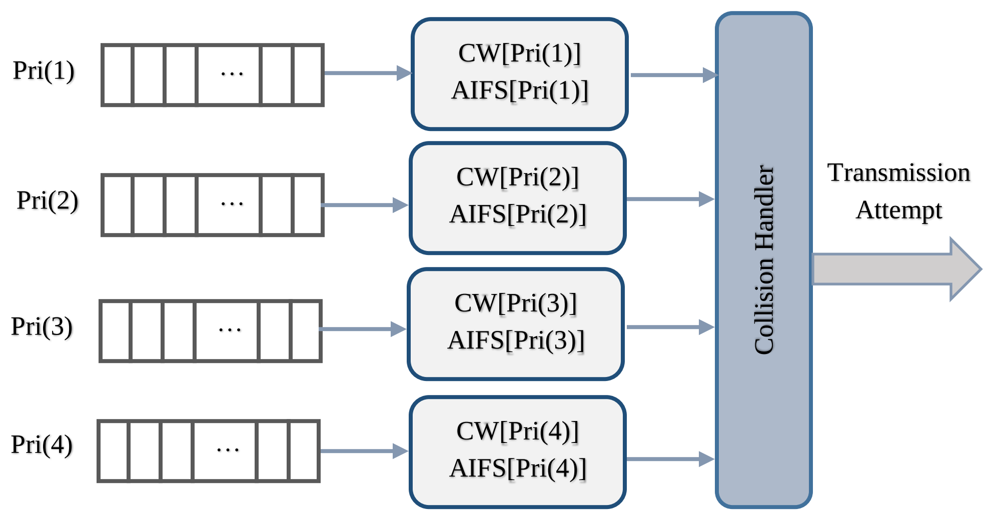


Figure 2.5: Architecture of queues in each vehicle [78].

#### 2.2.3.5 Hybrid Strategies

In Hybrid strategies, two or more parameters and means are used to control congestion. Tuning the transmission rate and power, adjusting the contention window size and AIFS, and defining a proper priority for each message and scheduling in channels are combined in hybrid strategies to avoid channel saturation and congestion in VANets [13].

Sepulcre et al. [15] introduced an application-based congestion control strategy. This strategy is an open-loop strategy that prevents the congestion occurrence by adapting the transmission rate and power. In this strategy, the channel loads are minimized globally in the network to satisfy the requirements of VANets applications for each vehicle individually. The authors investigated this strategy on the lane change warning application. In this application, a warning distance (DW) is considered as the application requirement calculated based on the local available information (e.g. operating and driving conditions). The transmission rate and power are dynamically calculated to provide the application reliability. However, this strategy does not efficiently perform for a single application that have multiple requirements, or for multiple applications with various requirements that operate concurrently in a single vehicle.

Djahel et al. [79] proposed a congestion control strategy by controlling the transmission power and rate of beacon messages. The periodic transmission of beacon messages consumes a large amount of available control channel bandwidth and lead to congestion. The proposed strategy was designed in three phases. In the first phase, the beacon messages are prioritized in three levels (i.e. low, medium, and high level) based on static and dynamic factors. The static factor is considered to be the content of beacon messages, and the dynamic factor is considered to be the transmission emergency condition. When a vehicle receives a beacon message, the priority is defined for the message. If the beacon messages have similar priority, the hop-count factor can be used for specifying the priority of the message. A higher priority is defined for the beacon message with lower hop-count due to its closer distance to the emergency situations. The Time-To-Live (TTL) factor was not considered for defining the priority because MAC layer does not have access to the TTL information.

In the second phase, the congestion is detected by measuring the Average Waiting Time (AWT), Collision Rate (CR), and Beacon Reception Rate (BRR). If the values of these metrics exceed the predefined thresholds, beacon congestion is detected in the control channel. In the third phase, the transmission power of beacon messages is adjusted based on the collision rate and the condition of one-hop neighboring vehicles. Then, the beaconing rate is tuned according to the fairness of bandwidth sharing. Then, the vehicle shares the calculated transmission power and rate with the neighboring vehicles to diminish the beaconing load in the control channel. The schematic view of the proposed strategy is shown in Figure 2.6. The proposed strategy improves the reception rate of the emergency messages and increases the safety and reliability of VANets. However, the delay of this strategy is significant due to detecting the congestion. Also, exchanging the information between the neighboring vehicles adds a high communication overhead in the channels.

Taherkhani and Pierre [12] introduced the Uni-Objective Tabu (UOTabu) strategy that is a closed-loop hybrid strategy to control congestion using the Meta-heuristic techniques. UOTabu employs the channel usage level parameter for detecting the congestion in the channels. When the congestion is detected in the channels, the proposed strategy tunes the transmission range and rate. The Tabu Search algorithm is used to obtain a proper value for transmission range and rate while the minimizing delay is considered as the objective function of Tabu Search algorithm. UOTabu improves the average delay, average throughput, and number of packet losses, and consequently the performance of VANets by tuning transmission range and rate for all message types.

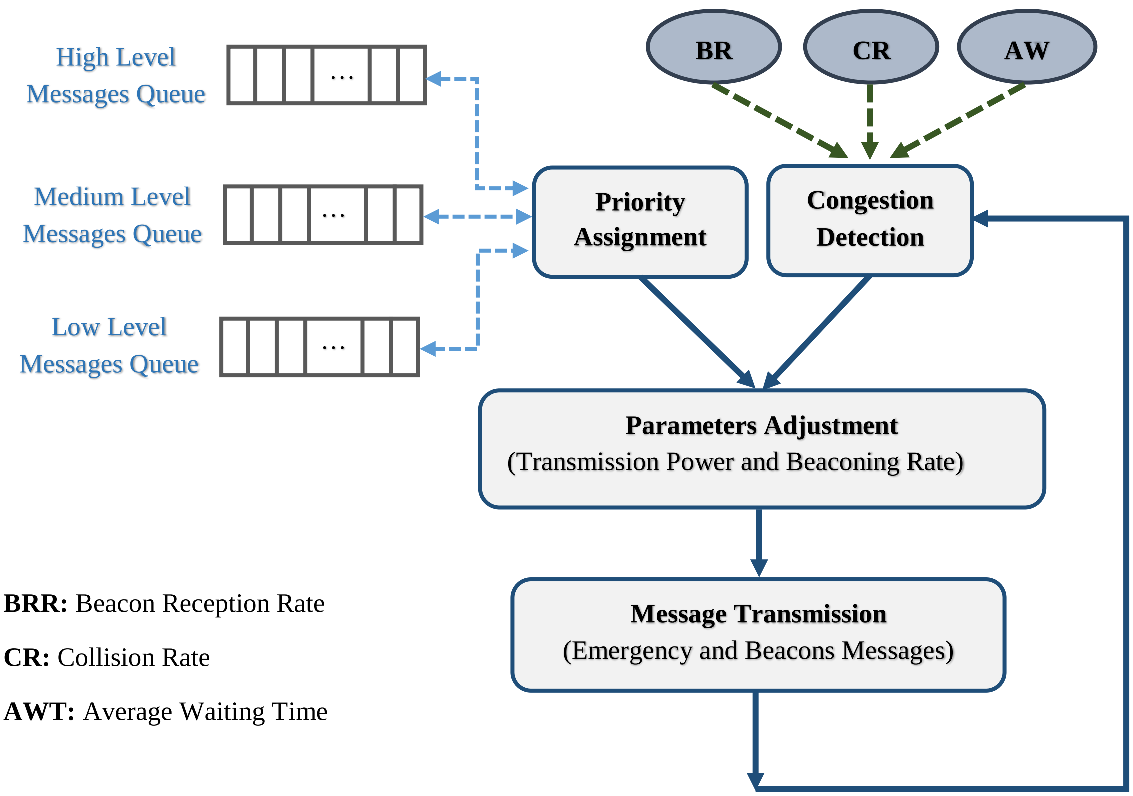



Figure 2.6: The schematic view of the proposed strategy in [79] for prioritizing the messages and controlling the congestion.

Guan et al. [80] proposed a centralized adaptive message rate control strategy to control the congestion at intersections. In this strategy, an offline simulator is used to find out the proper values for transmission rate and MAC layer back-off contention window based on the vehicle density at intersections. This strategy is investigated in the Event-driven Safety Applications (ESA) and Periodic Safety Applications (PSA) that send the safety messages on the control channel. Indeed, this strategy was proposed to provide a high availability and low latency for ESA messages, and increase the channel utilization for PSA messages at intersections. In the proposed strategy, an online Access Point was used to provide the optimal values for the transmission rate and MAC layer back-off contention window in the network. Although, this strategy improves the performance of VANets at intersections, inaccurate vehicle density estimation reduces the performance of large scale networks.

Sepulcre et al. [15] introduced a contextual communication congestion control strategy for cooperative vehicular networks. The introduced strategy uses the context of the communication information to reduce the channel collisions by considering the reliability of VANets applications. Indeed, in this strategy, each vehicle uses the position information of neighboring vehicles to tune the transmission parameters such that the requirements of applications are satisfied. The authors employed a lane change assistance application as a case study. Using this strategy, the channel load and unnecessary interferences significantly reduce due to cooperation between vehicles. In addition, the channel busy time reduces because the contextual information for controlling congestion is used. However, this strategy does not control the overall channel loads in the network.

Guan et al. [81] developed the Adaptive Message Rate Control (AMRC) strategy which is a two-level adaptation control strategy. The AMRC strategy controls congestion by adjusting the transmission rate and control channel interval based on the utility of packets. In this strategy, the scalability of vehicle communications is improved, the performance of safety messages is also guaranteed, and the non-safety applications can acquire bandwidth as much as possible to carry out efficiently. In this strategy, using an off-line procedure, the transmission rate and control channel interval are determined for the specific number of vehicles. Then, using an online procedure, RSU configures the determined values of transmission rate and control channel interval for the specified number of vehicles. Indeed, in the proposed strategy, the obtained values are broadcasted by RSUs. AMRC improve the performance of VANets.

Huang et al. [82] proposed A Vehicle Oriented Congestion Control Algorithm (AVOCA) which is a cross layer congestion control algorithm. In AVOCA, since the congestion is controlled in the network, the network coverage holes are taken into account. This algorithm was proposed to address the failure of the transport layer when the vehicles enter into a coverage zone. AVOCA employs a performance threshold defined in the transport layer to control packet transmission in this layer. When a vehicle enters into a coverage zone, the performance of the transport layer exceeds the threshold. Then, AOVCA resets the congestion control parameters and initiates the packet transmissions. In the other hand, when the vehicle exits from the coverage zone, the performance of the transport layer decreases. Then, AOVCA freezes the congestion control parameters and terminates the packet transmissions. This algorithm improves significantly the network throughput by considering fairness in channel allocation.

Baldessari et al. [56] developed a hybrid congestion control strategy that tunes the transmission rate and transmission power. In this strategy, the transmission rate and transmission power are determined based on the number of neighboring vehicles and a channel busy time threshold. Indeed, this strategy employs the channel busy time to estimate the number of neighboring vehicles in the surrounding area. Each node determines the transmission power and rate by considering the current situation of the node. For example, when the vehicle is close to the intersection, this strategy selects a high transmission rate and low transmission power. This strategy was developed to fairly allocate a fraction of available resources to the vehicles. In other words, when a node increases the transmission power, the transmission rate is decreased and vice versa in order to allocate the same fraction of resources to each node. While tuning transmission power and rate can efficiently avoid the collision, sharing the same fraction of the bandwidth is not often desirable for different safety applications.

Huang et al. [83] introduced a joint transmission power and rate control strategy to reduce the channel congestion. In this strategy, the authors tuned the beacon generation rate by tracking the errors (e.g. packet loss). Therefore, the beacons messages cannot receive successfully by neighboring vehicles. Moreover, the transmission power is adapted based on the channel busy time. In this strategy, the packets are sent when the estimated tracking error exceeds a predefined threshold. Also, a minimum and maximum transmission ranges are defined for bounding the transmission range of the safety applications. In this strategy, the transmission range is linearly tuned between these minimum and maximum bounds based on the channel load. This strategy uses the local information for adapting the transmission power and rate while this information is not shared between the neighboring vehicles. Therefore, some vehicles may control the congestion without being aware that they are not in the congestion situation. In this strategy, each vehicle can track all of the neighboring vehicles with a tolerable accuracy of tracking. Although, this strategy is a robust strategy for controlling congestion and can efficiently reduce the tracking error, diversity of the traffic priority is not considered in this strategy.

Fukui et al. [84] developed the Dynamic Integrated TRAnsmission Control (DITRAC) for inter-vehicle communications. The DITRAC strategy tunes the transmission rate and power using the information about the number of lanes and number of packets successfully received. When the vehicles decrease their speed in high vehicle density, this strategy decreases the transmission rate and power to avoid more collisions in channels. Indeed, this strategy controls the transmission rate, when the vehicle density is high, and controls the transmission power when the vehicle density is low to efficiently increase the performance of inter-vehicle communications. The DITRAC strategy improves the offset load and packet collision. However, when the vehicles stop, this strategy turns off the beaconing transmission that cause to decrease the performance of some applications.

# CHAPTER 3 PROCESS FOR ENTIRE RESEARCH PROJECT AND GENERAL ORGANISATION OF DISSERTATION

This dissertation has been structured based on published and submitted journal papers. This chapter describes the relation between the objectives of the dissertation (Chapter 1) and the submitted/published articles obtained from this research (Chapter 4, 5, and 6).

As mentioned in Chapter 1, the main objective of this dissertation is to enhance the performance of VANets by controlling the traffic communication and decreasing the channel collision. Accordingly, three sub-objectives are proposed in this dissertation to prevent and/or control the congestion in VANets.

The journal article presented in Chapter 4 discusses the first objective of the dissertation that is closed-loop congestion control strategies. The article is entitled “Improving Dynamic and Distributed Congestion Control in Vehicular Ad Hoc Networks”, and it was published in the “Ad hoc Networks” journal. In this article, a congestion control strategy is proposed that dynamically tunes the transmission range and rate for all type of messages. The proper values for transmission range and rate are obtained by a Meta-heuristic algorithm. A Tabu search algorithm adjusts the value of these parameters such that the delay and jitter are minimized. This strategy is a distributed strategy because it performs independently in each vehicle.

The journal article presented in Chapter 5 discusses the second objective of the dissertation that is open-loop congestion control strategy. The article is entitled “Prioritizing and Scheduling Messages for Congestion Control in Vehicular Ad Hoc Networks” and it was submitted in “Computer Networks” journal. In this article, two prioritizing and scheduling strategies are designed to avoid the congestion occurrence in the channels. The message prioritizing is conducted based on the content of messages, state of the network, and size of messages. For transferring the messages in the control and service channels, two queues are considered for each type of channels. The prioritized messages are scheduled in each queue using 1) the defined priorities, and 2) a Meta-heuristic algorithm to find the near-optimal transferring order in the channels in reasonable time.

The journal article presented in Chapter 6 discusses the third objective of the dissertation localized congestion control strategy. The article is entitled “Centralized and Localized

Congestion Control Strategy for Vehicular Ad-hoc Networks Using a Machine Learning Clustering Algorithm", and it was sent for publication to the "IEEE Transaction on Intelligent Transportation Systems". In this article, a localized strategy is proposed to control congestion centrally using RSUs set at intersections. The machine learning algorithms is used to cluster the messages transferred between the vehicles before red light traffics. A K-means algorithm clusters the messages based on their features. This strategy adjusts the communication parameters for each cluster of messages such that the delay of transferring the messages is minimized.

Consequently, three objectives of this dissertation can be achieved through the following three chapters related to the three articles. The contributions in this dissertation support the QoS in these networks by controlling the congestion. This improvement helps increase the reliability of VANets' applications by improving the performance of VANets.

# CHAPTER 4 ARTICLE 1: IMPROVING DYNAMIC AND DISTRIBUTED CONGESTION CONTROL IN VEHICULAR AD HOC NETWORKS

N. Taherkhani [1], S. Pierre [1]

[1]Mobile Computing and Networking Research Laboratory (LARIM), Department of Computer Engineering, Polytechnique de Montréal, Montreal, Canada

## Abstract

To provide reliable communications in Vehicular Ad hoc Networks (VANets), it is vital to take into account Quality of Services (QoS). Delay and packet loss are two main QoS parameters considered by congestion control strategies. In this paper, a Multi-Objective Tabu Search (MOTabu) strategy is proposed to control congestion in VANets. The proposed strategy is dynamic and distributed; it consists of two components: congestion detection and congestion control. In the congestion detection component, congestion situation is detected by measuring the channel usage level. In congestion control component, a MOTabu algorithm is used to tune transmission range and rate for both safety and non-safety messages by minimizing delay and jitter. The performance of the proposed strategy is then evaluated with highway and urban scenarios using five performance metrics including the number of packet loss, packet loss ratio, number of retransmissions, average delay, and throughput. Simulation results show that MOTabu strategy significantly outperforms in comparison with other strategies like CSMA/CA, D-FPAV, CABS, and so on. Conducting congestion control using our strategy can help provide more reliable environments in VANets.

***Keywords***: Congestion control, Meta-heuristic techniques, Multi-Objective Tabu Search, Quality of Service, Transmission range and rate, Vehicular ad hoc networks.

## 4.1 Introduction

Intelligent Transport Systems (ITSs) use Vehicular Ad hoc Networks (VANets) as wireless communications technology. Indeed, VANets are designed to provide a safe and efficient environment within transportation systems for reducing accidently dangers events for drivers, passengers and pedestrians in the roads. They are a new landscape of Mobile Ad-hoc Networks (MANets) that consider the vehicles as mobile nodes. VANets are equipped with two units that are called Road-Side Unit (RSU) and On-Board Unit (OBU). While the former is fixed on the roadside, the latter is carried on by vehicle. These units are used for carrying out wireless communications between vehicles (V2V communications) as well as between vehicles and roadside infrastructures (V2I communications) [1], [3].

Dedicated Short Range Communication (DSRC) is a set of protocols and standards that are employed in VANets. Bandwidth utilization, which is one of main factors in DSRC, defines transmission range up to 1000 m and transmission rate ranging from 3 to 27 Mbps. DSRC employs Wireless Access in a Vehicular Environment (WAVE) to norm performance of V2V and V2I communications. WAVE is formed by IEEE802.11p and IEEE1609 standards. The above standards are applied for managing resources and network services for selecting channels, security, and so on.

VANets offer a large number of applications including safety applications (e.g., forward collision, traffic signal violation, and emergency brake lights) and service applications (e.g., traffic optimization, infotainment, and payment services). Safety applications utilize beacon and emergency messages that are transmitted by means of control channel, while service applications utilize non-safety messages transmitted over service channels [4], [6]. VANets inherit most behaviour of MANets. However, they have different behaviours in comparison with MANets due to their special characteristics including high mobility of nodes, high rate of topology change, and high rate of node density. These unique characteristics in VANets raise new challenges related to data dissemination, scalability, security, and routing that lead to reduce performance of VANets [2], [4].

To enhance performance of VANets, Quality of Services (QoS) strategies must be considered to guarantee reliability of safety and service applications. Packet loss and delay are two important parameters that can be used to quantify QoS and evaluate the performance of VANets.

Congestion, which occurs due to the limitation of resources, leads to increase the number of packets loss and delay, and consequently to decrease the performance of VANets. Indeed, the channel bandwidth copes with congestion when the load of the network exceeds the capacity of the network nodes and links. Therefore, congestion control should be conducted for decreasing packet loss and delay to make a more reliable communication in VANets. Congestion control in VANets is a challenging task due to the special characteristics of the vehicular environment including sharing the wireless channel, frequently route break, dynamic topology, and so on. Thus, a dynamic and distributed strategy is required to handle congestion control [8]-[11].

Over the last decades, several strategies were proposed to address congestion problem in VANets. There are three main congestion control strategies for VANets: (1) controlling the transmission range that controls the range of transmission in channels, (2) controlling the transmission rate that controls the rate of packets transferring, and (3) scheduling messages in various channels based on their priorities [15]. Congestion control techniques can also be classified into end-to-end, and hop-by-hop techniques. The end-to-end techniques consider communication flows between senders and receivers, but they do not pay attention to intermediate nodes. The hop-by-hop techniques take into account the capacity of intermediate links [35]. However, using the existing strategies in practice revealed that there are a lot of problems associate with these congestion control strategies in VANets. Some of these problems include, but not limited to, high transmission delay, unfair resource usage, inefficient use of bandwidth, and communication overhead [10]. Therefore, a new strategy is needed to solve these problems, especially in emergency situations of VANets.

Tuning transmission range and rate to control congestion copes with computational overhead in VANets due to the large number of contributing parameters including size of messages, number of vehicles, number of lanes, vehicle velocity, and so on. Thus, the existing strategies conducting tuning transmission range and rate suffer from high delay and packet loss [15]. It will be shown that such a problem is NP-hard. Meta-heuristic techniques can be used to find near optimal solutions in a reasonable time for NP-hard problems [85].

In this paper, we propose a dynamic and distributed congestion control strategy to increase reliability of VANets. The remaining parts of this paper are structured as follow: Section 4.2 reviews the existing congestion control strategies in VANets. Section 4.3 proposes a congestion control strategy in VANets environments. Section 4.4 describes the Multi-Objective Tabu Search (MOTabu) algorithm for tuning transmission range and rate. Section 4.5 discusses the results obtained from applications of the proposed strategy in highway and urban scenarios.

## 4.2 Background and Related Works

Congestion control in modern wired/wireless communications plays an important role for providing reliable and fair environments. The main goals of a congestion control strategies are to obtain high bandwidth utilization, efficient fairness, high responsiveness, and proper compatibility with protocols and standards. To increase efficiency of a congestion control, some metrics such as convergence speed, smoothness and responsiveness must be considered. The convergence speed is estimated by measuring the time spent to reach the equilibrium state. The smoothness, which depends on the size of fluctuation, is calculated using reflection of fluctuation intensity. Finally, the responsiveness is measured by Round Trip Time (RTT) to reach equilibrium [35].

The congestion control strategies are used to control channels loads and increase the performance of wireless channels. Generally, the congestion control strategies in VANets are classified into four categories: window-based, rate-based, single-rate, and multi-rate. Window-based category employs the congestion window in sender and receiver sides. The size of congestion window increases/decreases in states of with/without congestion. In rate-based category, transmission rate is adapted using some feedback-based algorithms. In single-rate category, the congestion is controlled using unicast protocols. Thus, sending rate must be adapted according to just one receiver. On the other hand, multi-rate category uses a layered multicast approach [35].

Torrent-Moreno et al. [68] proposed Distributed-Fair Power Adjustment for Vehicular environment (D-FPAV). This congestion control strategy dynamically controls transmission range of the safety messages (i.e., beacons and emergency messages). Beacon messages are periodically broadcasted between the vehicles that are composed of some information like speed, position, direction, and so on, while emergency messages are broadcasted when an event happens within VANets. In the congestion situation, D-FPAV shrinks the transmission range of the beacon messages. For reducing communication overhead, the value of transmission range is obtained based on the vehicle density. The main drawback of this strategy is that the probability of receiving beacons messages in far distance reduces by decreasing transmission range.

High beaconing frequency consumes a high amount of channel bandwidth when the number of vehicles increases. This problem causes to diminish the performance of safety messages in VANets environments due to the special characteristics of these networks. Djahel and Ghamri-Doudane [79] proposed a three-phases congestion control strategy which consists of prioritizing the messages, detecting congestion, and tuning beacon transmission rate and power. Prioritizing is carried out based on the content of messages and the number of hops that a message has to be traveled. In second phase, congestion can be detected using the average waiting time, the collision rate, and the beacon reception rate metrics. In the third phase, the beacon transmission rate and power are adjusted based on previous phases for efficiently using the channel bandwidth. The proposed congestion control strategy guarantees reliability and safety of VANets, but the delay of this strategy is high.

Baldessari et al. [56] introduced a congestion control strategy by adjusting transmission rate. The proposed strategy aims at fairly assigning resources to all network nodes. This strategy uses channel busy time metric for counting the number of vehicles in the surrounding area and estimating the local vehicle density. Transmission rate in this strategy is adjusted based on either the estimated vehicle density or the predefined threshold. The proposed strategy could not provide a safe and fair channel usage for all users because sharing of the channel bandwidth was not considered in the strategy.

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) strategy, which is used to access communication channels, was redefined by IEEE 802.11p/WAVE standard for VANets [16]. CSMA/CA is used as default congestion control strategy in VANets. This strategy employs the exponential back-off mechanism to control congestion. However, in VANets, exponential back-off mechanism for broadcasting the beacon messages is not efficient. This mechanism does not work adequately for high frequency of message generation, especially when beacon messages have a time-out, that lead to drop packets before transmission.

Most of the congestion control strategies in VANets only adjust transmission range and rate. However, congestion sometimes occurs due to the malfunctioning of CSMA in MAC layer under dense vehicular networks. Stanica et al. [46] investigated the impacts of physical carrier sense on the probability of beaconing reception in VANets. A congestion control strategy was then proposed by controlling the contention window, physical carrier sense, and transmission power. The results showed that the proposed strategy can enhance the performance and reduce the collision in VANets channels.

Huang et al. [82] developed A Vehicle Oriented Congestion Control Algorithm (AVOCA) for optimizing the network throughput. The developed algorithm can solve the existing problems of congestion control in transport layer. Congestion control conducting in transport layer may fail during continuous connectivity with the nodes located at coverage zone. AVOCA uses a performance threshold to control packet transmissions in transport layer. When the vehicle enters in a coverage zone, performance threshold increases. Then, congestion control parameters are reset and packet transmissions are initialed. In other hand, when the vehicle leaves the coverage zone, the performance threshold decreases. The decrease in performance threshold causes to terminate the packet transmission as well as freezing the congestion control parameters. Although AVOCA algorithm increases throughput and fairness usage of services, delay in AVOCA is relatively high (up to 60 ms).

High rate of beacon messages can lead to congestion in control channel, especially in dense networks. Bai et al. [21] developed Context Awareness Beacon Scheduling (CABS) to address this challenge in vehicular networks. CABS is a new distributed strategy for scheduling beacon messages. To dynamically schedule the beacon messages, CABS employs spatial context information in beacon such as position, speed, and direction. Then, time slot is assigned to the node by means of TDMA-like transmission. In the proposed strategy, the packet reception rate and channel access delay are improved, and congestion problem is solved using tuning of beacon frequency. However, CABS does not consider the interworking in MAC layer to adjust time slot for different transmissions.

Taherkhani and Pierre [12] proposed a Uni-Objective Tabu Search (UOTabu) strategy for controlling congestion in VANets. In the proposed strategy, after detecting the congestion situation via measuring the channel usage level, transmission range and rate are tuned by minimizing the delay function. This heuristic strategy just used short-term memory as tabu list for Tabu Search algorithm. In addition, UOTabu is a Uni-Objective Tabu Search algorithm and considered just delay as objective function. A comparison was conducted between UOTabu, D-

FPAV [68], and CSMA/CA [16] strategies using a highway scenario. The comparison showed that the proposed strategy and reduce the delay, and number of packet loss, and increase the throughput, which results in improving the performance and reliability of VANets.

In the following, significant problems in applications of the introduced congestion control strategies in VANets are described. Some of the congestion control strategies conduct retransmissions of unnecessary packets, and drop undelivered packets to detect congestion [51]. However, applying such techniques in VANets is complicated and inefficient due to the special characteristics of VANets such as high mobility and topology change [10], [79].

One of the main goals of VANets is to make a safe environment for drivers and pedestrians. In order to reach this goal, it is critical to broadcast the emergency messages with less possible delay in VANets [2]. However, this factor is not considered by the most of congestion control strategies. In high vehicle density, high frequency of generation of beacon messages results in congestion over the control channels. Thus, the operations of safety applications are impaired due to the failure of receiving of beacon messages. Most of the introduced strategies reduce transmission rate of beacon messages during congestion situations. However, by reducing the frequency of generation of beacon messages, the applications face to staleness information. Thus, the applications required to get updated information cannot operate efficiently [48].

## 4.3 Problem statement and solving strategy

According to the previous section, congestion control based on tuning transmission range and/or transmission rate are very common in VANets. Tuning transmission range and rate are more challenging in VANets than in ad hoc networks due to high mobility of nodes, high rate of topology change, and high rate of node density. Moreover, tuning transmission range and rate in VANets is affected by various parameters such as vehicle velocity, vehicle density, number of lanes, and so on. Note that the number of effective parameters in VANets is more than in mobile ad hoc networks. Tuning transmission range and rate in the large scale networks copes with many challenges because by increasing the size of network, the number of effective parameters is also increased [14]. In this section, an efficient congestion control strategy is introduced for improving reliability and safety of VANets. For this purpose, tuning transmission range and rate in VANets is conducted by employing a Meta-heuristic algorithm.

To send safety messages to further distances, large transmission range is necessary. In other words, by increasing the transmission range, more vehicles located in transmission range can receive the safety messages. In other hand, large transmission range can lead to increase the number of packet collisions and channel contentions. A high transmission rate leads to more accuracy by updating information frequently. However, high transmission rate causes to saturation of channels and increasing message collision rate [14], [21]. Therefore, a strategy should be proposed to determine optimal values of transmission range and rate for efficient operation of VANets. As mentioned in [86], the delay and jitter are much higher in VANets than ad hoc networks. Consequently, it is essential to minimize both the delay and jitter. In this research, therefore, finding the optimal values of transmission range and rate is conducted by minimizing delay and jitter for transferring messages. Finding optimum values of transmission range and rate to conduct congestion control in VANets is complex.

The Multidimensional Knapsack problem is NP-hard, the best known algorithms require an exponential time complexity [87]. On the other hand, the Multidimensional Knapsack problem is similar to the problem of finding optimal values of the transmission range and rate. Indeed, the Multidimensional Knapsack problem can be reduced to the problem of finding the optimal values of transmission range and rate in polynomial-time, by transforming the parameters of the Multidimensional Knapsack problem into equivalent parameters of the problem of finding optimal values of the transmission range and rate. The bags parameters in the Multidimensional Knapsack problem can be transformed to the transmission range and transmission rate parameters in the proposed problem. The worth of goods parameter in the Multidimensional Knapsack problem can be transformed into the different values of transmission range and rate, which are determined based on the DSRC standard, in the proposed problem. Finally, maximizing the worth of goods in bags in the Multidimensional Knapsack problem can be transformed into minimizing the delay and jitter in the proposed optimization problem. Thus, the problem of finding the optimal values of transmission range and rate is an NP-hard problem, as demonstrated by reducing the Multidimensional Knapsack problem to the problem of finding optimal values of transmission range and rate [88]. Meta-heuristic techniques provide general solutions for coping with NP-hard problems. They are used for finding near-optimal solutions in the reasonable time

[89]. Therefore, in this paper, Meta-heuristic techniques are used for tuning transmission range and rate for congestion control in VANet. Several parameters should be considered for optimizing channel usage in VANets including packet size, transmission rate, transmission range, vehicle velocity, vehicle density, and number of lanes. Due to the large number of parameters, finding the optimal transmission range and rate is complex. Meta-heuristic techniques can also handle such a high complexity by considering the reliability of applications in vehicular environments.

The main Meta-heuristic algorithms are Tabu Search, Simulated Annealing, Genetic Algorithm, Mimetic Algorithm, Ant Colony, and so on [85]. Tabu Search is one of the most commonly used Meta-heuristic algorithms which are designed to solve optimization problems. Tabu Search has simpler but more comprehensive concepts than the other Meta-heuristic algorithms. For optimization, the algorithm continues searching until a near optimal solution is obtained. The algorithm also avoids entrapping in local optimum [90].

Generally, congestion control solutions can be divided into two groups: closed-loop and open-loop. The closed-loop solutions control the congestion after it happens while the open-loop solutions avoid the congestion before it happens [34]. This research proposes a closed-loop congestion control strategy. The proposed strategy consists of two components including 1) congestion detection component, and 2) congestion control component.

Congestion detection can be carried out by employing measurement methods. These methods sense communication channels and measure parameters like number of messages queue, channel usage level, and channel occupancy time [49]. In this paper, the congestion detection component measures the channel usage level periodically to detect congestion situation. Then, the value of the channel usage level is compared with a predefined threshold. Zang et al. [42] calculated congestion threshold equal to 70% in wireless communication channels. Similarly, in this paper, the channel usage level threshold is also assumed 70%. Thus, if channel usage level exceeds the threshold, it is assumed that the communication channels face to congestion. After congestion detection, congestion control is carried out by second component of the proposed strategy.

In congestion control component, tuning transmission range and rate is conducted for controlling congestion. As it was mentioned before, tuning transmission range and rate is an NP-hard problem and Meta-heuristic techniques are an appropriate tool to solve these types of problems.

Among different Meta-heuristic algorithms, Tabu Search algorithm is used in this paper since it provides a comprehensive and simple concept to handle complexity of congestion problem in VANets. Tabu Search is used to obtain the near optimal values of transmission range and rate whereas delay and jitter are minimized. Then, the optimal values of transmission range and rate are used for transferring data over communication channels. Figure 4.1 depicts the flowchart of the proposed congestion control strategy. The proposed congestion control strategy is a dynamic and distributed strategy. It is dynamic because tuning transmission range and rate is conducted based on the current situation of the network. It is also distributed because each node in VANets independently executes the proposed strategy, and obtains the optimal values of transmission range and rate.

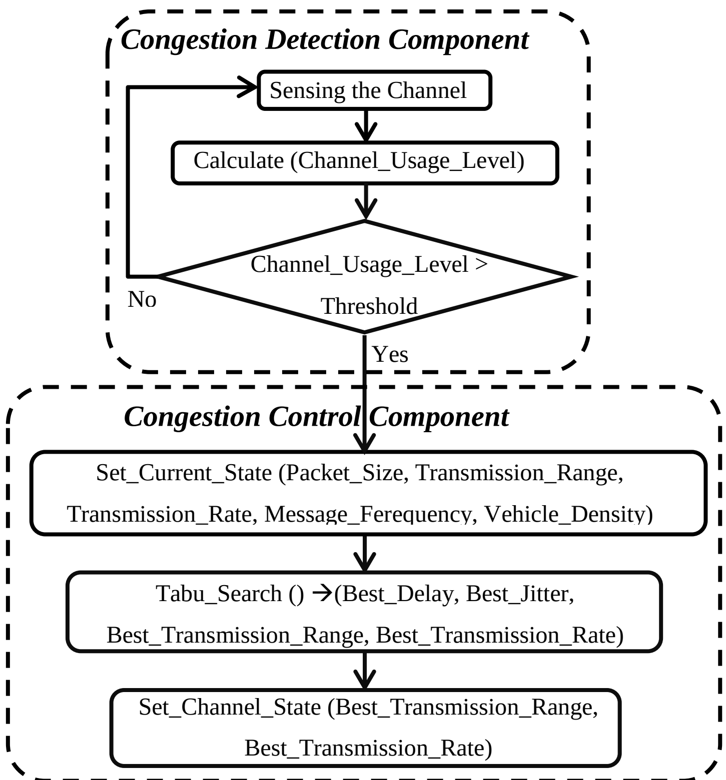



Figure 4.1: Flowchart of the proposed congestion control strategy.

## 4.4 The Proposed Tabu Search Algorithm

Tabu Search algorithm is one of the Meta-heuristic techniques used to obtain near optimal solutions to difficult optimization problems. In this section, Tabu Search algorithm is described according to the following steps: encoding resolution based on the algorithm, generating initial solution, defining conditions for algorithm termination, and determining neighbourhood solutions. Basically, a Tabu Search algorithm is composed by various elements including objective functions, initial solution, neighbourhood set, candidate list, searching strategy, memory mechanisms, tabu list, and terminating rules. The performance of Tabu Search algorithm is affected by the length of the tabu list, the number of iterations to terminate the algorithm, objective functions, and so on [90], [91]. These elements should be defined according to the features of congestion control problem in VANets for tuning transmission range and rate.

The main objective of a congestion control strategy is to minimize delay, jitter, packet loss, and number of retransmissions. However, in this paper for the purpose of making reliability and safe environment, only delay and jitter are considered whereas transferring the messages, specially emergency messages, is done in shorter time for making of safe environment in VANets. Thus, a multi-objective Tabu Search algorithm is developed while the objective functions of Tabu Search are delay and jitter.

Tabu Search generates various solutions to obtain near optimal solution. Each solution in the proposed Tabu Search algorithm is composed by transmission rate, transmission range, delay, and jitter. Delay and jitter are calculated using Equations (4.1) to (4.14) while current values of all required parameters (e.g. the packet size, vehicle density, number of lanes, and so on) are used.

Initial solution of Tabu Search algorithm can be defined using current state, previous state or random initialization methods [90], [91]. In this paper, current state method is used to define initial solution. Thus, the initial solution in the proposed Tabu Search is composed by delay and jitter, and current value of transmission range and rate.

Given initial solution, Tabu Search algorithm generates a collection of new solutions called neighborhood set [90], [91]. To obtain neighborhood set, Tabu Search selects the values of transmission range and transmission rate between 10-1000 meters, and 3-27 Mbps, respectively, based on DSRC standard [4], [6]. The standard values for transmission rate are defined 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps [92]-[94]. The potential values for transmission range are 10, 50, 100, 126, 150, 210, 300, 350, 380, 450, 550, 650, 750, 850, 930, 971, and 1000 m [17]. Then, by finding feasible solutions in the neighborhood set, candidate solution list is developed. Candidate list is searched for selecting the best solution [90], [91]. The best solution is the solution that has minimum values of delay and jitter.

In this paper, to obtain the new solutions, memory mechanisms (short-term, mid-term, and long-term) are applied. A short-term memory is used to avoid generating repeated solutions [90], [91]. Short-term memory performs based on a list of forbidden solutions called “tabu list”. A new solution, before to be selected as a best solution, is compared with the solutions in the tabu list. If the new solution exists in the tabu list, it should be neglected to avoid generating repeated solutions. When the best solution is selected, it is inserted in to the end of tabu list. When the tabu list is full, the first solution is removed from the list. The size of tabu list in this strategy is set with 50. Briefly, the short term memory stores the best solutions founded recently.

Mid-term and long-term memory mechanisms are used for intensification and diversification of optimal solutions, respectively. Mid-term memory mechanism can help intensify the search within some specific areas of solution space. This specific area is determined using the recently best solutions from the tabu list. Indeed, the mid-term memory mechanism intensifies the search in the neighborhood of the best solutions. Finally, the long-term memory mechanism restarts the search process to create various solutions to avoid entrapping in the local minima. For this purpose, the new solutions should be selected far from the previous solutions within the tabu list that often needs to generate new initial solution.

The last element of Tabu Search algorithm is the terminating rules which can be defined based on different criteria including the number of iterations, the expectation time, and the performance criteria. In this paper, Tabu Search is terminated based on the number of iterations. Considering 136 possible combinations of transmission range and rate values, half of these combinations is set for number of iterations within proposed Tabu Search algorithm. The pseudo code of Tabu Search algorithm in each node is presented in Figure 4.2.

As mentioned before, for tuning transmission range and rate, a multi-objective Tabu Search is applied in which the delay and jitter function are considered as the objective functions. In the following, the delay and jitter functions are described.

```
Input:
Max size of TabuList
Number of Iteration
Diversification Counter

Output:
S_best (Best_Delay, Best_Jitter, Best_Transmission_Range, Best_Transmission_Rate)

1. S_0 ← genInitSolution() // current delay and jitter based on current situation of node
2. S_best ← S_0
3. Divers_count ← 0
4. insert TabuList(S_best)
5. i ← 0
6. while (i< Iteration) do
7.      N(s) ← Identify (Neighborhood set) // Changing the value of parameters between the predefined boundaries with considering Mid-Term Memory
8.      T(s) ← Identify (TabuList) // Short-Term Memory
9.      CandidateList(s) ← N(s) – T(s)
10.     if empty ( CandidateList(s)) // Long-Term Memory
11.             Divers_Count++;
12.             if Divers_Count ==Diversification Counter // entrap in local minima
13.                     Go to 1
14.             End if
15.       End if
16.       while (! empty ( CandidateList(s)) )
17.             if ( Delay(S_candidate ) <  Delay_best AND Jitter(S_candidate ) < Jitter_best)
18.                  S_best ← S_candidate
19.                  Divers_Count ← 0;
20.                    break;
21.             End if
22.     End while

  // Update-Tabu-List

23. if (LengthTabuList < MaxSizeTabuList)
24.            Add S_best to TabuList
25. else
26.          Delete the oldest item in TabuList
27.          Add S_best to TabuList
28. End while

29. Return( S_best)
```

Figure 4.2: Pseudo code of Tabu Search algorithm in the proposed congestion control strategy.

Delay is a period of time under which a packet is delivered from source to destination. The delay is composed of the processing delay ($D_{proc}$), queuing delay ($D_{queue}$), transmitting delay ($D_{trans}$), and propagation delay ($D_{prob}$) [95]. The processing delay is the time needed for extracting header of packets and executing various algorithms (e.g., routing algorithms, congestion control algorithms, so on). The queuing delay is the waiting time of a packet in a queue before transferring. The transmitting and propagation delays are the required time for transferring, and propagation of the packet, respectively. Thus:

$$\boldsymbol{Delay} = \left(\boldsymbol{D_{proc}} + \boldsymbol{D_{queue}} + \boldsymbol{D_{trans}} + \boldsymbol{D_{prop}}\right)\left\lceil \frac{\boldsymbol{d}}{\boldsymbol{TX}} \right\rceil \quad (4.1)$$

where $d$ is the distance between the sender and the receiver, and $TX$ is transmission range. Thus, $\left\lceil \frac{d}{TX} \right\rceil$ is the number of hops between the sender and the receiver.

The processing delay can be omitted in our computations. This is due to the fact that processing delay (nanosecond) is smaller than other delay factors (millisecond). The queuing delay is calculated by Equation (4.2):

$$\boldsymbol{D_{queue}} = \frac{1}{\mu-\lambda} - \frac{1}{\mu} . \frac{Q_L \rho^{Q_L}}{1-\rho^{Q_L}} \quad (4.2)$$

where, $\rho$ is utilization which is equal to $\frac{\lambda}{\mu}$, where $\lambda$ and $\mu$ are packet arrival rate and packet service rate, respectively. $Q_L$ shows maximum queue length.

Transmission delay is calculated by Equation (4.3):

$$\boldsymbol{D_{trans}} = \boldsymbol{T_B} + \boldsymbol{T_F} + \boldsymbol{T_T} \quad (4.3)$$

where $T_B$ is back-off delay, $T_F$ is freezing back-off delay, and $T_T$ is successful transmission delay.

Back-off delay ($T_B$) is obtained using Equation (4.4):

$$\boldsymbol{T_B} = \begin{cases} \frac{W_{min}.\eta}{2}.\left(2^{N_{RT}} - 1\right) & N_{RT} \leq m \\ \frac{\eta}{2}.\left(W_{max} - W_{min} + W_{max}.\left(N_{RT} - m\right)\right) & N_{RT} > m \end{cases} \quad (4.4)$$

where $\eta$ shows the back-off time slot length which is equal to 20 microseconds in vehicular networks, $W_{max}$ is the maximum contention window size equal to 1024 timeslots, $W_{min}$ is the minimum contention window size equal to 32, $m$ is the maximum number of back-off stage that is calculated by $W_{max}=2^m W_{min}$, thus m is equal to 5 based on IEEE 802.11 standard. $N_{RT}$ is the number of expected (re)transmissions upon success delivery which is calculated by Equation (4.5):

$$\boldsymbol{N_{RT}} = \sum_{s=1}^{7} s{P_C}^{s-1}(1 - P_C) = \frac{1-8{P_C}^7+7{P_C}^8}{1-P_C} \quad (4.5)$$

where $s$ is the number of back-off stages, the maximum $s$ is equal to 7 based on IEEE 802.11 standard. $P_C$ is also the collision probability calculated in exponential back-off mechanism of 802.11:

$$\boldsymbol{P_C} = \frac{2W_{min}.N_C}{(W_{min}+1)^2+2W_{min}.N_C} \tag{4.6}$$

where $N_C$ denotes the number of contenders within the transmission range.

Freezing back-off time occurs when the channel is busy. $T_F$ is obtained using Equation (4.7):

$$\boldsymbol{T_F = N_C + (N_C + 1).\left(\frac{N_{RT}-1}{\sum_{t=2}^{N_C} t.f(t)}\right).P_T} \tag{4.7}$$

$P_T$ is the time period for packet transmission including SIFS, DIFS, Data and ACK. $t$ is a counter which tracks the number of contenders within the transmission range. $f(t)$ shows the number of retransmissions when the collision occurs:

$$\boldsymbol{f(t) = \binom{N_C}{t}\tau^t.(1-\tau)^{N_C-t} = \left(\frac{N_C}{t!(N_C-t)!}\right).\tau^t.(1-\tau)^{N_C-t}} \tag{4.8}$$

where $\tau$ is transmission probability that can be calculated based on formula Equation (4.9):

$$\boldsymbol{\tau = \frac{2(1-p_0)}{w_0-1}} \tag{4.9}$$

where $w_0$ is current back-off window size equal to $8V$, where $V$ is the number of vehicles in the transmission range ($V$ is constant during broadcasting), $p_0$ is the probability that there is no ready packet to transmit at the MAC layer in each vehicle:

$$\boldsymbol{p_0 = 1 - \frac{\lambda}{\mu}} \tag{4.10}$$

The success transmission delay is the time to transmit a packet successfully:

$$\boldsymbol{T_T = \frac{S}{TR}} \tag{4.11}$$

where $S$ and $T_R$ are the packet size and transmission rate, respectively.

Finally, the propagation delay is calculated by:

$$\boldsymbol{D_{prop} = \frac{d}{c}} \tag{4.12}$$

where $c$ is the light speed equal to 3×108 m/s.

The second objective function of Tabu Search is jitter function. The jitter function is usually expressed as the average of latency variance. In other words, the jitter is estimated iteratively based on the changes between inter arrival time of *i*th and *(i-1)*th packets :

$$\boldsymbol{J}(\boldsymbol{i}) = \boldsymbol{J}(\boldsymbol{i}-\mathbf{1}) + \frac{|\boldsymbol{D}(\boldsymbol{i}-\mathbf{1},\boldsymbol{i})| - \boldsymbol{J}(\boldsymbol{i}-\mathbf{1})}{\mathbf{16}} \qquad (4.13)$$

where *J(i)* is the jitter of *i*th packet, and *D(i-1,i)* is the difference between transmission times of *i*th and *(i-1)*th packets:

$$\boldsymbol{D}(\boldsymbol{i}-\mathbf{1},\boldsymbol{i}) = (\boldsymbol{R}_{\boldsymbol{i}-\mathbf{1}} - \boldsymbol{R}_{\boldsymbol{i}}) - (\boldsymbol{S}_{\boldsymbol{i}-\mathbf{1}} - \boldsymbol{S}_{\boldsymbol{i}}) = (\boldsymbol{R}_{\boldsymbol{i}-\mathbf{1}} - \boldsymbol{S}_{\boldsymbol{i}-\mathbf{1}}) - (\boldsymbol{R}_{\boldsymbol{i}} - \boldsymbol{S}_{\boldsymbol{i}}) \qquad (4.14)$$

where, $S_i$, and $R_i$ are the time stamp, and arrival time of *i*th packet, respectively. In Equation(4.13), the second term is divided by 16 to reduce the influence of large random changes, and the noises effecting on estimating jitter [96].

Therefore, Tabu Search calculates delay and jitter using Equations (4.1) to (4.14). Then, optimal transmission range and rate are obtained by minimizing the value of delay and jitter.

## 4.5 Performance Evaluation

### 4.5.1 Simulation Parameters and Scenarios

Mobility and network simulators are required to evaluate the performance of the proposed strategy. In this paper, the mobility simulator Simulation of Urban MObility (SUMO) was used for simulation of vehicular environments and vehicles movements [97], [98]. SUMO generates a microscopic movement pattern of vehicles traffics and roads topologies. The network simulator NS2 (version NS2.35) was used for simulation of VANet. NS2 is one of the best network simulator which has been used and confirmed by many researchers [99]. Application of SUMO and NS2 for evaluating the proposed strategy helps overcome the limitations and complexities associated with implementing of the proposed strategy in real vehicular networks. The MObility model generator for VEhicular networks (MOVE) is used to connect the mobility simulator to the network simulator [100]. MOVE converts microscopic movement patterns from SUMO to acceptable scenarios of nodes movement for NS2. Therefore, using SUMO, MOVE and NS2, an environment very similar to VANets can be created to evaluate the performance of the proposed strategy to control congestion.

In this paper, two scenarios were considered: i) a highway scenario (six lanes, three in each direction), and ii) an urban scenario (Manhattan road pattern). These two scenarios led to two different levels of congestion. According to VANets standards, communications between vehicles, and also between vehicles and infrastructures units are established by IEEE 802.11p protocol. Moreover, data transmissions in MAC layer are carried out based on CSMA/CA strategy. TwoRayGround and Nakagami propagation models were used for traffic propagation in highway and urban scenarios, respectively. Poisson distribution was used for data generations. The simulation time was set 200 seconds because the preliminary results showed that after 150 second the results become nearly steady. Table 4.1 shows the parameters used in the simulation of highway and urban scenarios.

Table 4.1: Configuration parameters for simulation of highway or urban scenarios.

| **Parameters** | **Value** |
|---|---|
| Total road length | 2400 m*, and 652 m×752 m** |
| Number of lanes | 6 (3 in each direction)*, and 4 (2 in each direction)** |
| Number of Vehicles | 50,80,100,120,150,200 |
| Vehicles speed | 80-120 km/h* and 0-40 km/h** |
| Transmission range | 15 – 1000 m |
| Transmission rate | 3-27 Mbps |
| Contention window size | 15-1023 |
| Bandwidth | 10MHz |
| Safety messages generation rate | 10 packet/s |
| MAC type | 802.11p |
| Propagation model | TwoRayGround*, and Nakagami (m=3)** |
| Simulation time | 200 s |
| Simulation runs | 20 |

* Highway Scenario
** Urban Scenario

### 4.5.2 Simulation Results

To assess the performance of the proposed congestion control strategy, a comparison is conducted between the results obtained from the proposed MOTabu strategy and five existing congestion control strategies: CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu that have been reviewed in background and related works. Note that PRBC represents congestion control strategy introduced in [79]. For the purpose of comparison, five metrics are evaluated:

*Average Delay*: This criterion shows the duration of time required to deliver a packet from the sender to the receiver;

*Number of Packets Loss*: The number of packets loss during simulation time is an appropriate criterion to estimate the network's performance;

*Average Throughput*: Average throughput measures the average rate of messages successfully transmitted over the communication channels;

*Packet Loss Ratio*: This metric is calculated by dividing the number of packet losses by the number of packet transmissions for each receiver;

*Number of Retransmissions*: This metric calculates the average number of retransmissions of packets during the simulation time.

In the following, the variations of these metrics with the number of vehicles and simulation time were investigated to compare the performance of the MOTabu with CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies. Figure 4.3 to Figure 4.8 show the performance of the Congestion Control (CC) strategies in highway scenario, whereas Figure 4.9 to Figure 4.14 show the performance of the congestion control strategies in urban scenario.

First objective of the proposed congestion control strategy is to decrease packet loss. Figure 4.3 depicts the variation of the number of packet loss/packet loss ratio with the number of vehicle for each congestion control strategies. Figure 4.3 (a) shows that the number of packet loss in Tabu Search congestion control strategies (i.e., MOTabu, and UOTabu) is less than the other strategies, regardless of the number of vehicles. Such improvement was obtained because Tabu Search strategies tune the transmission range and rate for the all safety and non-safety messages. Note that, to control congestion, CSMA/CA varies back-off and contention window size, D-FPAV varies the beaconing range, PRBC adjusts the beaconing rate and power, and CABS schedules the beacon messages. Figure 4.3 (a) also shows that the performance of MOTabu strategy is better than UOTabu strategy. Here, it should be emphasized that congestion control in MOTabu strategy is carried out by minimizing both delay and jitter, while in UOTabu strategy only delay is considered. Thus, MOTabu strategy makes a discipline to transfer the packets between the vehicles. Moreover, MOTabu increases the performance of data transmissions by generating a synchronous data transferring that results from a short transmission time (delay) and a small latency variance (jitter).

In Figure 4.3 (b), the variations of the packet loss ratio with the number of vehicle are depicted for each congestion control strategy. Figure 4.3 (b) shows that in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu and MOTabu strategies, the packet loss ratio for the number of vehicles 50 is equal to 19%, 16.5%, 12%, 8%, 3%, and 1%, while for the number of vehicles 200, the packet loss ratio is equal to 38%, 32%, 27%, 21%, 10%, and 3%, respectively. The results show that by increasing the number of vehicles from 50 to 200, the packet loss ratio increases in all the strategies. However, increasing the number of vehicles increases the packet loss ratio 17%, 15.5%, 15%, 13%, 7%, and 2% in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu, respectively. It means increasing the number of vehicles does not have a significant impact on packet loss ratio when MOTabu strategy is used to control congestion. As a result, the proposed Tabu Search congestion control strategy can be considered as a scalable distributed strategy.

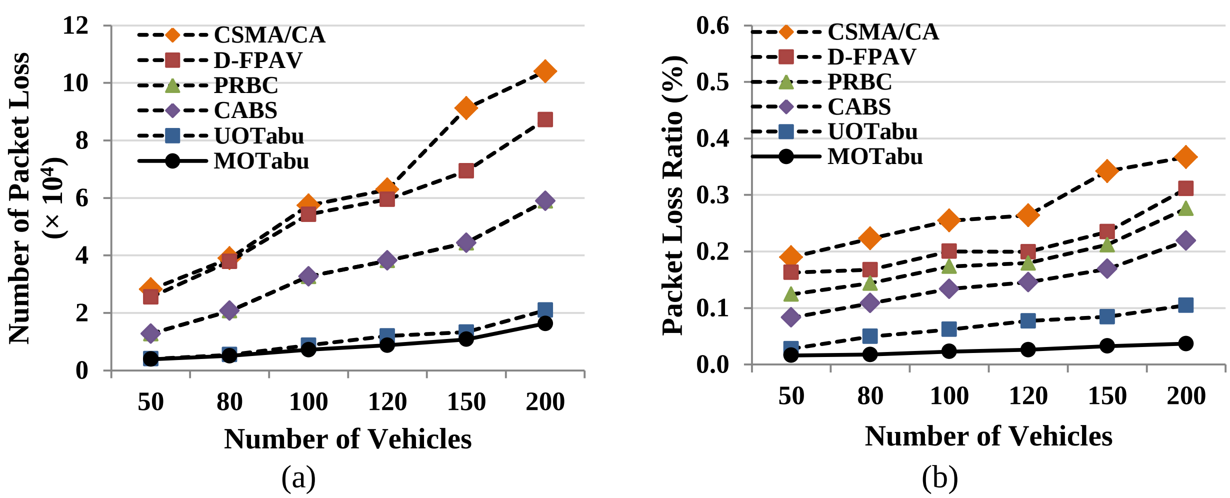



Figure 4.3: Variation of (a) the number of packet loss, and (b) the ratio of packet loss with the number of vehicles in highway scenario.

Briefly, the results shown in Figure 4.3 (a) and (b) prove that the proposed Tabu Search strategy can control the congestion in highways more efficiently than the other strategies. Decreasing the number of packet loss especially emergency messages can help provide a more reliable and safe environment in VANets.

Figure 4.4 illustrates the variation of the number of retransmissions with the number of vehicles for each congestion control strategy. As the figure shows, the number of retransmission for the number of vehicles 200 in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu and MOTabu strategies, is equal to 15.31×105, 14.21×105, 4.35×105, 3.15×105, 1.51×105, and 0.97×105, respectively. Thus, in Tabu Search strategies, especially MOTabu, the numbers of retransmissions are less than the other strategies. Note that the packets need to be retransmitted after the packet loss. Thus, reducing the packet loss (Figure 4.3) results in the reduction of the number of packet retransmissions (Figure 4.4). MOTabu strategy decreases the packet loss and the number of retransmissions through tuning transmission range and rate for both safety and non-safety messages. Note that although non-safety messages compose the larger portion of messages, the other congestion control strategies do not consider the non-safety messages during the congestion control process.

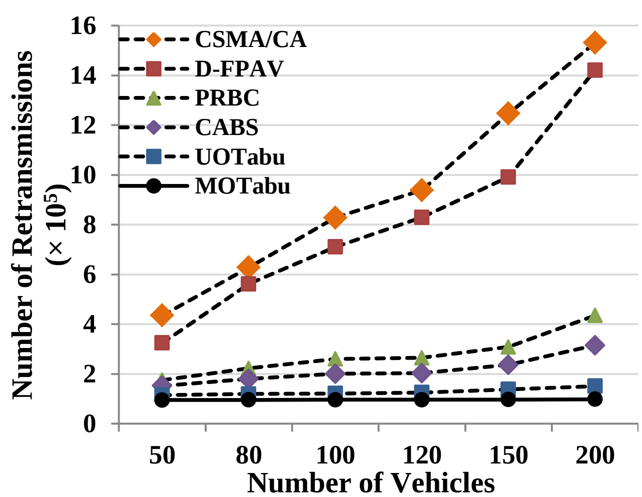



Figure 4.4: Variation of the number of retransmissions with the number of vehicles in highway scenario.

The second objective of the congestion control strategy is to decrease delay. Figure 4.5 depicts the variation of delay with the number of vehicles for each congestion control strategy. As the figure shows, when the number of vehicles increases from 50 to 200, the delay increase from 16.04, 14.82, 11.45, 7.84, 3.04, and 3.03 milliseconds to 72.59, 49.68, 45.98, 34.11, 8.71, and 7.27 milliseconds in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. The results show that the delay in Tabu Search strategies (MOTabu and UOTabu) is significantly less than the other strategies. It can be also seen that the delay in MOTabu is slightly less than the delay in UOTabu strategy. As it was mentioned before, in UOTabu, the delay is minimized for tuning transmission range and rate. However, in MOTabu, both the delay and jitter are minimized for tuning transmission range and rate. It should be emphasized that Tabu Search algorithm finds near optimal solution. The results show that using MOTabu strategy, an arranged messages transferring in reasonable time can be obtained.

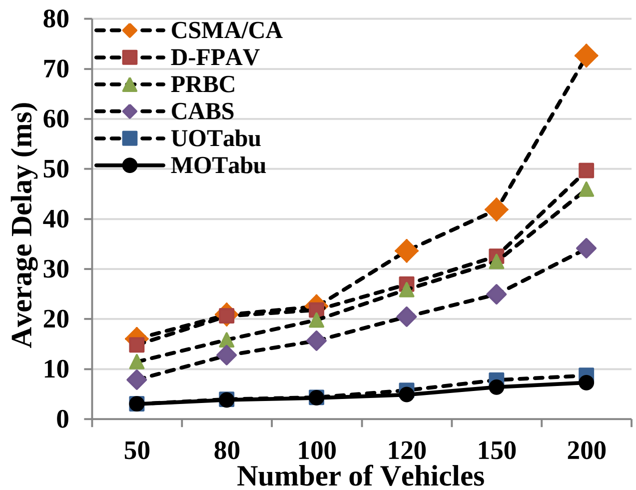



Figure 4.5: Variation of average delay with the number of vehicles in highway scenario.

The impacts of the number of vehicles on throughput were also studied to evaluate the performance of MOTabu Search strategy to control congestion in VANets. As Figure 4.6 shows, throughput increases by increasing the number of vehicles because increasing the number of vehicles leads to increase the number of delivered packets. In this figure, two comparison strategies were removed to make a sparse and readable graph. The figure shows that, for the number of vehicles 200, throughput is equal to 34.09, 35.71, 37.09, and 38.19 Kbps in

CSMA/CA, D-FPAV, UOTabu, and MOTabu strategies, respectively. MOTabu has slightly better performance than the compared strategies because, as it was shown in the previous figures, using MOTabu strategy, channel collisions decreased and channel utilization improved.

In Figure 4.3, Figure 4.4, Figure 4.5, and Figure 4.6, the congestion control strategies were evaluated using the variations of the performance metrics (i.e., number of packet loss, packet loss ratio, number of retransmission, average delay, and throughput) with the number of vehicles. The evaluations revealed that MOTabu strategy outperforms the other congestion control strategies. MOTabu creates a discipline to transfer the packets by minimizing the delay and jitter leading to dynamically tuning transmission range and rate based on the current situation of the network. In the following, the variations of the delay and throughput with the simulation time are illustrated in Figure 4.7 and Figure 4.8 for more evaluation of the proposed strategy when the number of vehicles is 50.

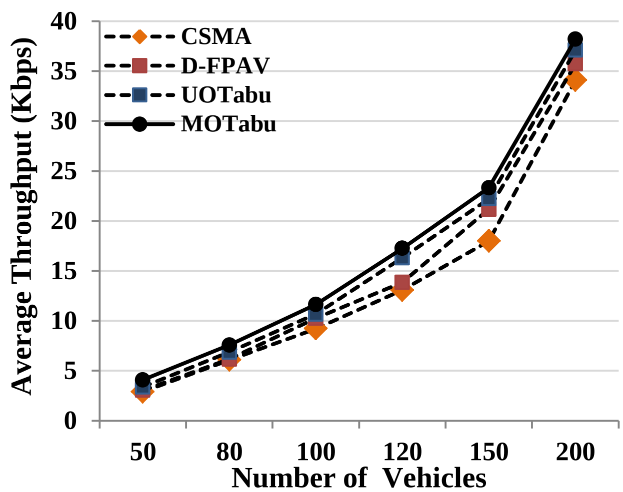



Figure 4.6: Impact of the number of vehicles on throughput in highway scenario.

Figure 4.7 shows the variation of the average delay with the simulation time. In this figure, the average delay is investigated at four levels of simulation time: 50, 100, 150, and 200 second. Note that the delay at the simulation time zero is zero. The results show that by advancing the simulation time, the delay of delivering data packets to destinations is decreased for all the strategies, as it is expected. The delay at simulation time 200 second for CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu is 1.04, 0.48, 0.69, 0.42, 0.29, and 0.25 second. As it is expected, the lowest delay is obtained using MOTabu strategy at each simulation time. Moreover, the results show that within first 50 second (from simulation time 50 to 100 second), the average delay decreases 0.16, 0.52, 0.45, 0.55, 0.64, and 0.71 second using CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. It means MOTabu strategy can reduce the average delay more rapidly within the simulation time compare to the other strategies. In other word, although the delay is high at the beginning of the simulation due to more collisions occurrence in the transmissions, it rapidly decreases as long as the congestion is controlled by MOTabu.

In Figure 4.8, the variations of the average throughput with the simulation time are shown for each congestion control strategy. The results show that the average throughput obtained from MOTabu strategy is larger than the other five strategies at any simulation time. In fact, controlling the congestion and decreasing the number of packet loss cause to increase the number of delivered packets over the simulation time, and consequently the throughput efficiency increases with passing the time.

In the following, urban scenario is investigated to evaluate the performance of the proposed congestion control strategy under a high level of congestion. In the urban scenario to consider existing obstacles in the urban environment (e.g. buildings, trees), Nakagami model is employed instead of TwoRayGround model for radio propagation. The Nakagami model is a suitable propagation model for simulating physical fading of mobile communication channels [14]. The other characteristics of urban scenario were shown in Table 4.1. Figure 4.9 to Figure 4.14 depict the results obtained from the urban scenario.

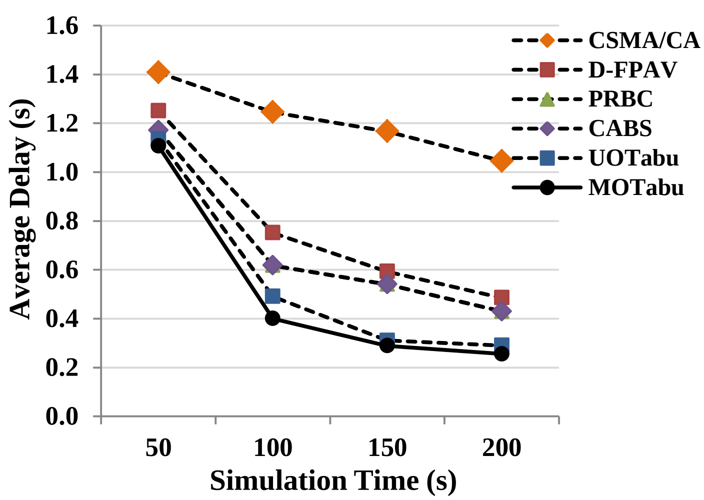



Figure 4.7: Variation of the average delay with the simulation time in highway scenario.

Figure 4.9 illustrates the variation of the number of packet loss/packet loss ratio with the number of vehicles for each congestion control strategies. The figure shows that the number of packet loss/packet loss ratio increases by increasing the number of vehicles regardless of the congestion control strategies. However, rate of changes in MOTabu strategy is much less than the other strategies. For example, in Figure 4.9 (a), the number of packet loss for number of vehicles 200 is 6.76, 6.49, 5.95, 4.58, 3.47, and 1.23 times more than the number of packet loss for number of vehicles 50, in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. Figure 4.9 (b) shows that the packet loss ratio obtained from MOTabu strategy is 10.5, 9.8, 7.4, 5.5, and 3.4 times less than CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu, respectively, for the number of vehicles 200. Such results show that MOTabu strategy can significantly reduce packet loss in urban scenario in regard to the other strategies.

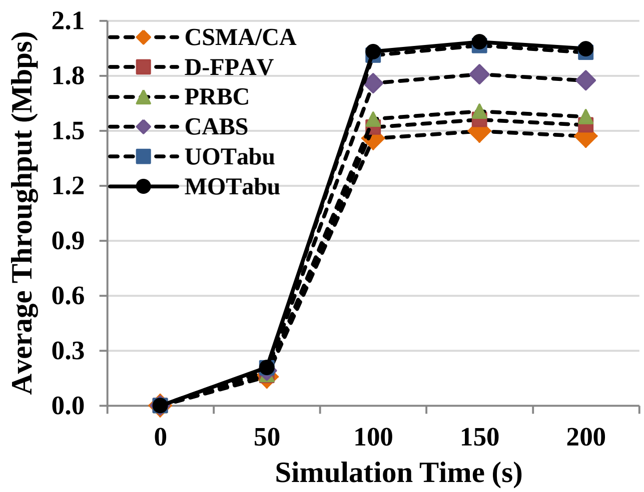



Figure 4.8: Variation of the average throughput within the simulation time in highway scenario.

Additionally, Figure 4.10, Figure 4.11, and Figure 4.12 show the impacts of the number of vehicles on the number of retransmissions, delay, and throughput for each congestion control strategy in the urban scenario, respectively. In MOTabu strategy, the number of packet loss/the packet loss ratio is less than the other strategies (Figure 4.9). Such improvement lead to reduce the number of retransmissions (Figure 4.10) and delay (Figure 4.11), and to increase the throughput (Figure 4.12) in MOTabu strategy in regard to CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies. Note that the performance metrics in urban scenario has larger values than that in the highway scenario due to the miscellaneous environment of urban scenario.

Figure 4.10 illustrates that the number of retransmissions obtained from MOTabu strategy, 94%, 93%, 90%, 84%, and 30% decreases in respect to CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies, respectively, for the number of vehicles 200. By investigating the results shown in Figure 4.11, it can be concluded that the average delay obtained from MOTabu for the number of vehicles 200 is at least 48% less than the other congestion control strategies. Figure 4.12 shows that the average throughput for the number of vehicles 200 is equal to 13.97, 21.12, 26.96, 30.42, 34.75, and 38.73 Kbps in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. It means at least 10% improvements can be obtained for the throughput using MOTabu strategy to control congestion in VANETs.

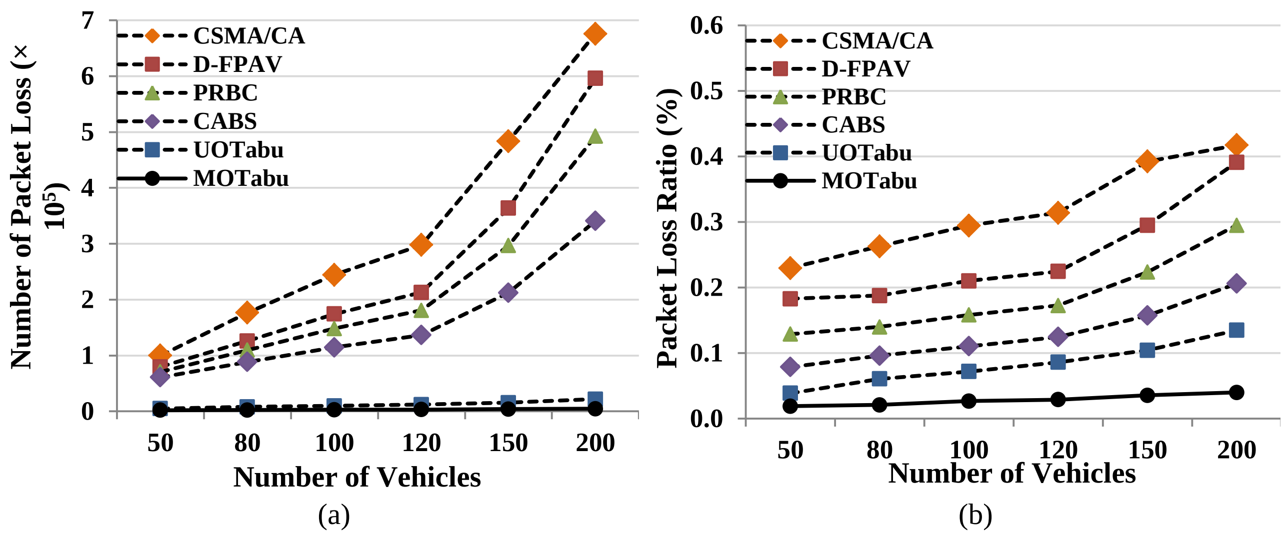



Figure 4.9: Variation of (a) the number of packet loss, and (b) the ratio of packet loss with the number of vehicles in urban scenario.

Finally, Figure 4.13 and Figure 4.14 illustrate the variation of the average delay and throughput with the simulation time in various congestion control strategies in urban scenario when the number of vehicles is 50. Figure 4.13 shows that after 150 second (from 50 to 200 second), 12.4%, 46.8%, 42.8%, 63.2%, 69%, and 76.8% reduction is observed in the average delay in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu strategies, respectively. Figure 4.14 shows that the throughput at simulation time 200 seconds in CSMA/CA, D-FPAV, PRBC, CABS, UOTabu, and MOTabu is 1.29, 1.36, 1.43, 1.57, 1.69, and 1.72 Mbps. These results shown in Figure 4.13 and Figure 4.14 conclude that in urban scenario similar to highway scenario, MOTabu strategy decreases average delay rapidly and increases average throughput significantly rather than the other congestion control strategies. In the other words, MOTabu strategy outperforms the other strategies because MOTabu strategy dynamically tunes transmission range and rate for all kinds of messages (safety and non-safety) in congestion situations by minimizing the delay and jitter.

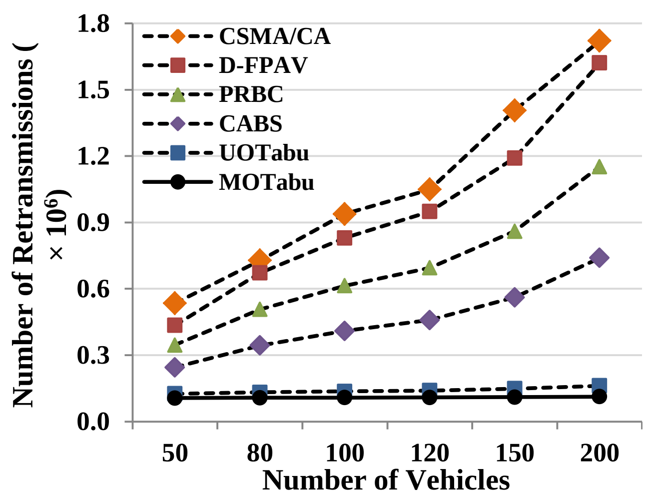



Figure 4.10: Variation of the number of retransmissions with the number of vehicles in urban scenario.

## 4.6 Summary and Conclusion

In this paper, a MOTabu strategy was presented to control congestion in VANets. The proposed strategy was a closed-loop congestion control strategy that consists of congestion detection and congestion control components. Channel usage level was measured to detect congestion. The Multi-Objective Tabu Search was used to control congestion. The proposed strategy controlled congestion dynamically by tuning transmission range and rate for all kinds of messages (safety and non-safety), whereas delay and jitter were minimized. The proposed strategy was also distributed that means the strategy was executed in each vehicle. To reduce the complexity related to implementation of Tabu Search algorithm in the proposed strategy, some simplifying assumptions were made (e.g. assuming discrete values for transmission range and transmission rate; and also assuming constant value for the iteration number for Tabu Search algorithm).

Considering a highway and urban scenario, the performance of MOTabu was compared with five existing congestion control strategies including CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu. For comparison purposes, variations of performance metrics with the number of vehicles and simulation time were investigated. The comparison showed that the proposed strategy can control congestion more efficiently by tuning transmission range and rate. MOTabu strategy improved the number of packet loss, packet loss ratio, number of retransmissions, average delay, and average throughput. Consequently, the transmission range and rate were optimally increased or decreased while it takes into account minimizing delay and jitter by MOTabu. Control congestion using MOTabu strategy help create more reliable environments in VANets.

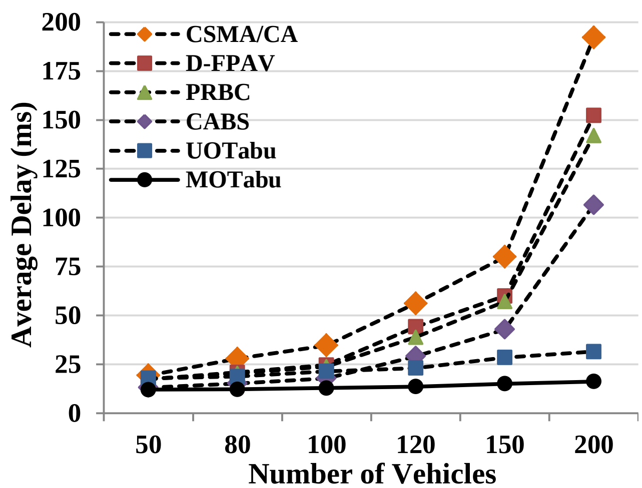



Figure 4.11: Variation of delay with the number of vehicles in urban scenario.

There are some limitations to implement the proposed strategies in real vehicular network. To implement this strategy, all the vehicles need to equip with an On-Board Unit (OBU) to do real time computations. The vehicles should be able to estimate channel usage level for detecting congestion situation. Also, the vehicles should be able to dynamically tune transmission range and rate. Moreover, the values of transmission range and rate need to be discretized due to the limitations of Tabu Search Algorithm. Finally, the vehicles should be equipped with GPS to determine speed, direction, and position of vehicles to estimate the delay and jitter.

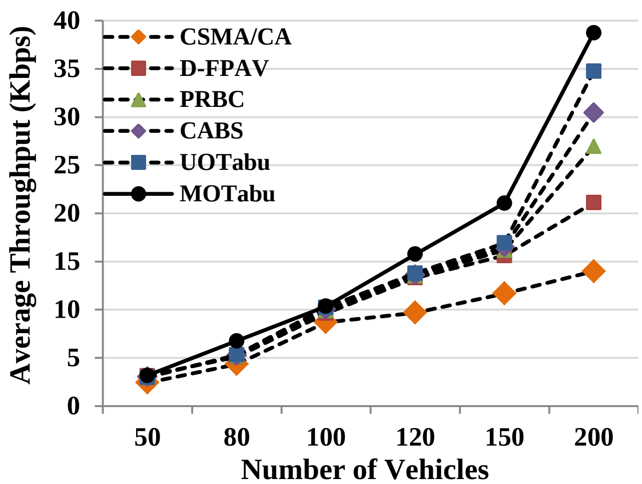



Figure 4.12: Impact of the number of vehicles on throughput in urban scenario.

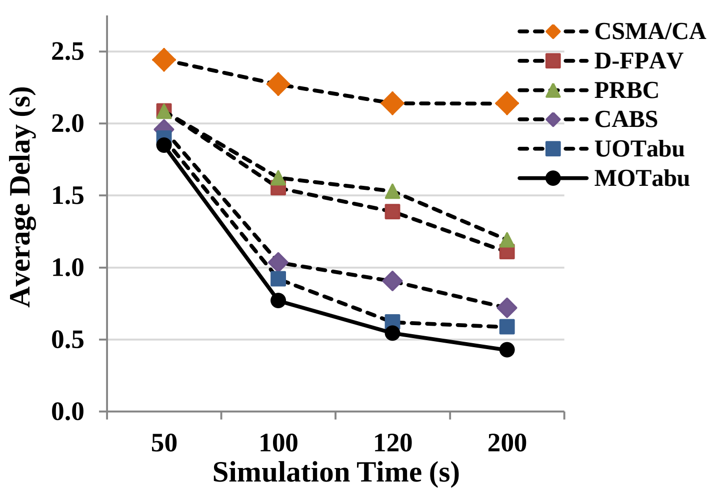



Figure 4.13: Variation of the average delay with the simulation time in urban scenario.

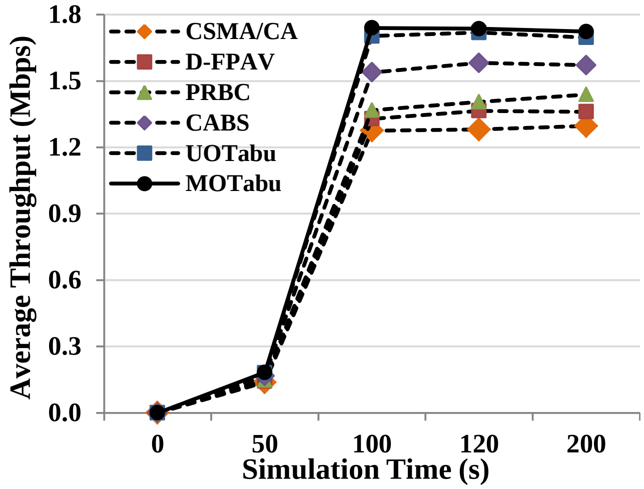



Figure 4.14: Variations of the average throughput within the simulation time in urban scenario.

# CHAPTER 5 ARTICLE 2: PRIORITIZING AND SCHEDULING MESSAGES FOR CONGESTION CONTROL IN VEHICULAR AD HOC NETWORKS

N. Taherkhani [1], S. Pierre [1]

[1]Mobile Computing and Networking Research Laboratory (LARIM), Department of Computer Engineering, Polytechnique de Montréal, Montreal, Canada

## Abstract

Vehicular Ad Hoc Networks (VANets) is considered as a technology which can increase safety and convenience of drivers and passenger. Due to channel congestion in high density situation, VANets' safety applications suffer of performance degradation. In order to improve performance, reliability, and safety over VANets, congestion control should be taken into account. However, congestion control is a challenging task due to the special characteristics of VANets (e.g. high mobility, high rate of topology change, frequently route break, and so on). In this paper, DySch and TaSch strategies are proposed. Those strategies assign priorities to the safety and service messages based on the content of messages (static factor), state of network (dynamic factor) and size of messages. DySch and TaSch strategies schedule the messages dynamically and heuristically, respectively. Their performance is investigated using highway and urban scenarios while the average delay, average throughput, number of packet loss, packet loss ratio, and waiting delay in queues are considered. Simulation results show that DySch and TaSch strategies can significantly improve the performance of VANets in comparison to the best conventional strategies. Employing the proposed strategies to control congestion in VANets helps increase reliability and safety by giving higher priority to the safety messages.

***Keywords*** — Congestion Control, Message Priority, Meta-heuristic Techniques, Queue Scheduling, Tabu Search, and Vehicular Ad Hoc Networks.

## 5.1 Introduction

Vehicular Ad hoc Network (VANet) is a sort of Mobile Ad hoc Network (MANet) that aims at employing wireless technologies within Intelligent Transport Systems (ITSs). Dedicated Short Range Communication (DSRC) defines protocols and standards for conducting the Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications in VANets. VANet has special characteristics such as high rate of topology change, high mobility of nodes, high nodes density, sharing the wireless channel, and frequently route break. Those special characteristics in VANets give rise to some challenges in data transferring and scheduling [1]-[4].

When the channels are saturated due to the increasing number of vehicles, congestion happens in the networks. In other words, when the vehicles send messages simultaneously in high density situations, the shared channels are easily congested. Congestion indeed leads to overload the Medium Access Control (MAC) channels, increases the packet loss and delay, and consequently decreases the performance of VANets. Therefore, congestion should be controlled for enhancing the reliability of VANets [8]-[11]. Congestion control strategies aim at controlling the load on the shared channels and provide a fair channel access among the vehicles. Various strategies have been designed in each layer of network communication to control the congestion in VANets. Some of these strategies, which are designed for MAC layer, define priority for the messages and schedule them in different communication channels [42], [43]. Data prioritizing and scheduling, that help serve more requests, reduce download delay and packet loss, and so on [29], [101].

DSRC uses a 75MHz bandwidth at 5.9 GHz for performing V2V and V2I communications and transferring the safety and service messages in VANets. DSRC employs IEEE 802.11p and IEEE 1609 standards for managing the performance of network by Wireless Access in Vehicular Environment (WAVE) systems. IEEE 1609.4 standard is also used to implement multi-channel in VANets. The DSRC bandwidth is composed of eight channels that consist of six 10MHz service channels (SCH) for non-safety communications, one 10MHz control channel (CCH) for safety communications, and one 5MHz reserved channel for future uses. Figure 1.1 shows channel allocation within DSRC. Normally, the control and service communication channels are used for different prioritized messages. Control channel is used to transmit high priority safety messages including emergency and beacon messages, and service channels are used to transmit low priority service messages [4]-[6].

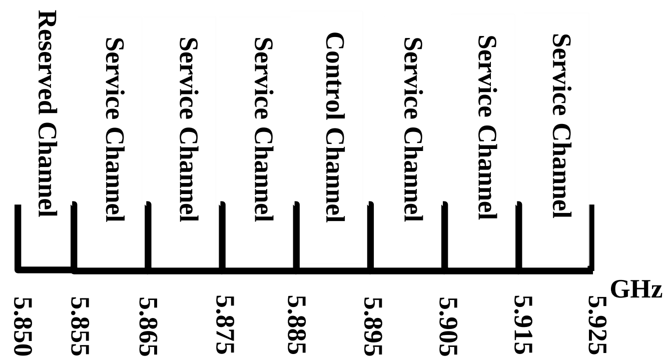



Figure 5.1: DSRC channel allocation [6].

All vehicles are synchronized by Coordinated Universal Time (UTC) to operate multi-channel on a single radio transceiver in VANets. The UTC is obtained based on information acquired from Global Positioning System (GPS) or the other vehicles. The vehicles adjust their time based on UTC and synchronously switch between CCH and SCH intervals. The IEEE 1609.4 WAVE protocol results in high delay to deliver high priority safety messages due to periodically switching between channels [30], [31].

To solve this issue, Enhanced Distributed Channel Access (EDCA) mechanism was considered in DSRC. EDCA assigns priorities to the messages such that the high priority messages have a higher chance to be sent. In other words, the high priority messages wait less than the low priority messages to occupy channel. This is accomplished by determining a shorter Contention Window (CW) and Arbitration Inter-Frame Space (AIFS) for high priority messages, as shows in Table 5.1 [17]-[19].

As it was mentioned before, when the number of vehicles increases, the control and service channels overload, and consequently congestion happens in the network that leads to increase delay and packet loss. Congestion in control channel can also occur when load of beacon messages increases due to high vehicle density. In this situation, safety messages (especially emergency messages) cannot be properly transmitted due to deficiency in the messages scheduling. It should be also noted that the scheduling in VANets is faced to some challenges because of sharing wireless communication channel, and employing multi-channel technology with single-radio transceivers. Therefore, an efficient scheduling is required to have more safe and reliable VANets [10], [15], [54].

In this paper, two congestion control strategies are presented to prioritize and schedule the safety and service messages. The proposed strategies consist of priority assignment unit, and message scheduling unit. The priority assignment unit assigns priority to each message based on static and dynamic factors. Then, the message scheduling unit reschedules the prioritized messages in the control and service channel queues. The performances of the proposed strategies are evaluated using various performance metrics including number of packet loss, packet loss ratio, average delay, and average throughput. The rest of the paper is organized as follows. Section 5.2 reviews the existing congestion control and messages scheduling strategies in VANets. Section 5.3 proposes the new strategies to control congestion that prioritize and schedule the messages. Section 5.4 applies the proposed strategies in a highway and urban scenarios and discusses the obtained results.

Table 5.1: Contention Window (CW) boundaries for each kind of the messages in EDCA [17].

| **Messages** | **$CW_{min}$** | **$CW_{max}$** | **AIFS** |
|---|---|---|---|
| Background | $CW_{min}^{*}$ | $CW_{max}^{*}$ | 7 |
| Best Effort | $CW_{min}$ | $CW_{max}$ | 3 |
| Video | $(CW_{min}+1)/2-1$ | $CW_{min}$ | 2 |
| Voice | $(CW_{min}+1)/4-1$ | $(CW_{min}+1)/2-1$ | 2 |

$^{*}CW_{min}=15$ and $CW_{max}=1023$ as the default in DSRC [17]-[19].

## 5.2 Background and Related Works

Congestion Control strategies are employed to achieve high communication reliability and bandwidth utilization within the networks. Generally, there are two types of congestion control mechanisms in networks: 1) open-loop mechanism that avoids the congestion before it happens, and 2) closed-loop mechanism that controls the congestion after it happens [34]. Congestion control strategies in VANets can be classified in to three categories: 1) controlling the power of transmissions, 2) controlling the rate of transmissions, and 3) prioritizing and scheduling the messages in communication channels [15].

The prioritizing and scheduling the messages is a very common open-loop congestion control strategy in communication channels. Some performance metrics should be considered to increase efficiency of message scheduling in VANets such as fairness, reliability, responsiveness, time constraint, data size, service ratio and data quality [57]. In the following, some existing algorithms to schedule the messages for transferring through the channels are introduced.

First-In First-Out (FIFO) algorithm is one of the simplest scheduling algorithms. In FIFO, the earliest arrival request is served first. Longest Wait Time (LWT) and Maximum Request First (MRF) algorithms schedule the messages based on the deadline of messages in the broadcast environment. Longest Total Stretch First (LTSF) algorithm considers a stretch metric for reducing waiting time. The stretch metric is defined as the ratio of request response time to its service time. First Deadline First (FDF) algorithm serves the most urgent requests, but it does not consider the service time for data. In Smallest Data Size First (SDF) algorithm, the data with smallest size serves first. However, the urgency of messages is not considered in SDF [57].

Maximum Quality Increment First (MQIF) algorithm schedules the messages based on Quality of Service (QoS) and Quality of Data (QoD) factors that consider the responsiveness and staleness of data, respectively. Least Selected First (LSF) algorithm gives opportunity to the messages that had least opportunity to be served before. Finally, D*S algorithm defines priorities of messages based on Deadline (D) and Size (S) of message [57]. In the rest of this section, some of the proposed congestion control strategies in VANets are presented.

Torrent-Moreno et al. [68] developed a distributed congestion control strategy called Distributed-Fair Power Adjustment for Vehicular environment (D-FPAV). In this strategy, after congestion detection, the beaconing transmission range is dynamically tuned based on vehicle density. However, when transmission range of beacon messages is decreased in congestion situation, the probability of receiving the beacon messages in far distances reduces. Therefore, the performance of applications that need information through beacon messages is disrupted.

Bai et al. [21] proposed Context Awareness Beacon Scheduling (CABS) strategy to control congestion that may occur due to the high broadcasting rate of beacon messages within dense vehicular networks. The proposed congestion control strategy was a distributed strategy. CABS scheduled the beacon messages dynamically by employing piggybacked context information in beacon messages like velocity, direction and position. Then, a time slot was assigned to each node using TDMA-like transmission. Although CABS improved channel access delay and packet reception rate by scheduling the beacon messages, MAC layer interworking was not considered during adjusting time slot to each node.

Taherkhani and Pierre proposed Uni-Objective Tabu search (UOTabu) [12] and Multi-Objective Tabu search (MOTabu) [102] congestion control strategies in order to increase reliability of applications in VANets. In these strategies, the congestion is detected by monitoring the channel usage, and then Tabu Search algorithm is used for tuning transmission rate and range. In UOTabu strategy, delay is considered as objective function of Tabu Search algorithm, whereas in MOTabu, delay and jitter are considered as objective functions of Tabu Search algorithm. In addition, MOTabu strategy consider the short-, mid-, and long-term memories in proposed Tabu searched for determining near optimal transmission range and rate. The application of UOTabu and MOTabu showed that these strategies can reduce the average delay and packet loss more than the other strategies.

Felice et al. [54] introduced WAVE-enhanced Safety message Delivery (WSD) that is compatible with IEEE 1609.4 and IEEE 802.11p standards. WSD solved the problems of multi-channel technology in VANets, and single-radio transceivers in vehicles by scheduling safety and non-safety messages. Although the proposed strategy reduced delivery delay of the safety messages, multi-hop communications in VANets were not considered.

The most of congestion control strategies in VANets are performed by prioritizing messages in MAC layer. Suthaputchakun et al. [78] proposed a priority-based strategy using EDCA mechanism to increase safety in highway environments. Each inter-vehicle communication message was prioritized based on urgency and average delay. This strategy increased the reliability in vehicular environments by giving more chance of transmission to messages with higher priority (emergency messages). This strategy improved the delay and ratio of successful retransmission.

Bouassida et al. [20] introduced a congestion control strategy that controlled the load of the wireless channels. The introduced strategy reduced congestion in control channel, and delay of safety messages. In this strategy, the priorities were assigned to messages based on utility and validity of messages, and speed of senders and receivers. Then, the messages were scheduled in the control and service channel queues. The simulation results showed that the delay of safety messages decreased in this strategy. However, in worse-case scenario, the delay was more than 50 milliseconds.

There are several deficiencies associated with these congestion control strategies when they are applied in practice. In the following, it is tried to point out these deficiencies. Some of the congestion control strategies do not pay enough attention to the emergency messages; the emergency messages are broadcasted with high delay [2], or the packet loss ratio of emergency messages is high [54] that leads to unsafe and unreliable situations in VANets.

Moreover, in some strategies that control the congestion by changing contention window size, congestion costs increases and throughput decreases. In these strategies, CSMA/CA protocol, which is used for accessing to communication channel, employs the exponential back-off mechanism [46]. Since this mechanism is not efficient for broadcasting the beacon messages in dense vehicular networks, in the case the messages have time-out, dropped packets increase before transmission [46]-[48]. We present a summary of iterated congestion control strategies for VANets in Table 5.2.

## 5.3 Problem Statements and Solving Strategies

IEEE 1609.4 WAVE enabling multi-channel communications in VANets prioritizes and schedules various messages. Prioritizing and scheduling the messages are crucial tasks in VANets because the large number of parameters should be considered, especially in large networks [10], [15], [54], [57], [58]. In this section, two different congestion control strategies are proposed by employing more efficient scheduling and prioritizing mechanisms in order to enhance safety and reliability of VANets. To assign the priority to the messages and schedule them in the control and service channels queues, many factors related to content of messages and situation of vehicles are taken into account such as size and type of messages, velocity of senders and receivers, validity of messages, and so on.

Figure 5.2 depicts the schematic of the proposed congestion control strategies. These strategies consist of two units: A) priority assignment unit, and B) message scheduling unit. The priority assignment unit defines priority of messages based on static and dynamic factors. The message scheduling unit reschedules the prioritized messages in the control and service channel queues.

The operation of message scheduling unit is different in two strategies. These strategies are distributed because each node in VANets independently prioritizes and schedules the messages. The proposed congestion control strategies are also open-loops strategies that avoid congestion occurrence by prioritizing and scheduling messages.

Table 5.2: Comparison of congestion control strategies for VANets.

| **Proposed Strategy** | **Used Technique** | **Considered Parameters** | **Limitations** |
|---|---|---|---|
| EDCA [17], [18], [19] | Message Prioritizing | CW and AIFS | High delay for service messages |
| D-FPAV [68] | Tuning Beacon Transmission Power | Beacon Load | Small probability of receiving beacon in far distance when the transmission power of beacon messages is reduced |
| CABS [21] | Beacon Scheduling | Time slot assignment | Mac layer internetworking was not considered |
| UOTabu [12] | Tuning Transmission range and rate | Minimum delay for transferring safety and service messages | Hidden terminal problem |
| MOTabu [102] | Tuning Transmission range and rate | Minimum delay and jitter for transferring safety and service messages | Hidden terminal problem |
| WSD [54] | Message scheduling | Scheduling Safety and Service Messages | Multi-Hop communications are not considered |
| Suthaputchakun *et al.* [78] | Message Prioritizing | Urgency and Average Delay | Disruption of ongoing transmissions on SCHs and Safety Messages suffer due to switching between channels, especially in dens network |
| Bouassida *et al.* [20] | Message Prioritizing | Speed of Vehicles, Utility and validity of Messages | High delay and system overhead |

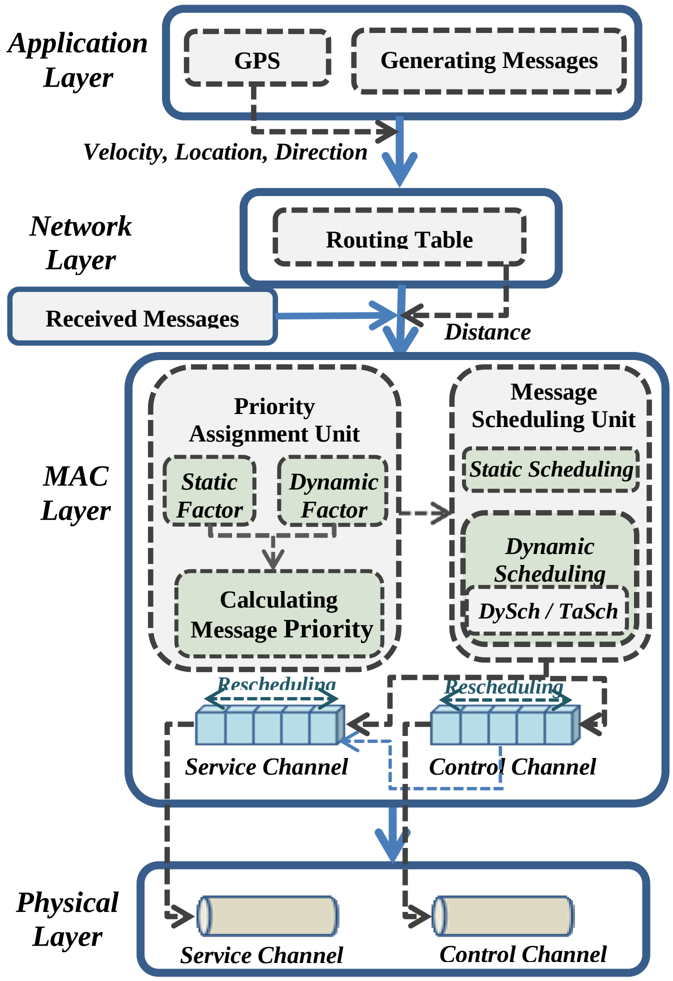



Figure 5.2: Schematic of the proposed congestion control strategies.

### 5.3.1 Priority Assignment Unit

In the priority assignment unit, priorities are assigned to the messages generated by applications in the vehicle or received from the other vehicles. Then, the relative times of transmission are determined for the messages based on the assigned priorities. In this paper, the priority of each message is defined based on static and dynamic factors as well as size of message:

$$Priority_{Message} = \frac{Static_{Factor} \times Dynamic_{Faactor}}{Message_{Size}} \tag{5.1}$$

$Priority_{Message}$ is directly proportional to $Static_{Factor}$ and $Dynamic_{Factor}$. However, because the emergency and high priority safety messages have smaller size compared to the other messages, $Priority_{Message}$ is opposite proportional to $Message_{Size}$.

The $Static_{Factor}$ is defined based on the content of messages and type of applications. $Static_{Factor}$ for a message is considered to be 1, 2, 3, 4, or 5 if the message belongs to $Priority_{Service\text{-}Low}$, $Priority_{Service\text{-}High}$, $Priority_{Safety\text{-}Low}$, $Priority_{Beacon}$, or $Priority_{Emergency}$ category, respectively [20]. In the following, each category is defined:

1. $\boldsymbol{Priority_{Service\text{-}Low}}$ is assigned to the messages generated by low priority service applications such as instant messaging (between vehicles), parking spot locator, electronic toll payment, internet service provisioning, and so on [103], [104].

2. $\boldsymbol{Priority_{Service\text{-}High}}$ is defined for the messages generated by high priority service applications such as intelligent traffic flow control and map download/update/GPS correction, and so on [103], [104].

3. $\boldsymbol{Priority_{Safety\text{-}Low}}$ is considered for low priority safety messages generated by the applications of forward collision, lane change warning, left turn assist, stop sign assist, and so on [103], [104].

4. $\boldsymbol{Priority_{Beacon}}$ is considered for the safety beacon messages that are periodically transmitted in VANets for broadcasting the vehicular information such as position, speed, direction, and so on. This information is important for many of the safety applications and some of the service applications.

5. $\boldsymbol{Priority_{Emergency}}$ is considered for the emergency messages. These messages have the highest priorities and should be delivered without any delay. Some of the applications that generate the emergency messages are emergency brake lights, emergency vehicle approaching warning, emergency vehicle at scene warning, intersection collision warning, pedestrian crossing information, and so on [103], [104].

In contrast, of static factor defined based on the content of messages and type of applications, dynamic factor is defined based on circumstances of VANets. The metrics considered for calculating the dynamic factor are velocity of vehicles, usefulness of messages, validity of messages, directions of sender and receiver vehicles, distance between sender and receiver vehicles. In the following, these metrics are described in details.

1. ***Velocity metric (Vel)***: This metric represents the relative speed of message sender that is defined based on the total coverage area of a vehicle traveling with velocity v during time *dt* (Figure 5.3):

$$\boldsymbol{Vel} = \frac{\pi \times R^2 + 2 \times R \times v \times dt}{\pi \times R^2} \tag{5.2}$$

   where *R* is communication range, and *v* is average speed of vehicle in time *dt*. A higher priority should be assigned to the message with higher *Vel* metric. Indeed, a vehicle moves with higher speed, covers a higher area in unit of time; however, the probability of disconnection for this vehicle is high.

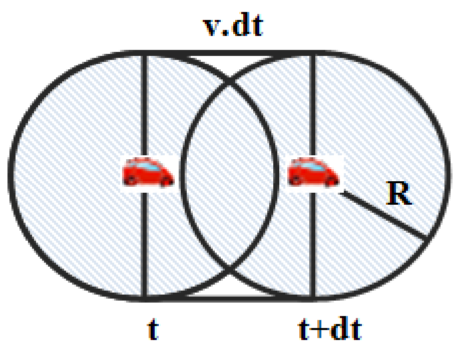



Figure 5.3: Velocity metric (Vel).

2. ***Usefulness metric (Use)***: This metric is defined according to the probability of message retransmissions by the neighbor vehicles. The usefulness is determined by ratio of total communication area and overlapped area (Figure 5.4):

$$\boldsymbol{Use} = \frac{Communication_{Area}}{Overlapped_{Area}} \tag{5.3}$$

   where the $Overlapped_{Area}$ is calculated using Equation (5.4):

$$Overlapped_{Area} = 4 \times \left( arccos\left(\frac{d}{2 \times R}\right) \times \frac{R^2}{2} - \frac{d}{4} \times \sqrt{R^2 - \left(\frac{d}{2}\right)^2} \right) \tag{5.4}$$

where $d$ is distance between sender and receiver vehicles. Therefore, the usefulness metric is:

$$\boldsymbol{Use} = \frac{\pi \times R^2}{4 \times (arccos\left(\frac{d}{2 \times R}\right) \times \frac{R^2}{2} - \frac{d}{4} \times \sqrt{R^2 - \left(\frac{d}{2}\right)^2})} \tag{5.5}$$

Based on Equation (5.5), when the $Overlapped_{Area}$ is relatively high, usefulness metric is low. In this case, because there is a high possibility that the message will be received again from the neighbor vehicles, it is not necessary to assign a high priority to the message to be sent. Thus, a lower priority should be assigned to the messages with lower Use metric.

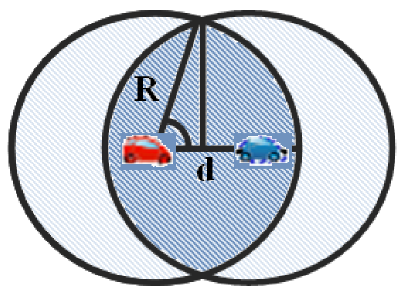



Figure 5.4: Usefulness metric (Use).

3. ***Validity metric (Val)***: Validity metric is posed as the age of the messages. In other words, it is defined as the remaining time to the message deadline in real-time applications. When the remaining time to the message deadline is short, the priority of a message is high. Therefore, the priority of message as well as dynamic factor is opposite proportional to the validity. The validity can be given by Equation (5.6):

$$\boldsymbol{Val} = \frac{\boldsymbol{Remaining\ Time\ to\ the\ Deadline}}{\boldsymbol{Transferring\ Time}} \tag{5.6}$$

Transferring Time in this equation, which is used for normalization, shows an estimated time to transfer message between sender and receiver vehicles.

4. ***Distance metric (Dis)***: This metric is considered as a relative distance between message sender and receiver. If the distance metric is high, the probability of disconnection between two vehicles is also high; therefore, a higher priority should be assigned to the message. On the other hand, if the distance between two vehicles is low, a lower priority

should be assigned to the message because the connection duration is relatively long; there is enough time for the message to be sent. This metric is therefore directly proportional to the message priority. When the messages are broadcasting, the closest vehicle is considered for estimating the distance factor.

5. ***Direction metric (Dir)***: direction metric shows that two vehicles (sender and receiver) are driving closer to each other (*Dir*=0) or they are driving away from each other (*Dir*=1). If the sender vehicle is being close to receiver, the probability of connecting increases; thus, the lower priority should be assigned to the message. In contrast, if two vehicles drive away from each other, the probability of disconnection and breaking the route between them increases; thus, a higher priority should be assigned to the message.

By combining Equations (5.2) to (5.6), the dynamic factor is calculated by Equation (5.7):

$$\boldsymbol{Dynamic_{Factor}} = \begin{cases} \frac{\boldsymbol{Vel \times Use}}{(\boldsymbol{Val+1}) \times \boldsymbol{Dis}} & \boldsymbol{Dir = 0} \\ \frac{\boldsymbol{Vel \times Use \times Dis}}{(\boldsymbol{Val+1})} & \boldsymbol{Dir = 1} \end{cases} \tag{5.7}$$

Based on Equations (5.7) and (5.1), dynamic factor and consequently message priority are directly proportional to *Vel* and *Use* metrics. However, dynamic factor and message priority are opposite proportional to *Val* metric. In this equation, Val metric is added to 1 to avoid ambiguous result when the validity is equal to zero.

Equation (5.7) shows that dynamic factor is opposite proportional to *Dis* metric when *Dir* is equal to 0. However, dynamic factor is directly proportional to Dis when *Dir* is equal to 1. When *Dir* is equal to 0, two vehicles are driving closer to each other and the distance between them decreases. Thus, lower (higher) priority should be assigned to the messages transmitted by the vehicles that are being close to each other and have a high (low) distance. The lower (higher) priority is given to this message because there is a high (low) chance that two vehicles have longer connection. On the other hand, when *Dir* is equal to 1, two vehicles are driving away from each other and the distance between them increases. Thus, higher (lower) priority should be assigned to the messages transmitted by the vehicles that are driving away from each other and have a high (low) distance. The higher (lower) priority is given to this message because there is a low (high) chance that two vehicles stay in communication range of each other.

Here, it should be mentioned that the required information for calculating dynamic factor is obtained from GPS and the routing table. In addition, for prioritizing the messages, EDCA is carried out in the background. EDCA is the default strategy of prioritizing in VANets [17]-[19].

Finally, the priorities of messages are calculated using Equation (5.1) based on static factor, dynamic factor and message size. Then, the calculated priorities are embedded in the header of packets.

### 5.3.2 Message Scheduling

To provide a reliable data transferring, the message scheduling is crucial. However, it is a challenging task in VANets due to unique characteristics of these networks (i.e. high mobility, high rate of topology change, distributed control, high speed of vehicles, and so on). In this paper, in order to enhance reliability and safety in VANets, IEEE 1609.4 multi-channel MAC was improved. Indeed, in the message scheduling unit, the control and service channel queues are rescheduled before transferring to the channels. For this purpose, the message scheduling is conducted in two steps of static and dynamic scheduling.

In the static scheduling step, the messages are transferred to either control channel queue or service channel queue based on static factor defined in priority assignment unit. Here, two channel queues (control and service) were assumed due to two types of channels (control and service) in VANets. In static scheduling step, the messages with $Priority_{Emergency}$, $Priority_{Beacon}$, and $Priority_{Safety\text{-}Low}$ priorities are transferred to control channel queue, and the messages with $Priority_{Service\text{-}High}$ and $Priority_{Service\text{-}Low}$ priorities are transferred to service channel queue. In addition, when the control channel queue is full, the messages with $Priority_{Emergency}$, $Priority_{Beacon}$, and $Priority_{Safety\text{-}Low}$ priorities are transferred to service channel queue for improving safety in VANets. Figure 5.5 shows the static scheduling process in the message scheduling unit.

The dynamic scheduling step is carried out in two different methods: i) using the message priorities calculated in priority assignment unit, and ii) using the Meta-heuristic techniques for rescheduling the messages in each queue. For dynamic scheduling based on the message priorities (i), the packets in each queue are rescheduled when a new packet is entered to the queue. Indeed, the packets in each queue are reordered descending based on their priorities calculated by Equation (5.1). Then, the packets are dequeued from the control or service channel queues to transfer to the control or service channels. The strategy uses this method for dynamic scheduling is referred as “DySch”.

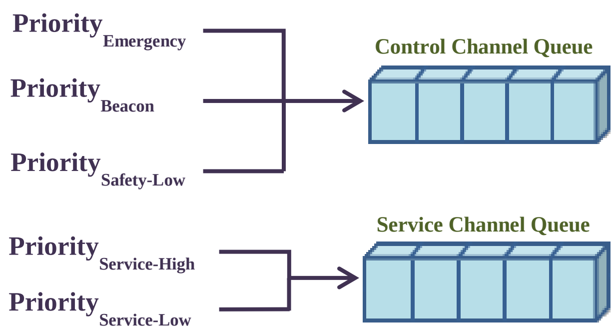



Figure 5.5: Static scheduling process.

For dynamic scheduling, the Meta-heuristic techniques can be also employed (ii). Considering that the simple scheduling problems are NP-hard [105], the message scheduling is also an NP-hard problem due to the constraints of the vehicular environments. The Meta-heuristic techniques can find near-optimal solutions in reasonable time for these kinds of the problems [85]. Tabu Search algorithm, which is one of the best Meta-heuristic techniques, is usually used for graph theory problems, scheduling, vehicle routing, multi criteria optimization, and real-time decision problems, and so on [91]. Therefore, it can be used for dynamic scheduling in order to reschedule the packets in each queue. The strategy using Tabu Search for dynamic scheduling is referred as “TaSch”.

Main elements of Tabu Search are objective function, memory mechanisms, tabu list, initial solution, neighborhood set, candidate list, termination rules, and so on [90], [91]. In the following, Tabu Search elements are described in more details.

To provide a safe and reliable environment in VANets, delay and jitter of the message transferring should be minimized. Also, higher chance should be given to the more important messages to be sent. Therefore, in this paper, to minimize the delay, jitter is considered as the objective of the Tabu search algorithm. In the Appendix A, the equations used for calculating the delay and jitter are presented.

Memory mechanisms of Tabu Search include short-, mid-, and long-term memories. The tabu list is considered as a short-term memory that keeps the best generated solutions. When a new solution is selected as a best solution, this solution is put on the tabu list. A new solution is compared with the solutions in tabu list to avoid selecting the repeated solutions. In this paper, the size of tabu list is assumed to be equal 50. Therefore, it is limited to add the best solutions in tabu list. If the tabu list is full, the oldest solution will be deleted from the list.

The mid-term memory is used to intensify the search in order to find the better new near-optimal solutions. The mid-term memory is considered as a list of best solutions found in specific areas. In this paper, the size of this list is assumed to be equal 5. The proposed Tabu Search algorithm periodically selects the initial solution among the mid-term memory list to generate a new solution. Initial solution of the Tabu Search algorithm is the current state of control and service channel queues. The long-term memory is used to diversify the search to help avoid entrapment in local optimum. In the proposed Tabu Search algorithm, new initial solution is periodically generated far from the best solutions of the tabu list to generate diverse solutions.

The neighborhood set is defined by changing the order of packets in the queues. The feasible solutions is selected among the solutions in the neighborhood set and then put in the candidate list. Feasible solutions are the solutions that are not included in tabu list. The last element of Tabu Search algorithm is termination rule that is the number of iterations. In the proposed Tabu Search algorithm, the number of iterations is assumed to be equal 25, which is half of the queues length in VANets. Figure 5.6 shows the pseudo code of the proposed Tabu Search algorithm.

## 5.4 Performance Evaluation

### 5.4.1 Scenarios and Simulation parameters

For evaluating the performance of the proposed scheduling strategies in VANet, mobility and network simulators should be employed. In this paper, Simulation of Urban Mobility (SUMO) [97], [98] and Network Simulator (NS) version 2.35 [99] were used for mobility and network simulation, respectively. Mobility model generator for Vehicular networks (MOVE) was also used for making connection between SUMO and NS [100].

```
Input:
        Max size of TabuList
        Number of Iteration
        Diversification Counter

Output:
        S_best (Best_Delay, Best_Jitter, Packet_Queue_Order)

1.      S_0 ← genInitSolution() // current delay and jitter based on current situation of
        queue
2.      S_best ← S_0
3.      Divers_count ← 0
4.      insert TabuList(S_best)
5.      i ← 0
6.      Intensific_Counter ← 0
7.      Intencifict_Variable ← 0
8.      Intencifict_Variable ← Rand (1, Iteration)
9.      while (i< Iteration) do
10.         N(s) ← Identify (Neighborhood set) // Changing the order of packets in the
            queue with  considering Mid-Term Memory
11.         T(s) ← Identify (TabuList) // Short-Term Memory
12.         CandidateList(s) ← N(s) – T(s)
13.         Intensific_Counter++
14.         If (Intensific_Counter== Intensific_Counter) //Mid-Term Memory
15.             S_best ← Select (MidTermList)
16.         End if
17.     if empty ( CandidateList(s)) // Long-Term Memory
18.             Divers_Count++;
19.             if Divers_Count ==Diversification Counter // entrap in local minima
20.                 S_0 ← genNewSolution()
21.                  Go to 2
22.              End if
23.         End if
24.         while (! empty ( CandidateList(s)) )
25.              if ( Delay(S_candidate ) <  Delay_best AND Jitter(S_candidate ) < Jitter_best)
26.                  S_best ← S_candidate
27.                  Divers_Count ← 0;
28.                  break;
29.             End if
30.         End while
   // Update-Tabu-List
31.         if (LengthTabuList < MaxSizeTabuList)
32.             Add S_best to TabuList
33.         else
34.             Delete the oldest item in TabuList
35.             Add S_best to TabuList
36.         End if
37.     End while
38.     Return (S_best)
```

Figure 5.6: Pseudo code of Tabu Search algorithm in TaSch strategy.

In this paper, a six-lane highway and Manhattan-pattern urban scenario were simulated to assess the performance of the proposed strategies. Table 5.3 shows the parameters used in the simulations of highway and urban scenarios. IEEE 802.11p was considered as the communication protocol. CSMA/CA strategy was also used as transmission strategy in MAC layer. TwoRayGround and Nakagami were employed to model the propagation in highway and urban scenarios, respectively. The Poisson distribution was also used for generating the data traffic. A table-driven routing protocol like Destination-Sequenced Distance-Vector (DSDV) is assumed in simulations.

### 5.4.2 Simulation Results and Performance Evaluation

In this section, the performance of the proposed scheduling strategies are compared with four congestion control/scheduling strategies including FIFO, EDCA, D-FPAV, and CABS. Note that DySch represents the scheduling strategy using the dynamic factor while TaSch represents the scheduling strategy using multi-objective Tabu Search. For evaluation of the performance of DySch and TaSch strategies, five performance metrics are evaluated:

*Average Delay*: The average time required to transfer the packets from senders to receivers;

*Average Throughput*: The rate of successfully received packets over communication channels in unit of time.

*Number of Packet Loss*: The number of packets loss during simulation time;

*Packet Loss Ratio*: The ratio of the number of packet loss to the number of transmitted packets;

*Waiting Delay in Queue*: The average time that the packets should wait in service or control channel queues before dequeuing and transferring to the channels.

Before simulation results, we show the expression of the average end-to-end delay in Appendix A. Figure 5.7 reveals the variations of the average end-to-end delay resulting from mathematic formulas with the packet arrival rate and the number of vehicles in transmission range. The figure shows that, without providing any congestion control strategy in VANet, the end-to-end-delay is increased with increasing packet arrival rate for all numbers of vehicles in transmission range. In addition, the amount of end-to-end delay is higher than acceptable delay for transferring messages in VANets. Therefore, we show in simulation results that by controlling congestion, the average delay is decreased in comparison to the mathematical result shown in Figure 5.7.

Table 5.3: Configuration parameters for simulation of the highway and urban scenarios.

| **Parameters** | **Value** |
|---|---|
| Total road length | 2400 m*, and 652 m×752 m** |
| Number of lanes | 6 (3 in each direction)*, and 4 (2 in each direction)** |
| Number of Vehicles | 50,80,100,120,150,200 |
| Vehicles speed | 80-120 km/h* and 0-40 km/h** |
| Transmission rate | 6 Mbps |
| Bandwidth | 10MHz |
| Message Size | Beacon: 522 Bytes , Emergency: 500 Bytes |
| Beacon messages generation rate | 10 packet/s |
| MAC type | IEEE 802.11p |
| Propagation model | TwoRayGround*, and Nakagami (m=3)** |
| Routing Protocol | DSDV |
| Simulation time | 200 s |
| Simulation runs | 20 |

* Highway scenario
** Urban scenario

In the following, the impact of number of vehicles, message generation rate, and simulation time on the above performance metrics is evaluated. Figure 5.8 to Figure 5.12 show the simulation results of highway scenario, while Figure 5.13 to Figure 5.17 show the simulation results of urban scenario.

Figure 5.8 shows the variations of average delay resulting from different congestion control/ scheduling strategies with numbers of vehicles in the highway scenario. The figure shows that the average delay increases with increasing the number of vehicles for all congestion control/scheduling strategies. However, the figure shows that the average delay resulted from DySch and TaSch strategies are less than the other strategies. TaSch strategy leads to the lowest average delay. The reason for this observation is that TaSch strategy minimizes the delay and jitter during message transferring for all the messages, especially high priority messages. DySch strategy can also reduce the average delay in some extend in compare to FIFO, EDCA, D-FPAV, and CABS strategies. Considering static and dynamic factors by DySch strategy leads to such an improvement.

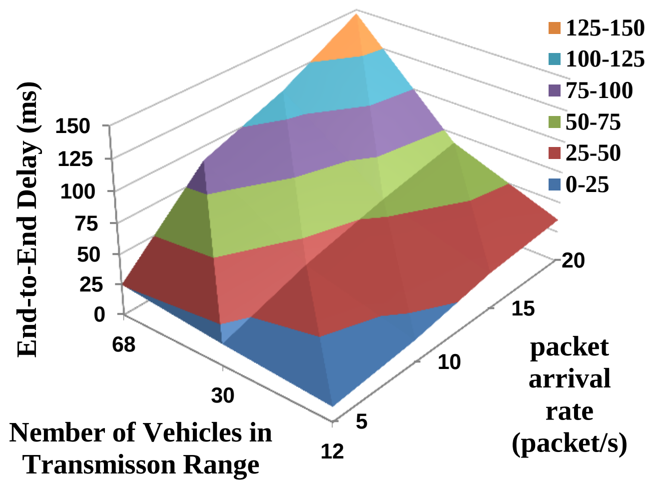



Figure 5.7: Impact of the packet arrival rate and the number of vehicles in transmission range on average end-to-end delay in analytical model.

FIFO cannot control congestion in high mobility vehicular environments since this algorithm dequeues the packets without any prioritizing. EDCA prioritizes messages to control congestion; however, when the number of high priority messages is high, the delay of transferring low priority messages increases. D-FPAV controls congestion by varying the transmission rate and power; CABS control congestion by scheduling of messages. However, both of these strategies are implemented only on beacon messages.

Figure 5.9 reveals the impacts of the number of vehicles on the number of packet loss for each congestion control/scheduling strategy. It can be observed that the number of packet loss in DySch and TaSch strategies is less than the other strategies. By scheduling and prioritizing all messages (safety and service messages), congestion is controlled; thus the number of collisions and consequently the number of packet loss decrease.

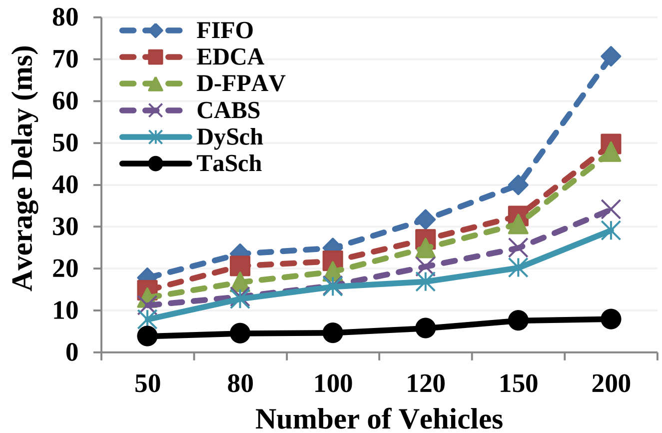



Figure 5.8: Impact of the number of vehicles on average delay in the highway scenario.

Figure 5.10 presents the plot of the average throughput versus the number of vehicles for each congestion control/scheduling strategy. Using FIFO, EDCA, D-FPAV, CABS, DySch and TaSch strategies, the average throughput for the number of vehicles equal to 200 is 2.72, 3.40, 3.53, 3.57, 4.63 and 5.01 Mbps, respectively. The results show that the proposed strategies outperform than the other strategies and can improve the performance of VANets. DySch and TaSch strategies increase the average throughput by dynamically and heuristically scheduling the queues, respectively. Such improvement in the average throughput was obtained due to the reduction in the average delay and number of packets loss shown in Figure 5.8 and Figure 5.9.

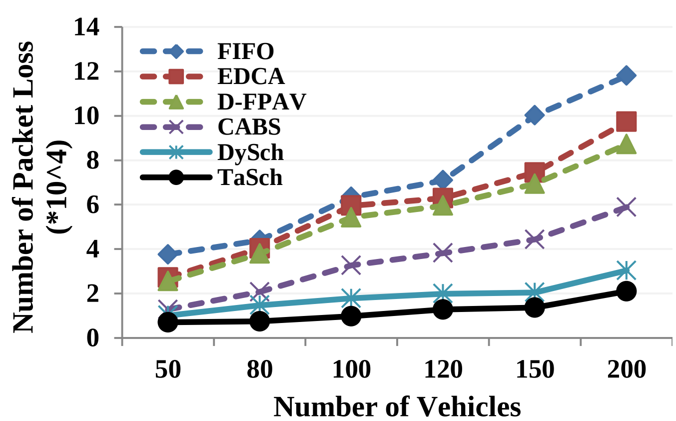



Figure 5.9: Impact of the number of vehicles on number of packet loss in the highway scenario.

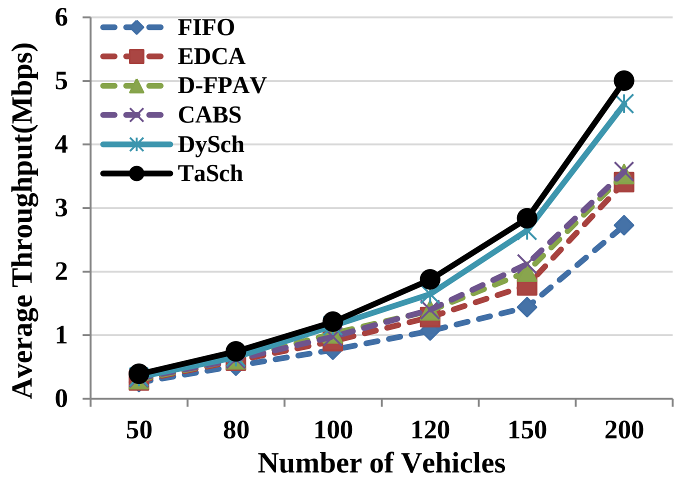



Figure 5.10: Variation of the average throughput with number of vehicles in the highway scenario.

For more evaluation of the proposed strategies, the variation of the average delay and throughput with simulation time are investigated in Figure 5.11 (a) and (b), respectively. Here, the number of vehicles is assumed to be equal 50. Figure 5.11 (a) illustrates that by advancing the simulation time, the average delay of the packet transmission decreases for all strategies, except FIFO. However, using TaSch and DySch strategies, the amount of reduction of average delay is higher than the other strategies. In Figure 5.11 (a), it can be also seen that the average delay using TaSch and DySch at simulation time 50 seconds is much lower than the other strategies. It means, using the proposed strategies, congestion is controlled before it occurs. Here, it should be emphasized that TaSch and DySch strategies are open-loop strategies.

Figure 5.11 (b) illustrates that TaSch and DySch can improve average throughput more than the other strategies during the simulation time. This figure shows that after 200 seconds the average throughput using FIFO, EDCA, D-FPAV, CABS, DySch and TaSch is improved to 1.27, 1.31, 1.53, 1.79, 2.39 and 2.73 Mbps, respectively. The average throughput obtained using DySch and TaSch is almost 2 times more than FIFO (basic scheduling strategy) or EDCA (default prioritizing strategy in VANets). Moreover, the results show that the rate of changes of average throughput calculated by DySch and TaSch strategies is positive. It means that the average throughput calculated by the proposed strategies may increase even after simulation time 200 seconds. Note that the rate of change of the average throughput obtained from the other strategies is almost zero after simulation time 100 seconds.

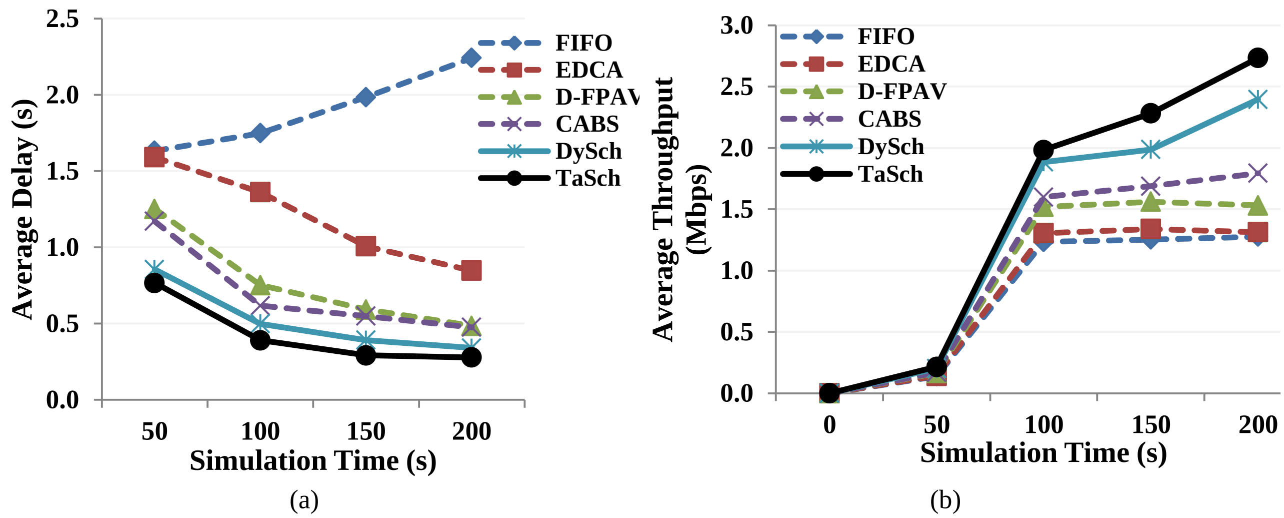
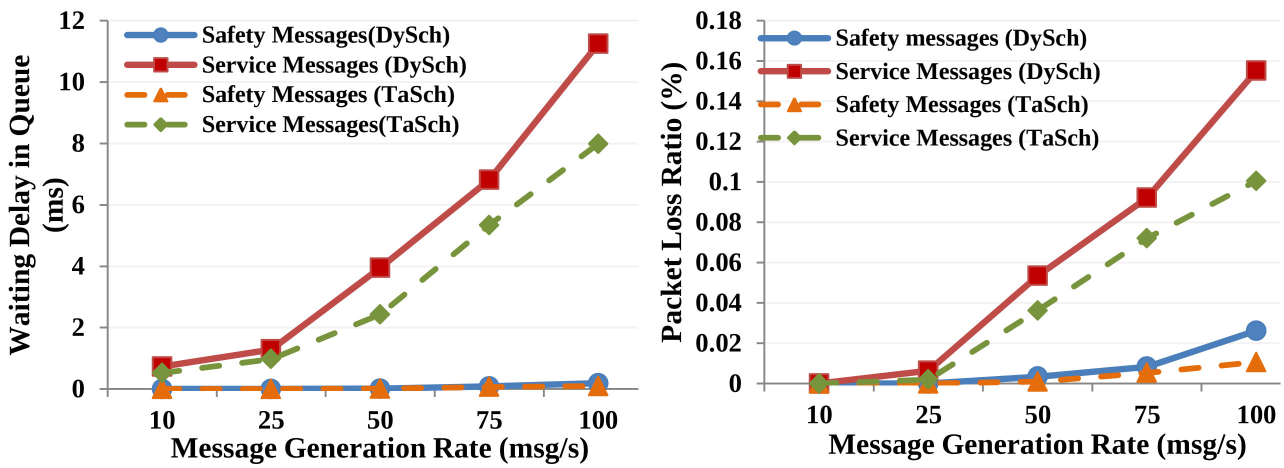



Figure 5.11: Variation of (a) the average delay, and (b) the average throughput with simulation time in the highway scenario.

In Figure 5.12, the impact of the message generation rate on average waiting delay in queue, and packet loss ratio is evaluated for safety and service messages while congestion control is conducted using DySch and TaSch. Figure 5.12 (a) illustrates that the average waiting delays in queue for safety messages are much lower than the average waiting delays in queue for service messages. This results show that DySch and TaSch transfer the safety messages without any significant waiting delay in queue by scheduling and prioritizing the messages that help provide a safe and reliable environment in VANet. A negligible delay for safety messages can be seen in Figure 5.12 (a) because the beacon messages generated periodically have to wait in control channel queue before transmitting. Similarly, Figure 5.12 (b) reveals that the packet loss ratio of safety messages is less than the packet loss ratios of service messages. Because the safety messages have higher priority for being transmitted compare to the service messages, their packet loss ratio is lower than the service messages.

In the following, an urban scenario is investigated to evaluate the performance of the proposed strategies in the vehicular environments with high level of congestion. For simulation of urban scenarios, Nakagami (m=3) propagation model is used to simulate the obstacles (e.g. buildings and trees). The other parameters used for simulation of the urban scenario can be seen in Table 5.3. Figure 5.13 to Figure 5.17 illustrate the simulation results of urban scenario.




(a) (b)

Figure 5.12: Impact of the message generation rate on (a) waiting delay in queue, and (b) packet loss ratio in the highway scenario.

Figure 5.13, Figure 5.14 and Figure 5.15 show the impact of the number of vehicles on the average delay, number of packet loss, and average throughput, respectively. In Figure 5.13, the average delay increases with increasing the number of vehicles because as it is expected, when the number of vehicles increases, the number of collisions increases. However, here, similar to the highway scenario, the average delay resulted from the proposed strategies is less than the other strategies. When the number of vehicles increases from 50 to 200, the average delay increases from 26.69, 19.55, 17.40, 13.14, 12.48, and 10.10 to 206.10, 171.86, 152.22, 106.53, 33.91, and 17.44 milliseconds for FIFO, EDCA, D-FPAV, CABS, DySch and TaSch, respectively. The results show that by increasing the number of vehicles, the average delay does not increase significantly using DySch and TaSch. Therefore, the proposed strategies are scalable congestion control strategies. It is also important to note that the average delay resulted from TaSch is less than DySch. As it was mentioned before, in TaSch strategy, delay is the objective function that is minimized to control the congestion.

Figure 5.14 shows that for the number of vehicles 200, the number of packet loss obtained from FIFO, EDCA, D-FPAV and CABS strategy are 31, 24, 16 and 9 times higher than DySch strategy, respectively. Also, the figure shows that TaSch strategy reduces the number of packet loss more than DySch strategy; the number of packet loss obtained from TaSch strategy is almost 1.4 times less than DySch strategy. In Figure 5.15, the average throughput obtained from DySch and TaSch are more than the other strategies due to control the congestion and decrease delay and collisions. Such results show that the performance of the proposed strategies (especially TaSch) to control congestion is better than the other strategies.

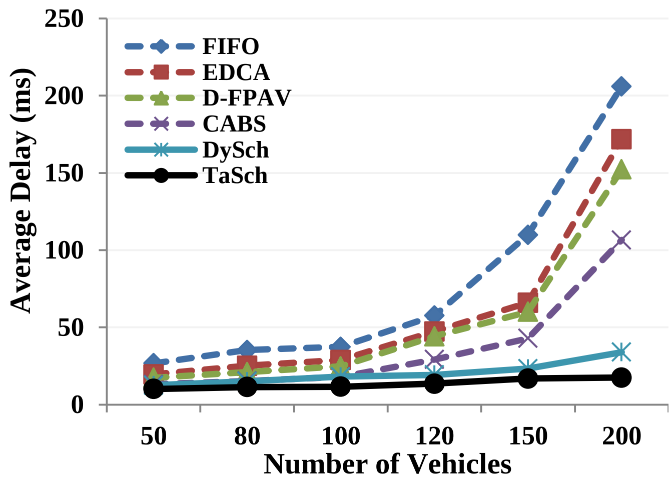



Figure 5.13: Variation of the average delay with number of vehicles in the urban scenario.

The variations of average delay and throughput with simulation time in the urban scenario are shown in Figure 5.16 whereas the number of vehicles is assumed to be equal 50. In the urban scenario, similar to the highway scenario, using TaSch strategy leads to the lowest average delay and the highest average throughput during the simulation time. Figure 5.16 (a) shows that, at simulation time 50, the average delay is equal to 3.45, 2.76, 2.07, 1.95, 1.33, and 1.04 seconds for FIFO, EDCA, D-FPAV, CABS, DySch, and TaSch, respectively. These results show that even at the beginning of simulations, the average delay computed by DySch and TaSch is less than the other strategies. The reason for this observation is that the proposed strategies control congestion before the congestion actually happens (open-loop strategies).

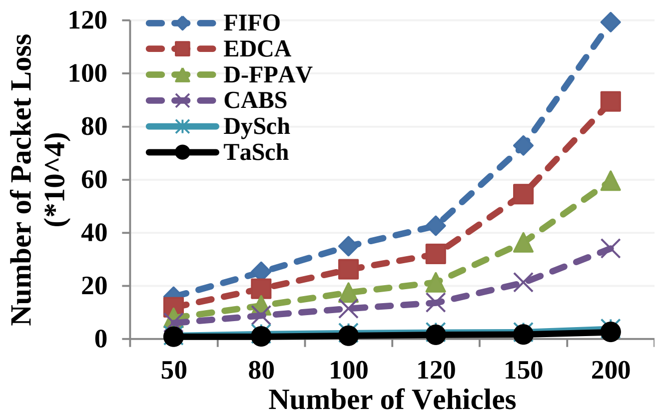



Figure 5.14: Impact of the number of vehicles on number of packet loss in the urban scenario.

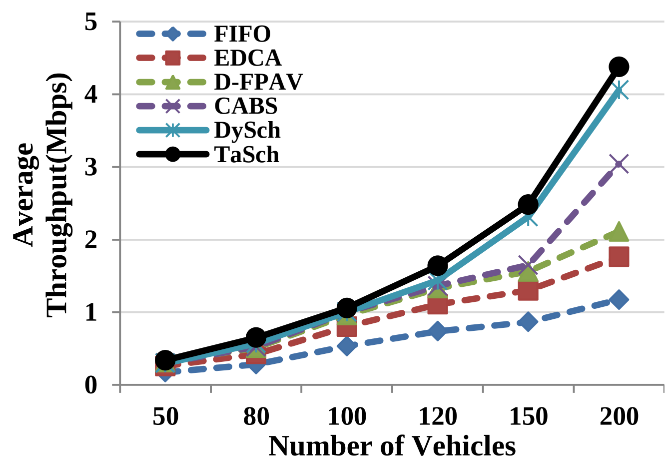



Figure 5.15: Variation of the average throughput with number of vehicles in the urban scenario.

Figure 5.16 (b) illustrates that the average throughput after 200 seconds of simulation increases to 0.73, 0.92, 1.35, 1.57, 1.77 and 1.99 Mbps for FIFO, EDCA, D-FPAV, CABS, DySch, and TaSch, respectively. As it was expected, the proposed strategies outperform than the other strategies. In contrast of the highway scenario shown in Figure 5.11 (b), the results show that the rate of change of the average throughput calculated by DySch, and TaSch strategies is reaching to the zero for simulations time larger than 100 seconds. It means that, in this scenario, the average throughput cannot increase significantly after simulation time 100 seconds due to high level of congestion in the scenario.

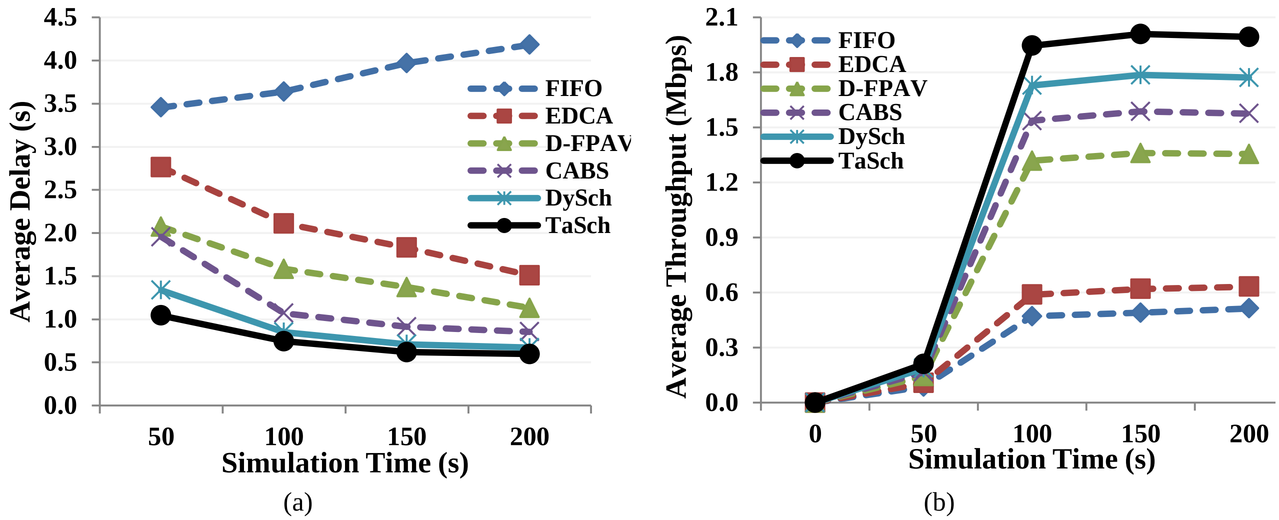



Figure 5.16: Variation of (a) the average delay, and (b) average throughput with simulation time in the urban scenario.

Finally, Figure 5.17 reveals the impact of message generation rate on waiting delay in queue, and packet loss ratio of safety and service messages for DySch and TaSch strategies in the urban scenario. The results show that the waiting delay in queue and packet loss ratio for safety messages is much less than the service messages. To control congestion, DySch and TaSch strategies schedule the messages while safety messages are prioritized for being sent. It should be also noted that the results obtained from urban and highway scenario are different because of the higher level of congestion and different characteristics of vehicular environment in the urban scenario.

## 5.5 Summary and Conclusion

In this paper, we proposed two novel open-loop congestion control strategies including DySch and TaSch strategies. The proposed strategies operated through two units: 1) priority assignment unit, and 2) message scheduling unit. In priority assignment unit, first, static and dynamic factors were calculated based on the content of messages, and situation of vehicles, respectively. Then, a priority was assigned to each message based on static and dynamic factors, and size of the message. In message scheduling unit, first, the messages were transferred to control and service channel queues based on the calculated static factors (static scheduling). Then, the packets in each queue were rescheduled for transferring to the channels (dynamic scheduling). Dynamic scheduling was performed differently in DySch and TaSch strategies. In DySch strategy, dynamic scheduling was carried out based on the priority of messages. However, in TaSch strategy, dynamic scheduling was conducted by minimizing the delay and jitter, and considering the priorities of messages. Both DySch and TaSch strategies were distributed strategies. It means each vehicle independently prioritized and scheduled all the generated/received messages by executing the proposed strategies.

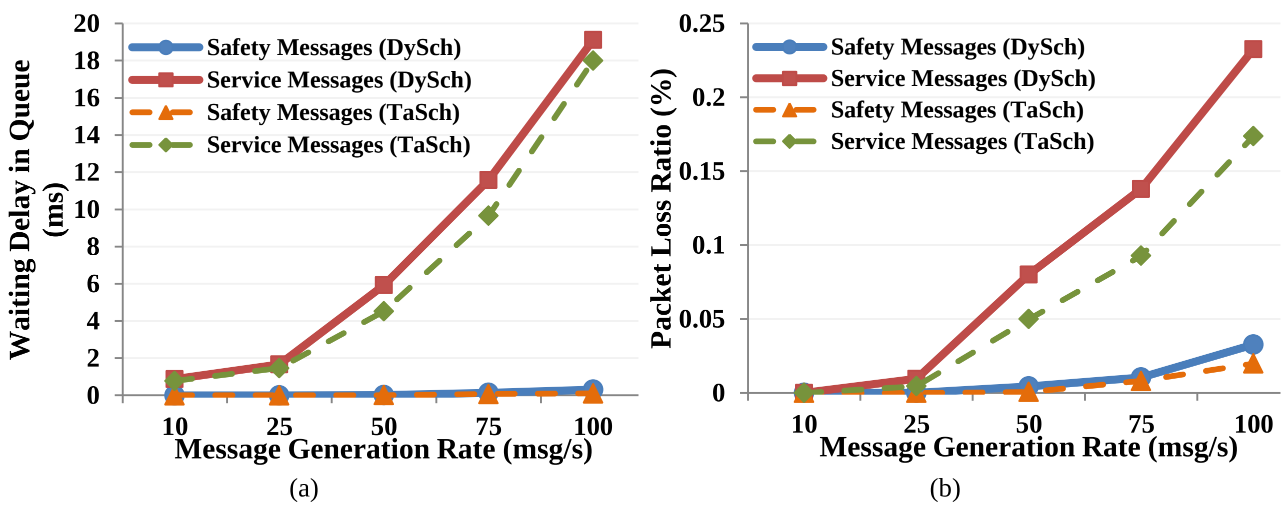



Figure 5.17: Impact of the message generation rate on (a) waiting delay in queue, and (b) packet loss ratio in the urban scenario.

The performance of DySch and TaSch strategies was evaluated and compared with other strategies in highway and urban scenarios whereas the average delay, number of packet loss, average throughput, waiting delay in queue, and packet loss ratio were used. The results of comparisons showed that the proposed strategies outperform other compared strategies. Application of DySch and TaSch strategies improved the performance of VANets by increasing the average throughput, and reducing the average delay, and number of packet loss. Comparisons between the proposed strategies also revealed that the improvements obtained from TaSch were greater than that of DySch strategy. TaSch strategy considered the delay, jitter, and priorities of messages while DySch strategy only considered the priority of messages. The results showed that the applications of the both strategies led to the lower waiting delay in queue, and packet loss ratio for safety messages rather than the service messages. Therefore, more safe and reliable environments can be provided in VANets using TaSch and DySch strategies.

# CHAPTER 6 ARTICLE 3: CENTRALIZED AND LOCALIZED CONGESTION CONTROL STRATEGY FOR VEHICULAR AD-HOC NETWORKS USING A MACHINE LEARNING CLUSTERING ALGORITHM

N. Taherkhani [1], S. Pierre [1]

[1]Mobile Computing and Networking Research Laboratory (LARIM), Department of Computer Engineering, Polytechnique de Montréal, Montreal, Canada

## Abstract

In an urban environment, the intersections are critical locations in terms of road crashes, number of killed and injured people. Vehicular Ad-hoc Networks (VANets) can help reduce the traffic collisions at intersections by sending warning messages to the vehicles. However, the performance of VANets should be enhanced to guarantee delivery of the messages especially safety messages to destination. Congestion control is an efficient way to decrease packet loss and delay, and increase the reliability of VANets. In this paper, a centralized and localized congestion control strategy is proposed to control the congestion using Road-Side Units (RSUs) at intersections. The proposed strategy consists of three units for detecting congestion, clustering messages, and controlling congestion. In this strategy, the channel usage level is measured to detect congestion in the channels. The messages are gathered, filtered, and then clustered by machine learning algorithms. K-means algorithm classifies the messages based on message size, validity of messages, and type of messages. The congestion control unit determines appropriate values of transmission range and rate, contention window size, and Arbitration inter-frame spacing (AIFS), for each cluster. Finally, RSUs at the intersections send the determined communication parameters to the vehicles stopped before the red traffic lights to reduce the communication collisions. Simulation results show that the proposed strategy significantly improves the delay, throughput, and packet loss ratio in comparison with the other congestion control strategy, using the proposed congestion control strategies.

***Keywords:*** Congestion Control, Machine Learning Algorithms, K-means Algorithm, Quality of Service, Vehicular Ad-hoc Network.

## 6.1 Introduction

Vehicular Ad-hoc Networks (VANets) were developed to provide vehicular communications with a reliable and cost-efficient data distribution. The vehicular communications can be used to reduce the road accidents, traffic congestion, traveling time, and fuel consumption, and so on [106], [107]. The vehicular communications allow the road users to be informed about the critical and dangerous situations, which may happen in their surrounding environment, by exchanging some information. Therefore, VANets can play a vital role to make a safe and comfort environment for road users [1], [2].

VANet is employed by Intelligent Transportation Systems (ITS) for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Communications in VANets rely on standards and protocols defined in Dedicated Short Range Communication (DSRC) and Wireless Access in a Vehicular Environment (WAVE). IEEE 802.11p and IEEE1609 are two WAVE standards. These standards are used to manage resources, network services, multi-channels operations, and security services, and so on. VANets employs the Road-Side Units (RSUs) and On-Board Units (OBUs) to conduct V2I andV2V communications. RSUs are fixed at the roadsides, while OBUs are fixed on vehicles [1]-[4].

The applications developed for VANets can be classified into three main categories: 1) safety applications (e.g. road hazard control notification, and emergency electronic break light), 2) convenience applications (e.g. parking availability notification, and congested road notification,), and 3) commercial applications (e.g. service announcements, and content map database download) [3], [7]. These applications generate two types of messages for communications in VANets, that includes safety and non-safety messages. The safety messages including beacon and emergency messages are transferred in control channel. The non-safety messages including the messages generated by convenience and commercial applications are transferred in service channels [4]-[6].

In urban environments, the intersections are the critical places because they are the most likely places for road crashes. In Canada, almost 800 road users killed and 7250 road users seriously injured at intersection crashes in 2005 [108]. Also, the recent statistical data of road crashes reported by Canada Road Safety Vision 2010 shows that approximately 47% of all people killed and 57% of all people injured at intersections crashes were at intersection on urban street [108]. In addition, based on the statistical data of road crashes occurred in Brampton roadways, between 2003 to 2007, 71% of pedestrian collisions happened at intersections [109]. To provide a safer and more reliable environment for road users at intersection on urban streets, the application of VANets seems to be essential. A high level of Quality of Service (QoS) is required at intersections to avoid any communication collisions that may happen due to heavy communications load. Enhancement of QoS in VANets is a challenging task due to some special characteristics of VANets such as dynamically topology changes and frequently breaken rout [102].

Congestion is one of the problematic issues in VANets. Congestion happens in the networks when the channels are overloaded in high dense network conditions. Due to the congestion, the packet loss and delay increase, that reduces the performance of network. Therefore, congestion control needs to be conducted to support QoS, as well as to ensure the safety and reliability in vehicular environments [8]-[11].

Basically, congestion control strategies for VANets can be classified into five categories including rate-based, power-based, CSMA/CA-based, prioritizing and scheduling-based, and hybrid strategies [13]. In rate-based strategies, transmission rate is decreased when the channels are congested [60], [61]. In power-based strategies, transmission power or transmission range is dynamically adjusted to decrease the channels loads [68], [69], [71]. In CSMA/CA-based strategies, congestion is controlled by modifying the CSMA/CA protocol and adjusting the contention window size and/or Arbitration inter-frame spacing (AIFS) to decrease the channel access [47], [73]. The prioritizing and scheduling-based strategies define a priority for each message and schedule them in control and service channels such that the emergency and safety messages get higher priorities and transfer with less delay [20], [21]. Finally, in hybrid strategies, all or some of the proposed solutions in previous categories are combined to control congestion [12], [79], [102].

In this paper, a Machine Learning Congestion Control (ML-CC) strategy is introduced. The proposed strategy is a centralized and localized strategy that employs Road Side Unites (RSUs) to control congestion. In this strategy, the messages are classified using machine learning algorithms at each RSU independently. The communications parameters for each class of the messages are determined based on the minimum delay for transferring the messages of each class. Then, the determined communication parameters are sent to the vehicles located in the congestion area in each intersection. Controlling congestion in these areas helps reduce the number of packet loss and delay and consequently increases the safety and reliability in VANets.

The rest of this paper is structured as follows. Section 6.2 reviews the background of congestion control and the best congestion control strategies in VANets. Section 6.3 proposes a strategy to control congestion centrally and locally. Finally, Section 6.4 evaluates the performance of the proposed strategy based on various QoS parameters.

## 6.2 Background and Related Works

Generally, congestion control strategies are classified into two groups of solutions: open-loop and closed-loop solutions. The open-loop solutions prevent congestion before it happens in the networks. In the closed-loop solutions, however, the congestion is controlled after its occurrence and being detected in the networks [34]. Detection of congestion can be carried out by employing the measurement methods that sense communication channels to measure some parameters like the number of messages in queue, the channel usage level, and the channel occupancy time [49].

In VANets, congestion control can be conducted using reactive, proactive and hybrid mechanisms. Each mechanism controls congestion by tuning of different transmission parameters [59]. The reactive mechanisms firstly detect the congestion based on some information about the channel condition (e.g. channel load). Note that the reactive mechanisms control the congestion after it happens in the vehicular network (closed-loop solution). These mechanisms tune the transmission rate and/or transmission range to decrease load of the channels and control congestion [110], [111]. The proactive mechanisms control the congestion by tuning the transmission power and/or rate based on some estimated information such as local vehicle density and data generation rate [47], [63]. Indeed, the proactive mechanisms are a subset of open-loop solutions that prevent the congestion. Finally, the hybrid mechanisms are designed to combine advantages of reactive and proactive mechanisms [79], [81]. Hybrid mechanisms control congestion by tuning transmission rate reactively and transmission power proactively.

As it was mentioned in introduction, the congestion control strategies in VANets are classified into rate-based, power-based, CSMA/CA-based, prioritizing and scheduling-based, and hybrid strategies [13]. In the following, these strategies are discussed.

### 6.2.1 Rate-Based Strategies

The rate-based strategies are type of closed-loop solutions that control the congestion after being detected in the networks. These strategies dynamically reduce the transmission rate or packet generation rate to reduce the packet collision rate in the congested channels. Ye et al. [61] measured optimal packet transmission rate based on the vehicle density in order to increase the broadcast efficiency and reliability. They modified the WAVE standard for adding a congestion control layer that communicates with MAC layer. Then, they investigated the packet reception rate of beacon messages by considering the impact of fading on one-dimension broadcasting. However, one-dimension broadcasting is not usual in real applications of VANets.

He et al. [60] proposed a cross-layer strategy to control congestion in control channel, and guarantee delivery of event-driven safety messages. In this strategy, first, the occupancy time of control channel in MAC layer is measured. The channel is considered to be congested if the occupancy time exceeds a predefined threshold. Then, MAC layer sends a signal to application layer for blocking all beacon messages. By blocking beacon messages, the control channel is reserved only for emergency messages, and consequently load of control channel is reduced. In this strategy, however, measuring of the channel occupancy time in MAC layer is difficult.

### 6.2.2 Power-Based Strategies

The power-based strategies control congestion by tuning transmission power (range). The transmission power is one of the most important factors in occurrence of channel collision. When so many nodes in the same communication rage compete to acquire the channel, channel collision and consequently congestion occurs. The power-based strategies are the open-loop strategies that avoid congestion by tuning transmission power and reducing channel loads.

Torrent-Moreno et al. [68] proposed a Distributed-Fair Power Adjustment for Vehicular environment (D-FPAV) strategy. This strategy dynamically adjusts the beaconing transmission range based on the vehicle density to reduce the load of channels. However, by shrinking the transmission range of beacon messages, the probability of delivering the beacon messages in far distances is reduced. Therefore, the VANets' applications, using the beacon information, face to some difficulties to obtain essential information.

Fallah et al. [69] designed a congestion control strategy by adapting transmission range whereas the channel occupancy time was measured to monitor congestion. The authors mathematically showed that there is a relationship between channel occupancy time, transmission range, transmission rate, and performance of network. The proposed strategy is a robust strategy; however, it is independent of the propagation model, vehicle density, and transmission rate of vehicles.

Sahu et al. [71] proposed Network Coding Congestion Control (NC-CC) strategy that uses network coding to control beacon overhead. The proposed strategy tunes the transmission range of beacon messages by network coding at the packet level. In this strategy, the number of forwarded beacon messages is reduced by forwarding the coded beacon messages only 2-hops over a predefined forwarding zone. Therefore, this strategy decreases channels overhead by reducing the transmission range of beacon messages. The proposed strategy is also a scalable strategy due to its ability to forward the beacons messages to a large number of receivers.

### 6.2.3 CSMA/CA-Based Strategies

CSMA/CA protocol is basically considered as the default congestion control protocol in VANets. This protocol determines the channel access ability for each node in MAC layer. CSMA/CA-based strategies adjust the channel access ability by modifying the channel access parameters such as contention widow size and AIFS, and consequently control the congestion in the channels [16].

Hsu et al. [47] proposed an Adaptable Offset Slot (AOS) strategy for reducing the channel load and delay. AOS uses the number of neighbor vehicles to obtain the minimum contention window size. AOS strategy linearly increases the contention window size by increasing the number of vehicles. In this strategy, however, the delay of emergency messages increases when the contention window size increases in high vehicle density condition.

Jang et al. [73] provided a detection-based MAC strategy. This strategy detects the congestion by exchanging RTS/CTS messages to predict the number of message collisions. Then, the contention window size is dynamically adapted according to predicted network status. In other words, to reduce the channels overloads, the contention window size is increased by increasing the number of collisions. Although using this strategy, throughput is improved and the number of collision is reduced, it is not a real-time strategy for broadcasting the messages.

### 6.2.4 Prioritizing and Scheduling-Based Strategies

The congestion control strategies in this category assign priority to the messages such that the more chance are given to the more important messages (e.g. emergency messages) for being transferred over the channels without delay. Bai et al. [21] introduced Context Awareness Beacon Scheduling (CABS) strategy to schedule the beacon messages dynamically. CABS strategy solves congestion resulted from high rate of beaconing in high dense vehicular networks. This strategy is a distributed strategy that piggybacks the information in beacon messages (e.g. velocity, direction and position of vehicles). Then, a unique time slot is assigned to each vehicle based on TDMA-like transmission. CABS strategy improves the packet reception rate and channel access delay. However, the internetworking in MAC layer that needs to be considered to allocate proper time slots for different transmissions is not taken into account.

Bouassida et al. [20] proposed a new strategy that controls the congestion by defining priority for messages based on static and dynamic factors. In this strategy, the messages are scheduled in control and service channels. The static and dynamic factors are defined based on the content of messages, and condition of network, respectively. This strategy can improve the delivery delay of safety messages.

### 6.2.5 Hybrid Strategies

The hybrid strategies combine all or some of the solutions employed in the previous strategies for solving congestion in VANets. Djahel et al. [79] proposed a three-phase hybrid strategy. In the first phase, the messages are prioritized based on the messages content and number of hops between senders and receivers to avoid congestion. In second phase, the average waiting time, beacon reception rate, and collision rate metrics are measured to detect congestion. If the values of these metrics exceed predefined thresholds, the congestion is considered to occur in the VANet. After detecting congestion, in third phase, the transmission rate and transmission range of beacon messages are adjusted to make an efficient usage of the channel bandwidth. Although the delay of the proposed strategy is significant, the reliability and safety of VANets are guaranteed using this strategy.

Taherkhani and Pierre [12], [102] introduced two hybrid congestion control strategies called Uni-Objective Tabu Search (UOTabu) and Multi-Objective Tabu search (MOTabu). These strategies are closed-loop strategies that detect the congestion by measuring the channel usage level. If the channel usage level exceeds 70%, the congestion is considered to occur in the network. Then, by tuning transmission rate and transmission range, the congestion is controlled. The optimal values for these parameters are obtained by a Tabu search algorithm. UOTabu determines transmission rate and range by considering the minimum delay [12], while MOTabu considers minimum delay and jitter to control congestion [102]. The results showed that UOTabu and MOTabu reduced the delay and the packet loss, and consequently improved the performance of VANets.

Despite the advantages of the introduced congestion control strategies, some drawbacks can be observed. Some of the strategies need to have extra interactions between the vehicles to detect the congestion in the network. These extra interactions increase the channel loads and the possibility of collision [13], [50], [74]. In some strategies, by reducing beaconing rate to control load of channels, the applications using the beacon information face to lack of information to operate efficiently [48], [55], [63].

Tuning the transmission power and rate to control congestion are affected by various parameters such as vehicle density, distance between sender and receiver, and message size, and so on. However, in a large scale network, tuning transmission rate and transmission power are faced to many challenges due to the large number of influential parameters [50], [56], [102].

The CSMA/CA protocol employs the exponential back-off mechanism. However, this mechanism is not efficient for broadcasting the beacon messages. This mechanism cannot work properly in high rate message situations, especially when the messages have a time-out that lead to the packets to be dropped before transmission. This is worse in the networks with high density [46]-[48].

In prioritizing and scheduling-based strategies, the priority of each message is independently determined by each vehicle. Then, the prioritized messages of each vehicle are sent to channel based on a scheduling algorithm. However, when a vehicle sends its emergency messages to control channel, it may face collision because it cannot prevent the other vehicles from sending their low priority messages. Therefore, channel may be occupied by low priority messages leading to delivering of high priority emergency messages with high delay [58].

## 6.3 Problem Statements and Solving Strategies

The intersections are the most likely places for communication congestion to occur. High vehicle density before the red traffic lights impacts QoS of VANets [80], [108], [109]. A critical area is formed before the red traffic lights due to the large amount of communications in this area. In this paper, this critical area is called congestion area (Figure 6.1). In the congestion areas, the number of packets loss and delay increase due to high packet collision rate. Thus, controlling congestion in congestion area helps have a more reliable communication as well as a safer environment.

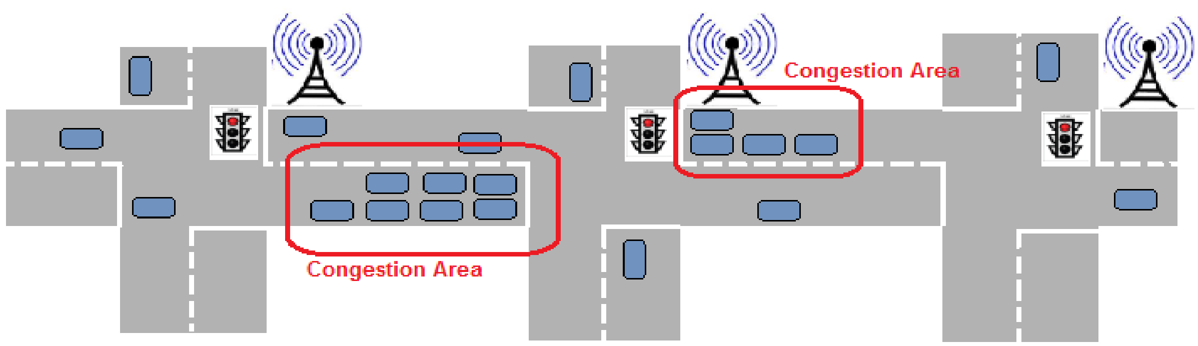



Figure 6.1: Schema of congestion areas and RSUs at intersections.

The proposed strategy in this paper employs RSUs installed at the intersections to control congestion locally. Note that in VANets, it is assumed that an RSU is set at each intersection. The proposed strategy adjusts the communication parameters including transmission range, transmission rate, contention window size, and AIFS in the congestion areas based on the minimum transferring delay for the messages of each class. This strategy is centralized strategy that independently operates in each RSU installed at each intersection to maintain the consistency and reliability of VANets. The proposed congestion control strategy is also a closed-loop and hybrid strategy. The strategy proposed in this paper consists of three units: 1) congestion detection unit, 2) data control unit, and 3) congestion control unit.

### 6.3.1 Congestion Detection Unit

In congestion detection unit, a measurement based strategy is used to detect congestion in the channels. Generally, in measurement strategies, the channels are sensed periodically to measure some parameters like the number of message in queues, channel usage level, and channel occupancy time [49]. In this paper, however, the channel usage level is measured to detect the congestion in the channels. If the measured parameter exceeds a predefined threshold, the congestion detection unit assumes that the congestion occurred and sends a signal to the other units to control the congestion. In this paper, this threshold is assumed to be equal to 70% as it was assumed in [42].

### 6.3.2 Data Control Unit

Data control unit is composed of data gathering, filtering, and clustering components. In data gathering component, all transferred messages between the vehicles are collected. In this paper, data gathering is conducted by two different techniques. In the first technique, after detecting the congestion, the messages are collected for 100 milliseconds. However, in second technique, the transferred messages between vehicles, which stop before the red traffic lights at intersections, are buffered in RSUs all the time. Thus, in the second technique, the messages are collected before congestion detection. In data filtering component, the redundant messages received by each RSU from different vehicles are deleted to eliminate the extra processing operations for the same messages. Then, in the data clustering component, the messages are classified based on their features using a machine learning algorithm.

Machine learning algorithms are robust means for classifying and clustering the large data sets due to their specific abilities such as short computing time, supporting the huge amount of data, automatically detecting pattern in data, predicting future data using the uncovered patterns, and planning to collect more data [112], [113]. In this paper, the machine learning algorithms are used for clustering the large data set and multi-dimensional features space of VANets. Generally, the machine learning algorithms can be divided into two categories: i) supervised (classification) learning algorithms such as Support Vector Machine (SVM), Neural Networks, Boosting, and K-Nearest Neighbors, and so on [114], and ii) unsupervised (clustering) learning algorithms, such as K-means, Fuzzy clustering, Decision tree, Expectation-maximization (EM), and Balanced Iterative Reducing and Clustering using Hierarchies (BIRCH), and so on [115]. The supervised algorithms that are used for labeled data need to employ a training data set for comparing the features [114], [116]. However, the unsupervised algorithms that are used for unlabeled data do not need to employ the training data set [115], [116]. In this paper, the unsupervised machine learning algorithms are used for data clustering due to diversity of messages over V2V and V2I communications and unlabeled data in VANets.

In this paper, the K-means algorithm is used for clustering the messages in VANets. The K-means algorithm is one of the most popular unsupervised learning algorithms widely used for the multi-dimensional features clustering [117], [118]. The K-means algorithm is a scalable, rapid, and simple learning algorithm. Also, this algorithm is an efficient algorithm to process the large data set [118], [119]. In the following, the K-means learning algorithm used in this paper is described in more detail.

***Proposed K-means Algorithm for Data Clustering***

K-means algorithm was initially introduced by James Macqueen in 1967 [120], but it is still one of the most popular unsupervised clustering algorithms due to its simplicity, empirical success, efficiency, and ease of implementation. K-means algorithm classifies a set of data into k number of clusters based on their features. For each data, K-means algorithm calculates the Euclidean distance to all cluster centroids (cluster centers), and then selects the minimum distance. The data belongs to a cluster that the distance to the centroid of that cluster is the minimum. Then, the new centroid is calculated for each cluster based on the average coordinate of all members of each cluster. Finally, all the data are classified based on the new centroid. K-means algorithm repeats this process until the members of each cluster do not move to the other clusters anymore [117]-[120].

The initial centroids for K-means algorithm can be chosen by Forgy and Random methods [121]. The Forgy method chooses k data randomly as the k initial centroids for each cluster. The

Random method divides the data set into k subsets, and then executes K-means algorithm to update the clusters. However, there is no guarantee that, using these methods, K-means algorithm converges [121], [122]. Therefore, the researchers use various methods for determining the initial centroids. In this paper, the initial centroids for k clusters are assumed to be the first k messages received by RSUs.

Basically, K-means algorithm consists of three main steps: 1) selecting initial centroids for k clusters; 2) computing squared Euclidean distance of each data to the centroids; 3) computing the new centroids cluster to find closest centroids. Steps 2 and 3 should be repeated until the cluster members no longer change [117]-[119].

K-means algorithm has three inputs including features, number of clusters, and number of iterations. Clustering algorithms classify a set of objects based on identified features; thus, features have a significant impact on performance of the clustering algorithms. In K-means algorithm, the features should be transformed to the dimensional values. Generally, there is no efficient strategy for determining the features. In fact the features should be determined specifically for each problem based on the knowledge about the domain of problem [117], [118], [120]. In this paper, the features of K-means algorithm are defined based on the features of messages including the message size, validity of messages, distances between vehicles and RSUs, type of message, and direction of message sender.

The number of clusters is the second input for K-means clustering algorithm. The best number of cluster for each problem can be defined by executing the clustering algorithm for different numbers of clusters [117], [118], [120]. However, there are some strategies which help estimate the number of clusters using the minimum message length (MML) in conjunction with the Gaussian Mixture Model (GMM) [123], Minimum Description Length (MDL) [124], Bayes Information Criterion (BIC) [125], and Akiake Information Criterion (AIC) [126], and so on [117]. In this paper, the number of clusters (k) for K-means algorithm is obtained by conducting a set of preliminary simulations shown in section 6.4.2.

The clustering algorithm is terminated when a predefined convergence is obtained. That means there are not any changes in the clusters' members. However, if the convergence is not obtained in the acceptable time, the clustering algorithm should be terminated after a predefined number of iterations. Theoretically, K-means algorithm does not rapidly converge especially for the big data sets [117]. In this paper, the number of iterations is assumed to be 100.

The complexity of K-means algorithm depends on the number of data in each data set, the number of features, number of clusters, and number of iterations. Therefore, proper initial conditions can result in a better clustering [127]. Figure 6.2 shows the pseudocode of the proposed K-means algorithm used for clustering in this paper.

### 6.3.3 Congestion Control Unit

Congestion control unit adjusts the communication parameters for each cluster determined in data control unit. The communication parameters considered in this unit are transmission rate, transmission range, contention window size, and AIFS. The performance of VANets is considerably affected by transmission range and rate. The messages, especially safety messages, are usually sent with high transmission range to increase the number of vehicles that can receive these types of messages. However, the number of collisions increases when the transmission range of messages is high. The transmission rate also impacts the saturation of the channels. High transmission rate improves the performance of VANets' applications due to the more frequently sending the information to these applications. However, high transmission rate may saturate the channels increasing the load of channels [14]. Contention window size and AIFS also impact the condition of channels. To define the priority of the messages for transferring in the channels, the contention window size and AIFS need to be determined for each type of messages [18]. Prioritizing and scheduling the messages help prevent the channels saturation and congestion occurrence in the networks [54].

For adjusting the communication parameters for each class of messages, the proposed strategy selects the proper values of these parameters among the range of values defined by DSRC standard [4], [6]. DSRC defines the transmission rate and range between 3- 27 Mbps and 10- 1000 m, respectively. Based on this standard, the possible values for transmission rate are 3, 4.5 6, 9, 12, 18, 24, and 27 Mbps [92], [93], [94], while the possible values for transmission range are 10, 50, 100, 126, 150, 210, 300, 350, 380, 450, 550, 650, 750, 850, 930, 971, and 1000 m [17]. Based on DSRC, the possible values for minimum and maximum contention window size ($CW_{min}$, $CW_{max}$) are assumed to be (3, 7), (7, 15), and (15, 1023); and the possible values for AIFS are assumed to be 1, 2, 3, and 7 [17]-[19].

```
Input:
        k // Number of clusters
        MaxIters // Limit of iterations
        n // Number of messages
        M = [m1, m2, … , mn] // Set of n filtered messages
Output:
        A set of k clusters and labels of cluster for each message

NewClusterLabel = [n1, n2, … , nn] // New label of cluster for each message
OldClusterLabel = [o1, o2, … , on] // Old label of cluster for each message
P = [p1, p2, …, pn] // Set of n data points
C = [c1, c2, … , ck] // Set of k centroids

        Represent (M by P )

// Determining the initial centroids of the clusters
        C = [p1, p2, …, pk] // assuming the first four messages as the initial centroids of the clusters
        for  i = 1 to n
            for j = 1 to k
                d( pi , cj ) = Compute (Euclidean distance of data point pi to the centroid cj)
            endfor
            Find (closest centroid cj to pi )
            NewClusterLabel [i] = j
            OldClusterLabel [i] = j
        endfor

// Main loop of clustering the items
        Changed = False
        Iters = 0

        Repeat

// Updating centroids, finding new ci ∈ C
            for i = 1 to k
                c′i = Calculate (average coordinate among all member of ci )
                Find ( closest pj (j=1 to n) ∈ P to c′i )
                ci = pj
            endfor

            for i = 1 to n
                for j = 1 to k
                    d( pi , cj ) = Compute (Euclidean distance of data point pi to the centroid cj)
                endfor
                Find (closest centroid cj to pi )
                NewClusterLabel [i] = j
                if NewClusterLabel [i] ≠ OldClusterLabel [i] then
                    OldClusterLabel [i] = NewClusterLabel [i]
                    Changed = True
                endif
            endfor
            Iters = Iters + 1

        Until Changed = True and Iters ≤ MaxIters
        Return ( C, NewClusterLabel )
```

Figure 6.2: Pseudocode of the proposed K-means algorithm.

In the proposed strategy, to adjust the communication parameters for each class, the delay for centroid of each class is calculated using the formulas shown in Appendix A, and by taking into account all possible combinations of the communication parameters values. Then, the values of communication parameters corresponding to the lowest delay are selected as the communication parameters of each class. RSU sends these communication parameters to the vehicles stopped before the red traffic light in the congestion area. Then, the vehicles operate based on these communication parameters to control congestion. Figure 6.3 shows the flowchart of the proposed strategy and its units.

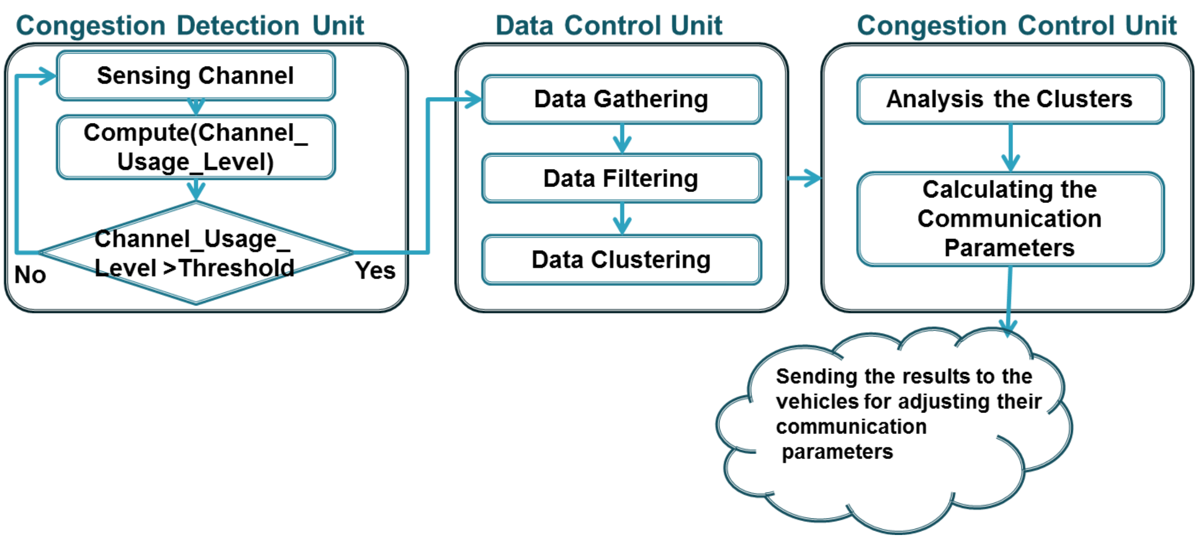



Figure 6.3: Flowchart of the proposed congestion control strategy.

## 6.4 Performance Evaluation

### 6.4.1 Simulation Parameters and Scenarios

For simulating the mobility of vehicles and vehicular network, two types of simulators were employed in this paper. Simulation of Urban Mobility (SUMO) was used for simulating the mobility of vehicles, vehicles' traffics, and road topologies [97], [98]. Network Simulator (NS, version 2.35) was also used to simulate vehicular networks [99]. In addition, the MObility model generator for VEhicular network (MOVE) was used to convert the mobility model generated by SUMO to an acceptable scenario for NS2 [100].

To evaluate the performance of the proposed strategy to control congestion in urban environments, an urban scenario was simulated. The pattern of this scenario was considered to be Manhattan road pattern with eight intersections. The simulation parameters used in the urban scenario was shown in Table 6.1. The communication protocol and MAC layer transmission strategy were considered to be IEEE 802.11p and CSMA/CA, respectively. In addition, to model the existing obstacles in urban scenario (e.g. building and trees), Nakagami model was employed as a propagation model. Finally, the Poisson distribution was used for data generation.

Table 6.1: Simulation parameters used in the urban scenario.

| **Parameters** | **Value** |
|---|---|
| Total road length | 1000 m × 1000 m |
| Number of lanes | 4 (2 in each direction) |
| Number of Vehicles | 50, 100, 150, 200, 250, 300, 350, 400, 450, 500 |
| Vehicles speed | 0-40 km/h |
| Transmission rate | 3-27 Mbps |
| Bandwidth | 10MHz |
| Message Size | Beacon: 400 Bytes , Emergency: 300 Bytes |
| Safety messages generation rate | 10 packet/s |
| MAC type | IEEE 802.11p |
| Propagation model | Nakagami (m=3) |
| Routing Protocol | DSDV |
| Simulation time | 1000 s |
| Simulation runs | 20 |

### 6.4.2 K-means Parameters

As it was mentioned before, the features of K-means algorithm used in this paper are defined based on the message size, validity of messages, distances between vehicles and RSUs, type of message, and direction of the message sender. The message size is different for various types of the messages. The size of emergency and beacon messages is 300 and 400 bytes, respectively [128], while the size of service messages can be 1000, 1024, and 1400 bytes [129]. The validity of message is defined based on the remaining time to the message deadline. The distance between vehicles and RSUs is estimated based on the position of vehicles at intersections. In this paper, the type of messages is represented by 1, 2, and 3 for the emergency, beacon, and service messages, respectively. Finally, the direction of the message sender is assumed to be 1, 2, 3, and 4 for the vehicle moves towards north, south, east, and west directions, respectively.

For selecting the proper number of clusters, a set of preliminary simulations is performed using the proposed K-means algorithm. Table 6.2 and Table 6.3 show the variations of the packet loss ratio and average delay with the variations of the number of vehicles for number of clusters 2, 4, and 6. Table 6.2 shows that increasing the number of clusters decreases the packet loss ratio for each number of vehicles. Indeed, by considering more class of messages, and determining specific communication parameters for each class, the number of collisions and consequently the packet loss ratio decrease.

Table 6.3 shows that the average delay decreases by increasing the number of clusters when the number of vehicles is less than or equal to 200. However, for a number of vehicles larger than 200, the lowest average delay is obtained for four clusters. When the number of clusters is equal to two, the average delay for transferring the messages over VANet is highest, due to the high collision rate between the messages. For the number of vehicles larger than 200, by increasing the number of clusters from four to six, the average delay increases, due to decreasing the consistency of clusters and increasing the clustering errors for separating the messages between the different classes.

Therefore, the number of clusters for the K-means algorithm is assumed to be equal to four. Note that based on Table 6.2, the packet loss ratio calculated for four clusters are very close to the packet loss ratio calculated for six clusters. Also, based on Table 6.3, the average delays calculated for four and six clusters are almost identical when the number of vehicles is less than 200.

For terminating the K-means algorithm, the number of iterations is assumed to be 100. Finally, the initial centroids for 4 clusters are also assumed to be the first 4 messages received by RSUs.

Table 6.2: Variations of the packet loss ratio with the number of vehicles for different number of clusters.

| | **Packet Loss Ratio** | | |
|---|---|---|---|
| | **Number of Clusters** | | |
| **Number of Vehicles** | **2** | **4** | **6** |
| **100** | 0.02935 | 0.01939 | 0.01860 |
| **200** | 0.07827 | 0.03586 | 0.03097 |
| **300** | 0.19355 | 0.07841 | 0.05535 |
| **400** | 0.28685 | 0.09474 | 0.07522 |
| **500** | 0.34655 | 0.11488 | 0.08466 |

Table 6.3: Variations of the average delay with the number of vehicles for different number of clusters.

| | **Average Delay (ms)** | | |
|---|---|---|---|
| | **Number of Clusters** | | |
| **Number of Vehicles** | **2** | **4** | **6** |
| **100** | 11.25480 | 10.64951 | 9.75480 |
| **200** | 18.65794 | 15.54763 | 15.24875 |
| **300** | 59.25471 | 26.54961 | 40.98510 |
| **400** | 94.21875 | 61.57150 | 81.74960 |
| **500** | 160.21450 | 103.47000 | 143.47560 |

### 6.4.3 Simulation Results and Performance Evaluation

In this section, the performance of the proposed congestion control strategy is evaluated and compared with some congestion control strategies in VANets. The comparisons were conducted between CSMA/CA [16], D-FPAV [68], CABS [21], NC-CC [71] and the proposed strategy in this paper (ML-CC). CSMA/CA strategy is the default congestion control strategy for avoiding collision in VANets. D-FPAV strategy controls congestion by dynamically tuning the transmission range of the safety messages. CABS strategy is a distributed strategy that controls the congestion by dynamically scheduling the beacon messages and tuning beaconing rate. Finally, NC-CC strategy reduces the number of beacon transmissions by network coding and reducing the transmission power of each node.

For evaluating the performance of the congestion control strategies, six performance metrics are employed:

*Average Delay:* This metric corresponds to the average of time needs to deliver the messages from senders to receivers.

*Average Throughput*: It corresponds to the average number of bytes received successfully by the receivers per time unit.

*Number of Packet Loss*: It corresponds to the total number of packets lost during the simulation time.

*Packet Loss Ratio*: It is defined as the ratio of the total number of packet loss over the total number of sent packets.

*Collision Probability*: It corresponds to the probability of collision occurrence in the channels during the packets transmissions.

*Packet Delivery Ratio*: It corresponds to the ratio of the total number of packets delivered to the destinations over the total number of packets sent by nodes.

A set of simulations was carried out to evaluate the impact of number of vehicles, simulation time, and vehicle density on the introduced performance metrics.

As it was mentioned in Section 6.3.2, the data gathering in data control unit can be performed by two techniques. The first technique operates based on the data collected after detecting the congestion (ML-CC(1)). However, the second technique operates based on previous data buffered in RSUs (ML-CC(2)). In the following, the performance of these two techniques are evaluated.

Figure 6.4 and Figure 6.5 show the variation of packet loss ratio and average delay with the number of vehicles, respectively. The figures show that the packet loss ratio and average delay resulted from ML-CC(2) are less than ML-CC(1). The second technique outperforms better than the first technique because using ML-CC(2), the vehicles set the communication parameters in congestion situation for all messages even for the new generated messages. Also, as it can be seen in the Figure 6.5, ML-CC(1) technique requires 100 ms time for collecting the messages that lead to the higher average delay in this technique. Therefore, in this paper, ML-CC(2) technique was selected for collecting data messages in data control unit.

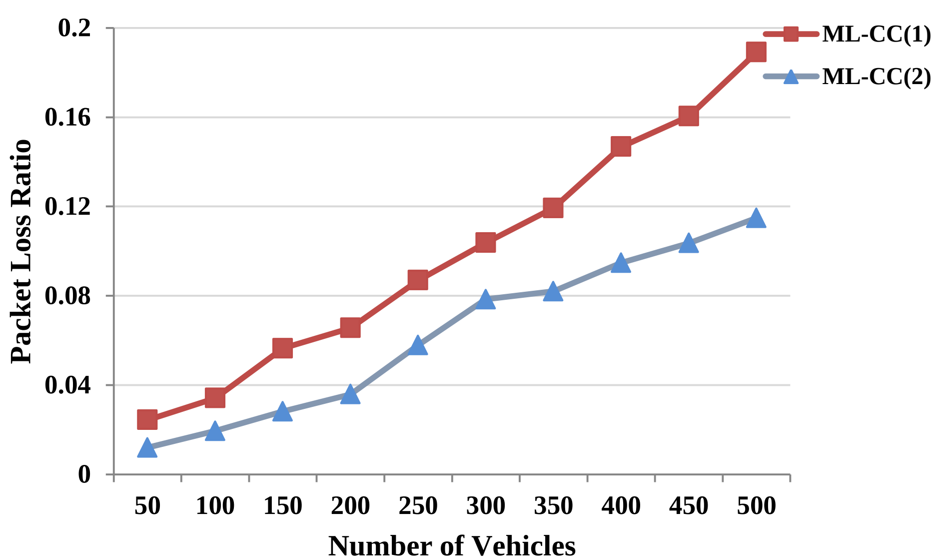



Figure 6.4: Variation of the packet loss ratio with number of vehicles for ML-CC(1) and ML-CC(2).

Figure 6.6 compares the average delay obtained by different congestion control strategies. As the figure shows, by increasing the number of vehicles from 50 to 500, the average delay increases for all strategies. When the number of vehicles increases from 50 to 500, the average delay increases from 19.4, 17.5, 13.1, 12.9, and 9.3 milliseconds to 1054.7, 510.3, 366.4, 300.8, and

103.4 milliseconds for CSMA/CA, D-FPAV, CABS, NC-CC, and ML-CC strategies, respectively. However, the rate of change of the average delay resulted from the proposed strategy (ML-CC) is less than the other congestion control strategies.

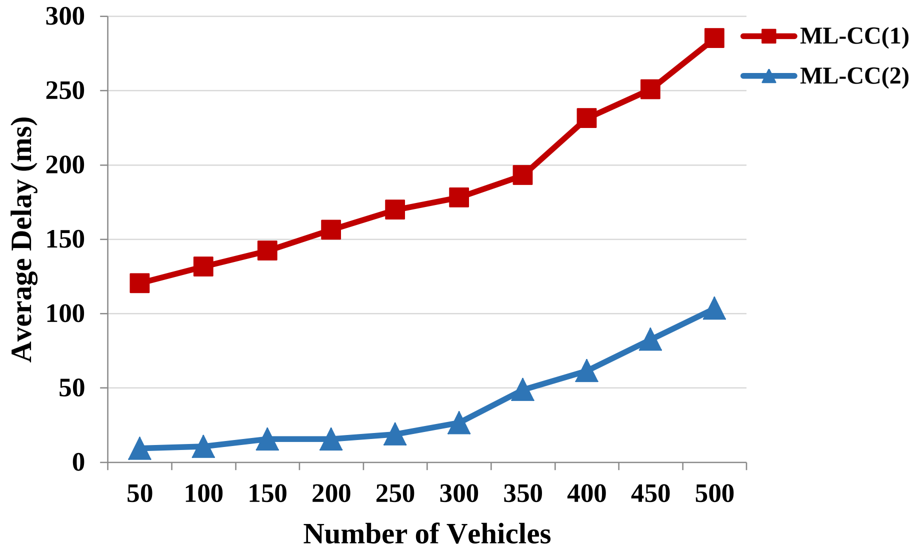



Figure 6.5: Variation of the average delay with number of vehicles for ML-CC(1) and ML-CC(2).

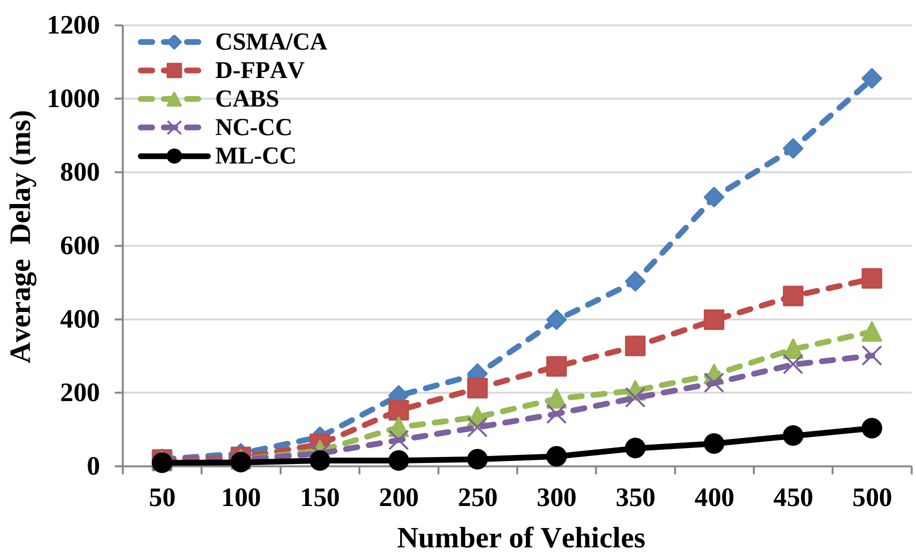



Figure 6.6: Impact of the number of vehicles on average delay.

The transmission range and rate, contention window size, and AIFS are the most important parameters that have direct impact on the condition of communication channels. ML-CC strategy dynamically adjusts these parameters. Using ML-CC strategy, the number of collisions decreases. Consequently, the average delay for delivering messages decreases. Moreover, the ML-CC considers all types of messages (i.e. safety and service messages), and determines the communication parameters for each class of messages, while D-FPAV, CABS, and NC-CC only consider the beacon messages for controlling congestion.

Figure 6.7 shows the variation of the average throughput with the number of vehicles for various congestion control strategies. It also shows that, by increasing the number of vehicles from 50 to 500, the average throughput increases 7.7%, 11.4%, 16.2%, 20.6%, and 27.9% for CSMA/CA, D-FPAV, CABS, NC-CC, and ML-CC, respectively. It can be observed that the average throughput obtained from ML-CC is more than the other strategies. By classifying all the messages, adjusting appropriate values for contention window size and AIFS, and also tuning transmission range and rate for each class of messages, congestion is better controlled using ML-CC.

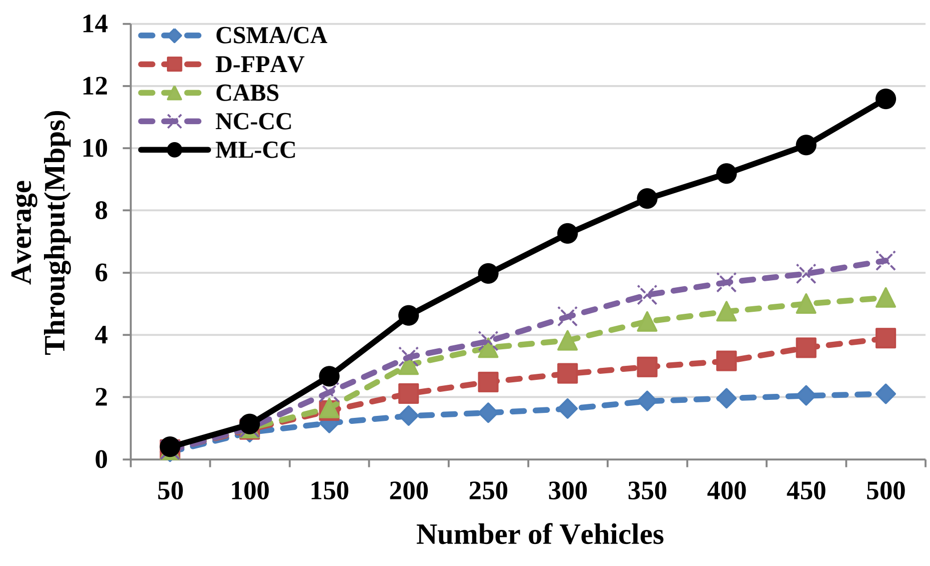



Figure 6.7: Impact of the number of vehicles on average throughput.

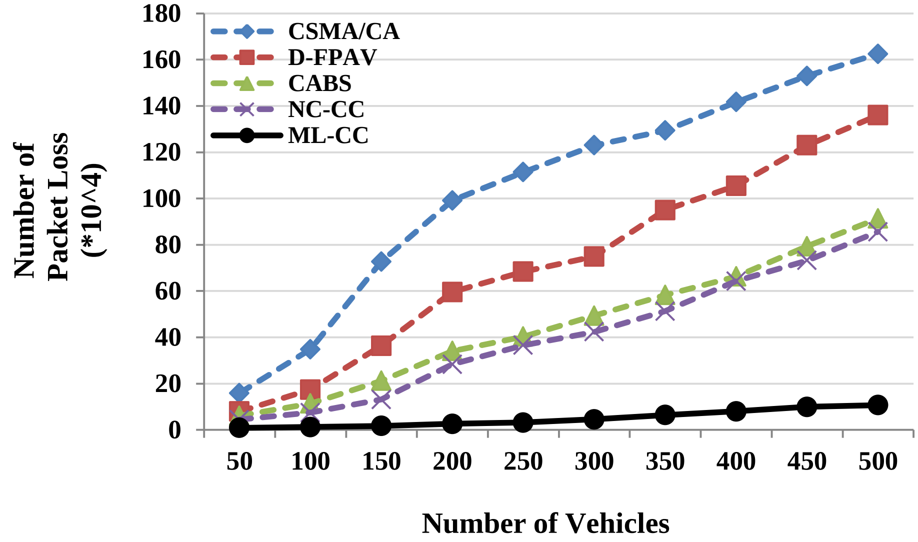
In Figure 6.8, the number of packet loss and the packet loss ratio are measured for different number of vehicles. Figure 6.8 (a) shows that the number of packet loss for CSMA/CA, D-

FPAV, CABS, NC-CC, and ML-CC are $162.5\times10^4$, $135.9\times10^4$, $91.3\times10^4$, $85.6\times10^4$, and $10.6\times10^4$, respectively, for the number of vehicles equal to 500. Using ML-CC strategy reduces the packet loss significantly in comparison with the other strategies, by diminishing channel collisions.

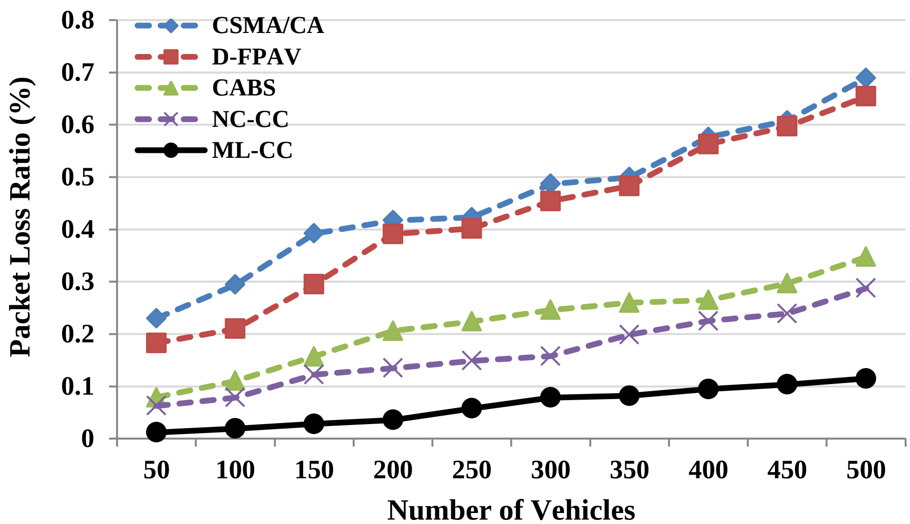
Moreover, Figure 6.8 (b) illustrates the variations of packet loss ratio with number of vehicles. As the figure shows, the packet loss ratio obtained for the number of vehicles equal to 50 is 22.9%, 18.2%, 7.8%, 6.2%, and 1.1% for CSMA/CA, D-FPAV, CABS, NC-CC, and ML-CC strategies, respectively, while these ratios increase to 68.9%, 65.4%, 34.7%, 28.7%, and 11.4% for the number of vehicles 500. Indeed, the packet loss ratio obtained from ML-CC strategy is 57.4%, 53.9%, 23.2%, and 17.2% less than the ratio obtained from CSMA/CA, D-FPAV, CABS, and NC-CC strategies, respectively, for the number of vehicles equal to 500. These results illustrate that ML-CC outperforms better than the other strategies and can improve packet loss ratio in communication channels, which is one of the main goals of every congestion control strategies.

In Figure 6.9 and Figure 6.10, the variation of average throughput and delay with simulation time is depicted, respectively, whereas the number of vehicles is assumed to be 500. Figure 6.9 shows that the average throughput obtained from ML-CC strategy is more than the average throughput obtained from the other strategies during the simulation time. The results also show that after 1000 milliseconds, the average throughput increases to 1.29, 1.35, 1.57, 1.69, and 2.09 Mbps, using CSMA/CA, D-FPAV, CABS, NC-CC, and ML-CC strategies, respectively. As the results show, using ML-CC strategy, the average throughput is improved significantly because V2V and V2I communications are conducted using the proper communication parameters; thus, the congestion is better controlled in the channels.

Furthermore, Figure 6.10 presents the plot of the average delay versus simulation time. In this figure, it can be seen that the average delay resulted from ML-CC strategy is less than the other strategies during simulation time. The results also show that, by advancing the simulation time from 250 to 500 seconds, using CSMA/CA, D-FPAV, CABS, NC-CC, and ML-CC strategies, the average delay decreases 0.17, 0.48, 0.51, 0.34, and 0.53 seconds. It means that the average delay obtained from ML-CC strategy decreases faster than the other strategies. The reason for such observation is that ML-CC strategy controls the transmission rate and range, and determines the priority of the messages for being sent in the channels by adjusting contention window size and AIFS for all types of messages.




**(a)**




**(b)**

Figure 6.8: Impact of the number of vehicles on (a) number of packet loss, and (b) packet loss ratio.

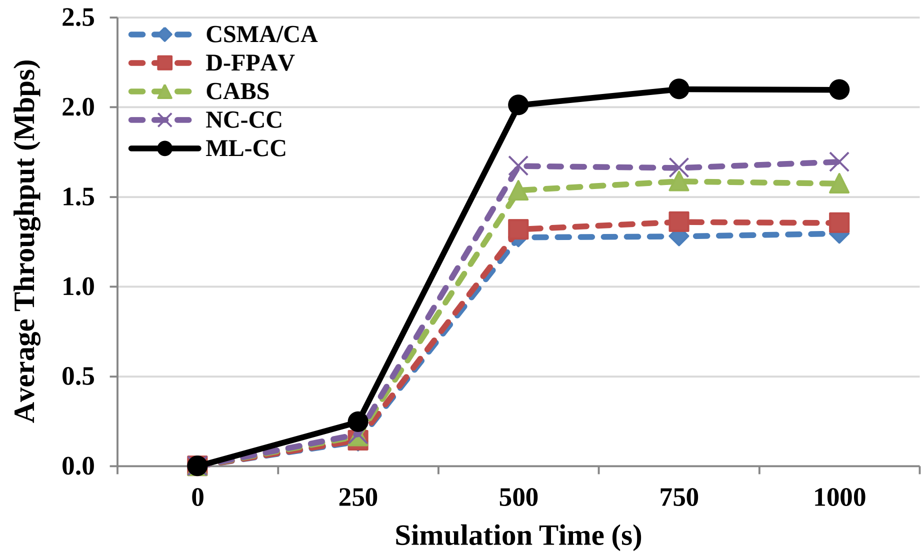



Figure 6.9: Variation of the average throughput with simulation time.

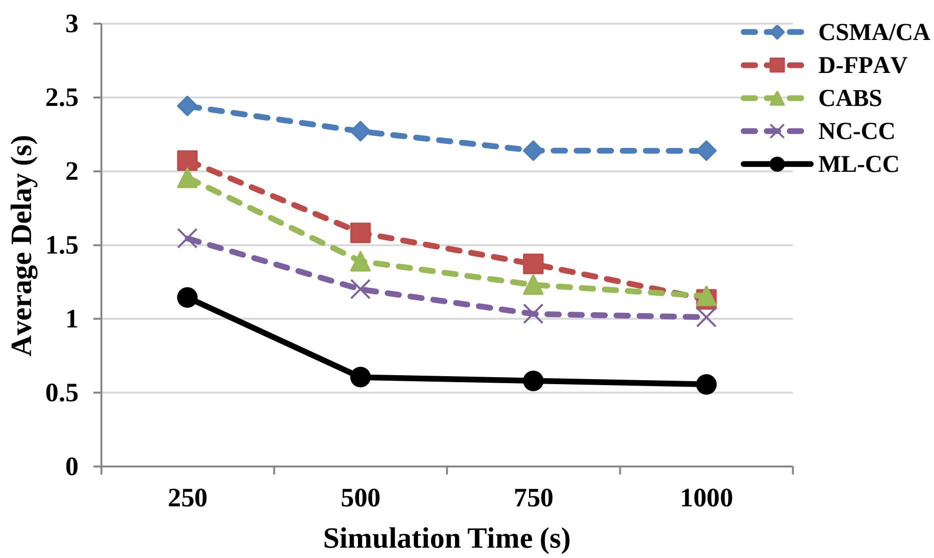



Figure 6.10: Variation of the average delay with simulation time.

The last set of results is depicted in Figure 6.11 and Figure 6.12 that denote a comparison between the proposed congestion control strategy (ML-CC), and CSMA/CA strategy as the default congestion control strategy in VANets. Figure 6.11 illustrates the variations of the collision probability with the number of vehicles. It shows that the collision probability increases by increasing the number of vehicles for both strategies. However, using ML-CC strategy, the collision probability does not increase significantly. It also shows that, for a number of vehicles equal to 500, the collision probability resulted from ML-CC strategy is 8.2 times less than the collision probability resulted from CSMA/CA strategy.

The variation of packet delivery ratio with vehicle density is illustrated in Figure 6.12. The figure shows that, by increasing the vehicle density, the packet delivery ratio decreases. However, the packet delivery ratio resulted from ML-CC strategy is more than CSMA/CA strategy. Indeed, by increasing the vehicle density from 40 to 100 vehicle/Km, the packet delivery ratio decreases to 0.08 and 0.04 for CSMA/CA and ML-CC strategies, respectively. Those results also clearly indicate that ML-CC strategy outperforms better than CSMA/CA congestion control strategy. It means ML-CC can deliver more packets in urban environments with high density of vehicles. As it was mentioned before, ML-CC strategy decreases the packet loss ratio (Figure 6.8 (b)) by determining the transmission range and rate, contention window size, and AIFS which are the most effective communication parameters in the performance of the networks. Therefore, ML-CC strategy can improve the collision probability and packet delivery ratio and consequently controls congestion in channels in urban intersections.

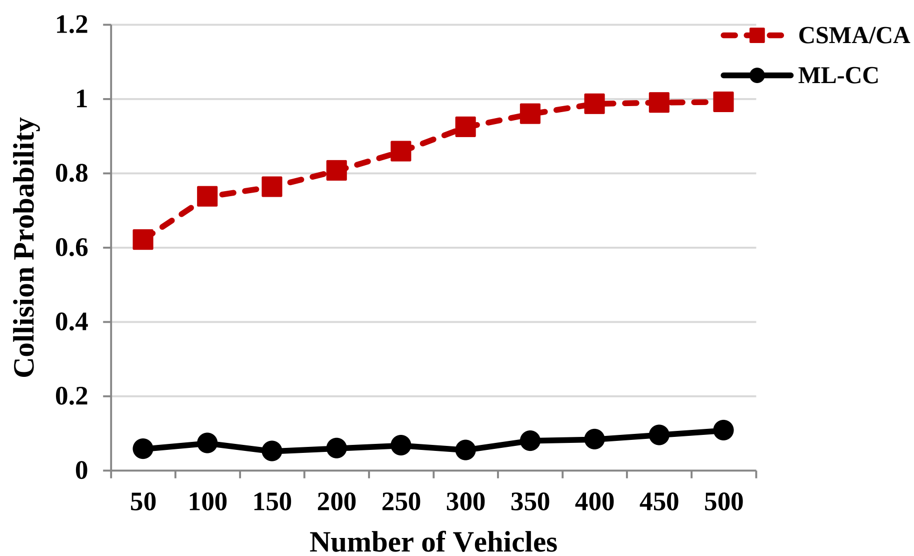



Figure 6.11: Variations of the collision probability with the number of vehicles.

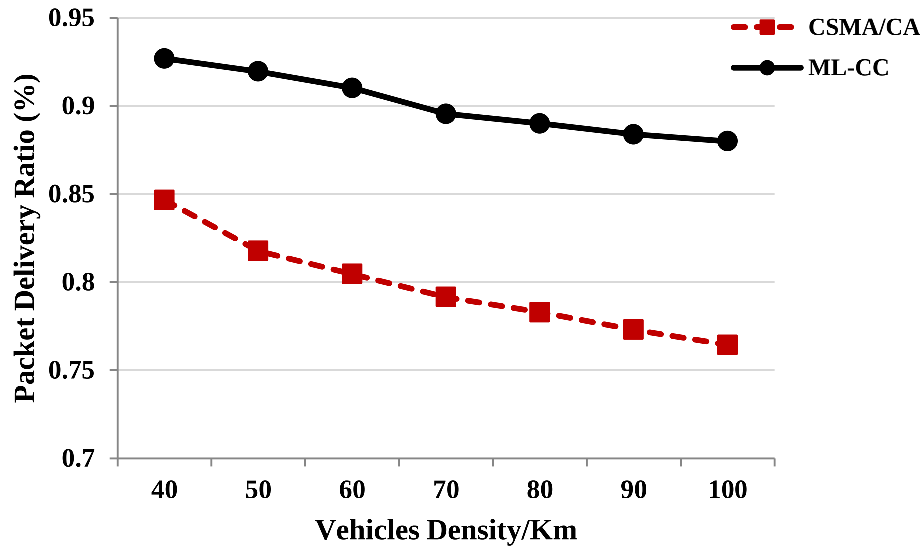



Figure 6.12: Variation of packet delivery ratio with vehicle density.

## 6.5 Summary and Conclusion

In this paper, a Machine Learning Congestion Control (ML-CC) strategy was proposed to address the congestion that may occur at intersections, due to the large amount of communications between vehicles stopped before red traffic lights. The proposed strategy was a closed-loop congestion control strategy. This strategy was also a centralized and localized strategy because each RSU set at each intersection is responsible for controlling the congestion occurring at that intersection. ML-CC strategy consisted of three units including congestion detection, data control, and congestion control units. The congestion detection unit measured the channel usage level to detect congestion. The data control unit collected and filtered the messages to eliminate the redundant messages, then clustered the messages into four separate clusters using a K-means algorithm. The congestion control unit determined communication parameters including transmission range and rate, contention window size, and AIFS for each cluster based on the minimum delay to transfer the messages. Finally, the communication parameters determined by ML-CC strategy are sent by RSU to the vehicles stopped before red traffic lights to reduce the collision in channels and control the congestion.

Taking into account an urban scenario, the performance of ML-CC strategy was compared with CSMA/CA, D-FPAV, CABS, and NC-CC strategies. The comparison showed that the proposed strategy outperformed better than the other congestion control strategies in VANets. ML-CC strategy improved the performance of VANets by reducing the packet loss ratio, the average delay, and collision probability. Moreover, ML-CC strategy increased the average throughput, and packet delivery ratio considerably. Based on the obtained results, it can be concluded that the proposed strategy is a scalable strategy because the performance metrics do not change significantly by increasing the number of vehicles in the network. ML-CC strategy improved the performance metrics by clustering all types of messages, and adjusting communication parameters for each cluster. Therefore, using ML-CC strategy, congestion can be controlled properly, and subsequently a safer environment can be provided for road users especially at the urban intersections.

To practically implement the proposed strategy in real vehicular networks, an RSU needs to be set at each intersection. Also, since congestion control is a real-time process, RSUs may need to be equipped with Graphic Processing Units (GPUs) for quickly executing machine learning algorithms. Note that the machine learning algorithms conduct a large number of calculations and operations that takes a lot of time.

# CHAPTER 7 GENERAL DISCUSSION

In this chapter, the techniques and algorithms employed in the proposed congestion control strategies are discussed. Considering the significant impact of the transmission range and rate on the channel conditions, these two parameters are used to control the channel loads as well as congestion. The high transmission range can increase the number of vehicles receiving the messages, especially the safety messages. However, the collision rate increases by increasing the transmission range. A high transmission rate also increases the performance of VANets' applications due to updating the information. However, the channels are overloaded by increasing the transmission rate. Therefore, the optimal values for these parameters should be obtained to avoid channels saturation. Obtaining the optimal values of transmission range and rate in reasonable time is a complex process in VANets due to the special characteristics of these networks [10], [13], [14], [55].

Moreover, the high density of vehicles leads to increasing the beaconing rate in the control channels and consequently the control channel is congested. For increasing the reliability of emergency messages, the messages should be prioritized, and the control and service channel queues should be scheduled. Therefore, in this dissertation, the prioritizing and scheduling of the messages are performed to control the congestion in VANets [22], [29], [57].

Obtaining optimal values for transmission range and rate corresponds to the multi-dimensional Knapsack problem. This problem is an NP-hard problem [88]. Therefore, based on the reduction of the problem of obtaining the optimal values of transmission range and rate to the multi-dimensional Knapsack problem, obtaining the optimal values is also an NP-hard problem [88], [89]. Generally, the Meta-heuristic techniques can provide a near-optimal solution for NP-hard problems in reasonable time [90]. Hence, in this dissertation, the Meta-heuristic techniques are used to obtain the near-optimal transmission range and rate in reasonable time for controlling congestion which is a real-time process.

Tabu Search, Genetic, Simulated Annealing, and Ant Colony algorithms are popular meta-heuristic algorithms [85]. The Tabu Search algorithm is one of the well-known Meta-heuristic algorithms which is able to find high-quality solutions in reasonable time for the optimization problems (e.g. real-time decision problems, scheduling, vehicle routing, multi-criteria optimization, and graph theory problems, and so on) [91]. This algorithm uses simple and comprehensive concepts. The algorithm also avoids entrapping in local optimal solutions. Therefore, in Chapter 4, the Tabu Search algorithm is used to solve theproblem of tuning transmission range and rate for controlling the congestion in VANets. The parameters of the Tabu Search algorithm can be easily adapted to this problem. In Chapter 5, the Tabu Search algorithm is used to schedule the control and service channel queues. The Tabu Search algorithm can optimize the message scheduling problem, which is an NP-hard problem [105]. In the implemented Tabu Search algorithm, the delay and jitter are considered to be the parameters of the objective function. In other words, the Tabu Search algorithm minimizes the delay and jitter by examining the various values of transmission range and rate. The delay and jitter are considered as the objectives of the Tabu Search due to higher values of these parameters in VANets as compared to other ad hoc networks.

In Chapter 6, the machine learning algorithms are used to cluster the messages in VANets. The machine learning algorithms are robust classification and clustering means. These algorithms can classify and cluster the large data sets with short computing time, whereas the patterns of data clustering can be detected automatically. In addition, using the machine learning algorithms, the future data can be predicted using the uncovered patterns [112], [113]. Therefore, in this dissertation, the machine learning algorithms are used to cluster the messages of VANets with multi-dimensional features. Because the data set in VANets cannot be labelled, and no existing learning data set is available in VANets, the unsupervised machine learning algorithms are used for this purpose.

Some unsupervised machine learning algorithms are K-means, Fuzzy clustering, Decision tree, Expectation-maximization (EM), and Balanced Iterative Reducing and Clustering using Hierarchies (BIRCH) [115]. The K-means algorithm is a most popular unsupervised learning algorithm, typically used for clustering the multi-dimensional features data sets [117]-[119]. This algorithm is rapid, simple, and scalable in comparison with the other unsupervised learning algorithms [117]-[119]. Therefore, due to the diversity of messages generated by vehicular communications in VANets, the clustering of unlabeled messages in VANets can be conducted efficiently by K-means learning algorithm.

In this dissertation, the mobility and network simulator are employed to evaluate the performance of the proposed congestion control strategies. The mobility simulator is used to simulate the vehicular environment and movements of vehicles, while the network simulator is used to simulate the vehicular communications (i.e. V2V and V2I communications). Some mobility simulator are Simulation of Urban MObility (SUMO), VISSIM, TRANSIMS, and so on [130]. The SUMO is used for mobility and traffic simulation in VANets because this simulator is an open source and has time-discrete microscopic road traffic simulation package [97], [98]. Therefore, in this dissertation, the mobility of vehicles, vehicles traffics, and road topologies are simulated by the SUMO simulator. The network simulators are used to simulate traffic communications among the nodes. Popular simulators can be used for simulating the VANets are NS2, NS3, OPNET, and NETSIM, and so on [131]. However, NS2 is most popular simulator between the networks researchers. This simulator is also open source, discrete-event, and object-oriented. Moreover, NS2 supports various protocols and platforms [99]. Therefore, in this dissertation NS2 is employed.

MOTabu improves the throughput and decreases the delay and packet loss in VANets in comparison with the CSMA/CA, D-FPAV, PRBC, CABS, and UOTabu strategies. MOTabu controls the congestion in VANets by tuning the transmission rate and range for all types of messages, whereas D-FPAV, PRBC, and CABS only consider the beacon messages for controlling congestion. Also, CSMA/CA avoids the congestion occurrence by an exponential back-off strategy, which is not efficient for beacon broadcasting, and the UOTabu strategy just consider the minimum delay in the proposed Tabu Search algorithm.

The performance of VANets improves using the DySch and TaSch strategies because of prioritizing and scheduling all safety and non-safety messages. The waiting delay in queues and packet loss ratio for safety messages decrease in comparison with non-safety messages using the DySch and TaSch strategies due to defining higher priority for safety messages and immediately transferring these messages in the control channel. Therefore, the safety and reliability increase in the safety applications of VANets.

The ML-CC strategy outperforms the compared CSMA/CA, D-FPAV, CABS, and NC-CC strategies and increases the performance of VANet due to clustering all types of messages and adjusting the communication parameters (the transmission range and rate, contention window size, and AIFS) for each cluster. Using ML-CC, the packet delivery ratio and the collision probability improves in the channels in comparison with the CSMA/CA strategy as the default congestion control strategy in VANets because of the decreasing packet loss ratio in the channels.

# CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

## 8.1 Summary of the Contributions

In this dissertation, a closed-loop congestion control strategy was developed that tunes dynamically the transmission range and rate using the Tabu Search algorithm for all types of messages in a reasonable time. This strategy is composed of two components including congestion detection and congestion control components. In the congestion detection component, the channel usage level is measured and compared with a predefined threshold. If the channel usage level exceeds the threshold, it is assumed that the congestion occurred in the network. In the congestion control component, the transmission range and rate are tuned. A multi-objective Tabu Search algorithm was employed for tuning the transmission range and rate. The objective function of the Tabu Search was to minimize the delay and jitter. Obtaining proper values for transmission range and rate was an NP-hard problem due to the high computing overhead. The proposed strategy was a distributed strategy, which means that each vehicle independently controls the congestion by increasing or decreasing the transmission range and rate for all types of messages. The simulations of the highway and urban scenarios showed that this strategy improves the performance of VANets such that the packet loss ratio and the average delay decrease, and the average throughput increases. Consequently, this strategy helps control the congestion, and creates a more reliable environment in vehicular environments.

In this dissertation, moreover, two open-loop congestion control strategies were introduced. These strategies prevent the occurrence of congestion in the channels by prioritizing and scheduling the messages. These strategies are composed of two units including priority assignment unit and a message scheduling unit. In the priority assignment unit, all types of messages are prioritized based on the static factor, the dynamic factor, and the size of messages. The priorities are defined for safety and service messages such that the high priorities are assigned to the safety messages to decrease the delay for acquiring the channel. The static factor is obtained based on the content of messages, while the dynamic factor is calculated based on the state of the network. Then, in the message scheduling unit, the prioritized messages are scheduled in the control or service queues. In the queues, the messages are scheduled in two ways. First, the messages are scheduled based on the priorities of messages. Second, the messages are scheduled using the Tabu Search algorithm such that the delay, jitter, and priority of messages are considered as objective functions. These strategies are distributed strategies which means that the prioritizing and scheduling the messages are conducted in each vehicle independently. The performance of these strategies was evaluated in highway and urban scenarios. The simulation results showed that the proposed strategies performed better than the other compared congestion control strategies. The reasons for such results were using more parameters to define the priorities for all messages, and scheduling the messages by the defined priorities or the Meta-heuristic algorithm. The average throughput, number of packet loss, and average delay were improved using the proposed strategies. In addition, the waiting delay in queues and packet losses of the safety messages were less than the service messages. Therefore, using the proposed strategy, the performance of VANet improves and consequently the safety and reliability in vehicular environments increase.

Finally, in this dissertation, a centralized congestion control strategy was developed to locally control the congestion at the intersections. The intersections in urban environments are critical areas due to the higher density of vehicles in these areas, which increase the congestion occurrence. The proposed strategy is a centralized strategy that used the RSUs set at the intersections to conduct the congestion detection and control. In this strategy, the congestion is detected by sensing the channels and measuring the channel usage level parameter. When the value of this parameter exceeds the predefined threshold, it is assumed that congestion occurs in the network. To control congestion, the messages, transferred between the vehicles stopped before the red traffics light, are gathered and filtered. Then, the filtered messages are clustered using K-means learning algorithm. Finally, this strategy determines the communication parameters (i.e. transmission range and rate, contention window size, and AIFS) for each cluster of messages such that the delivery delay is minimized. RSUs send these communication parameters to the stopped vehicles to control the congestion conditions at the intersections. Therefore, the channels loads are controlled and the safety messages can be transferred with less delay and packet losses. The simulation results of an urban environment showed that the average delay, packet loss ratio, and throughput improve using the proposed strategy. Using this strategy, the packet delivery ratio increases and the collision probability decreases in comparison with the default congestion avoidance protocol in VANets (i.e. CSMA/CA)). Therefore, the proposed strategy increases the performance of VANets’ safety applications, and decreases the fatalities and injuries of road users at vital intersections.

## 8.2 Limitations

The strategies proposed herein to control congestion have few limitations. To practically implement the proposed strategy in Chapter 4, some simplifying assumptions should be made such as using a discrete range for values of transmission range and rate. This is due to the complexity of implementing the Tabu Search algorithm. In addition, for implementing the proposed strategy, OBUs set in each vehicle should be able to do real-time processing because the congestion control is a real-time process. For detecting the congestion occurrence in the channels, each vehicle needs to measure the channel usage level. However, measuring the MAC layer parameter is a challenging task. Moreover, the vehicles should be able to dynamically adjust the value of the transmission range and rate.

The proposed strategies in Chapter 5 need to access some information such as the position, and speed, and so on to determine the priorities of messages. Therefore, each vehicle should be equipped with a GPS device for estimating this information. In addition, for determining the priority of messages, the distance between the sender and receiver should be calculated by considering the multi-hop communications, high mobility, and high rate of topology change of vehicular environments. For implementing the proposed strategies, two queues should be considered for control and service channels.

In Chapter 6, for implementing the proposed strategy in the vehicular environment, an RSU should be installed at each intersection to execute centrally and locally the proposed strategy for controlling the congestion in these critical areas. In addition, a GPUs need to be set at each RSU to execute the proposed strategy in reasonable time. The congestion control is a real-time process. However, the machine learning algorithms are the time-consuming process because they do a lot of calculations and operations. Thus, GPUs can help decrease the processing time of clustering using parallel processing.

## 8.3 Future Work

According to this research, some future research can be recommended as follows:

- Designing a hybrid congestion control by combining a proactive strategy (e.g. the proposed prioritizing and scheduling-based strategy) and a reactive strategy (e.g. the proposed closed-loop congestion control strategy). Using this hybrid congestion control strategy, the channel loads is controlled to avoid the channel saturation until the load of the channel increases such that the channel is overloaded. Then, the congestion is controlled using the reactive strategy to mitigate the channel load.

- Designing a dynamic congestion control strategy that considers the environment of roads (e.g. highways, streets, and intersections, and so on), and time of the day (i.e. in the rush hours or days). This strategy can tune dynamically the communication parameters based on different conditions. In addition, for performing efficiently, the learning algorithms can be used to make better decisions in different conditions.

- Considering the probability of congestion occurrence in vehicular environments based on different conditions (i.e. environment and time).

- Evaluating the performance of the congestion control strategies in the vehicular networks that operate based on the new generation (e.g. 4G, LTE, and 5G).

- Comparing the portion of packet losses that occurs due to the congestion and the portion of packet losses that occurs due to other reasons. Also, investigating the impact of the proposed strategies on improvement of packet losses that occur only because of congestion.

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# APPENDIX A – CALCULATING THE DELAY AND JITTER

Here, the delay and jitter formulas used in Chapter 5 for calculating the objective functions of Tabu Search algorithm and Chapter 6 for calculating minimum delay in congestion control unit are illustrated [1], [95], [102]. The notifications of these formulas are shown in Table Appendix A.

$$Delay = \left(D_{proc} + D_{queue} + D_{trans} + D_{prop}\right)\left\lceil \frac{d}{TX} \right\rceil$$

$$D_{queue} = \frac{1}{\mu - \lambda} - \frac{1}{\lambda} . \frac{Q_L \rho^{Q_L}}{1 - \rho^{Q_L}}$$

$$\rho = \frac{\lambda}{\mu}$$

$$D_{trans} = T_B + T_F + T_T$$

$$T_B = \begin{cases} \frac{W_{min}.\eta}{2} . (2^{N_{RT}} - 1) & N_{RT} \leq m \\ \frac{\eta}{2} . \left(W_{max} - W_{min} + W_{max} . (N_{RT} - m)\right) & N_{RT} > m \end{cases}$$

$$N_{RT} = \sum_{s=1}^{7} s {P_C}^{s-1} (1 - P_C) = \frac{1 - 8{P_C}^7 + 7{P_C}^8}{1 - P_C}$$

$$P_C = \frac{2W_{min} . N_C}{(W_{min} + 1)^2 + 2W_{min} . N_C}$$

$$T_F = N_C + (N_C + 1) . \left(\frac{N_{RT} - 1}{\sum_{t=2}^{N_C} t . f(t)}\right) . P_T$$

$$f(t) = \binom{N_C}{t} \tau^t . (1 - \tau)^{N_C - t} = \left(\frac{N_C}{t!\,(N_C - t)!}\right) . \tau^t . (1 - \tau)^{N_C - t}$$

$$\tau = \frac{2(1 - p_0)}{w_0 - 1}$$

$$p_0 = 1 - \frac{\lambda}{\mu}$$

$$T_T = \frac{S}{TR}$$

$$D_{prop} = \frac{d}{c}$$

$$J(i) = J(i-1) + \frac{|D(i-1, i)| - J(i-1)}{16}$$

$$D(i-1,i) = (R_{i-1} - R_i) - (S_{i-1} - S_i) = (R_{i-1} - S_{i-1}) - (R_i - S_i)$$

Table Appendix A: Notifications for calculating the delay and jitter.

| Notation | Description |
|---|---|
| $D_{trans}$ | Transmission Delay |
| $D_{queue}$ | Queuing Delay |
| $D_{prop}$ | Propagation Delay |
| $D_{proc}$ | Processing Delay |
| $P$ | Utilization |
| $\mu$ | Packet Service Rate |
| $\Lambda$ | Packet Arrival Rate |
| $T_B$ | Timer Back-off Delay |
| $T_F$ | Back-off Timer Freeze Delay |
| $T_T$ | Successful Transmission Delay |
| $N_{RT}$ | Number of (re)transmissions upon success delivery |
| $P_C$ | Collision probability |
| $W_{min}$ | Minimum contention window size = 32 |
| $W_{max}$ | Maximum contention window size = 1024 |
| $M$ | Maximum number of back-off stage ($W_{max}=2^m W_{min}$ , m=5 in IEEE 802.11) |
| $H$ | Back-off time slot length(=20 µs) |
| $f(t)$ | Number of retransmissions when the collision occurs |
| $T$ | Transmission probability |
| $p_0$ | Probability that there are no packet ready to transmit at the MAC layer in each vehicle |
| $w_0$ | Current back-off window size that is always a constant for broadcast |
| $S$ | Packet size |
| $TR$ | Transmission Rate |
| $TX$ | Transmission Range |
| $C$ | Light velocity = $3\times10^8$ m/s |
| $P_T$ | Time period for a packet transmission including SIFS, DIFS, Data and ACK |
| $V$ | Number of vehicles |
| $Q_L$ | Maximum queue length |
| $N_C$ | Number of contenders within the transmission range |
| $S$ | Number of back-off stages |
| $D$ | Distance between sender and receiver |
| $J(i)$ | jitter of *i*th packet |
| $D(i-1,i)$ | the difference between transmission times of *i*th and *(i-1)*th packets |
| $S_i$ | the time stamp of *i*th packet |
| $R_i$ | the arrival time of *i*th packet |