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Transmission Data Rate Control based Mechanism for Congestion Control in Vehicular Ad Hoc Networks (VANET)

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Abstract

Vehicular Ad Hoc Networks (VANET) supporting Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (v2I) communication can increase the efficiency and safety of the road transportation systems. VANET typically uses wireless communication technology and in scenarios with high vehicle densities, the communication channel faces congestion, negatively impacting the reliability of the safety applications. To prevent this, the European Telecommunication Standards Institute (ETSI) has proposed the Decentralized Congestion Control (DCC) methodology to effectively control the channel load, by controlling various message transmission parameters like message rate, data rate and transmission power. Currently, most research works focus on the transmission power to control congestion, while the other approaches such as data rate and message rate control are less common. In this research, a data rate control algorithm has been proposed to control the network congestion based on the Channel Busy Ratio (CBR). For the simulations, real world scenarios generated through SUMO are considered. After comparing the results with other data rate control algorithms, the proposed approach is anticipated to perform better in the scenarios where the CBR is dynamic and high.

Dedication

I would like to dedicate this thesis to my family, friends, my Supervisor, and to myself.

Acknowledgements

There are many people whom I would like to acknowledge for their help and support during the course of working on my master thesis.

First and foremost I would pay my gratitude to my supervisor Dr. Arunita Jaekel. Under her guidance, I had enjoyed a lot working on my research work. It was a great pleasure to work and discuss with her. Without her support, this would not have been possible.

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Chapter 1

Introduction

1.1 Vehicular Ad-Hoc Networks

Traffic collisions occur due to various factors like the vehicle and road nature, driving under the influence of alcohol/drugs, driver skill level, and speeding that could cause loss of property and lives[1]. There is a need to make the driving experience safe and comfortable for both drivers and pedestrians.

Vehicular Ad-Hoc Networks(VANET) is a subset of Mobile Ad-Hoc Networks(MANET)[42]. The Intelligent Transportation Systems(ITS)[7] uses VANET technology[44] to improve vehicle and road safety by transmitting the data between the nodes(vehicles) using wireless communication. This communication between different nodes is described as Vehicle-to-Vehicle(V2V) Communication [27], which allows the cars to communicate with other cars directly. Vehicle-to-Infrastructure(V2I) provides communication between static structures like traffic lights and buildings. Vehicle-to-Any(V2X) provides communication between different mobile aspects of the traffic system. Generally, VANETs are composed of high-speed mobile communication nodes, i.e., vehicles traveling at high velocities. Typical VANET characteristics include rapid changes in topology, high density of nodes on the network, and no energy restrictions[44][27].

1.1.1 WAVE Background

WAVE stands for Wireless Access in Vehicular Environment. Protocols like Vehicle-to-Vehicle(V2V), Vehicle-to-Infrastructure(V2I), and other related protocols are being adopted across North America. Vehicles are equipped with On-Board Units(OBU) that connects to the Controller Area Network(CAN)[41] bus of the cars to enable communication between them. The CAN bus constitutes the vehicles' internal network, which provides access to various controllers and sensors installed in the vehicles. At present, OBUs rely on GPS technology for information like location, speed, etc, since CAN bus cannot be integrated possibly in every car.

Apart from OBUs, there are Road-Side Units(RSU) that allow the vehicles to communicate with infrastructures like traffic lights, toll roads, parking garages, and construction zones. RSUs can also assist the emergency vehicles struggling to travel in a city during peak hours. Research on improving the emergency vehicle traffic will be an excellent example of how VANET can improve the present conditions with existing city infrastructure and services[6].

It will take some time to find a V2V unit in every car, similar to any new technology. Market penetration plays a significant role in the performance of VANET. For the vehicles to send and receive messages, they have to be installed with OBUs. The infrastructures which predict the congestion/traffic in a roadway also requires the vehicles to be equipped with OBUs.

1.1.2 Applications of VANET

VANET applications are categorized into service and safety applications[14]. Safety applications include forward collision warning, curve speed warning, pre-crash awareness, left turn to assist, emergency brake lights, lane change warning, etc.

Service applications include route guidance and traffic optimization, infotainment applications such as internet connectivity, media, payment services such as E-toll collection, etc.

1.1.3 Modern Technologies

The IoT (Internet of Things) has completely transformed the automotive industry with the concept of connected/autonomous vehicles. The primary sensors used in autonomous vehicles are the camera, lidar, and radar[22]. These sensors provide visuals of the surroundings and help detect the speed and distance of the nearby vehicles and objects. The inertial measurement sensors track a vehicle's location and acceleration. All these sensors provide rich data on the vehicle's surroundings. These sensors have their limitations and sometimes get faulty. Cameras can see the objects but cannot compute the distances between them. Radars cannot distinguish different types of vehicles. Lidars are more expensive and have a limited range. Hence a need arises for the vehicles to connect and start communicating with each other. Modern technologies have made advancements, and they will continue to grow[10]. Even though the proposed approach will not replace modern technologies, it is expected to complement the improvements taking place in VANET congestion control.

1.1.4 Motivation

VANET aims to increase the comfort and safety of the drivers and the pedestrians. This work is done by the nodes(vehicles) which are constantly sending and receiving messages or packets with the other nodes and infrastructure in a VANET environment. The types of messages transmitted are periodic messages, safety or event-driven messages, and data messages. These messages are sent through the channels allocated in the DSRC/WAVE system[21], with On-Board Units(OBU) placed inside the vehicles and Road-Side Units(RSU). This avoids vehicle collisions, thereby increasing safety and providing services essential for a comfortable driving experience.

Channel congestion occurs when the channel gets saturated, and the nodes start competing to acquire access to the channel[35]. Congestion control is a challenging research issue in any vehicular environment. The channels through which the messages are transmitted may get congested due to factors like the high density of nodes, GPS data, acceleration, etc. Due to packet collisions, these messages fail to reach the destination, leading to accidents and loss of life and property. So, it is crucial to develop congestion control algorithms[41] to reduce congestion and ensure the proper delivery of messages.

1.1.5 Problem Statement

In general, a vehicular network should consist of packets containing vital information sent and received by the nodes(vehicles) promptly. It should also have minimal loss of packets resulting in accurate delivery of safety messages. In VANET, congestion control faces various challenges due to communication overhead, inefficient utilization of bandwidth, high transmission delay, and inefficient resource usage. These factors affect the channel which is being utilized for network packet transmission for vehicle awareness[41].

In VANET, all the vehicles share the same 5.9GHz channel that uses a communication range of 300m with a power limit of 33dBm[29]. This channel is used for all the safety messages and service-related announcements. Each vehicle transmits 10 beacons per second, causing a heavy channel load and packet collisions. The packets are sent only when the channel is clear[13]. In VANET, the resources are not managed centrally, making it difficult to avoid channel congestion when the packets are broadcast. In situations where the packets are broadcast, acknowledgments are not done since the acknowledgment packets could add extra load on the channel. When the channel load goes above 40 percent of the channel capacity, packet collisions and packet delays grow rapidly[33]. Therefore, a congestion control algorithm is indeed required to avoid channel congestion.

1.1.6 Solution Outline

DSRC(Dedicated Short Range Communication) provides eight different data rates(3, 4.5, 6, 9, 12, 18, 24, and 27Mbps)[20]. Only limited research is done to select the data rates appropriately, based on network conditions. When lower data rates are chosen, the speed of packet transmissions will be slow. The signal strength will be high, making the packets reachable for distant vehicles and unsuitable for high-density vehicular environments due to the packet transmission rate. On the other hand, when higher data rates are chosen, the speed of packet transmissions will be increased, and signal strength will be less, making the packets unreachable to distant vehicles and suitable for high dense vehicular environments. Several works have been published explaining the effects of choosing different data rates[17][4][36][5].

In this thesis, a new approach is proposed for adaptive data rate selection. The data rate is chosen depending on the Channel Busy Ratio(CBR) of the network. Simulations are carried out using OMNET++, SUMO(Simulation of Urban Mobility), and Veins(Vehicles In Simulation). The proposed approach is tested and compared with the default case 10Hz and other existing algorithms that varied data rates to control channel congestion. The outcome and results are explained in chapter 4 of this thesis.

1.1.7 Thesis Organization

The remaining thesis will be organized as follows. Background knowledge will be discussed and reviewed in chapter 2. The proposed approach used for congestion control will be discussed in chapter 3. The results are analyzed and explained in chapter 4. Future research in VANET will be discussed in chapter 5.

Chapter 2

Background Review

2.1 Overview

Vehicle safety refers to the body strength of the vehicle and the vehicles' awareness of its surroundings. Current technologies like cameras have a limited scope, limited range, and requires good visibility. When cars start communicating with each other, most of these limitations could be avoided. The delivery of safety messages at the right time helps in avoiding collisions and emergencies. Radio communications have been used to improve vehicular safety since the 1920s[38]. The applications developed should be capable of transmitting the safety messages in different ways according to the vehicle's driving context[36].

In VANET, the safety messages are of two types: periodic and event-driven messages[9]. The beacons, also called Basic Safety Messages(BSMs), are periodically transmitted for the vehicle status announcement. When certain events like traffic or road hazards are detected, event-driven messages come into action. BSMs consist of two parts. Part 1 has the mandatory vehicle status, e.g., time, motion, position, vehicle size. Part 2 contains the optional safety extension, e.g., path history, event flags. BSMs' average size ranges between 320 and 350 bytes. The BSMs are transmitted ten times per second[12].

2.1.1 DSRC Spectrum

In the 75MHz spectrum allocated by the Federal Communications Commission(FCC), channel 172 is assigned to exchange safety messages. Some authors have proposed that channels 172 and 174 can be combined with a 20MHz channel to increase the capacity by lowering the transmission time. A higher Inter-Carrier Interference(ICI) and Inter-Symbol Interference(ISI) is reported in this 20MHz channel. Hence, the researchers focus mainly on the 10MHz channel[20].

Based on various modulation techniques and Orthogonal Frequency Division Multiplexing(OFDM), DSRC has given eight data transfer rates(3, 4.5, 6, 9, 12, 18, 24, and 27Mbps). Only a little research work has been carried out to choose the data transfer rates appropriately [20]. The DSRC channel is shown below in Figure 2.1.[20].

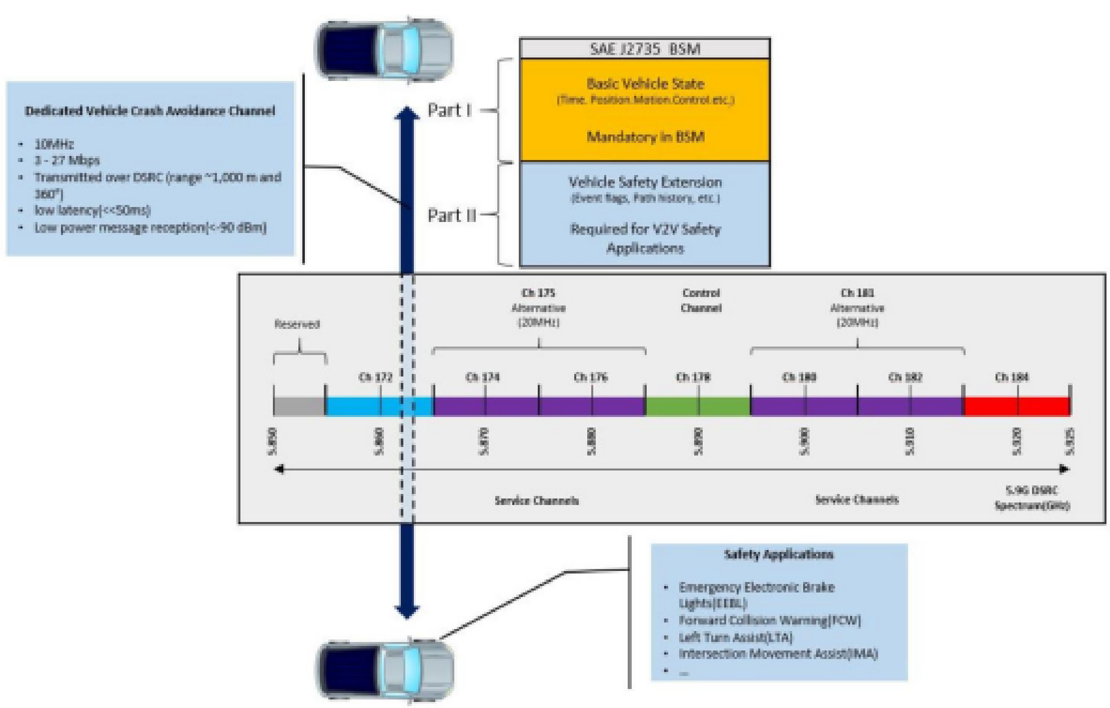

Figure 2.1: DSRC channel[20]

2.1.2 Channel Congestion

The protocol used for wireless communications in VANET is 802.11p [20]. The 802.11p protocol uses CSMA/CA(Carrier Sense Multiple Access/Collision Avoidance) to avoid collisions and provide fair channel access. CSMA/CA can lead to simultaneous transmissions, causing packet collisions since it is a contention-based random access protocol. Re-transmission of packets does not occur, which avoids acknowledgment (ACK) flooding. The absence of Request-To-Send(RTS) and Clear-To-Send(CTS) mechanisms in the 802.11p MAC layer results in hidden node problems. Following are the effects of high channel load[20].

- When the message generation increases, transmission delay increases, and successful reception of packets decrease.
- Transmission range (maximum distance a node can send its packets) decreases due to high channel load and
- Due to interference, the communication range (region in which a node can communicate with the other nodes) of a transmitter decreases.

2.2 Basic Terminologies

- **Dedicated Short Range Communication(DSRC):** It is a wireless communication technology based on 802.11p. It enables high-speed and highly secure communication between the vehicles and surrounding infrastructures. It operates in the 5.9GHz band, providing a low latency exchange of information between the cars and the infrastructures. A bandwidth of 75MHz in the 5.9GHz band was dedicated by the FCC(Federal Communications Commission) in 2004. DSRC can operate in extreme weather conditions and high speed/fast-changing environments[1].

- **Vehicle-to-Vehicle Communication(V2V):** It enables wireless information exchange between the vehicles about their location, heading, and speed. The messages can travel up to 300 meters. It enhances the current crash avoidance systems that use cameras and radars to detect collisions[41].

- **Vehicle-to-Infrastructure Communication(V2I):** It enables wireless information exchange between vehicles and road infrastructures. The communication is bidirectional. Infrastructures like traffic lights, road signs, and lane markings send data to the cars wirelessly and vice versa[41].

- **Intelligent Transportation Systems(ITS):** It provides services related to traffic management, making the transportation networks safer, coordinated, and smarter. Some applications include emergency services calling after accidents, cameras enforcing traffic laws and speed limits, etc[11].

- **Cooperative Awareness Messages(CAM):** These messages are exchanged to create and maintain awareness around the vehicles in the road network. It contains status and attribute information. The status information includes position, time, motion state, etc. The attribute information includes dimensions, vehicle type etc[41].

- **Basic Safety Messages(BSM):** It is a data packet that has information about a vehicles' position, speed, heading, current state, and predicted path. It does not contain any personal information. Safety applications focus mainly on BSM[41]. The BSM blob definition is depicted below in Figure 2.2.[41].

```
msgCnt      MsgCount,              1 byte
id          TemporaryID,           4 bytes
secMark     DSecond,               2 bytes
lat         Latitude,              4 bytes
long        Longitude,             4 bytes
elev        Elevation,             2 bytes
accuracy    PositionalAccuracy,   4 bytes
speed       TransmissionAndSpeed, 2 bytes
heading     Heading,               2 byte
angle       SteeringWheelAngle     1 byte
accelSet    AccelerationSet4Way, accel set (four way) 7 bytes
brakes      BrakeSystemStatus,     2 bytes
size        VehicleSize,           3 bytes
```

Figure 2.2: BSM blob[41]

- **Decentralized Congestion Control(DCC):** A European Telecommunications Standards Institute(ETSI) specification to avoid packet delays, packet losses, communication range reductions by not exceeding the channel threshold[11].

- **Medium Access Control(MAC):** It is a network sublayer that controls packet transmission. The MAC sublayer works with the Logical Link Control (LLC) sublayer to create the Data Link Layer of the Open Systems Interconnection (OSI) model. This layer is responsible for moving data packets to and from one node to another across a shared channel. .[1].

- **Roadside Units(RSU):** It is a communication unit located along the roads. It acts as a gateway between OBU and other roadside infrastructures. It provides information support and connectivity to the vehicles, including traffic information and safety warnings[11].

- **On-Board Units(OBU):** It is a communication unit that enables wireless communication between the other on-board units and roadside units. These units are installed inside the vehicles. They are used in safety driving systems and other autonomous driving systems[1].

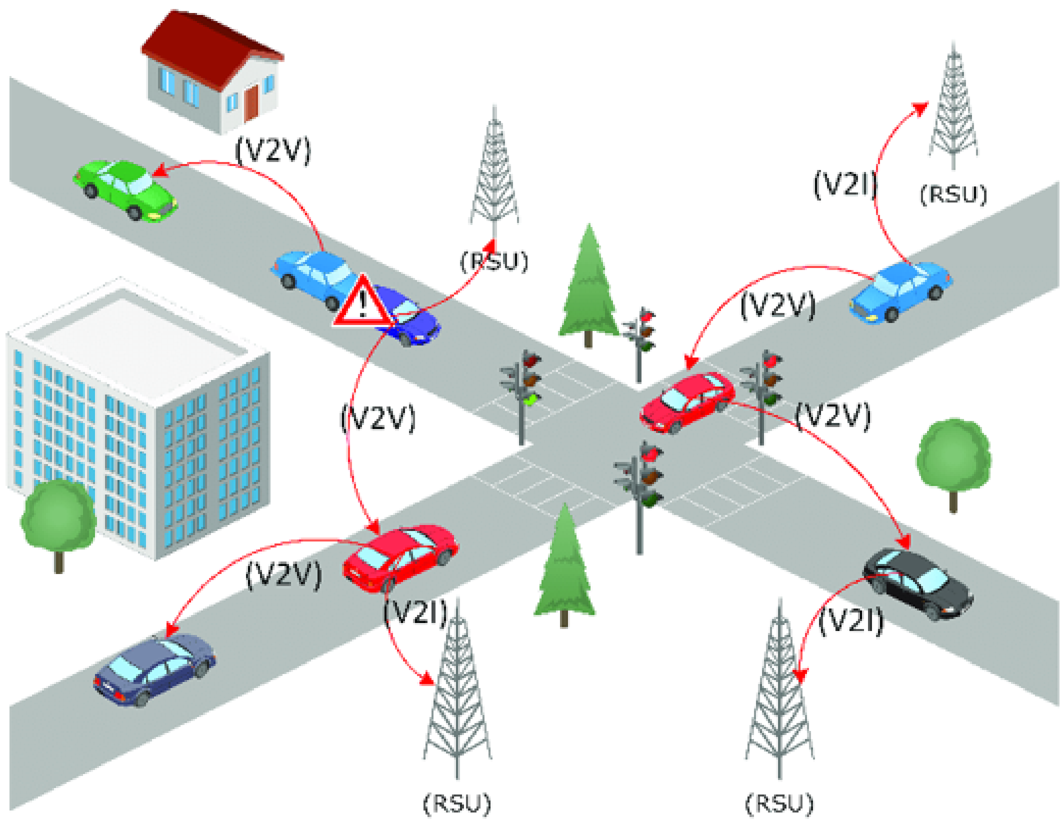

Figure 2.3: VANET components[41]

Various components of VANET like roadside units(RSU), vehicles and the onboard units(OBU) and other infrastructures are shown in Figure 2.3. It can be seen how communication happens between RSUs and OBUs and between the vehicles and other infrastructures.

2.3 Current Research Problems in VANET

Apart from the advantages of VANET, there are plenty of challenges which the technology has to face. These challenges could be viewed as future research directions where advancements are still required. Some challenges are as follows.

- **Mobility:** In general, an ad-hoc network comprises devices that are less mobile in nature. In VANET, the nodes(vehicles) are highly mobile. Cars can come and lose contact in seconds. Hence it becomes hard to transfer information in a small amount of time. So, a topology model with a high level of interaction between the sender and receiver is required to develop this issue[15].

- **Data storage and administration:** In VANET, there are no restrictions on the number of vehicles. So the number of nodes(vehicles) in VANET can increase to millions, generating vast amounts of data. Storing, monitoring, and managing large quantities of data is a challenging research issue. New technologies like Big Data can solve these issues[43].

- **Security and Privacy:** In VANET, the network is open, and any node can join the network. There is no mechanism to ensure whether the nodes can be trusted. Hence, security is a significant concern since the communication happens over a wireless medium, and any node can send malicious data causing harm to the other nodes. The identification of malicious vehicles is also tricky due to the high volume of nodes. It can be a severe threat to the privacy of the drivers[39].

- **Delivery of Quality Service:** In VANET, the nodes are highly mobile and very dynamic. Factors like topology, node position, node distance, connectivity, etc., constantly vary, making the routing protocols incapable of delivering a good service. So, it is crucial to design, model, and develop mechanisms to ensure good quality of service[39].

- **Standardization:** VANET consists of highly heterogeneous nodes like cars, trucks, buses, traffic lights, and other road-side units. These nodes have different ways to communicate and have their communication mechanisms. To deal with such highly different nodes, standardization of protocols is required. The standardization should involve the government and industry standards[39].

- **Routing protocols:** Traditional protocols will not be appropriate for VANET since the nodes are highly mobile and the network topology changes every second. The development of robust routing protocols is required for information propagation to deliver better service, high Packet Delivery Ratio(PDR), and higher throughput[39].

- **Congestion Control:** The safety messages broadcasted in VANET consume a significant bandwidth of the control channel, causing congestion. This leads to loss of packets and delays in the delivery of safety messages. The process which maintains the channel load below the high threshold level preventing the channel congestion, is called congestion control. Congestion control is important in reducing the packet delays and loss of packets to ensure road safety. To attain this, two types of message transmission take place. 1) Beacons exchanging status information and 2) Event-driven messages. Since both these messages use the same Control Channel, the channel load also increases whenever the traffic increases. This could cause a delay in the exchange of beacons, and event-driven messages would not access the channel at all, providing no safety. The strategies developed should ensure that the channel congestion is kept in control during different traffic densities. The upcoming sections deal with the congestion control approaches.

2.4 Congestion Control Approaches

Congestion control aims to improve the VANET networks' performance by reducing the packet delays and losses, increasing throughput, etc. This section discusses some fundamental concepts in the area of VANET congestion control. Congestion control algorithms use different approaches to determine and adjust the transmission parameters. They are:

- **Proactive:** These approaches reduce the channel load before congestion is detected on the channel[30]. Optimization algorithms are used to select the required transmission power or rate to limit the congestion. Data generation patterns are used for the estimation of transmission parameters.

- **Reactive:** These approaches reduce the channel load after congestion is detected on the channel[31]. Channel congestion status is gathered to determine the actions to be taken[37].

- **Hybrid:** These approaches combine both reactive and proactive strategies for controlling channel congestion[16].

2.5 Literature Review

This section discusses some research done in the field of VANET congestion control. It is divided into three sections according to the parameter that was changed to control the channel congestion.

2.5.1 Power based approaches

Transmission power determines how far a message can travel and get delivered successfully. The goal of power control is to adapt the transmission range based on performance metrics like speed, density, etc. Power reduction means only nearby vehicles can see the BSMs. Distant vehicles will not see any packets. Transmission power impacts the awareness of the surrounding vehicles.

In [11], the vehicles adjusted their transmission power according to their speed. This approach was able to reduce the beacon error rate and channel busy time. There were three stages: vehicle speed assessment, transmission range calculation, and power assignment. Firstly, parameters like minimum and maximum transmission power, target to be reached, and speed density approximation were initialized. The transmission range was calculated using the initialized parameters. This transmission range was used to decide the required transmission power. OMNET++, SUMO, and VEINS were used for simulations. The results indicated that this approach had a better beacon reception rate and a low beacon error rate than 10Hz and other vehicular density-based techniques.

In [1], the vehicles made their packet transmissions using different transmission power levels. Three states were assigned depending on the vehicle count: dense state(vehicle count more than 100), moderate state(vehicle count between 50 and 100), and sparse state(vehicle count less than 50). When the vehicle density was high, low transmission power was used. During moderate conditions, medium transmission power was used. High transmission power was used when the vehicle density was less. OMNET++, SUMO, and VEINS were used for simulations. This approach had low Inter-Packet Delay(IPD), and better Beacon Reception Rate(BRR) than other DCC approaches.

In [40], the authors proposed a method called D-FPAV (Distributed Fair Transmit Power Adjustment for VANET). It controlled the beacon load. It achieved congestion control by adjusting the transmission power based on the application-layer traffic and number of vehicles in the surrounding. The transmission power was calculated using a predefined Maximum Beaconing Load (MBL). The authors also considered strategies to deal with event-driven messages.

In [26], all vehicles in the network transmitted beacon messages with initial transmission power. If the forecasted value was less than the threshold value, then all cars increased their transmission power. Else, all the vehicles decreased their transmission power. **Paramics**[34] was used for simulations. The results were indicated by plotting power assignments over simulation time. This approach showed better performance in controlling congestion.

In [19], the authors proposed to increase the awareness quality. Random transmission power was selected for each packet transmission. Each vehicle controlled its power selection by using probability transmission over an interval. This random power selection shifted the radio propagation conditions for each transmission. It also provided statistical fairness since all the vehicles used the same probability distribution. This approach reduced packet collisions and interference.

2.5.2 Data Rate based approaches

Data rate-based approaches adapt the speed with which the messages are sent and transferred between the vehicles.

In [36], the authors proposed a new congestion control strategy called PULSAR (Periodically Updated Load Sensitive Adaptive Rate Control). CBR was measured at the end of a fixed time interval and compared against the target value. When the measured value was higher than the target value, the transmission rate was increased. This approach handled the channel congestion by maintaining the CBR below the predefined target value.

In [28], the vehicles adapted their data rate based on the network's channel load. The channel load was calculated in terms of the channel busy ratio. Only the data rates between 3 and 12 Mbps were considered to avoid flooding. Four states were assigned depending on the channel load: relaxed state, active state 1, active state 2, and restrictive state. Each state had a different data rate for the vehicles to transmit the packets. GEMV2 and SUMO were used for simulation s. The results indicated that this approach performed better in reducing the channel load compared to other DCC approaches.

In [25], the algorithm increased the data rate levels to reduce the CBR of the network. The CBR was monitored each second. Parameters like mean threshold, minimum and maximum threshold was initialized. Higher data rates were chosen when the current CBR was higher than the mean threshold. The same data rate was maintained when the current CBR was less than the mean threshold and higher than the minimum threshold. NS-3 and SUMO were used for simulations. This approach had a lower mean CBR during the entire simulation when compared with other DCC approaches.

In [24], the vehicles adjusted the data rates based on the CBR of the network. Maximum and minimum CBR threshold values were initialized. When the observed CBR was higher than the maximum CBR threshold, the data rates were increased. The data rates were decreased when the observed CBR was less than the minimum CBR threshold. NS-3 and SUMO were used for simulations. This approach kept the channel load below the maximum threshold, achieving fairness and reliability.

2.5.3 Message Rate based approaches

The default BSM transmission rate is 10Hz, i.e., ten messages per second. This rate will cause the channel load to exceed the channel capacity during high vehicle densities. Message-rate based approaches adapt the rate at which the messages are generated per second.

In [4], the authors proposed a new scheme called LIMERIC (Linear Message Rate Control algorithm) that used linear feedback to adapt the message rate. The vehicles in a specific region sensed the channel load and adapted their message rates to meet the required predefined CBR. LIMERIC adapted the message rate according to the parameters influencing stability and speed. The final rate was highly dependent on the vehicle count of the region.

In [18], the vehicles transmitted their packets by varying the beacon rates. The cars requested their neighboring vehicles whether to increase/decrease the Beacon Transmission Rate(BTR). The beacons were broadcasted by attaching the BTR adjustment requests according to the channel condition. The decision to increase/decrease the BTR was made using the collected requests. NS-2 and SUMO were used for simulations. This approach performed better in terms of Packet Delivery Ratio(PDR) compared to other DCC approaches.

In [32], the approach had two types of DCC queries: *queuesafety* (DCC queue for safety messages) and *queueothermsg* (DCC queue for other event-driven messages). Only *queuesafety* was considered for changing the transmission rate. The beacon messages were scheduled according to the priorities and transmission power. Messages were dequeued automatically according to the priority queue model. When the messages were dequeued, LIMERIC was applied to adjust the transmission rate. With this approach, high-priority beacon messages were transferred within a significant time without occupying the channel for too long. NS-2 and SUMO were used for simulations. This approach had a better Packet Delivery Ratio(PDR) and decreased packet delay.

In [3] the authors proposed a method that extended the LIMERIC algorithm. The messages were weighted according to specific criteria. The proposed algorithm controlled the total channel load according to a predefined target value. Each vehicle converged to a message rate according to its weight. It was mathematically proven that the steady-state was proportional to the weight. Linear systems theory was used to establish the steady-state convergence and fairness.

In [8], the congestion control scheme consisted of two phases. First, a detection phase was used to detect the presence of congestion. The congestion was detected by monitoring the number of collisions in the network. Second, a regulation phase was used to adapt the message rate according to the local density. It was computed using the number of neighbors in range. The message generation rate was dynamically adjusted based on the number of detected collisions.

2.5.4 Hybrid approaches

In [41], the vehicles adjusted their transmission power to send the packets. Two different transmission power levels and transmission rates were maintained. Packets were transmitted with high transmission power to nearby vehicles. To the distant cars, the packets were sent with high transmission power. In this way, two different groups of cars were targeted separately. OMNET++, SUMO, and VEINS were used for simulations. This approach had more beacons and a low Beacon Error Rate(BER) than other DCC approaches.

In [2], the authors proposed a new mechanism called CPRC (Combined Power and Rate Control). The algorithm made the rate and power adjustments in a single loop rather than a two-phase approach. CPRC exhibited cooperative behavior by increasing the transmission rate of the nodes involved in a potentially dangerous situation and reducing the transmission power of the other nodes. This approach prevented the channel load from exceeding the predefined threshold value.

In [19], the authors proposed a new congestion control strategy. RTPC (Random Transmission Power Control) was used to reduce the channel load. RTPC was combined with TRC (Transmit Rate Control), and the sending rate was increased until the target load was reached. It relied upon random transmit power providing heterogeneous awareness. This approach relaxed the strict transmission range to power mapping.

In [23], the authors proposed a combined data rate and message rate congestion control scheme. Beacon frequency was kept above the required minimum value by reducing the message rate. During high traffic densities, the data rate was increased to provide more channel capacity. This approach performed better in reducing the channel busy time.

Chapter 3

Proposed Approach

3.1 High Level Outline

The proposed approach is based on how each vehicle can choose its data rate appropriately to transmit safety messages according to the current channel load/CBR of the network. There is a need for intelligent data rate selection strategies as:

- Higher data rates can reduce signal strength. It also limits the transmission range making the packets unreachable to distant vehicles. This causes packet loss even though it can reduce the channel load due to faster packet transmission.

- Lower data rates increase the channel load due to slower packet transmission even though it does not reduce the signal strength.

- Using the same data rate at different vehicular densities causes wastage of resources and leads to poor performance.

The situations above are addressed in the proposed approach. The proposed algorithm is split into two parts. Firstly, higher and lower CBR threshold values are chosen as per the vehicular network and given as input to the algorithm. Part 1 is for selecting a suitable data rate, when the current CBR falls below the lower CBR threshold. Part 2 chooses a suitable data rate when the current CBR goes above the higher CBR threshold.

The overall motive of the proposed approach is to maintain the CBR between high and low channel thresholds to achieve more packet deliveries and maximum throughput. Thus, when there is very little traffic, the transmission bitrate is reduced, making the packets visible to distant vehicles. On the other hand, when congestion is high, a higher bitrate is used that results in faster packet transmission to the nearby vehicles. Varying the transmission bitrate as affects different performance metrics such as packet delivery ratio and channel busy time. The effect of the bitrate on these parameters are discussed in detail in Chapter 4.

3.1.1 BSM transmission time

The amount of time it takes to transmit a packet of a given size depends on the bitrate used for transmission. Using a higher bitrate reduces transmission time but also reduces the distance the signal can travel. We consider a BSM transmission with the following parameters:

- L: The total packet size in bytes. This includes the BSM headers and all related data.
- BR: The bitrate (in bps)used for transmitting the BSM
- T_{tr}: The time (in sec.) needed to transmit the BSM. This does not include the propagation delay.

Then the transmission time for the BSM is given by:

$$T_{tr} = \frac{8 \cdot L}{BR} \tag{3.1}$$

Using eqn 3.*, a BSM of 512 bytes transmitted with bitrate of 6 Mbps will require a transmit time of

$$T_{tr} = \frac{8 \cdot 512}{6 * 10^6} = 682 * 10^{-6} sec = .682 ms$$

The same packet transmitted with a bitrate of 9 Mbps would require a transmit time of

$$T_{tr} = \frac{8 \cdot 512}{9 * 10^6} = 455 * 10^{-6} sec = .455 ms$$

So, changing the bitrate from 6Mbps to 9Mbps will reduce the channel busy time by over 30%. The DSRC/WAVE protocol, discussed in Chapter 2, assumes that each vehicle transmits 10 BSMs per sec. This means that with fewer than 150 vehicles the channel will become completely full, when using a bitrate of 6Mbps. If we want to allow more BSM transmissions, then we will need to increase the bitrate. Using a bitrate of 9Mbps, the channel will be full with about 220 vehicles. We note that these values for the number of vehicles are the upper limits; normally packet collisions and packet loss will start well before 100% channel capacity is reached.

3.2 Proposed Algorithm

The *data rate control algorithm* (DRCA) shown in Algorithm 1 is used to determine the bitrate that will be used to transmit each BSM. Each vehicle runs this algorithm each time it is ready to send the next BSM. The bitrate to be used for the next BSM transmission is determined based on the current observed value of the *channel busy ratio* (CBR). The steps for calculating the CBR is shown in Algorithm 2 and this calculated value is used as an input to the proposed DRCA scheme.

Algorithm 1 Data Rate Control Algorithm

Input: List of bitrate values (B), index indicating which bitrate in B is currently being used ($level$), high ($cbrhigh$) and low ($cbrlow$) CBR threshold values, and current CBR (cbr)

Output: Updated bitrate values and newlevel

```
if cbr < cbrlow then
    newlevel = level
    bitrate = B[newlevel]
    for i ∈ (0, level) do
        if cbr ∗ (B[level]/B[i]) < 0.95 ∗ cbrhigh then
            newlevel = i
            bitrate = B[i]
            break
        end if
    end for
end if
if cbr > cbrhigh then
    newlevel = maxlevel
    bitrate = B[newlevel]
    for i ∈ (level + 1, maxlevel) do
        if cbr ∗ (B[level]/B[i]) < 0.95 ∗ cbrhigh then
            newlevel = i
            bitrate = B[i]
            break
        end if
    end for
end if
if cbrlow ≤ cbr ≤ cbrhigh then
    newlevel = level
    bitrate = B[level]
end if
```

In addition to the current CBR value, the algorithm also receives as input the lower (*cbrlow*) and upper (*cbrhigh*) threshold levels for the desired range of cbr values. The goal of the algorithm is to maintain the measured CBR within this specified range. The algorithm also receives as input a list (B) of allowed bitrates in Mbps as well as the bitrate used by the vehicle in the previous BSM transmission. Based on the current standards, the available bitrates that can be used are: 3Mbps, 6Mbps, 9Mbps, 12Mbps, 18Mbps and 24 Mbps[20]. So, we use B = [3, 6, 9, 12, 18, 24]. The previous bitrate is specified using the parameter *level*, which is used as an index for the list B, to determine bitrate being used. For example, if $level = 1$ then the corresponding bitrate is $B[1] = 6Mbps$. Finally, the parameter *maxlevel* corresponds the the highest possible index value for the list B and is given by $maxlevel = len(B) - 1$.

Steps 2 to 11 are executed when the current CBR (*cbr*) goes below the low CBR threshold (*cbrlow*). Step 1 checks if the current CBR (*cbr*) is below the threshold (*cbrlow*). If the condition is satisfied, then steps 2-11 are used to determine if a lower bitrate can be used. Steps 2 and 3 are used to assign the previous BSM bitrate as the new value. This will be used only if a lower bitrate cannot be found. Steps 4-10 are used to iterate through each potential bitrate value from bitrate from $B[0]$ to $B[level]$ to see if it can be used, i.e. the condition in step 5 is satisfied. Step 5 checks whether the expected CBR, when using the new bitrate $B[i]$ falls below 95% of the high CBR threshold (*highcbr*). If so, the corresponding value of i is used to determine the bitrate to use (step 7), the loop is terminated (step 8) and these updated values of *newlevel* and *bitrate* (steps 6 and 7) are returned. This means that the *lowest* possible bitrate that satisfies the the condition in step 5 is selected as the new bitrate.

Steps 13 to 22 are executed when the current CBR (*cbr*) is higher than the threshold (*cbrhigh*). This means that the channel is getting congested and a higher bitrate must be used. Step 12 checks if the current CBR (*cbr*) is below the threshold (*cbrhigh*). If the condition is satisfied, then steps 13-22 are used to determine if a a suitable higher bitrate for BSM transmission. Steps 13 and 14 are used to assign the highest possible bitrate as the new value. This will be used only if even the highest bitrate does not satisfy the condition in step 16. Steps 15-21 are used to iterate through each potential bitrate value from bitrate from next higher bitrate $B[level + 1]$ to the highest bitrate $B[maxlevel]$ to see if it can be used, i.e. the condition in step 16 is satisfied. Step 16 is similar to step 5 and checks whether the expected CBR, when using the new bitrate $B[i]$ falls below 95% of the high CBR threshold ($highcbr$). If so, the corresponding value of i is used to determine the bitrate to use (step 18), the loop is terminated (step 19) and these updated values of *newlevel* and *bitrate* (steps 17 and 18) are returned. This means that the *lowest* possible bitrate that satisfies the the condition in step 16 is selected as the new bitrate.

Steps 24 to 26 are executed when the CBR (cbr) falls between high ($cbrhigh$) and low CBR ($cbrlow$) thresholds, i.e. the condition in step 23 is satisfied. This means that the CBR is within the proper range and no bitrate variation is required since the channel load is already balanced. So, the *level* which is already in use will be assigned as the *newlevel* by step 24. Step 25 assigns the *newlevel* as the next *bitrate* for the packet transmission.

3.2.1 CBR Measurement Algorithm

In this section, we discuss the CBR measurement algorithm (CMA), shown in Algorithm 2, which is used to measure the CBR of the network for each second. This algorithm gets executed throughout the simulation and is used to calculate the current CBR value, which is given as input to Algorithm 1 to vary bitrates for packet transmission.

Algorithm 2 CBR Measurement Algorithm

Input: Total busy time of the vehicle (tbt), last total busy time of the vehicle ($ltbt$), last time (lt) and the current simulation time ($curSimTime$)

Output: Current CBR (cbr)

1: **if** $ltbt \mathrel{!}= tbt$ **then**
2: $\quad cbr = (tbt - ltbt)/(curSimTime - lt)$
3: $\quad$ **return** cbr
4: **else**
5: $\quad$ **return** -1
6: **end if**

The algorithm receives as input the total busy time of the vehicles (tbt) which is the amount of time in the simulation that a vehicle encounters a busy channel, last total busy time of the vehicles ($ltbt$) which is the previous total busy time (tbt), and the last time at which the CBR was calculated in the simulation (lt). The algorithm also receives the current simulation time ($curSimTime$). All these values are acquired from the MAC layer of the network with the help of OMNET++ simulation framework.

Steps 1 to 6 are executed throughout the simulation to monitor the channel CBR every second because the CBR needs to be cheked whenever a vehicle sends and receives the packets. Step 1 checks whether the previous total busy time and the currently measured total busy time are equal. This step is done so we do not get 0 as the channel CBR (cbr) when the calculations are done by step 2. If the CBR (cbr) is 0, it means no messages are being sent and received by the vehicles. After the CBR calculation, step 3 returns the calculated CBR (cbr) value. If the condition in step 1 is not true, then a negative value is returned by step 5 referring to invalid CBR.

3.2.2 Overall Congestion Control Process

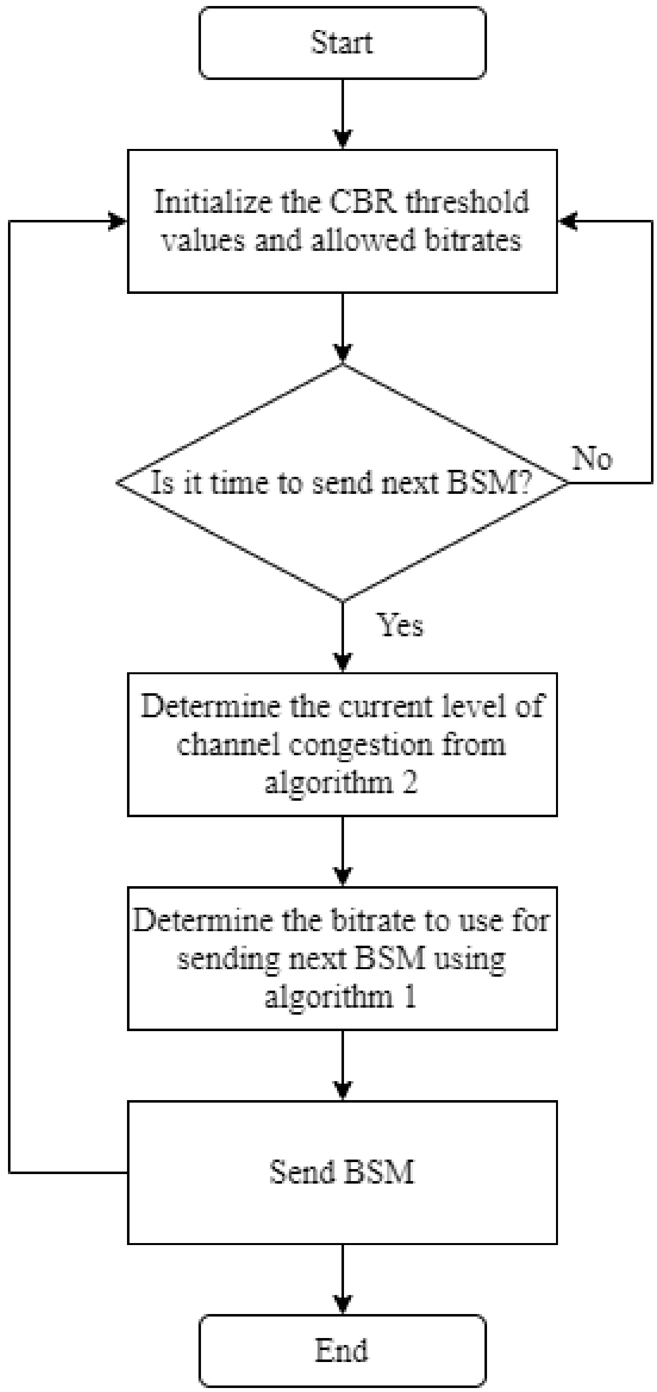

Figure 3.1: Flowchart of the Proposed Approach

The overall congestion control process is shown in figure 3.1. In the beginning, high ($cbrhigh$) and low CBR ($cbrlow$) thresholds are initialized. In addition, a list containing the bitrate values (B) is also declared. Then we are checking whether it is time to send the next BSM. If it is, algorithm 2 executes and we determine the current level of channel congestion (cbr). Depending on the cbr value, algorithm 1 executes and changes (if necessary) the bitrate for sending the next BSM. This same process is executed for the next BSM and so on. Each vehicle runs this process in its OBU, independently of the other vehicles. This means that it is a decentralized congestion control process, which does not require coordination with other vehicles.

3.2.3 How DRCA Differs from Existing Approaches

A number of congestion control algorithms that modify the BSM transmission bitrate have been proposed in recent years. These algorithms typically increment the bitrate only one level at a time. For example if the the current bitrate is 6 Mbps and the current CBR is above the threshold, the next next transmission will automatically use the next allowed bitrate (i.e. 9 Mbps), regardless of how high the CBR is. If this is not sufficient, then in the next cycle the bitrate will again increment by one level (i.e. will change to 12 Mbps) and so on until the desired level of CBR is achieved.Contrary to this, the proposed DRCA algorithm directly calculates the appropriate bitrate to use based on the current CBR value and uses the appropriate bitrate for the next transmission. This allows the channel congestion to converge to the desired level much faster, leading to lower packet loss and improved packet delivery ratio. Similarly, when current CBR is below the desired threshold, DRCA calculates the appropriate bitrate and starts transmitting directly using this bitrate, rather than moving through intermediate levels.

3.3 Illustrative Example

In this section, we give some examples of how the bitrate for BSM transmission is changed using the proposed DRCA scheme. First, we note that if the current CBR is within the specified thresholds, i.e. $cbrlow \leq cbr \leq cbrhigh$, then there is no need to change the bitrate and the next BSM is transmitted with the same bitrate as the previous one. Therefore, in the following sections, we consider the remaining two cases: i) $cbr < cbrlow$ and ii) $cbr > cbrhigh$.

3.3.1 Example for Low CBR

In this section, we consider an example where the current CBR value (cbr) is lower the the low threshold. We assume that the following parameters are given:

- A list of allowed bitrate values: $B = [3, 6, 9, 12, 18, 24]$
- The CBR thresholds: $cbrlow = 0.3$ and $cbrhigh = 0.5$.
- The current level and bitrate being used: $level = 2$, $B[level] = 9Mbps$.
- The current measured CBR: $cbr = 0.2356$.

Since the current CBR (cbr) falls below the low CBR threshold ($cbrlow$), the algorithm starts to traverse from the beginning of the list till the current index level in use ($B[level]$) to send the next BSM as mentioned in step 4 of the DRCA algorithm. In the beginning, our approach checks with the first index value of 3Mbps by executing step 5 of the DRCA algorithm. Since the value of 0.7068 is higher than 95% of $cbrhigh(0.475)$, it moves to the next index value of 6Mbps. In this case, step 5 holds true ($0.3534 < 0.475$). So, 6Mbps is chosen as the bitrate for the next BSM transmission.

3.3.2 Example for HighCBR

In this section, we consider an example where the current CBR value (cbr) is higher the the high threshold. We assume that the following parameters are given:

- A list of allowed bitrate values: $B = [3, 6, 9, 12, 18, 24]$
- The CBR thresholds: $cbrlow = 0.3$ and $cbrhigh = 0.5$.
- The current level and bitrate being used: $level = 2$, $B[level] = 9Mbps$.
- The current measured CBR: $cbr = 0.6514$.

Since the current CBR (cbr) falls above the high CBR threshold ($cbrhigh$), the algorithm starts to traverse from the current index level in use ($B[level]$) till the end of the list for sending the next BSM as mentioned in step 4 of the DRCA algorithm. In the beginning, our approach checks with the next index value of 12Mbps by executing step 5 of the DRCA algorithm. Since the value of 0.4886 is higher than 95% of $cbrhigh(0.475)$, it moves to the next index value of 18Mbps. In this case, step 5 holds true ($0.3257 < 0.475$). So, 18Mbps is chosen as the bitrate for the next BSM transmission.

Chapter 4

Results and Analysis

4.1 Simulation

Testing the effectiveness of DCC algorithms becomes difficult in real-world situations due to the costs incurred, required equipment, resources, and safety concerns. Therefore, simulation frameworks are used to conduct experiments digitally. This is a cheaper and safer way to test the algorithms and analyze the results. For the experiments, three software simulation frameworks were used. It consists of a network simulator, traffic simulator, and communication software for interaction between the two. Simulation of Urban Mobility (SUMO)[20] was the traffic simulator used. It is a free and open-source simulation software using C++ and API libraries to simulate pedestrians, vehicles, and public transport. The network simulator used was the Objective Modular Network Testbed (OMNET++)[20]. It is a C++ simulation library and framework. Vehicles in Network Simulation (VEINS) is a software package that ties the other two simulators[20]. It handles communication between SUMO and OMNET++ by using Traffic Control Interface (TraCI). The figure shows how all the three simulation software work together.

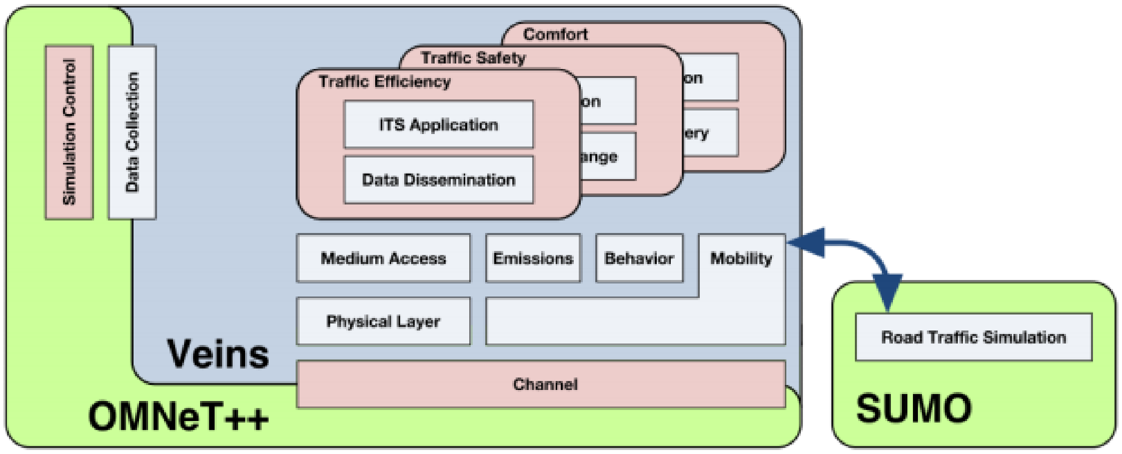

Figure 4.1: Simulation Software Setup[11]

Figure 4.1 depicts the simulation software setup used to carry out experiments in this thesis. SUMO performs road traffic simulation and OMNET++ performs network simulation. Both these simulators are bi-directionally coupled and simulations are performed by VEINS. In this way, influence of vehicles on road traffic can be modeled and complex interactions can be examined.

4.1.1 Simulation Setup

Altogether, three traffic different scenarios are used to analyze the performance of the proposed algorithm.

- A four-lane highway composed of two lanes in either direction, with a speed limit of 50km/hr. This simulation was run for 120 seconds and it was considered to be a normal speed environment.
- A four-lane highway composed of two lanes in either direction, with a speed limit of 0km/hr. This simulation was run for 120 seconds and the vehicles were not allowed to move considering it to be a stationary speed environment.
- A four-lane highway composed of two lanes in either direction, with a speed limit

of 100km/hr. This simulation was run for 120 seconds and it was considered to be a fast speed environment.

The road in each scenario consisted of a 1000m long horizontal stretch of road. Traffic was unidirectional. In each traffic scenario, the following parameters remained consistent:

Parameters	**4-lane(normal)**	**4-lane(stationary)**	**4-lane(fast)**
Simulation time	120 seconds	120 seconds	120 seconds
BSM generation rate	10Hz	10Hz	10Hz
BSM size(bytes)	256,512,1024	256,512,1024	256,512,1024
Beacon interval	0.1,0.01	0.1,0.01	0.1,0.01
Vehicle length	2m	2m	2m
Vehicle speed(max)	50km/hr	0km/hr	100km/hr
Generated vehicles	80	80	80

Table 4.1: Parameter Configuration

4.2 Comparison with Constant Bitrate Transmissions

In this section of results discussion, we are comparing constant bitrate performance with the proposed DRCA approach. Each traffic environment was simulated with 3Mbps, 6Mbps, 12Mbps, 18Mbps, and 24Mbps as the constant bitrates. Each algorithm had different BSM sizes such as 256, 512, and 1024 bytes. The BSM generation rate was also varied by assigning 0.1 and 0.01 as the beacon intervals. The performance is analyzed based on the total number of BSMs received and the average CBR of the network.

4.2.1 Comparison of Received BSMs

We can get a general idea on the awareness of the algorithms based on the total number of packets received. Figures 4.2, 4.3, and 4.4 depict the total amount of packets received when each traffic environment was simulated with different bitrates(i.e.,constant bitrates) and the DRCA approach. From the graphs, it can be noticed that our proposed approach performed better or performed similar to the other best bitrates(24Mbps) which had successfully received the most amount of BSMs during the simulation. It can also be seen that 3Mbps performed better in low congestion scenarios(10 packets/sec) and 24Mbps topped in high congestion scenarios(100 packets/sec) in terms of the total amount of packets received. Hence it is better to adapt the bitrate according to the congestion happening in the network. It can be inferred that there were less collisions happening and less packets were being lost in our proposed approach.

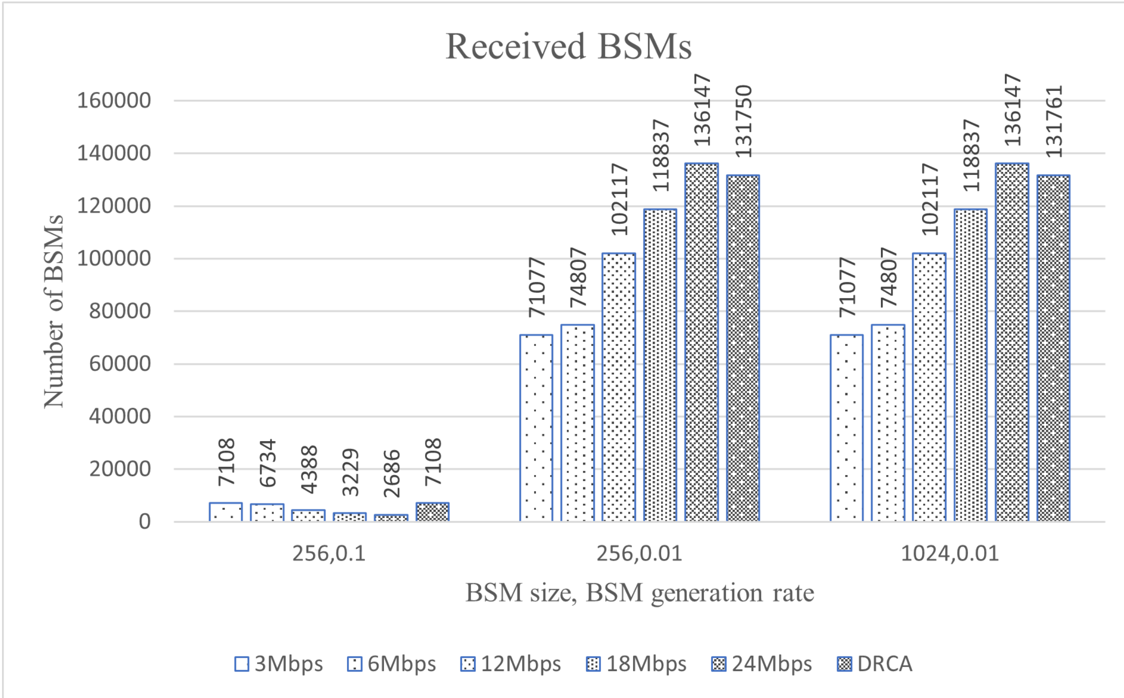

Figure 4.2: Received BSMs in normal traffic environment

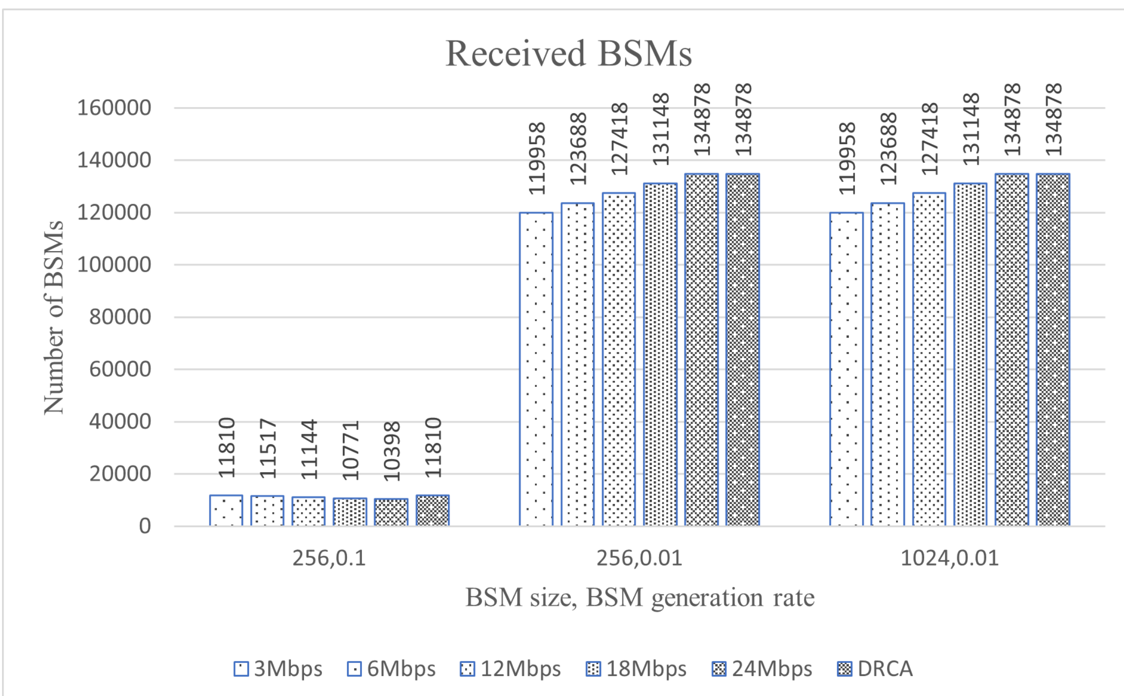

Figure 4.3: Received BSMs in stationary traffic environment

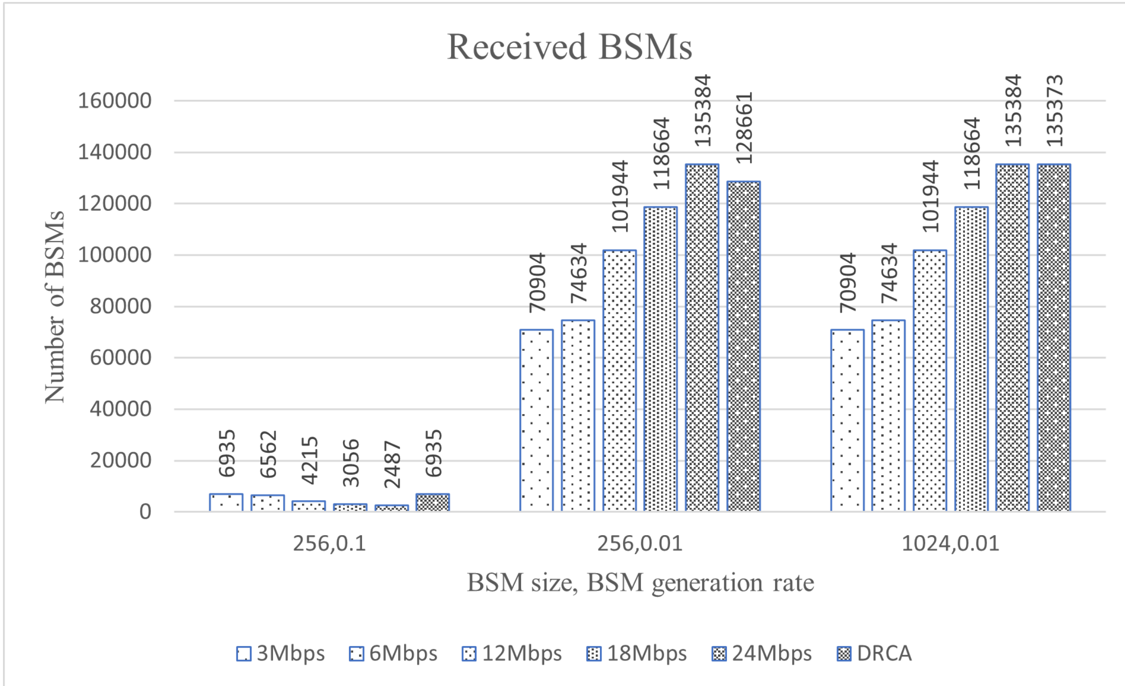

Figure 4.4: Received BSMs in fast traffic environment

4.2.2 Comparison of CBR Values

In this section, we are comparing the average CBR the network had when simulated with the constant bitrates and the DRCA approach. Figures 4.5, 4.6, and 4.7 depict the average CBR of each traffic environment. It can be noticed that DRCA approach was successful in maintaining the average CBR to the minimum value possible when compared with the constant bitrates. It can be inferred that this helped the DRCA approach in achieving high packet reception rate as discussed in the previous section since the network was prevented from high congestion situations.

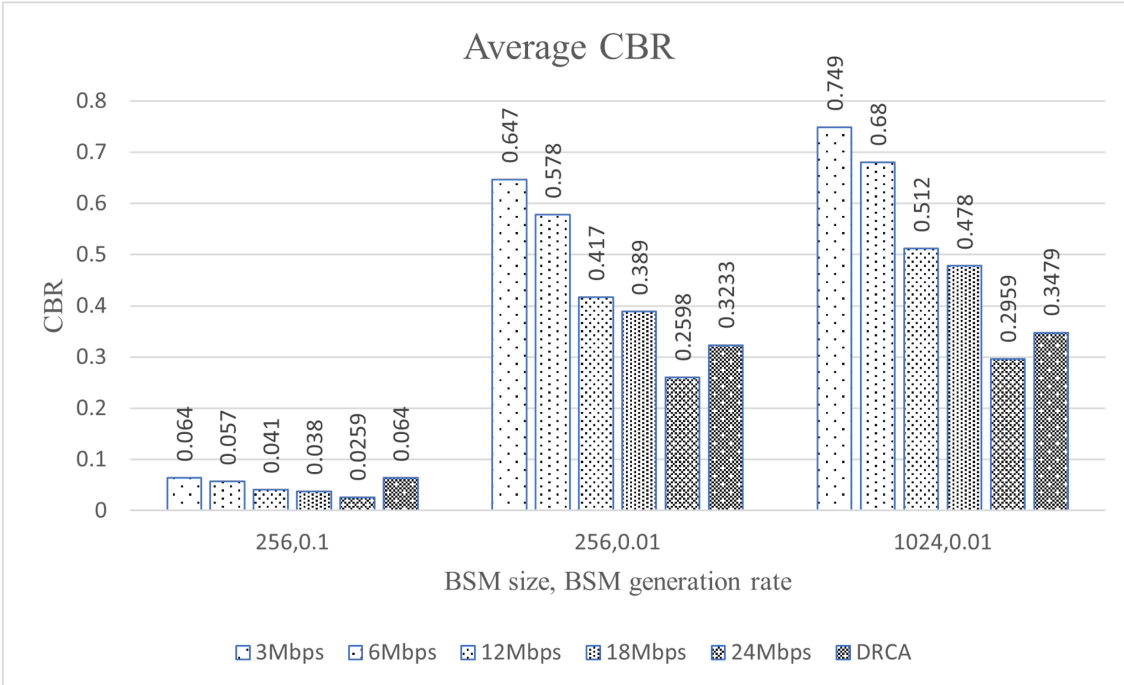

Figure 4.5: Average CBR in normal traffic environment

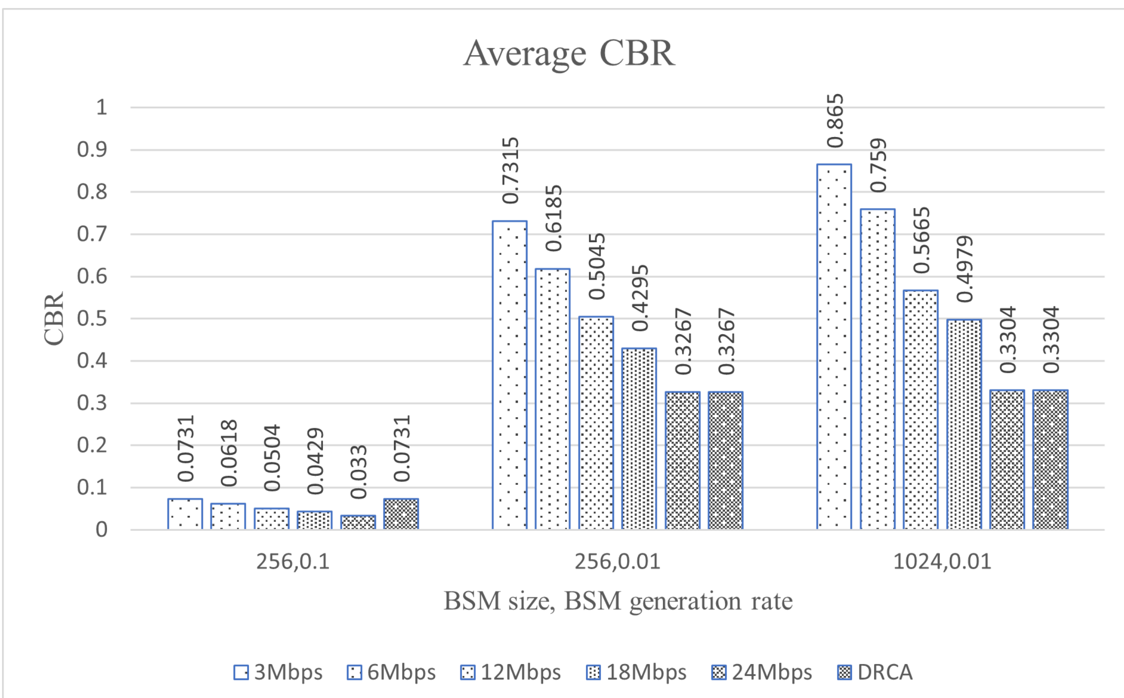

Figure 4.6: Average CBR in stationary traffic environment

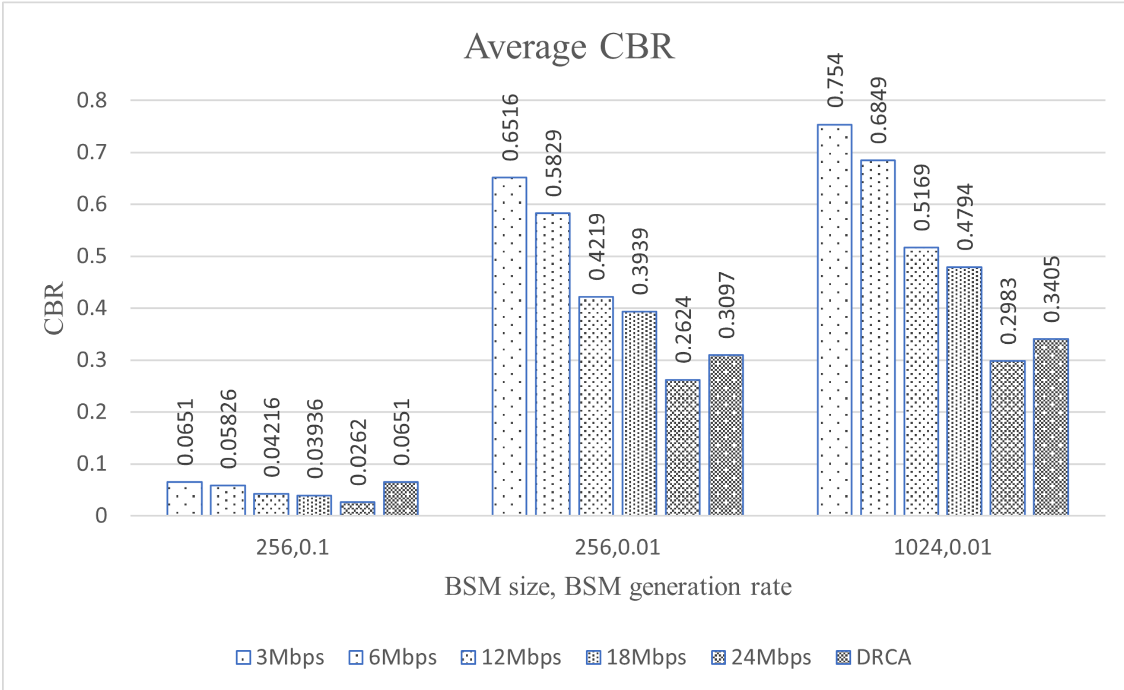

Figure 4.7: Average CBR in fast traffic environment

4.3 Comparison with Existing Congestion Control Techniques

In the previous section, we saw the performance of constant bitrates and the DRCA approach. It was better to have an approach that can adapt bitrates according to the congestion happening in the network. In this section of result discussion, we are comparing the proposed DRCA approach with other existing data rate control approaches in [25] and [28]. The proposed DRCA approach was run with two different high (*cbrhigh*) and low (*cbrlow*) thresholds. For DRCA1, *cbrhigh* was 0.5 and *cbrlow* was 0.3. On the other hand, DRCA2 had 0.4 and 0.2 as *cbrhigh* and *cbrlow* respectively.

4.3.1 Comparison of Received BSMs

Figures 4.8, 4.9, and 4.10 depict the total amount of BSMs received in each traffic environment when simulated with different data rate control approaches and the proposed DRCA approach. It can be noticed that both DRCA approaches performed relatively better in terms of packet receptions when compared with existing approaches. It can be inferrred that the proposed DRCA approach was more aware of the network than the existing approaches in comparison.

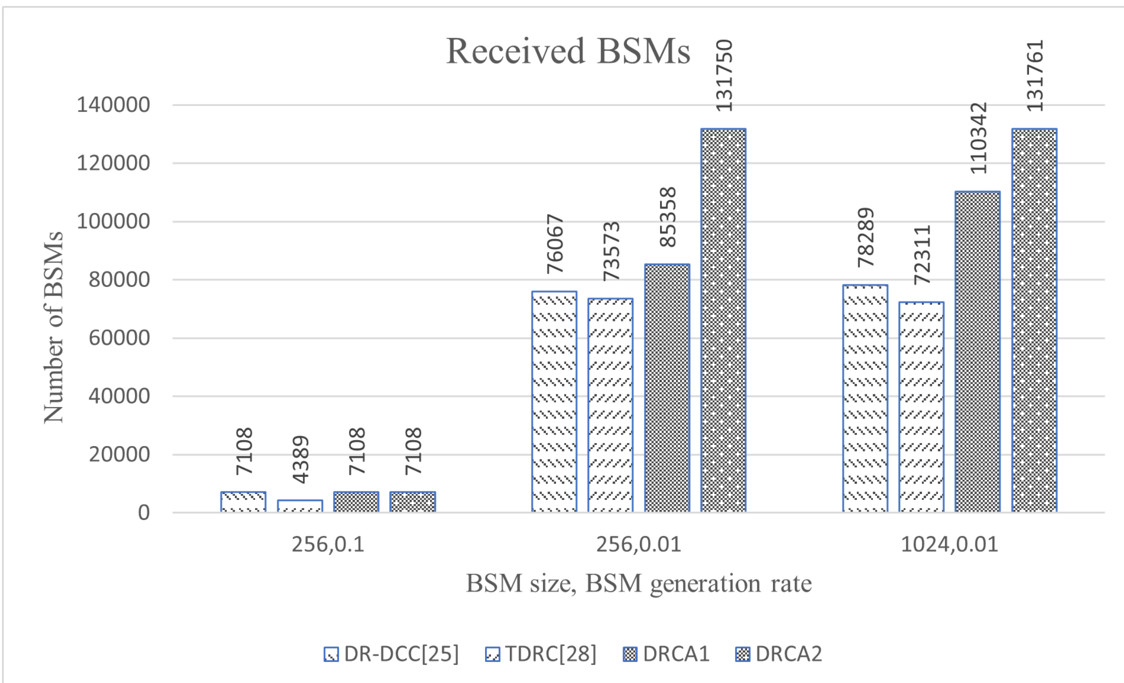

Figure 4.8: Received BSMs comparison in normal traffic environment

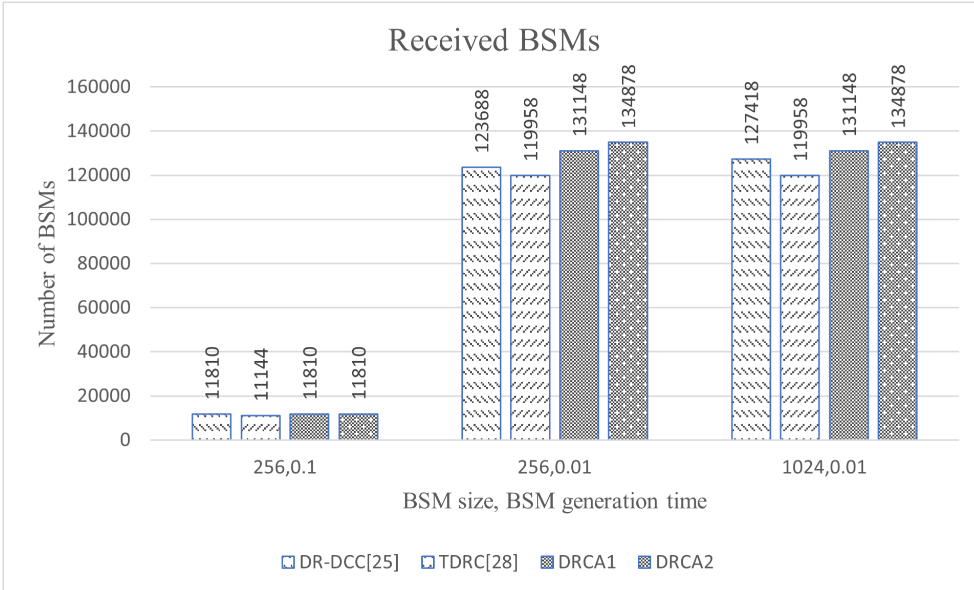

Figure 4.9: Received BSMs comparison in stationary traffic environment

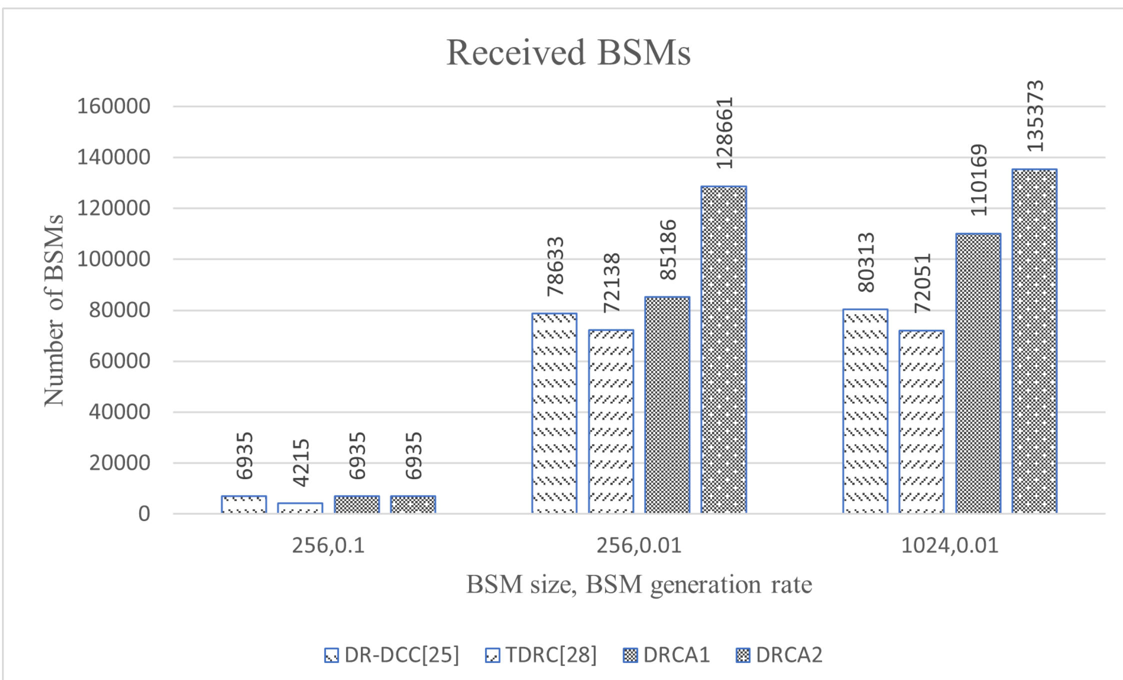

Figure 4.10: Received BSMs comparison in fast traffic environment

4.3.2 Comparison of CBR Values

Figures 4.11, 4.12, and 4.13 show the average CBR in each traffic environment. It can be noticed that both DRCA approaches performed relatively better in maintaining the CBR pf the network to the least minimum level possible. This reduction in the overall CBR helped the DRCA approach in achieving better packet reception compared to other DRCA approaches as discussed in the above section.

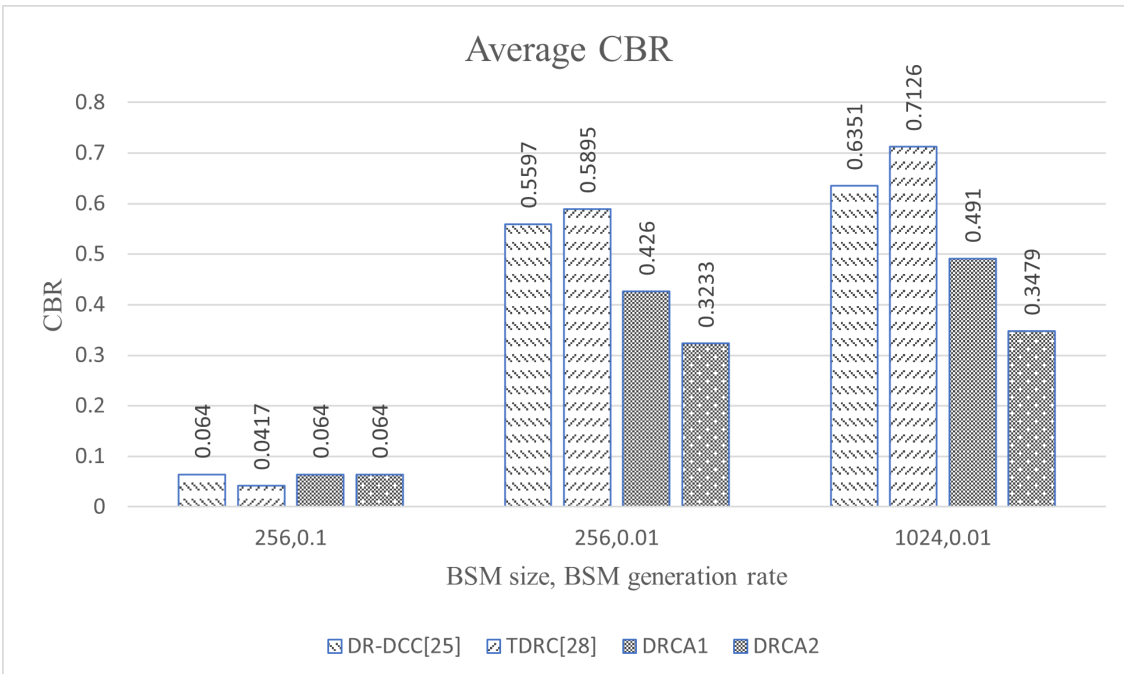

Figure 4.11: Average CBR comparison in normal traffic environment

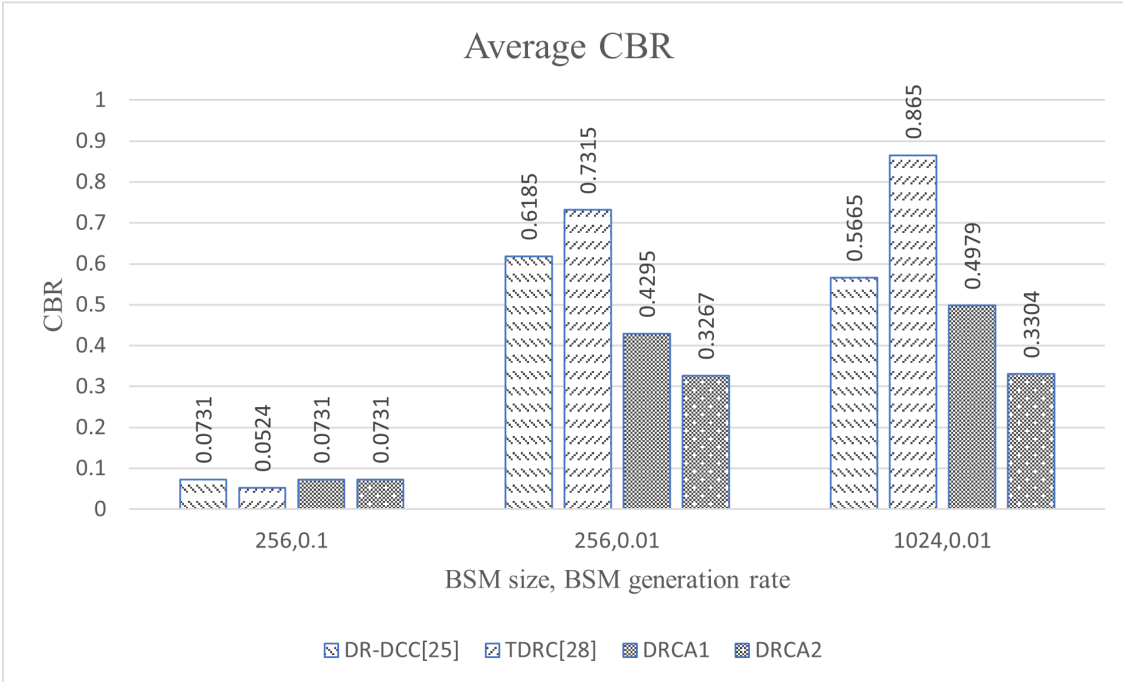

Figure 4.12: Average CBR comparison in stationary traffic environment

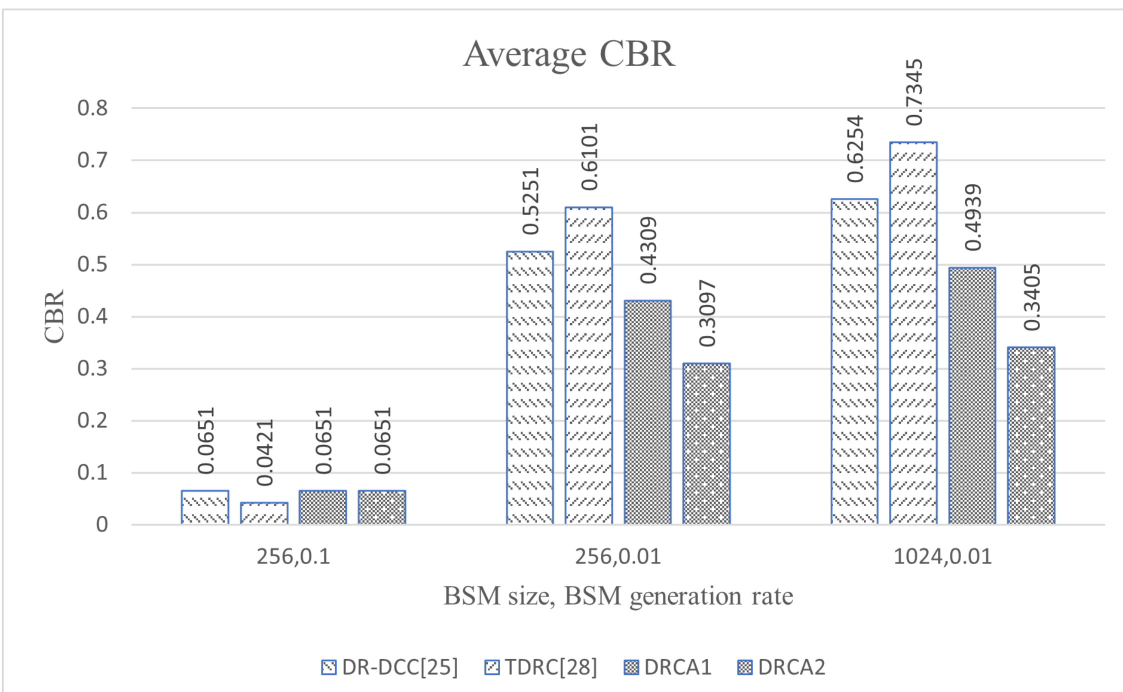

Figure 4.13: Average CBR comparison in fast traffic environment

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this thesis, we proposed and analyzed a new approach for adapting the bitrates used for BSM transmission, based on the level of congestion happening in the network. From the results, we can conclude that DRCA showed a significant improvement when compared with constant bitrates and existing data rate control approaches. CBR is an important parameter to be considered in order to attain maximum packet reception and timely delivery of BSMs. Different traffic scenarios have different levels of congestion happening in them i.e., more number of collisions in a dense network than a sparse network. Controlling the network congestion depending on the CBR might suit for almost all the traffic situations. We also noticed when the CBR is balanced, it helps in achieving more successful packet receptions.

5.2 Future Work

There are a number of factors such as transmission of event-driven non-BSMs packets and more complex road networks and traffic scenarios, which were not considered in the simulations. Additional simulations that consider the impact of these factors on channel congestion can be carried out. It would also be exciting to see how transmission power control could affect the proposed approach and how the performance would be compared to other power adaptation approaches. It would also be interesting to see the performance of the DRCA when combined with power adaptation. The accuracy of the CBR function used in the proposed approach could also be improved.

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