Adaptive Data Rate Based 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. V2V communication uses wireless technology and in scenarios with high vehicle densities, the communication channel faces congestion, negatively impacting the reliability of the safety applications. To address this, various decentralized congestion control techniques have been proposed to effectively lower the channel load, by controlling different transmission parameters like message rate, data rate and transmission power. In this paper, we propose a novel data rate control algorithm to control the network congestion based on the Channel Busy Ratio (CBR). Simulation results demonstrate that the proposed approach outperforms existing data rate based algorithms, in terms of both packet reception and overall channel load.

Keywords: VANET · Congestion control · Vehicular communication · V2V · Basic safety message (BSM) · Intelligent Transportation System (ITS)

1 Introduction

Traffic accidents can occur due to various factors, such as hazardous road conditions, driving under the influence of alcohol/drugs, driver skill level, and speeding that could cause loss of property and lives [1]. Vehicular Ad-Hoc Networks (VANET) [2], a subset of Mobile Ad-Hoc Networks (MANET) [3], forms an integral part of an Intelligent Transportation Systems (ITS) [4] aimed at improving vehicle and road safety. Generally, VANETs are composed of high-speed mobile communication nodes, i.e., vehicles traveling at high velocities, as well as infrastructure nodes, such as roadside units (RSUs). Typical VANET characteristics include rapid changes in topology, high density of nodes in the network, and no energy restrictions [2,5]. Participating nodes (vehicles) in a VANET use wireless

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technology to directly communicate with each other. This type of direct communication between different nodes is known as vehicle-to-vehicle (V2V) communication [5], and will be main focus of this paper. In addition to V2V, VANET also supports vehicle-to-infrastructure (V2I) and infrastructure-to-infrastructure (I2I) communications.

VANET applications are categorized into service and safety applications [6]. Safety applications include forward collision warning, curve speed warning, precrash 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. Many safety applications rely on periodic beacons sent by each vehicle, containing its status information. These periodic messages are referred to as *Basic Safety Messages* (BSMs) in the U.S. [7] and *Cooperative Awareness Messages* (CAMs) in Europe [8] and contain important information, including a vehicle's current position, speed, acceleration, heading etc. These messages are sent through the channels allocated in the DSRC/WAVE system [9], and processed using the On-Board Units (OBUs) that are placed inside each vehicle.

In the United States, the FCC has allocated 75 MHz spectrum in the 5.9GHz band for Dedicated Short Range Communication (DSRC) [10]. This spectrum is divided into seven 10 MHz channels with associated guard bands, from which channel 172 is assigned for exchange of safety messages [11]. A 6 Mbps data rate for BSM transmissions has been widely adopted for many VANET simulations [10,12,13], and also used in some standardization activities [14]. Other data rates have also been considered in some papers, e.g., in [15–17] 3 Mbps is used due to its low SINR requirement. Each vehicle typically transmits 10 beacons per second, which can cause heavy channel load as vehicle density increases. Channel congestion occurs when the load is high enough that the nodes start competing to acquire access to the channel [18]. It has been shown that when the channel load exceeds 40% of the channel capacity, packet collisions and packet delays grow rapidly [19]. Therefore, appropriate congestion control algorithms should be implemented to avoid channel congestion and ensure the proper delivery of messages.

Most VANET congestion control techniques either reduce the BSM transmission rate or transmission power, or a combination of both, to reduce channel load. However, these can have a significant impact on the level of awareness of surrounding vehicles. In recent years, a number of papers have investigated adjusting the BSM transmission *data* rate (i.e. bitrate) to control congestion. For the remainder of the paper, we will use the terms *data rate* and *bitrate* interchangeably. When lower data rates are chosen, packet transmissions take longer, but the signal strength is high, reducing the chance of corrupted or lost packets. On the other hand, when higher data rates are chosen, packet transmissions are faster, reducing channel congestion, but signal strength is also reduced. Therefore, it is important to choose a suitable data rate for each BSM transmission that can balance the need for lower channel congestion and error-free packet reception.

In this paper, we propose a new approach that dynamically selects an appropriate data rate for each BSM transmission, based on the current *channel busy ratio* (CBR). Unlike existing algorithms that typically increment the bitrate only one level at a time, regardless of how high the CBR is, the proposed algorithm directly estimates the appropriate bitrate to use based on the current CBR value. 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, the proposed algorithm calculates the appropriate bitrate and starts transmitting directly using this bitrate, rather than moving through intermediate levels. Our simulation results indicate that the proposed approach is able to outperform existing data rate based algorithms in terms of both successful packet delivery rate and overall channel congestion.

The remainder of the paper is organized as follows. In Sect. 2, we provide an overview of existing VANET congestion control approaches. In Sect. 3, we present our proposed congestion control approach. We discuss our simulation results in Sect. 4 and present our conclusions and some directions for future work in Sect. 5.

2 Background Review

In VANET, the safety messages are of two types: periodic and event-driven messages. Event-driven messages are sent whenever certain events like traffic accidents or road hazards are detected. On the other hand, Basic Safety Messages (BSMs), are sent periodically by each vehicle in the network, regardless of traffic conditions. This means that as the vehicle density increases, the total number of BSMs being transmitted also increases correspondingly. It has been shown that even with relatively simple traffic scenarios, the bandwidth of the allocated channel can quickly become depleted, leading to channel congestion [19]. In this section, we will first briefly review some of the important congestion control techniques that use message rate and power control. Then, we will focus on how the transmission data rate can be used for congestion control, as well as some hybrid approaches.

2.1 Message Rate Based Approaches

The default BSM transmission rate is 10 Hz, i.e., each vehicle normally transmits ten BSMs per second. Message-rate based approaches adapt the rate at which the messages are generated per second. As congestion increases, the message rate is reduced accordingly. The main limitation of these approaches is that reducing the message rate also reduces awareness and can affect vehicle safety, as most safety applications rely on up-to-date information from neighboring vehicles. Some well-known congestion control algorithms using message rate control are discussed below.

In [13], the authors proposed a new scheme called Linear Message Rate Control algorithm (LIMERIC) 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. In [20], the authors proposed a new congestion control strategy called Periodically Updated Load Sensitive Adaptive Rate Control (PULSAR), where 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 decreased. This approach handled the channel congestion by maintaining the CBR below the predefined target value. In [15] the transmission rate was a function of both channel load (LIMERIC component) and vehicle dynamics (Suspected Tracking Error (STE) component). The LIMERIC component executed the LIMERIC algorithm and computed a periodic message rate based on the channel load. This message rate was used to schedule the next packet after every transmission. Meanwhile, STE component determined a time when the channel is expected to reach a threshold, and ensured that the packet is sent no later than that time. In [21] the authors proposed a method that extended the LIMERIC algorithm to control the total channel load according to a predefined target value. In [22], the vehicles transmit their packets by varying the beacon rates. The cars request their neighboring vehicles whether to increase/decrease the Beacon Transmission Rate (BTR). The BTR adjustment requests, which depend on the channel condition, are sent by attaching them to the beacons that are broadcast by each vehicle. In [23], the beacon messages were scheduled according to the priorities and transmission power. Messages were dequeued automatically according to the priority queue model. In [24], the congestion control scheme adapts the message rate according to the local vehicle density.

2.2 Power Control 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 the level of channel congestion. A low-power transmission means that only nearby vehicles can see the BSMs. This reduces awareness, but also lowers channel congestion.

In [25], the vehicles adjusted their transmission power according to their speed. This approach was able to reduce the beacon error rate and channel busy time. In [26], the vehicles made their packet transmissions using different transmission power levels, based on the surrounding vehicle density. When the vehicle density was high, low transmission power was used. During moderate conditions, medium transmission power was used and high transmission power was used when the vehicle density was low. In [27], the authors proposed a method called Distributed Fair Transmit Power Adjustment for VANET (D-FPAV) to achieve congestion control by adjusting the transmission power based on the application-layer traffic and number of vehicles in the surrounding. In [28], all vehicles in the network transmitted beacon messages with an initial transmission power. Then a forecasted value of congestion was calculated and if it was less than a given threshold, then all cars increased their transmission power; otherwise, all the vehicles decreased their transmission power. In [29], the authors proposed to increase the awareness quality. Random transmission power was selected for each packet transmission and each vehicle controlled its power selection by using Complementary Cumulative Distribution Function (CCDF) because of its strong correlation with awareness quality.

2.3 Data Rate Based Approaches

The most commonly used data rate for BSM transmissions is 6 Mbps [12]. However, it is possible to use other bitrates and DSRC has specified 8 possible rates that can be used: (3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps). Data rate-based approaches adapt the bitrate used for BSM transmissions and this approach is gaining more attention in recent years [12].

In [30], the vehicles adapted their data rate based on the network's channel load, which 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. In [31], the algorithm increased the data rate levels to reduce the CBR of the network. The transition from one state to another was done based on CBR measurements for every T seconds, where the states corresponded to the levels of congestion. The algorithm increased the level if the CBR was higher than the mean threshold $C1$, and maintained same level when the CBR was lower than the mean threshold $C1$ and greater than $Cmin$. In [32], packet count Pc was used together with the CBR measurements to adjust the data rate. The data rate D was adjusted depending on the packet count Pc measured for every second.

2.4 Hybrid Approaches

Instead of using a single parameter to control congestion, a number of recent approaches have proposed using a combination of different parameters, e.g. power and message rate, to effectively reduce channel load. Some interesting hybrid approaches that use multiple control parameters are discussed in this section.

In [33], two different transmission power levels were maintained, where each vehicle sent a certain percentage of BSMs with high power and the rest with low power. This technique was combined with LIMERIC to further reduce congestion. This approach had a lower Beacon Error Rate (BER) compared to other approaches. In [34], the authors proposed a new mechanism called Combined Power and Rate Control (CPRC), which 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 a predefined threshold value. In [29], the authors proposed a new congestion control strategy called Random Transmission Power Control (RTPC) 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. In [32], 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.

3 Proposed Approach

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 (and hence channel congestion) but also reduces the signal strength and the distance the signal can travel.

In the proposed approach, each vehicle participating in the network estimates the channel load based on its measured *channel busy ratio* or CBR value. The CBR value measured by a vehicle represents the percentage of time the channel was sensed as "busy" by its OBU over a given interval. The overall motive of our congestion control algorithm is to maintain the CBR between two specified thresholds ($cbrhigh$) and ($cbrlow$), by adjusting the data rate of the transmitted BSMs. Thus, when there is very little traffic, the transmission bitrate is reduced, making the packets visible even to distant vehicles. On the other hand, when congestion is high, a higher bitrate is used that results in faster packet transmission, but potentially increasing the beacon error rate for distant vehicles.

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 transmission data rate is calculated based on the most recent CBR value measured by the vehicle, which is given as an input to the proposed DRCA scheme.

During initialization, the high CBR ($cbrhigh$) and low CBR ($cbrlow$) thresholds are set and a list (B) of allowed bitrate values is also specified. Based on the current standards, the available bitrates that we have used are: 3 Mbps, 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps and 24 Mbps. So, we set 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 $B[1] = 6$ Mbps. Finally, the parameter $maxlevel$ corresponds the highest possible index value for the list B and is given by $maxlevel = len(B) - 1$.

After initialization, depending on the above parameters and current measured CBR value (cbr), 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.

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 condition in step 5 is selected as the new bitrate.

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

```
 1: if $cbr < cbrlow$ then
 2:     $newlevel = level$
 3:     $bitrate = B[newlevel]$
 4:     for $i \in (0, level)$ do
 5:         if $cbr * (B[level]/B[i]) < 0.95 * cbrhigh$ then
 6:             $newlevel = i$
 7:             $bitrate = B[i]$
 8:             break
 9:         end if
10:     end for
11: end if
12: if $cbr > cbrhigh$ then
13:     $newlevel = maxlevel$
14:     $bitrate = B[newlevel]$
15:     for $i \in (level + 1, maxlevel)$ do
16:         if $cbr * (B[level]/B[i]) < 0.95 * cbrhigh$ then
17:             $newlevel = i$
18:             $bitrate = B[newlevel]$
19:             break
20:         end if
21:     end for
22: end if
23: if $cbrlow \leq cbr \leq cbrhigh$ then
24:     $newlevel = level$
25:     $bitrate = B[newlevel]$
26: end if
```

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 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 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 $B[newlevel]$ as the next *bitrate* for the packet transmission.

4 Results and Analysis

4.1 Simulation Setup

Testing the effectiveness of congestion control algorithms for VANET becomes difficult in real-world situations due to the costs incurred, required equipment, resources, and safety concerns. Therefore, we have used a simulation environment to evaluate our proposed approach. We used Simulation of Urban Mobility (SUMO) [35] as the traffic simulator and Objective Modular Network Testbed (OMNET++) [36] as our network simulator.

For our traffic model, we considered a 1000 m long four-lane highway composed of two lanes in either direction. There was a total of 80 vehicles in the simulation, each with a maximum speed of 50 km/h. The simulation was run for 120 s. To generate different levels of channel load, we used different combinations of BSM packet sizes and beacon intervals, as indicated below:

- LOW load: Packet size = 256 Bytes and Beacon interval = 0.1 s.
- MEDIUM load: Packet size = 256 Bytes and Beacon interval = 0.01 s.
- HIGH load: Packet size = 1024 Bytes and Beacon interval = 0.01 s.

4.2 Comparison with Constant Bitrate Transmissions

In this section, we compare the performance of the proposed DRCA approach, which dynamically adapts the data rate, with using a constant bitrate for different bitrate values, viz., 3 Mbps, 6 Mbps, 12 Mbps, 18 Mbps, and 24 Mbps.

The performance is analyzed based on the total number of BSMs successfully received by the vehicles and the average CBR of the network.

Comparison of Received BSMs

Figure 1 shows the total amount of packets received with different bitrates (i.e., constant bitrates) and the DRCA approach. From the graph, we can see that using 3 Mbps performed better in low congestion scenarios and 24 Mbps performed best for medium to high congestion scenarios, in terms of the total amount of packets received. The proposed DRCA achieved the highest received BSMs (same as with 3 Mbps) for low load, and was very closed to the best results for medium and high loads. The above results indicate the advantages of using an adaptive congestion control technique, such as DRCA, since channel load can vary widely over time.

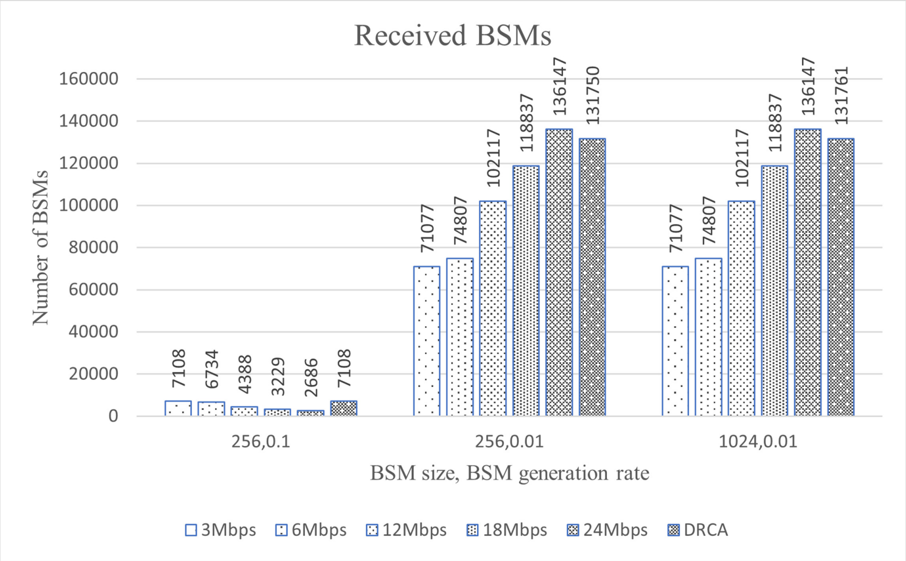

Fig. 1. Comparison of received BSMs with DRCA vs using constant bitrates

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. Figure 2 shows the average CBR over the entire duration of the simulation, when using DRCA as well as different constant bitrates. It can be seen that DRCA approach was successful in maintaining a lower average CBR, close to the minimum value possible, for medium and high loads when compared with the constant bitrates. For low channel loads, lowering the CBR is not really necessary so DRCA tries to achieve better packet reception (as shown in Fig. 1) at the cost of higher CBR.

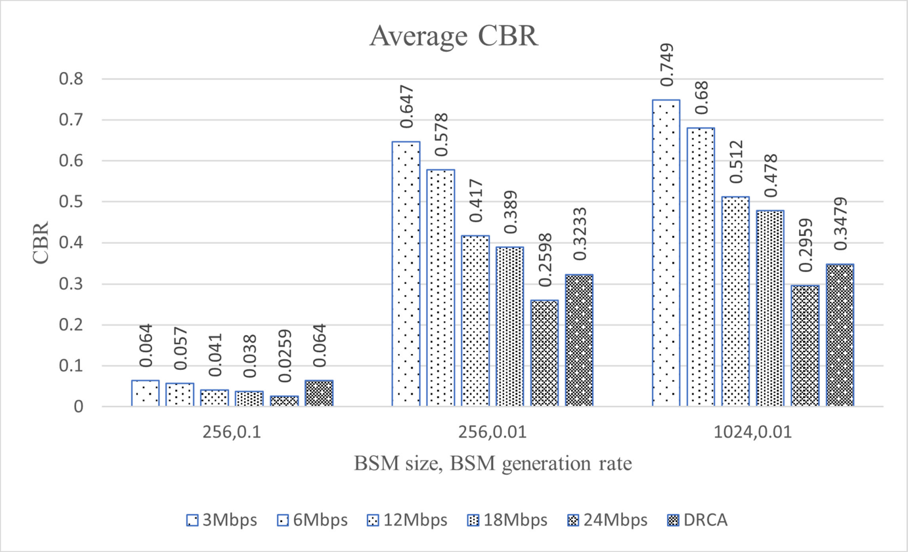

Fig. 2. Comparison of CBR with DRCA vs using constant bitrates

4.3 Comparison with Existing Congestion Control Techniques

The results from the previous section demonstrated the advantages of adapting bitrates according to the current congestion in the network. In this section, we compare the proposed DRCA approach with 2 other existing data rate control approaches: Data Rate- Decentralized Congestion Control(DR-DCC) [31] and Transmission Data Rate Control (TDRC) [30]. The proposed DRCA approach was run with two different high (*cbrhigh*) and low (*cbrlow*) thresholds. For DRCA1, we set $cbrhigh = 0.5$ and $cbrlow = 0.3$, while for DRCA2 we used $cbrhigh = 0.4$ and $cbrlow = 0.2$.

Comparison of Received BSMs
Figure 3 compares the total number of BSMs received under different channel loads, using DRCA, DR-DCC and TDRC. Under low loads, the performance of all 3 approaches were very similar. For medium and high loads, both DRCA1 and DRCA2 outperformed the other techniques. In particular, DRCA2 was able to achieve a significantly higher number of successfully received packets.

Comparison of CBR Values
Figure 4 shows the average CBR for the 3 techniques, under different channel loads. Under low load, all techniques report very low values of CBR, with TDRC having the lowest value. For medium to high loads, both DRCA1 and DRCA2 were able to significantly reduce the average CBR value compared to the other 2 approaches. Finally, we note that DRCA2 achieved the lowest overall CBR, showing that it can effectively reduce channel congestion, while improving packet delivery ratio.

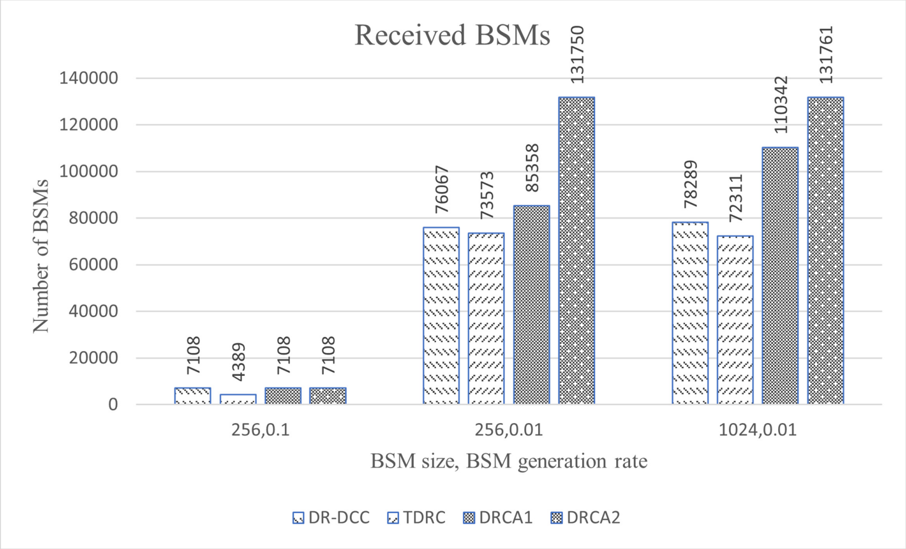

Fig. 3. Comparison of received BSMs with DRCA vs existing approaches

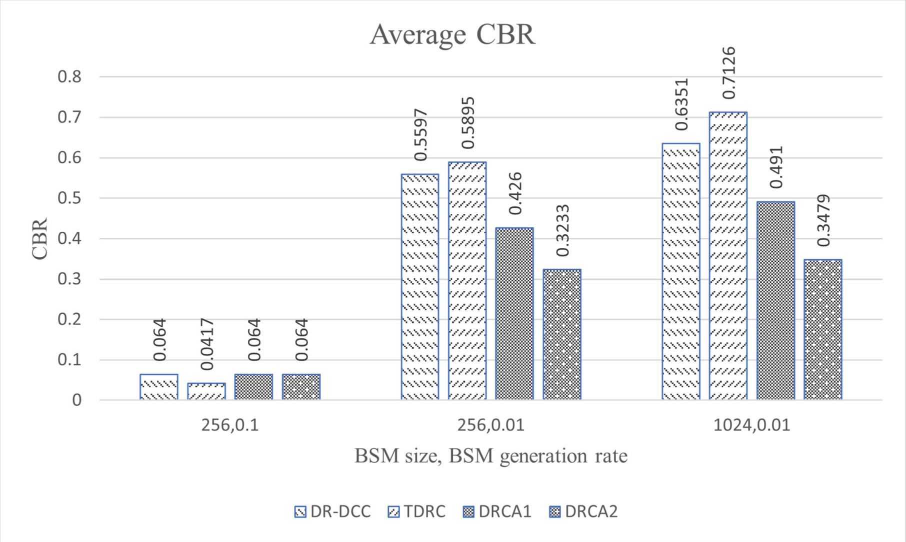

Fig. 4. Comparison of CBR with DRCA vs existing approaches

5 Conclusion and Future Work

In this paper, we have proposed and analyzed a new approach for dynamically adapting the bitrates used for BSM transmission, based on the level of congestion in the network. The proposed *data rate control algorithm* (DRCA) was able to significantly improve packet reception and control channel congestion, compared to both constant bitrates and existing data rate control approaches. For future work, we are extending the proposed approach to automatically select appropriate threshold values for CBR, based on current traffic conditions. It will also be interesting to combine DRCA with power-control techniques to further reduce congestion.

References

1. National Highway Traffic Safety Administration: Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application, August 2014
2. Zeadally, S., Hunt, R., Chen, Y.S., Irwin, A., Hassan, A.: Vehicular ad hoc networks (VANETS): status, results, and challenges. Telecommun. Syst. **50**(4), 217–241 (2012)
3. Jha, R.K., Limkar, S.V., Dalal, D.U.: A performance comparison of routing protocols (DSR and TORA) for security issue in MANET (mobile ad hoc networks). IJCA Special Issue MANETs, **2**, 78–83 (2010)
4. Calabuig, J., Monserrat, J.F., Gozalvez, D., Klemp, O.: Safety on the roads: LTE alternatives for sending ITS messages. IEEE Veh. Technol. Mag. **9**(4), 61–70 (2014)
5. Nassar, L., Jundi, A., Golestan, K., Sattar, F., Karray, F., Kamel, M., Boumaiza, S.: Vehicular Ad-hoc Networks (VANETs): Capabilities, Challenges in Context-Aware Processing and Communication Gateway. In: Kamel, M., Karray, F., Hagras, H. (eds.) AIS 2012. LNCS (LNAI), pp. 42–49. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-31368-4_6
6. Hartenstein, H., Laberteaux, K. (eds.): VANET: Vehicular Applications and Inter-Networking Technologies, vol. 1. Wiley, Hoboken (2009)
7. SAE J2735: Dedicated Short Range Communications (DSRC) Message Set Dictionary; Society of Automotive Engineers, DSRC Committee: Warrendale, PA, USA (2009)
8. ETSI (2013) ETSI EN 302 637–2 (V1.3.0)-Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service; Vehicular Communications (2013). https://www.etsi.org/deliver/etsi_en/302600_302699/30263702/01.03.02_60/en_30263702v010302p.pdf. Accessed 10 May 2019
9. Liu, Y., Dion, F., Biswas, S.: Dedicated short-range wireless communications for intelligent transportation system applications: state of the art. Transp. Res. Rec. **1910**(1), 29–37 (2005)
10. Kenney, J.B.: Dedicated short-range communications (DSRC) standards in the United States. Proc. IEEE **99**(7), 1162–1182 (2011)
11. Amendment of the Commission's Rules Regarding Dedicated Short-Range Communication Services in the 5.850-5.925 GHz Band (5.9 GHz Band); Technical Report; U.S. Federal Communications Commission: Washington, DC, USA (2006)
12. Liu, X., Jaekel, A.: Congestion control in V2V safety communication: problem, analysis, approaches. Electronics **8**(5), 540 (2019)

13. Bansal, G., Kenney, J.B., Rohrs, C.E.: LIMERIC: a linear adaptive message rate algorithm for DSRC congestion control. IEEE Trans. Veh. Technol. **62**(9), 4182–4197 (2013)
14. ETSI. Intelligent Transport Systems (ITS); European Profile Standard on the Physical and Medium Access Layer of 5 GHz ITS (2009). https://www.etsi.org/deliver/etsi_es/202600_202699/202663/01.01.00_50/es_202663v010100m.pdf. Accessed 20 Dec 2018
15. Bansal, G., Lu, H., Kenney, J.B., Poellabauer, C.: EMBARC: error model based adaptive rate control for vehicle-to-vehicle communications. In: Proceeding of the Tenth ACM International Workshop on Vehicular Inter-Networking, Systems, and Applications, pp. 41–50, June 2013
16. Huang, C.L., Fallah, Y.P., Sengupta, R., Krishnan, H.: Intervehicle transmission rate control for cooperative active safety system. IEEE Trans. Intell. Transp. Syst. **12**, 645–658 (2011)
17. Torrent-Moreno, M., Mittag, J., Santi, P., Hartenstein, H.: Vehicle-to-vehicle communication: fair transmit power control for safety-critical information. IEEE Trans. Veh. Technol. **58**, 3684–3703 (2009)
18. Taherkhani, N.: Congestion control in vehicular ad hoc networks. Doctoral dissertation, Ecole Polytechnique, Montreal (Canada) (2015)
19. Weinfeld, A.: Methods to reduce DSRC channel congestion and improve V2V communication reliability. In: Proceedings of the 17th ITS World Congress, Busan, Korea, 25–29 October 2010 (2010)
20. Tielert, T., Jiang, D., Chen, Q., Delgrossi, L., Hartenstein, H.: Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications. In: 2011 IEEE Vehicular Networking Conference (VNC), pp. 116–123. IEEE, November 2011
21. Bansal, G., Kenney, J.B.: Achieving weighted-fairnessin message rate-based congestion control for DSRC systems. In: 2013 IEEE 5th International Symposium on Wireless Vehicular Communications (WiVeC), pp. 1–5. IEEE, June 2013
22. Kim, G., Lee, S., Park, H., Kim, D.: A request based adaptive beacon rate control scheme for vehicular ad-hoc networks. In: 2016 Eighth International Conference on Ubiquitous and Future Networks (ICUFN), pp. 67–69. IEEE, July 2016
23. Sharma, S., Chahal, M., Harit, S.: Transmission rate-based congestion control in vehicular ad hoc networks. In: 2019 Amity International Conference on Artificial Intelligence (AICAI), pp. 303–307. IEEE, February 2019
24. Chaabouni, N., Hafid, A., Sahu, P.K.: A collision-based beacon rate adaptation scheme (CBA) for VANETs. In: 2013 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), pp. 1–6. IEEE, December 2013
25. Facchina, C., Jaekel, A.: Speed based distributed congestion control scheme for vehicular networks. In: 10th IEEE ISCC MoCS Workshop (MoCS 2020), July 2020
26. Akinlade, O., Saini, I., Liu, X., Jaekel, A.: Traffic density based distributed congestion control strategy for vehicular communication. In: IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS 2019) Santorini Island, Greece, 29–31 May 2019 (2019)
27. Torrent-Moreno, M., Santi, P., Hartenstein, H.: Distributed fair transmit power adjustment for vehicular ad hoc networks. In: 2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks, vol. 2, pp. 479–488. IEEE, September 2006

28. Mo, Y., Yu, D., Song, J., Zheng, K., Guo, Y.: A beacon transmission power control algorithm based on wireless channel load forecasting in VANETs. PLoS ONE **10**(11), e0142775 (2015)
29. Kloiber, B., Härri, J., Strang, T.: Dice the tx power-improving awareness quality in vanets by random transmit power selection. In: 2012 IEEE Vehicular Networking Conference (VNC), pp. 56–63. IEEE, November 2012
30. Patil, A., Deeksha, M., Shekar, N., Shet, V., Kulkarni, M.: Transmit data rate control based decentralized congestion control mechanism for VANETs. In: 2019 International Conference on Data Science and Communication (IconDSC), pp. 1–5. IEEE, March 2019
31. Math, C.B., Ozgur, A., de Groot, S.H., Li, H.: Data rate based congestion control in V2V communication for traffic safety applications. In: 2015 IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT), pp. 1–6. IEEE, November 2015
32. Math, C.B., Li, H., de Groot, S.H., Niemegeers, I.: Fair decentralized data-rate congestion control for V2V communications. In: 2017 24th International Conference on Telecommunications (ICT), pp. 1–7. IEEE, May 2017
33. Willis, J.T., Jaekel, A., Saini, I.: Decentralized congestion control algorithm for vehicular networks using oscillating transmission power. In: WTS 2017, Chicago, USA, 26–28 April 2017 (2017)
34. Baldessari, R., Scanferla, D., Le, L., Zhang, W., Festag, A.: Joining forces for vanets: a combined transmit power and rate control algorithm. In: 6th International Workshop on Intelligent Transportation (WIT), March 2010
35. https://www.eclipse.org/sumo/
36. https://omnetpp.org/