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Balancing Awareness and Congestion in Vehicular Networks Using Variable Transmission Power

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Abstract: Vehicular ad Hoc networks (VANETs) support a variety of applications ranging from critical safety applications to "infotainment" or "comfort" applications. In North America, 75 MHz of the spectrum in the 5.9 GHz band has been allocated for vehicular communication. Safety applications rely on event-driven "alert" messages as well as the periodic broadcast of Basic Safety Messages (BSMs) containing critical information, e.g., position, speed, and heading from participating vehicles. The limited channel capacity and high message rates needed to ensure an adequate level of awareness make the reliable delivery of BSMs a challenging problem for VANETs. In this paper, we propose a decentralized congestion control algorithm that uses variable transmission power levels to reduce the channel busy ratio while maintaining a high level of awareness for nearby vehicles. The simulation results indicate that the proposed approach is able to achieve a suitable balance between awareness and bandwidth usage.

Keywords: VANET; congestion control; V2V; transmission power control

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1. Introduction

The number of motor vehicle deaths in the United States, which includes all types of motor vehicles, e.g., passenger cars, trucks, and buses, was almost 40,000 in 2019 [1,2]. Besides driver attitudes and behaviors, vehicle safety technology is a key factor to make car travel safer. VANETs [3] have been widely perceived by government, car manufacturing industries, and academia as a valid measurement to achieve safety and efficiency in the motorway. In VANET, vehicles communicate directly with each other, as well as with infrastructure nodes to create a connected network that can facilitate the dissemination of the necessary safety-related information. Vehicles equipped with communication devices known as On Board Units (OBUs) can connect with other vehicles and RoadSide Units (RSUs) to implement various safety applications.

In North America, 75 MHz of the spectrum in the 5.9 GHz band have been allocated using Dedicated Short-Range Communications/Wireless Access for Vehicular Environment (DSRC/WAVE) [4,5] for Vehicle-to-Vehicle (V2V) communication, and another 30 MHz of the spectrum is proposed for Cellular Vehicle-to-Everything (C-V2X) [6]. Safety applications rely on up-to-date information on surrounding vehicles, including their position, speed, acceleration, heading, etc. Therefore, each vehicle periodically broadcasts its status, containing such information, in the form of BSMs [7] (also referred to as Cooperative Awareness Messages (CAMs) [8] in Europe). The information contained in these packets are used as input to safety-critical applications, e.g., collision avoidance, lane change warnings, and hard braking warnings. The availability and freshness of the BSM data are essential for the proper operation of the different algorithms designed to improve vehicle safety.

In order to achieve a suitable level of awareness, the target transmit rate for the BSM packets is set as 10 Hz with a transmit radius of 300 m [9]. The total allocated bandwidth for BSM transmission from all vehicles is expected to be fully utilized, with 200 vehicles sending their BSMs at the standard transmission rate [10]. This is for an ideal case that

assumes that there are no other types of transmissions and that all BSM packets are perfectly scheduled back-to-back, without any (packet) collisions. The IEEE 802.11p Carrier Sense Multiple Access (CSMA) protocol that is used for V2V communication will actually be able to support far fewer vehicles. The relatively high level of channel congestion [11], even at moderate vehicle densities, means that appropriate congestion control mechanisms are needed that will lead to efficient use of available channel bandwidth and allow a timely delivery of BSMs, while limiting channel congestion as the number of vehicles increases.

The limited channel capacity and high message rates (to ensure an adequate level of awareness) make the reliable delivery of BSMs a challenging problem for VANET, and a number of different congestion control approaches have been proposed for vehicular communication [12]. Message transmission rate used in [10,13,14] and power control used in [15–19] (or a combination of both used in [20–23]) are the common parameters that are controlled to mitigate channel congestion, although other parameters, e.g., data rate, carrier sense threshold, have also been suggested [24,25]. Both message rate and power control reduce awareness of the neighboring vehicles either by increasing Inter-Packet Delay (IPD) for BSMs received from a vehicle or by limiting the distance at which such packets can be received correctly. In this paper, we propose a new congestion control algorithm that balances the need for high vehicle awareness with maintaining a low channel congestion level. In this approach, each vehicle uses a variable transmission power for each BSM so that nearby vehicles receive more BSMs and more distant vehicles receive fewer BSMs from the same vehicle.

The remainder of the paper is organized as follows. In Section 2, we review existing approaches for congestion control in VANET, and we present our proposed algorithms in Section 3. In Section 4, we discuss and analyze our simulation results, and finally, we present our conclusions and some directions for future work in Section 5.

2. Related Work

Existing Decentralized Congestion Control Approaches

In order to make distant vehicles aware of the Ego Vehicle (EV), i.e., the particular vehicle that sends the BSMs, the transmission power should be increased. Similarly, to ensure that all vehicles have up-to-date information on the EV, it is desirable to increase the number of BSMs sent per second. However, when BSMs are transmitted with high rate and high power, the channel congestion increases quickly as the number of vehicles increases. Therefore, existing congestion control techniques in VANET typically reduce the message rate or transmission power, or a combination of both. In paper [26], the authors propose a comparative review of congestion control mechanisms. Papers [27,28] introduce theory and methods about general traffic information collection and diffusion from the Internet of Vehicle (IoV) point of view.

The nominal message rate for BSMs is 10 packets per second. Rate-based congestion control algorithms attempt to reduce this to a predetermined fixed rate [29] or a new rate that is calculated based on an input parameter which describes the current congestion level [30,31]. One of the most well-known rate-based congestion control approaches is the LInear MEssage Rate Integration Control (LIMERIC) algorithm [10]. The main objective in LIMERIC is to share the available channel bandwidth fairly among all vehicles by adapting the rate of the BSM transmission dynamically in each iteration. LIMERIC is able to effectively mitigate congestion [30], but this is achieved at the cost of increased IPD from neighboring vehicles. In [13], the authors present a new algorithm called Error Model Based Adaptive Rate Control (EMBARC), which updates LIMERIC by also considering vehicle position error estimation. Another rate-based approach, BSM RAte control over IEEE802.11p VEhicular networks (BRAEVE) [14], uses the estimated number of vehicles rather than channel utilization as the input parameter. BRAEVE is shown to provide smoother convergence and result in lower packet error ratio, IPD and tracking error compared to the other algorithms.

In addition to the message rate, another common parameter that can be adjusted to achieve congestion control is the transmission power [32]. A packet sent with a higher power is able to travel a greater distance (and potentially reach more vehicles) compared to one sent with a lower power. This means we can control the number of vehicles that a BSM can reach by adjusting the transmission power. When selecting a suitable transmission power, it is usually calculated based on the measured or estimated level of channel load. Another approach, proposed in [15], is to select the transmission power randomly from a known probability distribution.

One of the most cited power control algorithms is Distributed Fair Transmit Power Adjustment for VANETs (D-FPAV) [16], which proposes a fully distributed, asynchronous and localized approach by setting the node transmission power based on the prediction of application-layer traffic and the observed number of vehicles in the surrounding area. In [33], the authors propose a distributed congestion control algorithm based on non-cooperative game theory, which has better performance in terms of fairness and bandwidth usage. In [17], an adaptive beacon transmission power algorithm based on vehicle position prediction error is proposed, which increases the beacon transmission power of vehicles with large vehicle position prediction errors and reduces the transmission power of vehicles with small errors. Other power control based algorithms include Segment-based Power Adjustment for Vehicular environments (SPAV) [18], Speed Based Adaptive Power Control (SBAPC) [34], Adaptive transmit power Cooperative Congestion Control (AC3) [19], etc. Paper [12] gives a comprehensive review for the details about these power control based algorithms.

Existing VANET congestion control approaches generally attempt to mitigate congestion by calculating a message rate or power level based on some input parameters, e.g., Channel Busy Ratio (CBR) and vehicle density. In such approaches, all neighboring vehicles are treated in the same way. In other words, all vehicles within the transmission range will receive the same number of BSMs from the EV. However, in practice, the awareness of vehicles that are nearby should be more important than those that are farther away. This is because interactions with nearby vehicles are likely to occur more quickly, leading to a smaller margin for error. Unlike existing approaches, the congestion control algorithm proposed in this paper balances the awareness of near and distant vehicles, so that more packets are received from nearby vehicles and fewer from vehicles that are farther away. A preliminary version of this work, with some initial results was presented in [35]. In this paper, we have updated the algorithm to separate the power control and rate control components so that each part can be adjusted independently. We have also used a random rate control algorithm in Section 3.2.1, which does not require coordination among different vehicles, and added an illustrative example and comprehensive simulation results, including a range of performance metrics, e.g., average CBR, number of received BSMs, and IPD, that were not considered previously.

3. The Balancing Awareness and Congestion Power Control Algorithm

3.1. Algorithm Design Methodology

From the safety point of view, vehicles that are closer to the EV have more impact on its safety. This is because the time to reach a nearby vehicle is much shorter compared to distant vehicles, leading to a smaller margin for error. Hence, delivering safety messages to the near vehicles in a timely fashion is of critical importance. The actual distance that BSMs from a vehicle can reach, i.e., the transmission range (*Tx* range) of the BSM, depends on the corresponding transmission power (*Tx* power). A receiving vehicle within the transmission range of the EV should be able to receive the BSM correctly (assuming there is no channel congestion or other interference). As the transmission power increases, the transmission range also increases. In addition to the *Tx* power, other factors, e.g., the presence of obstacles and the number of surrounding vehicles, can also affect the range. Table 1 shows how the number of received BSMs between two vehicles varies with the distance between the vehicles.

To generate the above data, we considered two stationary vehicles separated by different distances, e.g., 50 m and 100 m, sending periodic BSMs to each other. We have assumed a simple free space path loss model to approximate the transmission range, which does not consider obstacles. With *Tx* power = 20 mW, we observe that most BSMs can be delivered within 500 m and almost all BSMs are lost when the two vehicles are separated by 600 m or more. With 5 mW, the *Tx* range is much shorter due to the lower *Tx* power. In this case, most BSMs can be received if the vehicle separation is 250 m or less, and beyond that, more and more BSMs will be lost. For 5 mW power, there is actually a gradual drop-off for received BSMs between 250 m and 350 m, similar to what occurs between 450 m and 650 m for 20 mW. However, this is not apparent in Table 1, as the tested distances between vehicles were all multiples of 50 m. A smaller vehicle spacing would allow this effect to be seen more clearly. The values shown in Table 1 represent an ideal case, where there are no other vehicles on the road segment. If we have more vehicles, i.e., a high vehicle density, the valid *Tx* range will be further reduced due to the interference between the vehicles.

Table 1. Maximum transmission distance.

Distance (m)	Sent BSMs	10 Hz 20 mW		10 Hz 5mW	
		Received BSMs	Lost BSMs	Received BSMs	Lost BSMs
50	5982	5980	2	5980	2
100	5982	5980	2	5980	2
150	5982	5980	2	5980	2
200	5982	5980	2	5980	2
250	5982	5980	2	5969	13
300	5982	5980	2	2872	3110
350	5982	5980	2	0	5982
400	5982	5980	2	0	5982
450	5982	5978	4	0	5982
500	5982	5957	25	0	5982
550	5982	5481	501	0	5982
600	5982	1728	4254	0	5982
650	5982	0	5982	0	5982
700	5982	0	5982	0	5982

In summary, a high *Tx* power is able to deliver BSMs to distant vehicles, but can also lead to higher interference and channel congestion. The key strategy of this paper is to prioritize BSM delivery to nearby vehicles, which can be achieved using a lower *Tx* power level, instead of persistently transmitting at the maximum 20 mW *Tx* power. It is still desirable to maintain some level of awareness for distant vehicles as well, but the frequency of updates can be lower than needed for the closest vehicles. Therefore, by varying the *Tx* power, it is possible to maintain high awareness for nearby vehicles, while still allowing some BSMs to reach distant vehicles, by using a high *Tx* power for selected BSMs. With this strategy, the awareness of EVs will remain high as needed for nearby vehicles and the congestion of the whole channel will be mitigated at the time because fewer BSMs are sent with a high *Tx* power.

3.2. Proposed Algorithm

In this section, we discuss our proposed Balancing Awareness and Congestion with Variable *Tx* Power (BACVT) algorithm for VANET congestion control. With this algorithm, vehicles at close range see all packets at their full rate and those farther away see only those packets sent with a higher transmission power. The algorithm can be implemented assuming a constant message transmission rate (the standard rate is 10 BSMs per second) or in conjunction with a message rate control algorithm, e.g., LIMERIC. Algorithm 1, as shown below, outlines the BACVT algorithm when using the standard BSM message rate.

Algorithm 1: Balancing awareness and congestion with variable Tx power (BACVT) algorithm.

Result: Tx power for near and far transmission
1 Initialization ;
2 $TotalSend = 10$;
3 $setrate(R_n, R_f)$;
4 $N_{low} = \left\lceil R_n / R_f \right\rceil - 1$;
5 $PktNum = 0$;
6 $CLPP = 0$;
7 **while** *No rate control* **do**
8 **if** $(CLPP \geq N_{low})$ *or* $(PktNum\%TotalSend == 0)$ **then**
9 $Tx_c \longleftarrow Tx_f$;
10 $CLPP = 0$;
11 $PktNum = PktNum + 1$;
12 **else**
13 $Tx_c \longleftarrow Tx_n$;
14 $CLPP = CLPP + 1$;
15 $PktNum = PktNum + 1$;
16 **end**
17 Send packet with Tx_c ;
18 **end**

During the initialization phase, we first define two transmission ranges d_n and d_f as the near and far ranges (in m), respectively, with respect to the EV. The corresponding Tx powers needed in order to achieve these ranges are Tx_n and Tx_f, respectively, where $Tx_n < Tx_f$. In practice, the required Tx powers depend not only on the target distance, but additional factors, e.g., atmospheric conditions, obstacles and vehicle density. We note that the proposed algorithms simply assume that suitable values of Tx_n and Tx_f have been calculated separately to be given as input, and we are not proposing new models to calculate such values. We expect that a vehicle v at a distance d from the EV will receive:

- All BSMS from the EV, if $d \leq d_n$;
- The BSMs transmitted with high Tx power (Tx_f), if $d_n \leq d \leq d_f$;
- No BSMs from the EV, if $d > d_f$.

The value of *TotalSend* is set to the number of BSMs to send in each cycle in step 3. Unless otherwise specified, we assume that the duration of each cycle is 1 s. In step 3, we define two transmission rates, R_n and R_f, as the near and far distance reception rates, respectively, i.e., the number of BSMs received per second from the EV by the near and far vehicles, respectively. Clearly, $R_n > R_f$, as nearby vehicles will receive all BSMs, those sent with low power as well as those sent with high power. The parameters R_n and R_f are used by the algorithm to determine which packets are sent with a higher power level in order to maintain the two perceived reception rates for the remote vehicles. These values depend on the current level of congestion in the network, as well as the awareness level needed for the specific applications. For our simulations, we have specified fixed values for R_n and R_f, where all vehicles use the same values for R_n and R_f. However, this is not strictly required and different vehicles can use different values, based on their current needs. In step 4, the value of N_{low} is calculated using Equation (1). N_{low} determines the number of low-power BSMs that should be sent between two high-power BSMs for each cycle. This will allow the high and low power BSMs to be evenly distributed over each cycle. An example of how N_{low} is calculated based on Equation (1) is given in Section 3.3.

$$N_{low} = \left\lceil R_n / R_f \right\rceil - 1 \tag{1}$$

Once the value of N_{low} is determined, the algorithm initializes the total number of packets sent so far ($PktNum$) and the number of *Consecutive Low-Power Packets* ($CLPP$) to

0 in steps 5 and 6, respectively. These two values maintain a counter of the total number of packets and the number of consecutive low-power packets that have been sent since the last high power transmission. The first BSM of each cycle is sent using the high Tx power, i.e., Tx_f. Then, N_{low} packets are transmitted with the low Tx power, i.e., Tx_n, and this pattern repeats until the end of the cycle is reached, i.e., $TotalSend$ number of packets have been sent in the current cycle.

After setting the initial parameters, steps 7–18 are repeated for each BSM to determine the Tx power for the individual BSM. If it is the first BSM in the cycle, or N_{low} consecutive low-power BSMs have been sent, then the Tx power is set to *high* (step 9), $CLPP$ is reset to 0 and the packet count is updated (step 10 and step 11). Otherwise, the Tx power is set to *low* (step 13) and both the $CLPP$ values and packet count are incremented (step 14 and step 15). Finally, in step 17, the BSM is broadcast by the EV with the appropriate Tx power. The time complexity of Algorithm 1 is $O(n)$, where n is the number of BSMs sent by a vehicle.

3.2.1. Hybrid Approach

The BACVT approach described in Algorithm 1 assumes that each vehicle will use a constant message Tx rate to send the BSMs (the default is 10 BSMs per second). However, the proposed approach can also be used in conjunction with other rate control algorithms to further reduce congestion, if power adaptation alone is not sufficient. In this case, the initial steps (steps 1–6) must be carried out for each cycle, rather than just once at the beginning. The modified algorithm (BACVT-H), which is a "hybrid" of rate control and power control approach, is very similar to the original algorithm, and is shown in Algorithm 2. The main difference is in step 2, where the value of $TotalSend$ is determined at the beginning of each cycle by a suitable rate control algorithm, e.g., LIMERIC, BRAEVE or any other approach. So, the value of $TotalSend$ is not a fixed quantity (as in Algorithm 1), but will vary based on the current CBR and the rate control algorithm that is being used. We have used $TotalSend$ values between 5 and 10 for the message rate control. Therefore, the expected values for the beacon intervals will vary between 0.1 s and 0.2 s. The remaining parameters are set as before (steps 3–6). Finally, the process for determining the Tx power of each BSM (steps 7–18) is similar to Algorithm 1, except that these steps are repeated only for the current cycle and not continued for multiple cycles. At the end of the cycle, the message rate control algorithm is applied to determine the new value of $TotalSend$, and the initial parameters are recalculated before BSM transmission starts. Since the only difference is the value of $TotalSend$, Algorithm 2 has the same time complexity with Algorithm 1, i.e., $O(n)$.

3.3. Illustrative Example

Figure 1 shows the pattern of high-power and low-power BSM transmissions for a vehicle, using the following parameters:

- $TotalSend = 10$
- $R_n = 10$
- $R_f = 2$

Then, using Equation (1), we get $N_{low} = 4$. As shown in the figure, the first packet in the cycle ($PktNum = 0$) is always transmitted with high Tx power. This is followed by $N_{low} = 4$ low-power packets and another high-power packet. This pattern continues until the last packet in the cycle ($PktNum = 9$) and the next packet ($PktNum = 10$) starts a new cycle.

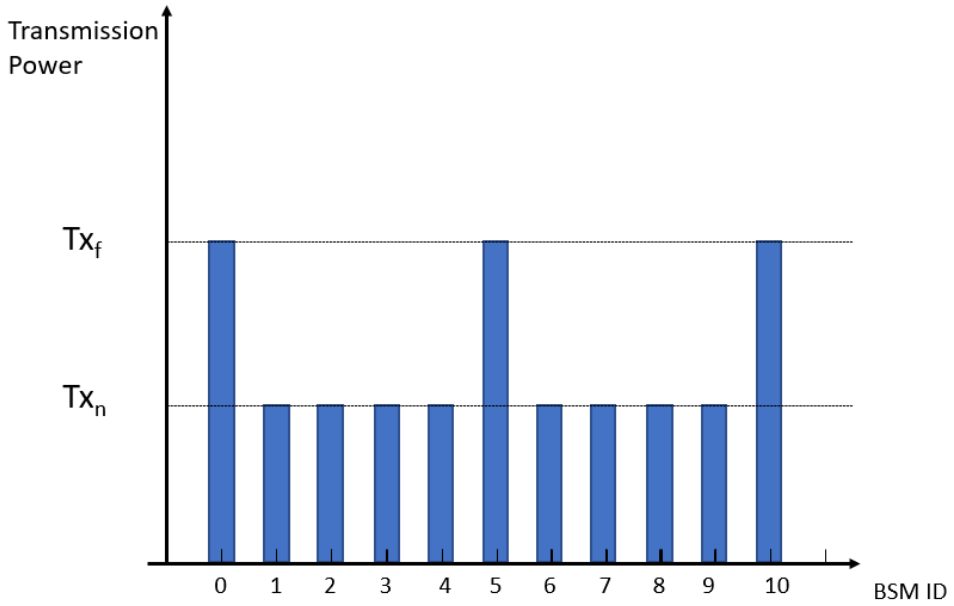


Figure 1. Desired transmission pattern.

Algorithm 2: A hybrid approach combined with random rate control (BACVT-H).

Result: Tx power for near and far transmission
Initialization ;
$TotalSend = MsgRateControl()$;
$setrate(R_n, R_f)$;
$N_{low} = \left\lceil R_n / R_f \right\rceil - 1$;
$PktNum = 0$;
$CLPP = 0$;
while $PktNum < TotalSend$ **do**
  if $CLPP \geq N_{low}$ **then**
    $Tx_c \longleftarrow Tx_f$;
    $CLPP = 0$;
    $PktNum = PktNum + 1$;
  else
    $Tx_c \longleftarrow Tx_n$;
    $CLPP = CLPP + 1$;
    $PktNum = PktNum + 1$;
  end
  Send packet with Tx_c ;
end

4. Simulation Results

4.1. Simulation Parameters

In this section, we evaluate the performance of the proposed congestion control algorithms (BACVT and BACVT-H) in terms of various metrics. To simulate the proposed algorithms, we use a framework of *Vehicles in network simulation* (Veins) [36], which contains a basic implementation of the IEEE 802.11p and IEEE 1609 protocols in order to facilitate the testing of V2V networks. Veins connects a widely used network simulation tool, *Objective Modular Network Testbed in C++* (OMNeT++) [37], and the traffic mobility simulator *Simulation of Urban MObility* (SUMO) [38].

In our simulations, the BSM packet size is set to 512 Bytes and the default beacon interval, i.e., 0.1 s, is used for all approaches except BACVT. In other words, each vehicle transmits its BSMs at the rate of 10 BSMs per second. For the BACVT-H algorithm, the

beacon rate is randomly selected between 5 and 10 BSMs per second, which means the beacon interval will be between 0.1 s and 0.2 s. The transmission power for the far and near range used in BACVT are set to $Tx_f = 20$ mW and $Tx_n = 5$ mW, respectively. We note that it is possible to use the proposed algorithms with different values of Tx_f and Tx_n. We have selected 20 mW for high power as it is the FCC standard for wireless transmitters and maximum power that can be used without registering [5]; we selected 5 mW for the low-power value as it is still able to achieve a reasonable transmission range of around 300 m. The data rate for BSM transmissions is set to 6 Mbps, which is the most commonly used value [16]. We use two straight 4-lane highway (2 lanes in each direction) traffic models with two kinds of vehicle densities: 200 vehicles (high density) and 100 vehicles (low density). All vehicles, regardless of direction, share the same communication channel. In order to simulate a steady-state traffic scenario and avoid the impact of vehicles entering and leaving the simulation, we assume that all the vehicles are stationary. A summary of the configuration parameters is given in Table 2.

Table 2. Configuration parameters.

Name	Value
Default Beacon Rate	10 BSMs
Random Beacon Rate	5–10 BSMs
BSM Size	512 Bytes
Transmission Power for Far Range	20 mW
Transmission Power for Near Range	5 mW
Data Rate	6 Mbps
Min. Power Level	−110 dBm
Noise Floor	−98 dBm
High Vehicle Density	50 Vehicles/km
Low Vehicle Density	25 Vehicles/km
Highway Length/Lanes	4 km/4
Simulation Time	300 s

The following algorithms are used to compare the performance. Each algorithm will be evaluated with low and high density traffic scenarios. The low density traffic scenario has 100 vehicles (25 in each lane), with vehicles in the same lane spaced 160 m apart, whereas the high density traffic scenario has 200 vehicles (50 in each lane), with vehicles in the same lane spaced 80 m apart.

1. 10 Hz 20 mW (All BSMs transmitted with 20 mW power);
2. 10 Hz 5 mW (All BSMs transmitted with 5 mW power);
3. BACVT8_2 (8 BSMs with Tx power = Tx_n, 2 BSMs with Tx power = Tx_f);
4. BACVT5_5 (5 BSMs with Tx power = Tx_n, 5 BSMs with Tx power = Tx_f);
5. BACVT-H (A hybrid approach combining BACVT with random rate control).

4.2. Average Channel Busy Ratio

CBR is defined as the ratio between the time the channel is sensed as busy and the total observation time. CBR is an effective indicator of the level of channel load. A higher CBR value typically indicates a higher channel load and vice versa. In order to observe the change of the channel's CBR throughout the simulation process, each vehicle will calculate the current CBR based on the status of the channel it detects before it sends each BSM. Figure 2 shows the individual CBR values observed by each vehicle over the simulation interval for the 10 Hz 20 mW case. Clearly, it is difficult to observe the overall variations in channel CBR from this plot. So, we use a new metric called "Average CBR", which calculates the average value of the CBR from all vehicles in 5 s intervals until the end of the simulation time.

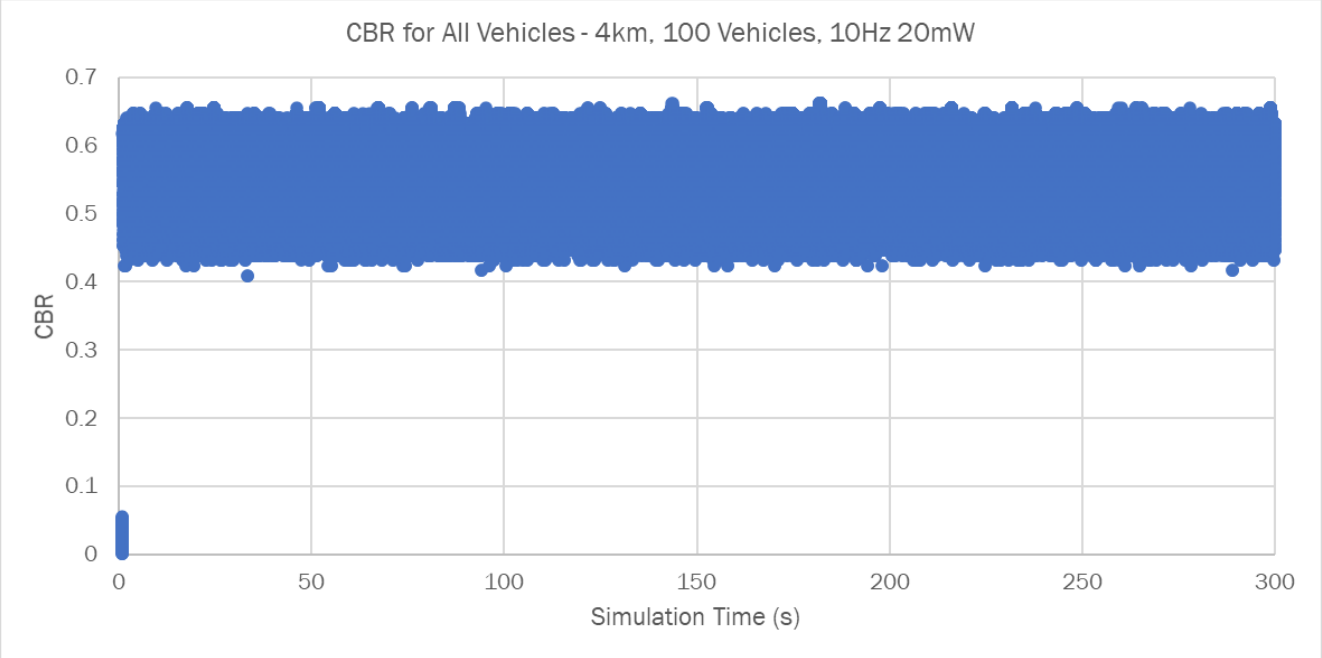


Figure 2. Real time CBR.

Figures 3 and 4 show the Average CBR values obtained using the different approaches for the low density and high density traffic models, respectively. As expected, 10 Hz 20 mW has the highest CBR, and both BACVT8_2 and BACVT5_5 can reduce the CBR. The 10 Hz 5 mW algorithm has an even lower CBR because the low *Tx* power results in a significantly shorter transmission range. The BACVT-H approach has the best performance in terms of CBR values and is able to reduce congestion by 25% compared to 10 Hz 20 mW and 20% compared to 10 Hz 5 mW. This is because the total number of BSMs sent per second in this approach is less than all the other algorithms.

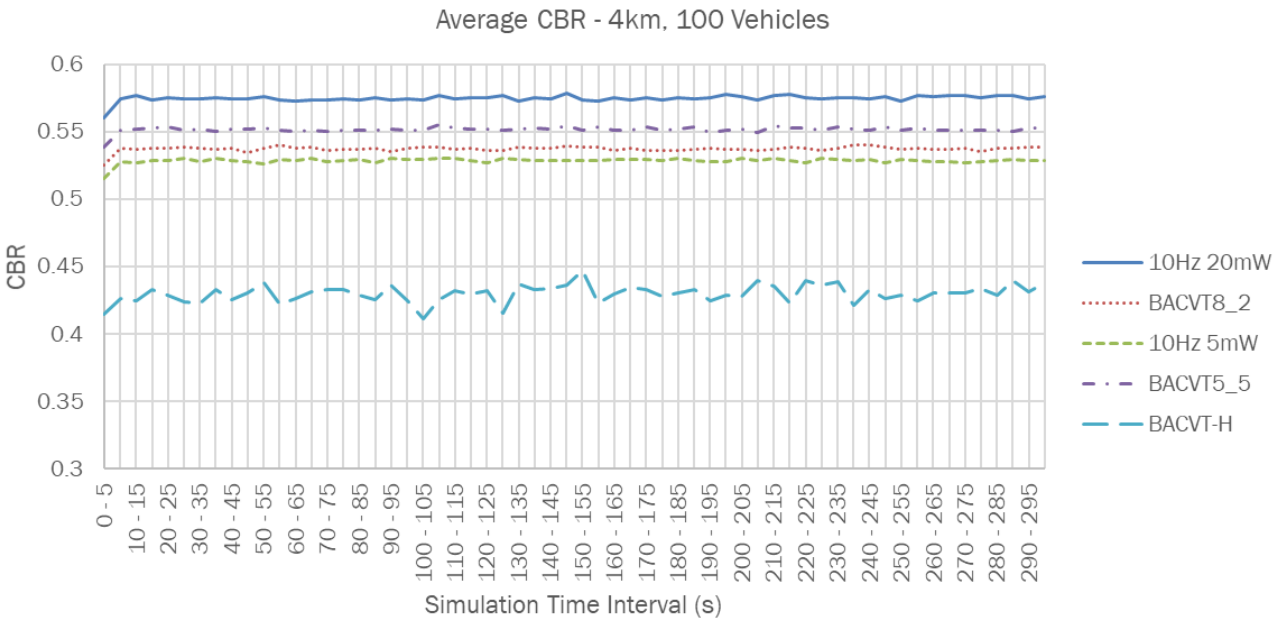


Figure 3. Average CBR in low vehicle density.

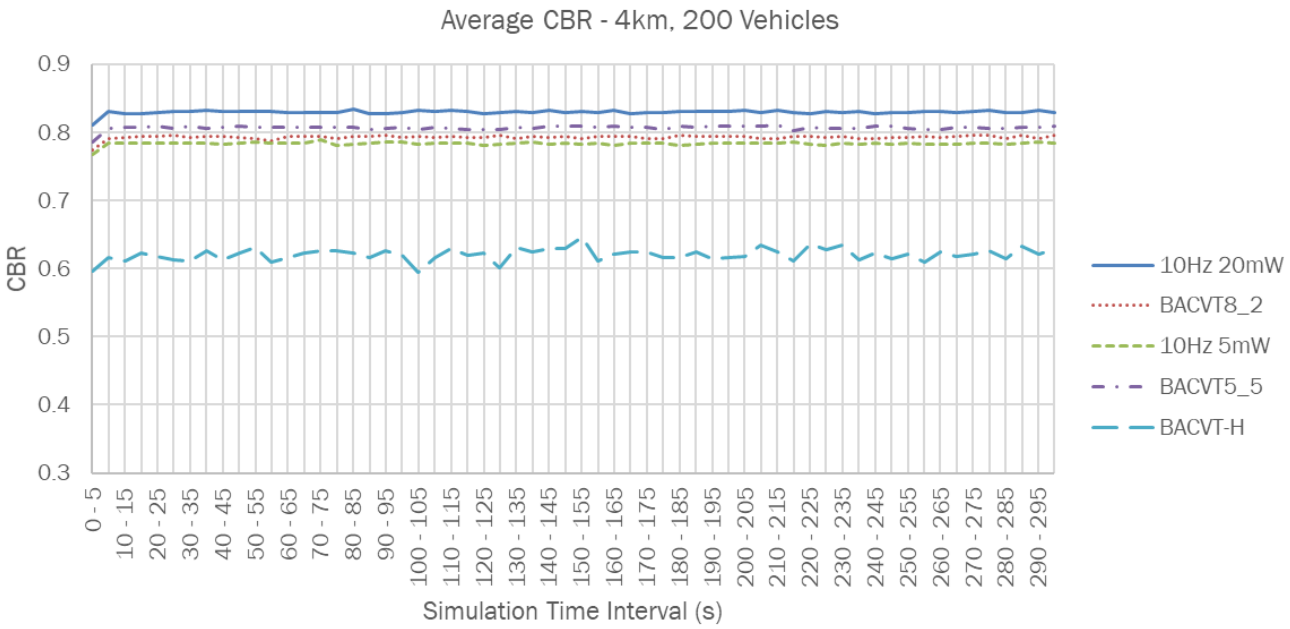


Figure 4. Average CBR in high vehicle density.

4.3. Received BSMs over Different Distances

When a vehicle can receive more BSMs, it has more awareness of the other vehicles, which is an important performance metric in vehicular communication. However, the awareness of the near neighbors (e.g., vehicles within 300 m of the EV) is more important than the awareness of distant vehicles (e.g., vehicles more than 1 km away). The target of the proposed algorithm is to improve the awareness of the near neighbors while still maintaining an adequate level of awareness of distant vehicles.

Tables 3 and 4 show the number of received BSMs of the different approaches for low and high vehicle density scenarios, respectively. The proposed BACVT8_2 and BACVT5_5 approaches show improved reception rates for low distances, while maintaining some awareness (at lower levels) for higher distances. On the other hand, although the 10 Hz 5 mW approach shows higher reception rates for low distances, the awareness drops to 0 for distances greater than 300 m. The BACVT-H approach maintains a moderate level of awareness for different distances. The above results indicate that with the proposed BACVT algorithm, it is possible to achieve the desired level of awareness for near and far vehicles by appropriately tuning the relative number of high-power and low-power transmissions (i.e., R_n and R_f values) in each cycle. In this context, we note that 10 Hz 20 mW and 10 Hz 5 mW can be viewed as special cases of BACVT, corresponding to BACVT0_10 and BACVT10_0, respectively.

Table 3. Received BSMs in low vehicle density.

Received BSMs—4 km, 100 Vehicles					
Distance (m)	**10 Hz 20 mW**	**10 Hz 5 mW**	**BACVT8_2**	**BACVT5_5**	**BACVT-H**
$x \leq 100$	840,606	845,217	844,049	843,161	595,147
$100 < x \leq 300$	2,178,771	2,202,846	2,196,500	2,191,305	1,542,993
$x > 300$	3,760,760	0	750,529	1,879,596	2,142,281

Table 4. Received BSMs in high vehicle density.

Received BSMs–4 km, 200 Vehicles					
Distance (m)	**10 Hz 20 mW**	**10 Hz 5 mW**	**BACVT8_2**	**BACVT5_5**	**BACVT-H**
$x \leq 100$	5,091,994	5,249,359	5,218,042	5,174,255	3,612,076
$100 < x \leq 300$	6,346,860	6,056,645	6,116,713	6,208,877	4,477,210
$x > 300$	7,328,452	0	1,465,741	3,663,096	4,153,365

4.4. Beacon Error Rate

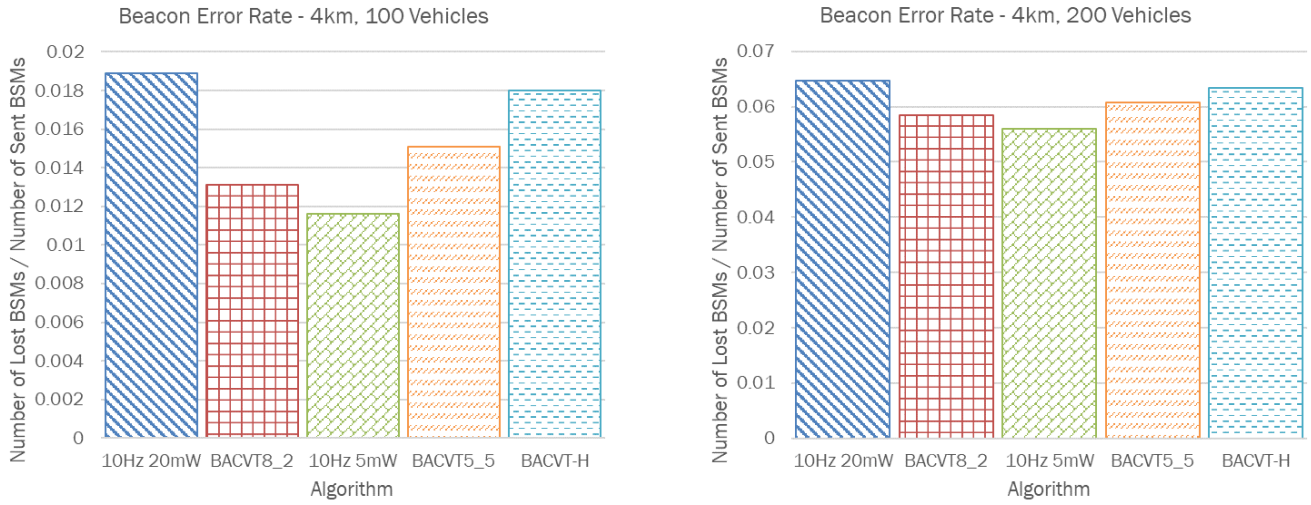
The *Beacon Error Rate* (BER) is the proportion of all BSMs sent throughout the simulation that are lost (i.e., not received successfully by a vehicle). If L is the total number of lost BSMs in the simulation and S is the total number of sent BSMs in the simulation, then $BER = L/S$.

Figure 5 shows the BER values obtained using the different approaches for low density and high density traffic scenarios. All the BACVT algorithms (without rate control) have a lower BER compared to 10 Hz 20 mW, as they will have a lower chance of packet collision. As expected, 10 Hz 5 mW has the lowest BER due to low power transmissions, which means the chance of packet collisions is reduced further. The BER value of BACVT-H is slightly anomalous, since the number of *sent* BSMs in this case is lower than all the other approaches. So, even though the number of *lost* packets is smaller compared to most of the other approaches, as shown in Figure 6, the calculated BER value is actually higher.

4.5. Inter-Packet Delay

We consider V as the set of all vehicles in the simulation. The IPD for a vehicle pair (s, r), where $s, r \in V, s \neq r$, is the average delay between successive BSMs from s received by r. Let $M_{s,r}$ be the set of all successfully received BSMs for vehicle pair (s, r) and $t_{s,r,i}$ be the time when the i^{th} BSM $i \in M_{s,r}$ from s is received at r. Then the average IPD over all vehicles in the simulation is:

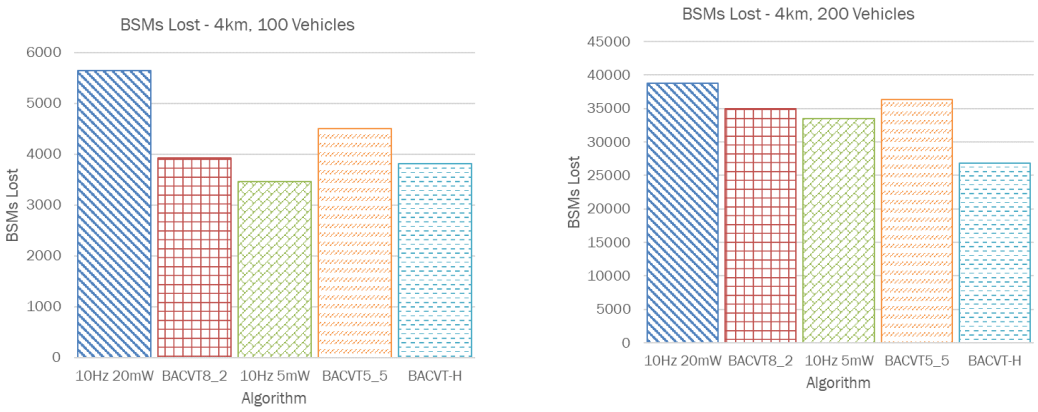
$$AverageIPD = \frac{\sum_{s \in V} \sum_{r \in V, s \neq r} \sum_{i \in M_{s,r}} (t_{s,r,i} - t_{s,r,i-1})}{\sum_{s \in V} \sum_{r \in V, s \neq r} |M_{s,r}|} \quad (2)$$



(**a**) BER in low vehicle density

(**b**) BER in high vehicle density

Figure 5. BER in different vehicle densities.



(**a**) Number of lost BSMs in low vehicle density

(**b**) Number of lost BSMs in high vehicle density

Figure 6. Number of lost BSMs in different vehicle densities.

To calculate the average IPD with respect to vehicles within a specific range d ($d_1 < d \leq d_2$) of a vehicle $u \in V$, we define the set V_{u,d_1,d_2} as the set of all vehicles that are within a distance d from u, where $d > d_1$ and $d \leq d_2$. Then, we update Equation (2) as follows:

$$AverageIPD_{d_1,d_2} = \frac{\sum_{s \in V} \sum_{r \in V_{s,d_1,d_2}} \sum_{i \in M_{s,r}} (t_{s,r,i} - t_{s,r,i-1})}{\sum_{s \in V} \sum_{r \in V_{s,d_1,d_2}} |M_{s,r}|} \quad (3)$$

From Table 1, we see that the number of received BSMs decreases significantly between 250 m and 350 m for 5 mW transmission power. Our simulation results, as shown in Figures 7 and 8, show that all the algorithms (except for BACVT-H) have very similar IPD performance for messages from vehicles within a range of 320 m. After 320 m, BACVT8_2 has the highest delay because it sends more BSMs with low Tx power. However, when we adjust the ratio of high Tx power and low Tx power with BACVT5_5, the value of IPD is improved. As expected, 10 Hz 20 mW has the lowest value of IPD for larger distances, because all the BSMs are sent with 20 mW. Finally, we note that although 10 Hz 5 mW performed well in terms of BER, it has the poorest performance when considering IPD for vehicles beyond 320 m, as no packets are received from such vehicles.

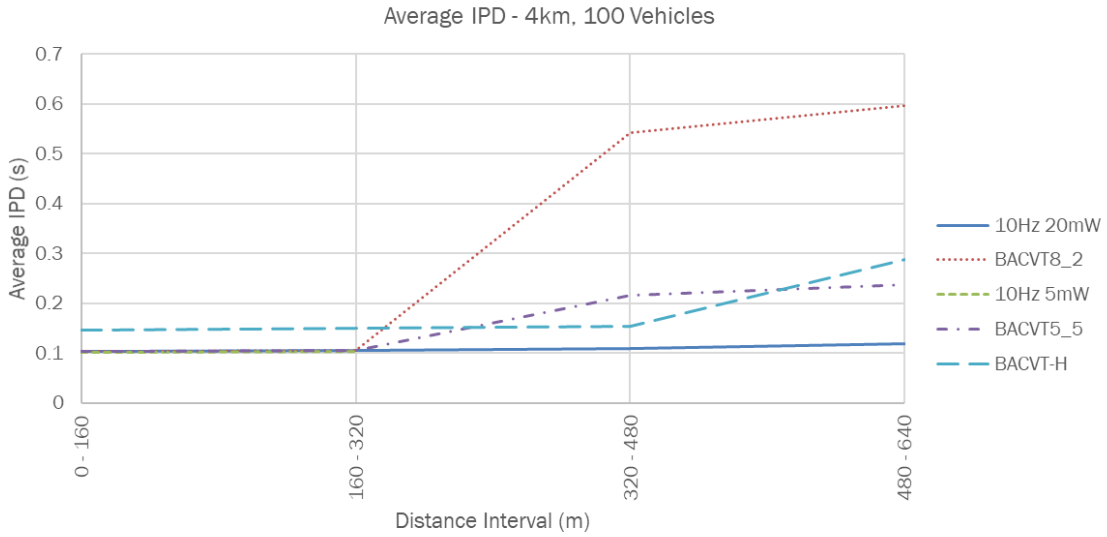


Figure 7. IPD in low vehicle density.

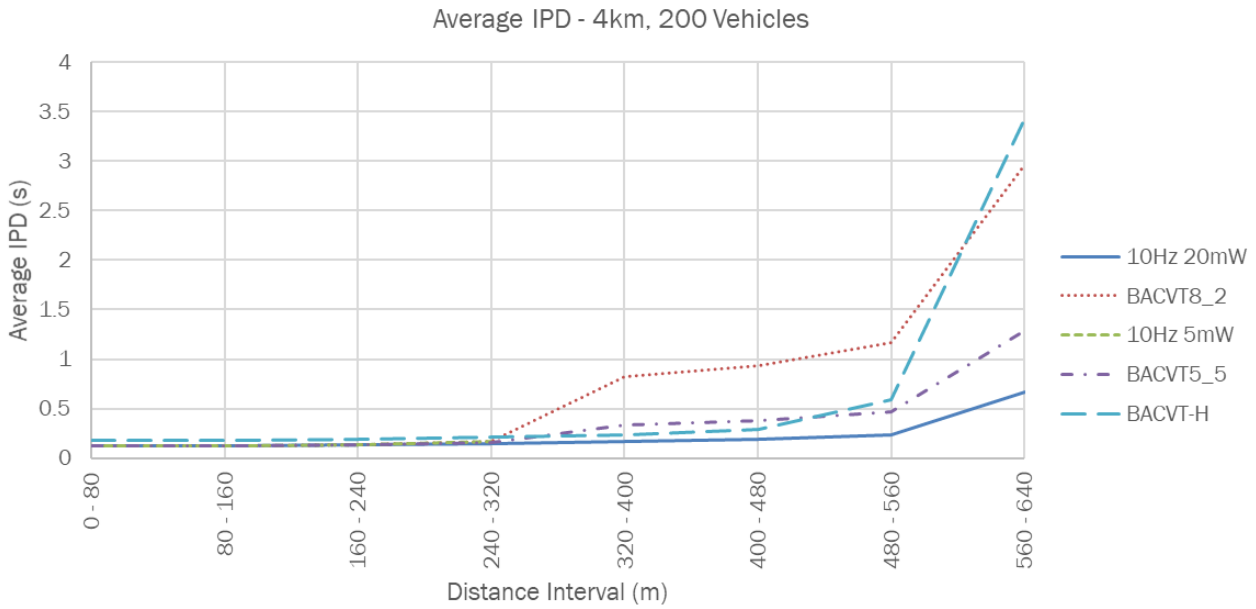


Figure 8. IPD in high vehicle density.

It is interesting to note that for vehicles within 320 m, even with a lower transmission rate, BACVT-H is able to achieve an IPD value that is comparable to (but still slightly exceeding) 10 Hz 20 mW. This is shown in Figures 9 and 10, where BACVT-H has a a slightly higher IPD compared to all the other approaches, which have almost identical performance.

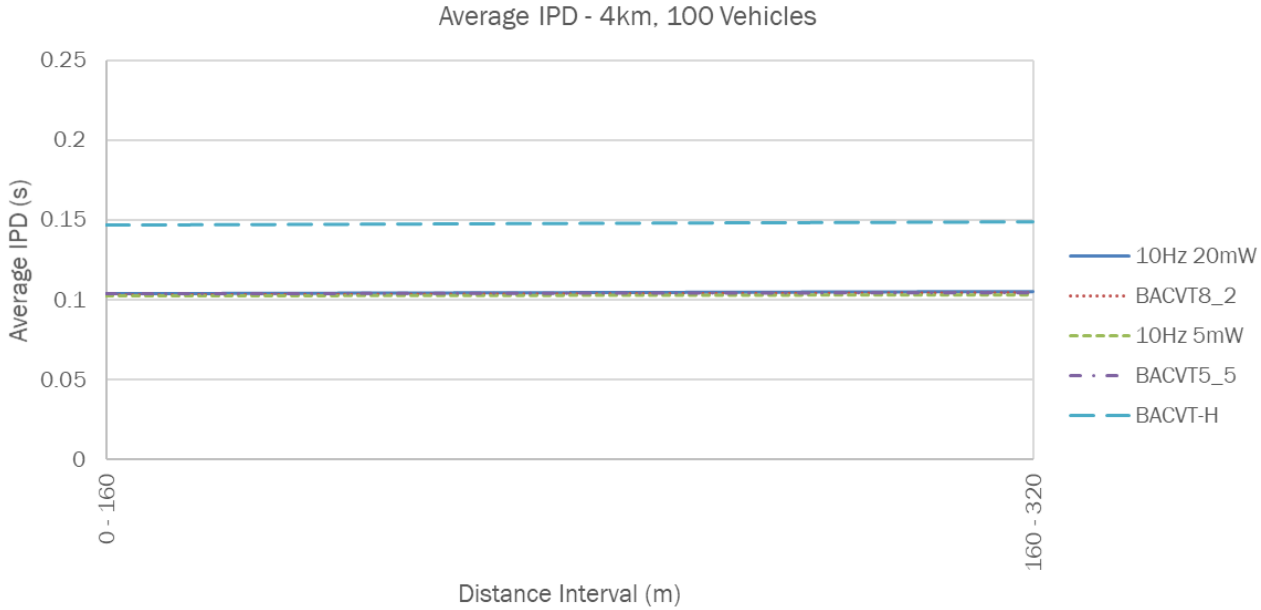


Figure 9. IPD in low vehicle density.

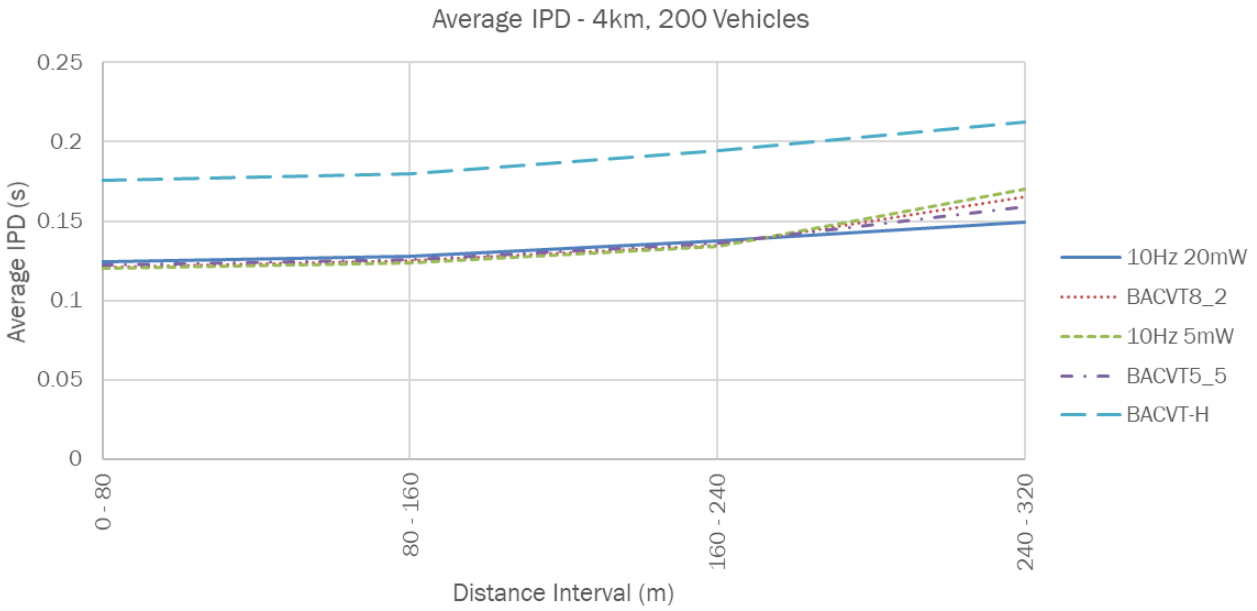


Figure 10. IPD in high vehicle density.

5. Conclusions

In VANET, the available 10 MHz channel can quickly get congested, and the allocated bandwidth is not sufficient to guarantee the delivery of safety messages without latency and error when vehicle density increases. Reducing the transmission rate or the transmission power can indeed mitigate the congestion. However, this is achieved at the cost of reducing the awareness of surrounding vehicles. In this paper, we proposed a novel congestion control approach, where the goal is to effectively balance the channel congestion with the need for vehicle awareness. The main idea is that awareness of nearby neighbors should be prioritized compared to distant vehicles. We first proposed a variable power control method (BACVT) that uses different power levels for transmitting different BSMs. The simulation results show that BACVT achieves a better balance between awareness and congestion compared to traditional methods. To further mitigate the congestion, we also proposed a hybrid approach BACVT-H, which combines rate control with power control to limit the number of the total BSMs. The results demonstrate that BACVT-H indeed has the lowest CBR, while still keeping a good awareness (IPD) performance. The balance of awareness and congestion is always a challenging topic for safety communication in VANET.

In our future work, we will perform more detailed studies on this topic by considering a target-oriented active hybrid congestion control method based on dynamic prediction of vehicle density. Our goal is to make the vehicles predict the next possible near and distant traffic status based on the current status and adjust the transmission parameters to meet some metrics of congestion and awareness. We also plan to develop accurate propagation models that calculate the transmission powers and transmission rates, based on the target transmission range, vehicle density, obstacles, weather conditions, etc.

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References

1. Harding, J.; Powell, G.; Yoon, R.; Fikentscher, J.; Doyle, C.; Sade, D.; Lukuc, M.; Simons, J.; Wang, J. *Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application*; Technical Report; United States National Highway Traffic Safety Administration: Washington, DC, USA, 2014.
2. Car Crash Deaths and Rates. Available online: https://injuryfacts.nsc.org/motor-vehicle/historical-fatality-trends/deaths-and-rates/ (accessed on 6 June 2019).
3. Toh, C. *Ad Hoc Mobile Wireless Networks: Protocols and Systems*; Pearson Education: England, UK, 2001.
4. Li, Y. *An Overview of the DSRC/WAVE Technology*; Springer: New York, NY, USA, 2012; Volume 74.
5. Kenney, J.B. Dedicated Short-Range Communications (DSRC) Standards in the United States. *Proc. IEEE* **2011**, *99*, 1162–1182. [CrossRef]
6. Eggerton, J. FCC to Split up 5.9 GHZ. 2019. Available online: https://www.nexttv.com/news/fcc-to-split-up-5-9-ghz (accessed on 7 July 2021).
7. SAE International. *SAE J2735: Dedicated Short Range Communications (DSRC) Message Set Dictionary*; Technical Report; SAE International: Warrendale, PA, USA, 2009.
8. ETSI. *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*; Technical Report; ETSI: Sophia Antipolis Cedex, France, 2013.
9. Bray, D.A. *Modernizing the FCC's IT*; Federal Communications Commission Std.: Washington, DC, USA, 2015.
10. Bansal, G.; Kenney, J.B.; Rohrs, C.E. LIMERIC: A linear adaptive message rate algorithm for DSRC congestion control. *IEEE Trans. Veh. Technol.* **2013**, *62*, 4182–4197. [CrossRef]
11. Bilstrup, K.; Uhlemann, E.; Strom, E.G.; Bilstrup, U. Evaluation of the IEEE 802.11 p MAC method for vehicle-to-vehicle communication. In Proceedings of the 2008 IEEE 68th Vehicular Technology Conference, Calgary, AB, USA, 21–24 September 2008; pp. 1–5.
12. Liu, X.; Jaekel, A. Congestion Control in V2V Safety Communication: Problem, Analysis, Approaches. *Electronics* **2019**, *8*, 540. [CrossRef]
13. 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, Taipei, Taiwan, 25 June 2013; pp. 41–50.
14. Ogura, K.; Katto, J.; Takai, M. BRAEVE: Stable and adaptive BSM rate control over IEEE802. 11p vehicular networks. In Proceeding of the 2013 IEEE 10th Consumer Communications and Networking Conference (CCNC), Las Vegas, NV, USA, 11–14 January 2013; pp. 745–748.
15. Kloiber, B.; Härri, J.; Strang, T. Dice the TX power—Improving awareness quality in VANETs by random transmit power selection. In Proceeding of the 2012 IEEE Vehicular Networking Conference (VNC), Seoul, Korea, 14–16 November 2012; pp. 56–63.
16. Torrent-Moreno, M.; Santi, P.; Hartenstein, H. Distributed fair transmit power adjustment for vehicular ad hoc networks. In Proceeding of the 2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks, Reston, VA, USA. 25–28 September 2006; Volume 2, pp. 479–488.
17. Wang, M.; Chen, T.; Du, F.; Wang, J.; Yin, G.; Zhang, Y. Research on adaptive beacon message transmission power in VANETs. *J. Ambient. Intell. Humaniz. Comput.* **2020**. [CrossRef]
18. Mittag, J.; Schmidt-Eisenlohr, F.; Killat, M.; Härri, J.; Hartenstein, H. Analysis and design of effective and low-overhead transmission power control for VANETs. In Proceedings of the Fifth ACM International Workshop on VehiculAr Inter-NETworking, San Francisco, CA, USA, 15 September 2008; pp. 39–48.
19. Shah, S.A.A.; Ahmed, E.; Rodrigues, J.J.; Ali, I.; Noor, R.M. Shapely value perspective on adapting transmit power for periodic vehicular communications. *IEEE Trans. Intell. Transp. Syst.* **2018**, *19*, 977–986. [CrossRef]
20. Kloiber, B.; Härri, J.; Strang, T.; Sand, S.; Garcia, C.R. Random transmit power control for DSRC and its application to cooperative safety. *IEEE Trans. Dependable Secur. Comput.* **2015**, *13*, 18–31. [CrossRef]
21. Bansal, G.; Kenney, J.B. Achieving weighted-fairnessin message rate-based congestion control for DSRC systems. In Proceedings of the 2013 IEEE 5th International Symposium on Wireless Vehicular Communications (WiVeC), Dresden, Germany, 2–3 June 2013; pp. 1–5.
22. Tielert, T.; Jiang, D.; Hartenstein, H.; Delgrossi, L. Joint power/rate congestion control optimizing packet reception in vehicle safety communications. In Proceedings of the Tenth ACM International Workshop on Vehicular Inter-Networking, Systems, and Applications, Taipei, Taiwan, 25 June 2013; pp. 51–60.
23. Huang, C.L.; Fallah, Y.P.; Sengupta, R.; Krishnan, H. Adaptive intervehicle communication control for cooperative safety systems. *IEEE Netw.* **2010**, *24*, 6–13. [CrossRef]
24. Math, C.B.; Ozgur, A.; de Groot, S.H.; Li, H. Data Rate based Congestion Control in V2V communication for traffic safety applications. In Proceedings of the 2015 IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT), Luxembourg, 24 November 2015; pp. 1–6.
25. Schmidt, R.K.; Brakemeier, A.; Leinmüller, T.; Kargl, F.; Schäfer, G. Advanced carrier sensing to resolve local channel congestion. In Proceedings of the Eighth ACM International Workshop on Vehicular Inter-Networking, Las Vegas, NV, USA, 23 September 2011; pp. 11–20.

26. Sharmaa, R.; CSb, L.; VSc, R. Congestion control mechanisms to avoid congestion in VANET: A comparative review. In *Artificial Intelligence and Speech Technology, Proceedings of the 2nd International Conference on Artificial Intelligence and Speech Technology,(AIST2020), Delhi, India, 19–20 November 2020*; CRC Press: Nottingham, UK, 2021; p. 453.
27. Wang, J.; Jiang, C.; Zhang, K.; Quek, T.Q.; Ren, Y.; Hanzo, L. Vehicular sensing networks in a smart city: Principles, technologies and applications. *IEEE Wirel. Commun.* **2017**, *25*, 122–132. [CrossRef]
28. Wang, J.; Jiang, C.; Han, Z.; Ren, Y.; Hanzo, L. Internet of vehicles: Sensing-aided transportation information collection and diffusion. *IEEE Trans. Veh. Technol.* **2018**, *67*, 3813–3825. [CrossRef]
29. Boban, M. *ECPR: Environment-and Context-Aware DCC Algorithm'*; NEC Laboratories Europe: Heidelberg, Germany, 2015.
30. Bansal, G.; Cheng, B.; Rostami, A.; Sjoberg, K.; Kenney, J.B.; Gruteser, M. Comparing LIMERIC and DCC approaches for VANET channel congestion control. In Proceedings of the 2014 IEEE 6th International Symposium on Wireless Vehicular Communications (WiVeC 2014), Vancouver, BC, Canada, 14–15 September 2014; pp. 1–7.
31. Sepulcre, M.; Gozalvez, J.; Altintas, O.; Kremo, H. Adaptive beaconing for congestion and awareness control in vehicular networks. In Proceedings of the 2014 IEEE Vehicular Networking Conference (VNC), Paderborn, Germany, 3–5 December 2014; pp. 81–88.
32. Aygun, B.; Boban, M.; Wyglinski, A.M. ECPR: Environment-and context-aware combined power and rate distributed congestion control for vehicular communications. *Comput. Commun.* **2016**, *93*, 3–16. [CrossRef]
33. Goudarzi, F.; Asgari, H. Non-cooperative beacon power control for VANETs. *IEEE Trans. Intell. Transp. Syst.* **2018**, *20*, 777–782. [CrossRef]
34. Joseph, M.; Liu, X.; Jaekel, A. An adaptive power level control algorithm for DSRC congestion control. In Proceedings of the 8th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications, Montreal, QC, Canada, 28 October–2 November 2018; pp. 57–62.
35. Willis, J.T.; Jaekel, A.; Saini, I. Decentralized congestion control algorithm for vehicular networks using oscillating transmission power. In Proceedings of the 2017 Wireless Telecommunications Symposium (WTS), Chicago, IL, USA, 26–28 April 2017; pp. 1–5.
36. Sommer, C.; German, R.; Dressler, F. Bidirectionally coupled network and road traffic simulation for improved IVC analysis. *IEEE Trans. Mob. Comput.* **2010**, *10*, 3–15. [CrossRef]
37. Varga, A.; Hornig, R. An overview of the OMNeT++ simulation environment. In Proceedings of the 1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops, Marseille, France, 3–7 March 2008; ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering: Brussels, Belgium, 2008; p. 60.
38. Behrisch, M.; Bieker, L.; Erdmann, J.; Krajzewicz, D. SUMO–simulation of urban mobility: An overview. In Proceedings of the Third International Conference on Advances in System Simulation, Barcelona, Spain, 23–29 October 2011.