Rethinking Transmit Power Control for SAE J3161/1 Congestion Control Algorithm

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***Abstract*—The Society of Automotive Engineers (SAE) has specified wireless channel congestion control algorithm for vehicle-to-everything (V2X) communication: J2945/1 for Dedicated Short Range Communication (DSRC) and J3161/1 for cellular V2X (C-V2X) environment. Although J2945/1 utilizes both transmit (Tx) power control and message rate control, the more recently specified J3161/1 standard for C-V2X environment has opted to abandon the power control. It is understandable as previous studies have demonstrated the inefficacy of power control in J2945/1, resulting in the rate control solely fighting congestion. Consequently, channel congestion leads to a fast increase in packet inter-reception time (PIR) and potentially tracking error. This letter advocates for the reinstatement of Tx power control in J3161/1 as a means to minimize PIR, while proposing a distinct approach from J2945/1 to show the feasibility of an effective combined control. Based on vehicle traffic engineering principles, the approach switches control modes to use power control to cope with increased vehicle density and rate control with increased channel utilization. It leads to significant improvements in packet delivery characteristics while more effectively managing channel load.**

***Index Terms*—SAE J3161/1, SAE J2945/1, V2X communication, congestion control, Tx power control, rate control.**

I. Introduction

In the initial implementation of vehicle-to-everything (V2X) communication, known as "Day 1," each vehicle periodically broadcasts Basic Safety Message (BSM) [1] that contains the vehicle's position, speed, acceleration, heading, and other relevant data according to SAE J2735. This enables vehicles to track each other and predict the short-term trajectories of surrounding vehicles to prevent traffic accidents. Upcoming "Day 2" and "Day 3" V2X traffic will also use periodic broadcast traffic as specified in ETSI TS 103 324 and TR 103 578. As dedicated Intelligent Transportation System (ITS) band is narrow, however, the increased density of the V2X-capable vehicles will easily cause channel congestion to negatively impact the effectiveness of V2X communication in preventing accidents.

To address the channel congestion issue, Society of Automotive Engineers (SAE) J2945 standard [2] stipulates a channel congestion control algorithm for a Dedicated Short Range Communications (DSRC) environment and J3161/1 for cellular V2X (C-V2X) communication environment [3]. Although J2945/1 utilizes both transmit (Tx) power control and message rate control, the more recently specified J3161/1 has opted to abandon the power control. It is because previous studies have demonstrated the inefficacy of power control, leaving the rate control to solely bear the burden [4], [5]. The consequence was a fast increase in packet inter-reception time (PIR) hence potential tracking error under channel congestion.

In contrast to the pessimistic view on the combined rate-power control, this letter argues that Tx power control should be reinstated in J3161/1 to address the issue of increased PIR, only with a different approach from J2945/1. It first highlights that J3161/1 suffers the same problem of increased PIR as J2945/1. If it was the inefficacy of power control in J2945/1, it is the lack of power control in J3161/1 that leads to the PIR problem. This paper demonstrates that Tx power control can be effective as J2945/1 had intended, if used correctly. It suggests that vehicle traffic engineering should be taken into account when utilizing power control in conjunction with rate control. Specifically, control modes be switched to use power control to handle increased vehicle density and rate control for increased channel utilization, which is the opposite approach to J2945/1. This approach leads to significant improvements in packet delivery characteristics while more effectively managing channel load. Finally, this letter focuses on the newly standardized J3161/1 for the C-V2X communication environment. However, similar improvements can also be made in J2945/1.

The contributions of this paper can be summarized as follows. First, it shows that the Tx power control should be reinstated in J3161/1 because controlling the Tx rate alone based on vehicle density causes PIR to become highly inflated and threatening driving safety by making the neighbor vehicle tracking less frequent. Indeed, there are previous works that show Tx power control can be an effective congestion control component [6], [7]. Second, the paper goes on to show how the power control can be effectively combined with rate control to lower the PIR. Specifically, it proposes to switch the inputs of rate control and power control, as J3161 uses vehicle density to control Tx rate.

II. SAE J2945/1 and J3161/1 Algorithms Issue

According to SAE J2945/1, Inter-Transmit Time (ITT) and Tx power of each on-board unit (OBU) are regulated according to the Vehicle Density (VD) and Channel Busy Percentage (CBP), respectively. VD is determined by counting the number of vehicles within a 100-meter radius (`vPERRange`), while CBP represents the percentage of time the DSRC channel is sensed as busy. These values are averaged every 100 ms using weight factors of 0.05 (`vDensityWeightFactor`) and 0.5 (`vCBPWeightFactor`), respectively. Then, J2945/1 specifies the congestion control as follows. First, the rate control is given as a function of the smoothed vehicle density

$\overline{VD}$ as:

$$ITT \text{ [s]} = \begin{cases} 0.1, & \overline{VD} \leq 25 \\ \overline{VD}/250, & 25 < \overline{VD} < 150 \\ 0.6, & 150 \leq \overline{VD} \end{cases} \tag{1}$$

where $\overline{VD(t)} \leftarrow 0.05 \times VD + 0.95 \times \overline{VD(t-1)}$.

Second, the Tx power is controlled by

$$P_{tx}[\text{dBm}] = \begin{cases} 20, & \overline{CBP} \leq 50 \\ 20 - (\overline{CBP} - 50)/3, & 50 < \overline{CBP} < 80 \\ 10, & 80 \leq \overline{CBP} \end{cases} \tag{2}$$

where $\overline{CBP(t)} \leftarrow 0.5 \times CBP + 0.5 \times \overline{CBP(t-1)}$.

Unfortunately, J2945/1 combined control of Eqs. (1) and (2) is not well designed. In DSRC environment, Lim [4] observed that in most congestion regimes the Tx power is stuck at the maximum while only the ITT adapts to reduce CBP. Our experiments in Section IV confirm this observation for C-V2X environment as well. If transplanted to the C-V2X environment, Yoon [5] also observed that the rate control would intervene too strongly before the power control engages. To solve the problem, Lim [4] forces the power control to engage first, while Yoon [5] proposes tempering down the rate control to coerce the power control to work. Although these prior work correctly points out the problem of J2945/1, their approach is ad hoc. This letter proposes another approach to re-engineering J2945/1 and J3161/1, firmly standing on traffic engineering principles.

Although J3161/1 may have abandoned power control due to its perceived lack of efficacy (i.e., no Eq. (2)), this may not be the best decision as power control can still be highly effective if only correctly used. In fact, we argue that absent power control is the worst power control as rate control alone must cope with channel congestion. Thus, omitting power control in J3161/1 does not address the power control failure issue of J2945/1 but instead inherits the high ITT values during congestion and the resulting increase in PIR. Below, however, this letter demonstrates that J3161/1 can effectively harness Tx power in a combined congestion control.

III. Proposed method

Vehicle traffic engineering principles anticipate slower vehicle movement during road congestion [8], [9]. In terms of driving safety, the V2V communication with vehicles that are far away is less crucial in low-speed driving situations than in high-speed situations so that Tx power can be reduced accordingly. Therefore, the increase in VD should be addressed by Tx power reduction. Notice that this observation does not align well with J2945/1 where VD regulates not Tx power but ITT. On the other hand, ITT is not necessarily coupled with VD as J2945/1 specifies. For instance, some applications such as platooning require higher message rate for tighter topology control irrespective of VD. Therefore, CBP would be a more appropriate input for ITT control.

Based on above observations, this letter proposes to switch the control modes, using power control to manage increased VD and rate control to handle increased CBP. Furthermore, corresponding switch is also made between the smoothing factors for VD and CBP. Specifically, we set the smoothing value for VD (`vDensityWeightFactor`) to 0.5 and the smoothing value for CBP (`vCBPWeightFactor`) to 0.05. Then, the proposed congestion control is as follows, which is a switched version of J2945/1. First, the rate control is defined as a function of CBR as:

$$ITT \text{ [s]} = \begin{cases} 0.1, & \overline{CBR} \leq 0.5 \\ 0.1 + 5/3 \cdot (\overline{CBR} - 0.5), & 0.5 < \overline{CBR} < 0.8 \\ 0.6, & 0.8 \leq \overline{CBR} \end{cases} \tag{3}$$

where $\overline{CBR(t)} \leftarrow 0.05 \times CBR + 0.95 \times \overline{CBR(t-1)}$. Notice there is a change of term from CBP to Channel Busy Ratio (CBR), as CBR is used instead in the cellular V2X standards. Accordingly, the numbers have been scaled from percentage to ratio. Second, the Tx power control is given as:

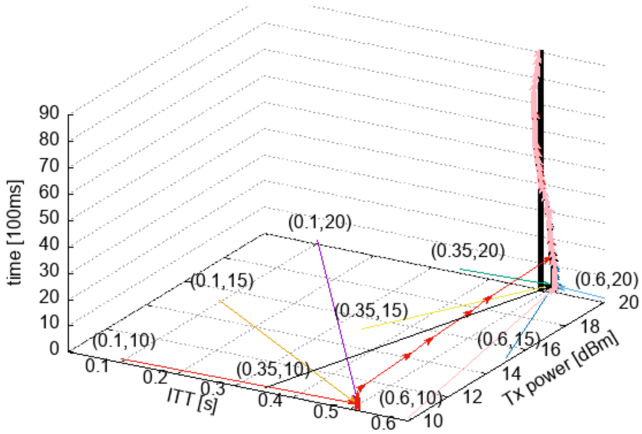
$$P_{tx} \text{ [dBm]} = \begin{cases} 20, & \overline{VD} \leq 25 \\ 20 - 2/25 \cdot (\overline{VD} - 25), & 25 < \overline{VD} < 150 \\ 10, & 150 \leq \overline{VD} \end{cases} \tag{4}$$

where $\overline{VD(t)} \leftarrow 0.5 \times VD + 0.5 \times \overline{VD(t-1)}$. In Eqs. (3) and (4), coefficients have been adjusted to exactly meet the minimum and maximum values of ITT and P_{tx} in J2945/1. No other heuristic changes have been applied. However, as demonstrated in the next section, this proposed change revitalizes the Tx power control and addresses the issue of increased PIR upon channel congestion while effectively controlling the CBR as J2945/1 had originally intended.

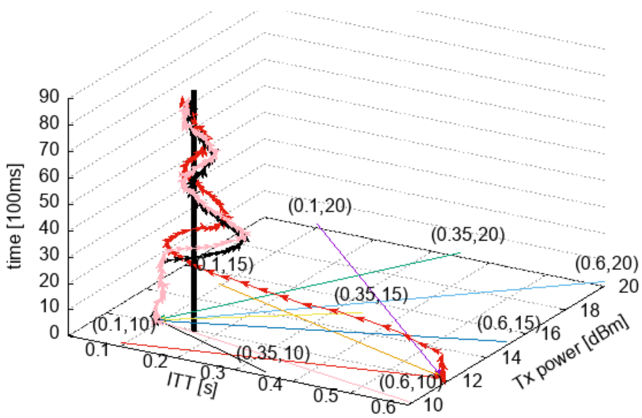
The impact of the modified combined control can be illuminated by Fig. 1 that shows the control trajectories at an observed vehicle. To investigate the response from the compared congestion control algorithms, we intentionally force the initial message rate and Tx power at each vehicle in the simulation to start from nine different values in the ITT-Tx power plane, which are combinations of $ITT \in \{0.1, 0.35, 0.6\}$ [s] and $P_{tx} \in \{10, 15, 20\}$ [dBm]. Then the vehicles bounce back and adjust according to the given control (proposed control vs. J2945/1). We present only the case for $\rho = 600$ veh./km for space reason, but qualitatively identical results can be observed for other vehicle traffic densities. The converging equilibriums for other vehicle densities are given in Fig. 2 in Section IV.

With J2945/1, Tx power quickly evolves to the maximum limit (i.e., 20 dBm) no matter where the system starts from (Fig. 1(a)). This is because ITT reacts to VD too sensitively. The rapidly increased ITT pushes down CBR so that the Tx control is rendered unnecessary. Within two seconds the system converges to [0.49 s, 20 dBm] represented by a thick perpendicular line to the ITT – Tx power plane, resulting in the ITT more than three times larger than the proposed algorithm. Note that J3161/1 would converge to the same ITT, because Tx power is fixed at 20 dBm according to J3161/1 (see Fig. 2(a)). There is no Tx power control to become ineffective to begin with.

Fig. 1(b) shows that over time, the system under the proposed control converges to approximately [0.14 s, 12 dBm]. The control produces upward spiraling trajectories towards



(a) J2945/1



(b) Proposed

Fig. 1. Control trajectories of J2945/1 and proposed algorithm at an observed vehicle, $\rho = 600$ veh./km; (ITT [s], Tx power [dBm]) is shown for the starting point of each trajectory

the converging equilibrium no matter where the initial configuration started from. The shrinking spirals are an evidence that the two controls are interacting in a more cooperative manner than J2945/1. Lastly, the slower convergence is due to the coefficients used in the switched CBP and VD averaging, which will need finer tuning in future work.

IV. Performance evaluation

In this section, we evaluate the impact of the proposed control modes change in terms of packet delivery performance. To this end, we conducted experiments comparing three different schemes in the C-V2X environment, as follows:

1) J2945/1 transported to C-V2X environment ("J2945/1c")
2) J3161/1 ("J3161/1")
3) Proposed solution, which is J2945/1c with switched Tx power and rate control modes ("Proposed")

A. Metrics

To evaluate the effectiveness of each scheme, we utilized Packet Reception Ratio (PRR), Packet Inter-Reception time (PIR), Channel Busy Ratio (CBR), throughput-normalized CBR. Note that while PRR is a significant measure of packet delivery performance in V2X communication [10], it can be misleading and myopic when rate control is employed [11], [12]. In an extreme hypothetical scenario, vehicles could arbitrarily improve PRR of individual packets by excessively reducing the message rate hence CBR (see in Fig. 2(c) that J2945/1c and J3161/1 reveal this aspect to some extent) and thereby virtually eliminating packet collisions. However, it would defeat the very purpose of V2X safety communication as the arbitrarily expanded ITT will correspondingly increase the message update interval (i.e., PIR) and consequently the tracking error. Therefore, PIR is a more appropriate measure when rate control is in use because it sums up the effects of individual PRR and ITT. Along with the message processing delays at the sending and the receiving sides, PIR comprises the update delay (UD). UD is directly related to tracking error that is the ultimate evaluation criterion for V2X driving safety communication [12]. Finally, throughput-normalized CBR is the ratio of CBR to throughput, where throughput is defined by the message size divided by PIR. It represents how well a congestion control scheme controls the channel load to obtain a given throughput. The metric degrades if a scheme loses too many packets to obtain the given throughput or achieves only low throughput to control the CBR, either of which is not desirable for a congestion control mechanism.

B. Simulation setting

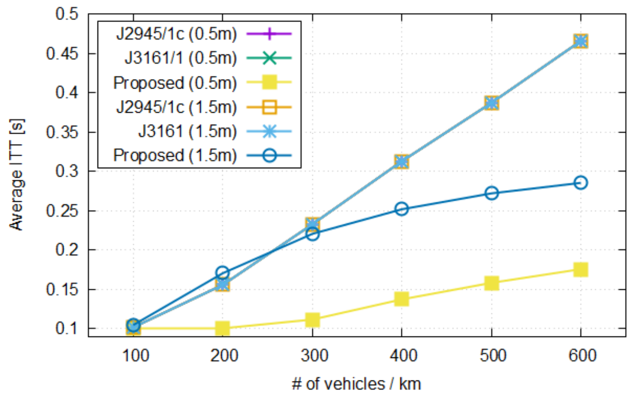
For simulation experiments, we employed LTEV2Vsim [13], an open-source simulator designed for C-V2X environment that incorporates modeling of in-band emission interference. Specific simulation parameter values are summarized in Table I.

TABLE I
Simulation parameter configuration

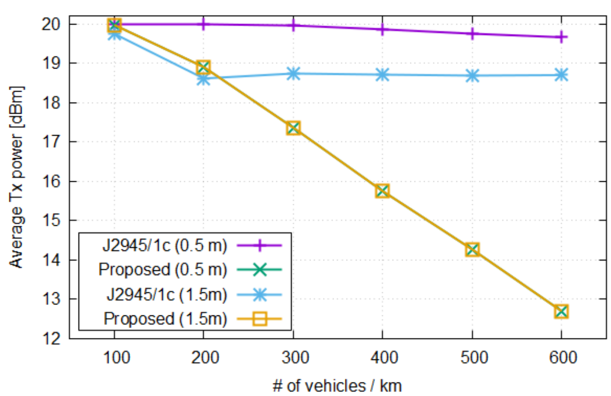
	Parameter	Value
PHY	Bandwidth (MHz)	20 [3]
	No. subchannels	10
	Subchannels/transport block	2
	Antenna gain (dB)	3
	Maximum Tx power (dBm)	20 [3]
	Noise figure of receiver (dB)	9
	Pathloss model	WINNER+B1 [14]
	Shadowing distribution	Log-normal
	Shadowing std. dev. (dB)	0 (LOS), 4 (NLOS)
	Antenna height (m)	1.5
	Effective antenna height (m)	0.5 (urban), 1.5 (highway)
	MCS index	11
MAC	Reselection counter value	(5:15)
	One-shot counter value	(2:6) [3]
	Selection window width (ms)	100
	Resource keep probability	0.8 [16]
Application	Message size (bytes)	300
	Awareness range (m)	200 (urban), 300 (highway)
Vehicles	Traffic density (veh./km)	(100:600) $= VD \times 5$
	Speed of vehicles (km/h)	μ = 50, σ = 3
	Road length (km)	2

C. Control dynamics

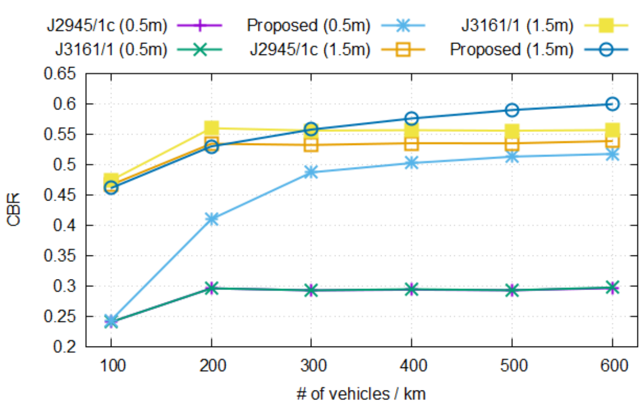
1) ITT: Fig. 2(a) illustrates the average ITT values under different vehicle traffic densities. In particular, it demonstrates the consequence of lacking an effective power control. Regardless of the effective antenna height H_{ea}, the standard schemes have linearly increasing ITT in the vehicle density. This is either because there is no power control assisting the rate control (J3161/1) or because the power control does not help at all (J2945/1c). In contrast, the proposed scheme's power control complements rate control, better curbing the increase in ITT as congestion worsens. Moreover, the proposed scheme is sensitive to H_{ea}. Recollect that in the proposed scheme, ITT is regulated by CBR. The lowered H_{ea} that produces smaller CBR leads to smaller ITT. It implies that the proposed scheme will be more effective in urban environments.



(a) ITT



(b) Tx power



(c) Channel busy ratio

Fig. 2. Average measures of system dynamics under varying vehicle density and effective antenna heights

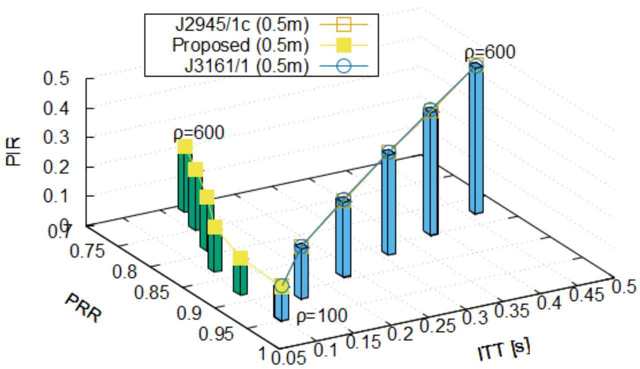
2) Tx power: Fig. 2(b) shows that the power control in J2945/1c hardly works when $H_{ea} = 0.5$ m. As H_{ea} is raised, the power control is first seen to react to increasing traffic density, but then stall beyond $\rho = 200$ veh./km. This is because its power control is designed to react to CBP, which is strongly intervened and lowered by the rate control component. Such incoordination problem between the two control components in J2945/1 is well documented in the literature [4], [5]. J3161/1 is not shown in the figure because it always applies the maximum power. Compared with J2945/1c, the power control in the proposed scheme begins to engage consistently and proportionally to the increasing vehicle traffic density. This is the result of directly coupling the power control with the vehicle density. Combining Fig. 2(a) and (b), we can observe that the rate control and the power control operate simultaneously and synergistically.

3) CBR: The CBR as a function of vehicle density under the compared schemes is illustrated in Fig. 2(c). It is noteworthy that the J2945/1c and J3161/1 curves overlap when $H_{ea} = 0.5$ m, testifying to the inefficacy of the Tx power control in the J2945/1 design. There, the CBR is strictly limited to 0.3 under both J2945/1c and J3161/1 as vehicle traffic density exceeds 200 veh./km. Considering the target operating range of CBR (0.5–0.8) in the J2945/1 design [2], the result clearly reveals a design flaw that excessively suppresses the message rate. In contrast, the CBR under the proposed scheme more naturally and gradually converges toward 0.55 with $H_{ea} = 0.5$ m. When $H_{ea} = 1.5$ m, on the other hand, the standard schemes fare better. However, their CBR values are shown to stall at around 0.55 irrespective of the increasing vehicle density. In contrast, the proposed scheme more naturally increases CBR in the target operating range.

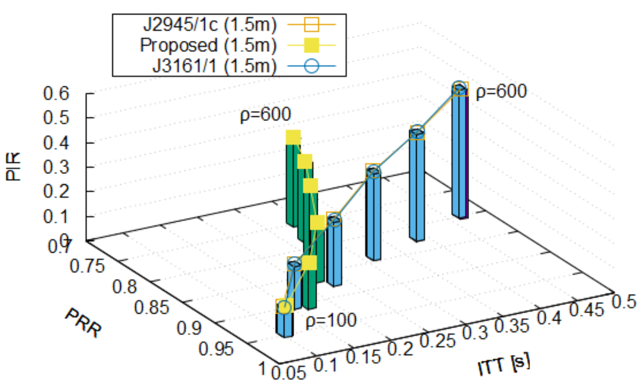
D. Periodic communication performance

Although packet reception ratio (PRR) is considered the most important metric in V2X communication, it is a myth. If a V2X message is an event-driven message, it is true that PRR is the critical metric. However, in periodic safety communication, the whole purpose is updating neighboring vehicles' information as to the ego vehicle as frequently as possible. Therefore, the most important metric is packet inter-reception ratio (PIR). Note that PIR is a function of not only PRR but also ITT. Namely, it is determined by how frequently BSMs are sent (ITT) and how much of them survive (PRR). What is most elusive here is the fact that high PRR does not necessarily mean good PIR if the rate control is used. ITT needs to be additionally accounted for. Otherwise, rate control can virtually eliminate packet collisions hence arbitrarily improve PRR for an *individual* packet but obtain poor PIR. Note that minimizing BSMs only to improve PRR would beat the very purpose of V2X safety communication. Indeed, J2945/1c and J3161/1 exhibit this behavior that leads to a CBR even below the J2945/1's target operating range (Fig. 2(c), $H_{ea} = 0.5$ m). This has been noticed early on [11], [12] in the literature.

Fig. 3 sheds light on the dynamics of ITT and PRR on PIR for the compared schemes. J2945/1 and J3161/1 inflate ITT in response to increasing ρ (Eq. 1). Again, reduced packets alleviate packet collisions and result in better PRR than the proposed scheme. However, it does not lead to a better PIR performance than the proposed scheme regardless of the effective antenna height. For H_{ea} = 0.5 m, the PIR doubles from 100 ms to 200 ms as ρ rises from 100 veh./km to 600 veh./km in the proposed scheme, whereas in the standard schemes the PIR grows to 500 ms. For $H_{ea} = 1.5$ m, it is 350 ms vs. 510 ms.



(a) $H_{ea} = 0.5$ m

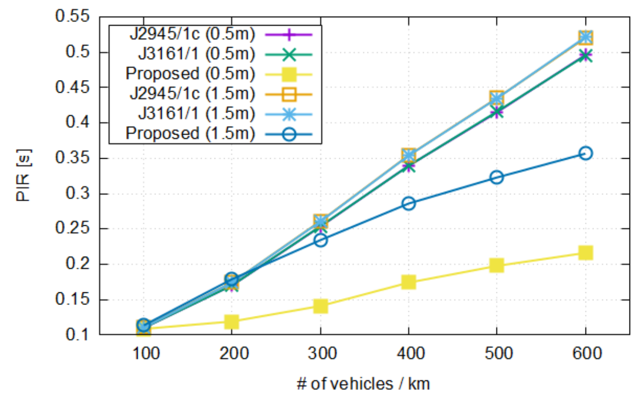


(b) $H_{ea} = 1.5$ m

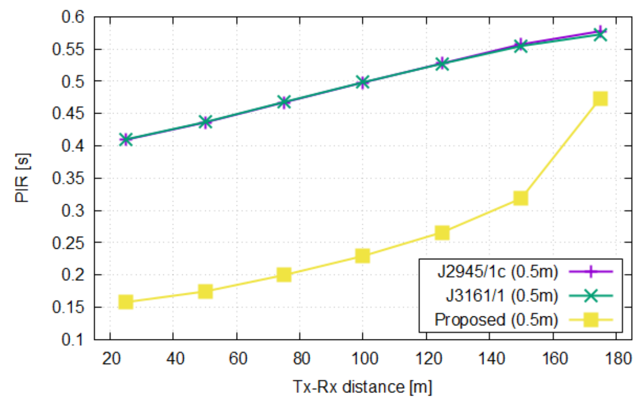
Fig. 3. Comparison of PIR as a function of ITT and PRR

Fig. 4 shows the PIR for each scheme in more detail. In Fig. 4(a), the PIR is averaged within Tx-Rx distance of 300m for H_{ea} =1.5 m and 200m for H_{ea} =0.5 m. Under the standard schemes J2945/1c and J3161/1, PIR almost linearly rises as congestion worsens. This is the result of the rate control linearly inflating ITT as a function of vehicle density while the power control almost being inert. In contrast, the proposed scheme better controls PIR with the assistance from the power control that is conditioned on the vehicle density. Fig. 4(b) and (c) show the average PIR as functions of Tx-Rx distance. In all distances that the given effective antenna height enables communication, the proposed scheme significantly lowers the PIR. Fig. 4(d) shows the PIR distributions for each scheme under $\rho = 600$ veh./km. Notice that the distributions for the standard schemes are almost identical and not affected by the effective antenna height. In contrast, the proposed scheme is sensitive to H_{ea}, because the raised antenna height increases CBR which in turn increases ITT (Eq. 3).

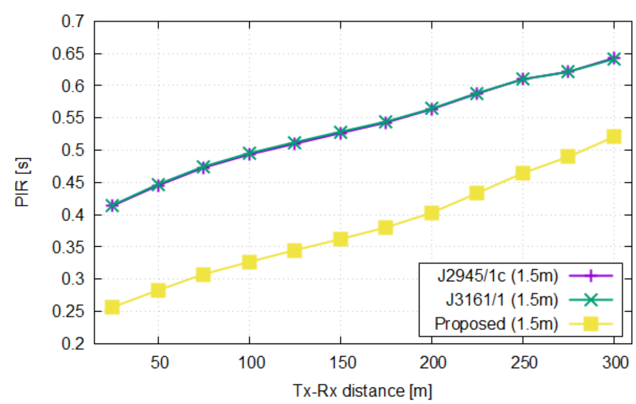
In order to relate the above results to CBR, we plot two graphs in Fig. 5. The first and foremost objective of congestion control is to contain the channel utilization within a target in all traffic situations. But at the same time, data flow should be



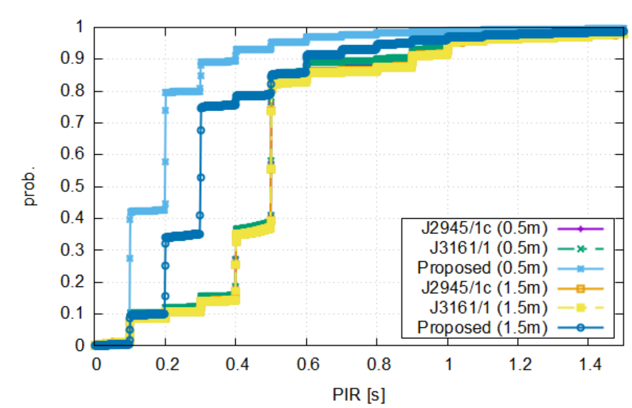
(a) PIR as functions of vehicle density



(b) PIR as functions of Tx-Rx distance, $H_{ea} = 0.5$ m, $\rho = 600$ veh./km



(c) PIR as functions of Tx-Rx distance, $H_{ea} = 1.5$ m, $\rho = 600$ veh./km

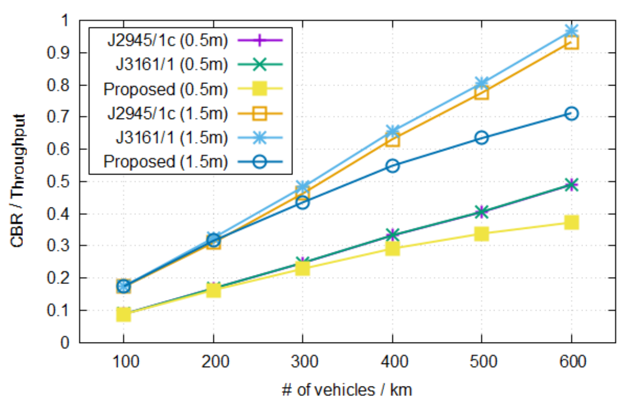


(d) CDF of PIR, $\rho = 600$ veh./km

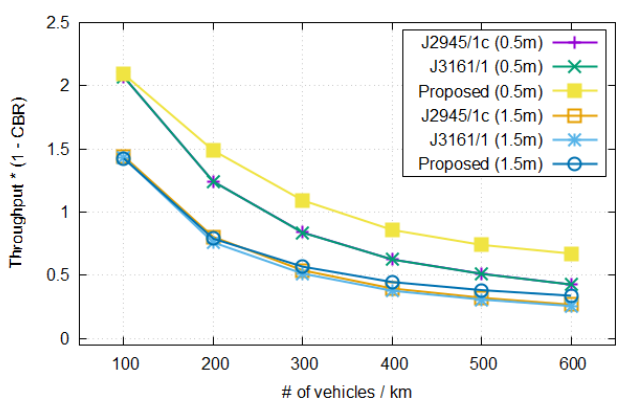
Fig. 4. Average PIR performance

maximally secured under the constraint. Fig. 5(a) shows how these two objectives are combined in the compared schemes. For this purpose, we define the throughput as the number of bytes delivered every PIR, namely $S = L/PIR$ where L is the BSM size. We call the ratio $CBR/S = CBR{\cdot}PIR$ as the throughput-normalized CBR. Interestingly, the metric linearly increases in vehicle density for the standard schemes. Namely, in these schemes, the throughput can only be increased with proportional CBR increase. Although the difference is not substantial, the proposed scheme is distinguished by a sublinear growth, i.e., it more effectively curbs CBR for the given throughput.

Fig. 5(b) interprets the same result from the perspective of the remaining channel capacity $(1 - CBR)$ after obtaining throughput in each scheme. The proposed scheme outperforms the standard schemes in both effective antenna heights in all vehicle densities. It has a larger improvement over the standard schemes with lower H_{ea}, because it regulates ITT based on CBR that is lower. Improved ITT leads to higher throughput.



(a) Throughput-normalized CBR



(b) Throughput × (1-CBR)

Fig. 5. CBR-based interpretation

V. Conclusion

This paper argues against the hasty abandonment of Tx power control in J3161/1 due to its perceived inefficacy in J2945/1. Instead, it demonstrates that power control, when used correctly with rate control, enables more frequent state updates about neighboring vehicles, helping to improve driving safety. Therefore, we strongly recommend reinstating power control in J3161/1 by switching the two control modes from J2945/1. Moreover, given that periodic broadcast is a fundamental means of communication in all V2X use case scenarios (Day 1, 2, and 3), the improved congestion control performance enabled by the reinstated power control requires more attention in the standardization process for cellular V2X communication.

Some future works are in order for the theoretical soundness, practicality, and optimality of the proposed control scheme. They include finding appropriate control threshold values, vehicle speed-based power control, fairness between individual vehicles, and mathematical proof of control convergence. A more systematic study on the congestion control thresholds in Eqs. (3) and (4) is called for in the cellular V2X environment, in a similar manner to the throughput-maximizing control considered for DSRC systems [17].

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