# Data Preference Matters: A New Perspective of Safety Data Dissemination in Vehicular Ad Hoc Networks

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***Abstract*—Vehicle-to-vehicle safety data dissemination plays an increasingly important role in ensuring the safety and efficiency of vehicle transportation. When collecting safety data, vehicles always prefer data generated at a closer location over data generated at a distant location, and prefer recent data over outdated data. However, these data preferences have been overlooked in most of existing safety data dissemination protocols, preventing vehicles getting more precise traffic information. In this paper, we explore the feasibility and benefits of incorporating the data preferences of vehicles in designing efficient safety data dissemination protocols. In particular, we propose the concept of packet-value to quantify these data preferences. We then design PVCast, a packet-value-based safety data dissemination protocol in VANET. PVCast makes the dissemination decision for each packet based on its packet-value and effective dissemination coverage in order to satisfy the data preferences of all the vehicles in the network. In addition, PVCast is lightweight and fully distributed. We evaluate the performance of PVCast on the ns-2 platform by comparing it with three representative data dissemination protocols. Simulation results in a typical highway scenario show that PVCast provides a significant improvement on per-vehicle throughput, per-packet dissemination coverage with small per-packet delay. Our findings demonstrate the importance and necessity of comprehensively considering the data preferences of vehicles when designing an efficient safety data dissemination protocol for VANET.**

## I. INTRODUCTION

The vehicle ad hoc networks (VANET) play an essential role in supporting the functionality of Intelligent Transportation System (ITS) [5]. The FCC of the United States has allocated a wireless spectrum with 75MHz bandwidth in the 5.9-GHz band for the next generation of VANET, which is also known as the dedicated short-range communication (DSRC) spectrum. Among various road applications provided by VANET, safety-related applications, such as accident warning, collision avoidance and intelligent navigation, are the most important ones to improve the quality of vehicle transportation [28]. These applications feed driver traffic information by collecting and analyzing safety-data generated from other vehicles.

Different from disseminating non-safety-related data, e.g, content distribution [20] [14], the dissemination of safety-data in VANET has more stringent QoS requirements, e.g., small dissemination delay and high dissemination coverage. And it has gained increasing attention from both academia and industry [17][26][7][9][3]. In the DSRC [8] standard, the one-hop communication range of safety-data in V2V communication is about 300-400 meters and the intended coverage range of safety-data is usually over 1000 meters. Therefore multi-hop broadcast is necessary for disseminating safety-data. And it aggravates the well-known *broadcast storm* phenomenon in VANET. Under imperfect wireless channel, i.e., high contention and collision, vehicles prefer to receiving certain safety data over others. These preferences include data from nearby vehicles, data generated more recently and data regarding an emergency. Receiving preferred data is crucial for safety applications in providing driver precise safety information.

Researchers have proposed different safety-data dissemination protocols, e.g. [11][12][15][27][13], for different scenarios. These protocols mainly adopt farthest-first dissemination, counter-based dissemination and probabilistic dissemination strategies in order to mitigate the broadcast storm. However, most existing dissemination protocols overlook vehicles' data preferences under the dynamic communication environment of VANET. One example is that farthest-first dissemination protocols assign higher transmission priority to data packets from a farther location while vehicles actually prefer safety data packets generated in a nearby location. Another example is that most dissemination protocols do not differentiate the priority of two packets generated at different time, while vehicles always prefer to getting the more recent packet.

In this work, we model vehicles' data preferences and explore the feasibility and benefits of incorporating these preferences into the design of safety data dissemination protocols. These are non-trivial tasks because we need to address a series of challenges. 1) A comprehensive model for data preferences of vehicles is needed. A model focusing on only one aspect of preferences could lead to a significance performance degradation in multi-hop dissemination, e.g., small coverage and long delay [2] [18]. 2) An efficient dissemination protocol should satisfy the data preferences of all the vehicle in the network. 3) An efficient dissemination protocol should be lightweight and fully distributed. A central dissemination controller is inefficient in a distributed and highly-dynamic environment such as VANET.

Towards addressing these challenges, we propose the concept of *packet-value* to quantify the complete data preferences of vehicle on a per-packet level. We then design PVCast, a packet-value-based safety data dissemination protocol. PVCast operates on a per-packet basis. For each packet, PVCast computes its *one-hop dissemination utility* as the product of packet-value and the effective dissemination coverage. Packets with a higher dissemination utility are assigned a higher broadcast probability and a smaller minimum contention window (CW) size. In this way, PVCast assigns a higher transmission priority to packets that can satisfy a higher total data preferences

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of vehicles in the network by broadcasting. As a result, the differentiated transmission priorities of packets reduce the contention and collision in VANET. It also satisfies the data preferences of all the vehicles in the network instead of sacrificing the data preferences of farther vehicles.

The **main contribution** of this paper is two-fold;

- We propose the concept of *packet-value* to quantify the total data preference of vehicle towards a given packet. Packet-value integrates all three classes of data preferences, i.e., spatial preference, temporal preference and type preference, into a single metric. To the best of our knowledge, this is the first comprehensive attempt to mathematically quantify the whole data preferences of vehicle.
- We propose PVCast, a packet-value-based safety data dissemination protocol. PVCast is lightweight and fully distributed. It satisfies the data preferences of all the vehicles in the network by making dissemination decisions based on each packet's one-hop dissemination utility. We evaluate the performance of PVCast on the ns-2 simulation platform by comparing with three representative safety data dissemination protocols. Simulation results in a typical highway scenario show that PVCast provides a significant improvement on per-vehicle throughput and per-packet dissemination coverage while incur small per-packet delay.

The rest of the paper is organized as follows. We review related work on safety data dissemination in Section II. We discuss our motivation and the corresponding challenges in Section III. We propose the packet-value concept to quantify the data preferences of vehicle in Section IV. We present the design of PVcast in Section V and evaluate its performance in Section VI. We make concluding remarks in Section VII.

## II. RELATED WORK

Early VANET dissemination protocols tried to inherit dissemination strategies from mobile ad hoc networks (MANET) [22] since VANET is a variation of MANET. However, VANET has some distinctive characteristics from MANET and sensor networks [10], which prevent these strategies from providing good dissemination performance. First, vehicles have a higher mobility, leading to a highly dynamic network topology in VANET. Secondly, there is no central controller in VANET. Thirdly, the data traffic load in VANET is heavy and typically broadcast. These features cause a high level contention and collision, making the well-known *broadcast storm* problem [24] more severe in vehicular networks. To cope with these features and the corresponding challenges, researchers have designed various dissemination protocols for different application scenarios in VANET, e.g. [11] [12] [15] [27] [13] and etc. We review representative protocols in the following based on their main dissemination strategies, i.e., farthest-first dissemination, counter-based dissemination, probabilistic dissemination and etc.

The most common strategy of safety data dissemination protocols in VANET is farthest-first dissemination. Farthest-first dissemination protocols achieve fast dissemination by selecting vehicle(s) farthest from the sender as dissemination relay nodes. Korkmaz *et al.* [11] propose the urban multihop broadcast (UMB) protocol. UMB chooses one vehicle in the farthest segment of a road to maximize one-hop dissemination progress. Martinez *et al.* [15] propose the Street Broadcast Reduction (SBR) protocol, which utilizes the farthest-first dissemination to minimize the one-hop dissemination delay in urban scenarios with lots of obstacles and intersections. Tseng *et al.* [24] and Wisitpongphan *et al.* [27] propose different prioritization methods to help neighbor vehicles make rebroadcast decisions based on their location information. In order to further improve the scalability of data dissemination, Li *et al.* [12] later propose OppCast, a two-phase safety data dissemination protocol. In the first phase of OppCast, data is disseminated as far as possible using farthest-first dissemination. A make-up dissemination phase is initiated afterwards to ensure the reliability of dissemination.

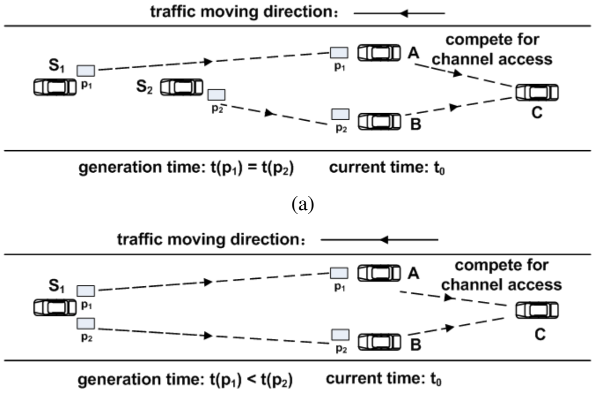
Another common safety data dissemination strategy is counter-based dissemination. Its basic idea is that for each incoming packet, the vehicle sets a timer to count how many duplicates are received during this period. If the number of duplicates is lower than a threshold, this packet will be rebroadcast after the timer ends. Otherwise it will be discarded. Tseng *et al.* [24] propose to set the length of timer inverse proportional to the distance between current vehicle to the source. Zhang *et al.* [29] build an analytical framework for this approach and show that the counter-based dissemination approach yields a higher delay than farthest-first dissemination. Tseng *et al.* [25] propose to adaptively adjust the counter threshold so that the performance of counter-based dissemination can be improved. Schwartz *et al.* [19] take the encounter probability of two vehicles into computing the length of the timer and show that their counter-based solution improve the fairness of data dissemination in vehicle networks.

Other than farthest-first dissemination and counter-based dissemination protocols, researchers also propose to use probabilistic forwarding to mitigating the broadcast storm in VANET. Wisitpongphan *et al.* [27] propose the slotted-p persistence protocol, in which each vehicle has the same probability, e.g., 50%, to forward the packet if no duplicate is received during the waiting timer. Mohammad *et al.* [16] propose to set the forwarding probability based on the count of duplicates received for each packet. Compared to deterministic rebroadcasting, probabilistic dissemination is shown to be effective in reducing the broadcast storm in VANET.

The common drawback of these protocols above is that they overlook the data preferences of safety applications in vehicle networks, which is of great importance in providing precise and real-time safety informations to vehicles. There are some efforts trying to incorporating data preference into the design of dissemination protocols. For example, WAVE adopts four access categories (AC) designed in 802.11 EDCA to queueing data from different applications based on their important for vehicle safety. Each AC has different priorities to access communication channel. Gallardo *et al.* [6] described the applications in each access category. AC[0] is for emergency safety data, which has the highest priority . AC[1] is for routine safety data, which has a lower priority than emergency safety data. The other two ACs are for data from non-safety-related applications. However, data type is only one aspect of data preferences in safety applications. Zhuang *et al.* [30] propose to adopt different modulation schemes during the dissemination so that vehicles closer to the source can decode more details from safety data with a trade-off from the information integrity delivered to farther vehicles. Other work such as [2] [4] [18] focus on disseminating emergency safety data only within a small area and thus reducing the contention in the network. However, the dissemination delay for farther vehicles to receive emergency safety data is significantly increased in these protocols.

## III. DATA PREFERENCES OF VEHICLE: MOTIVATION AND CHALLENGES

In order to ensure the safety and efficiency of transportation, vehicles collect and analyze various safety data from other vehicles. When collecting data, vehicles exhibit various preferences on collected data because different data has different effects on providing driver precise safety information. As discussed in Section II, most existing safety data dissemination protocols view each data packet as equally important and overlook the data preference of vehicles. WAVE proposes to use 802.11 EDCA to provide multiple access categories for data from different applications, but it only considers the preference of different types.



(a)

(b)

Fig. 1: Examples of data preferences in dissemination

We use two examples to illustrate the difference between the dissemination strategies with and without considering the data preferences of vehicle. In Figure 1(a), two packets $p_1$ and $p_2$ are generated at the same time but at different locations. In most existing protocols, e.g. farthest-first and counter-based dissemination, vehicle $A$ will have a higher priority to access the channel for broadcasting because $A$ can disseminate a packet farther away from its source than $B$ does. This higher priority is usually expressed in the form of a shorter waiting period or counter threshold. However, $C$ prefers to receiving packet $p_2$ than $p_1$ because $p_2$ contains the status of a vehicle closer to $C$. The earlier $C$ receives $p_2$, the more accurate traffic information $C$ can get. In order to satisfy this class of data preferences, therefore, vehicle $B$ should have a higher priority to access the channel for broadcasting.

In Figure 1(b), two packets are generated at the same location but at different time. Existing dissemination protocols do not assign different priorities to $p_1$ and $p_2$. Therefore $A$ and $B$ have the same priority to broadcast, e.g., the same waiting period. However, vehicle $C$ prefers to receiving packet $p_2$ than $p_1$ because $p_2$ contains the more recent status of vehicle $S$ and therefore is more important to $C$. To satisfy this class of data preference, vehicle $B$ should have a higher priority to access the channel for broadcasting.

From these examples, we observe that the general principles of existing dissemination protocols cannot satisfy the data preferences of vehicle, which has a significant impact in providing accurate safety information. This observation motivates us to conduct a comprehensive study on the data preference of vehicle, and to explore the potentials and benefits of incorporating vehicles' data preferences into safety data dissemination protocols. The data preferences of vehicle are complicated as they cover different aspects. We categorize all the data preferences of vehicle into the following classes:

- **Spatial data preference:** A vehicle prefers to receiving safety data generated by vehicles closer to its current location over that from farther vehicles;
- **Temporal data preference:** A vehicle prefers to receiving safety data generated more recently over older data;
- **Type data preference:** A vehicle prefers to receiving safety data about an emergency over periodic routine safety data;

Quantifying all three classes of data preferences and incorporating them into dissemination protocol design are nontrivial. Towards accomplishing these objectives, we need to address the following challenges:

**Challenge 1**: *An appropriate model to quantify the data preference of vehicle.* The data preference of vehicle have been overlooked in most dissemination protocols. Focusing on partial data preference would lead to severe dissemination performance degrading, e.g., high dissemination delay [2] [4]. No comprehensive model has been proposed to completely quantify the data preferences of vehicle. And it is crucial in designing an efficient safety data dissemination protocol.

**Challenge 2**: *The new dissemination protocol should satisfy the data preferences of all the vehicles in VANET.* A safety data dissemination protocol is designed to serve the whole VANET instead of individual vehicle. Therefore, our solution should satisfy the data preference of all the vehicles. In other words, when disseminating a safety packet, the new protocol should *not* sacrifice the dissemination QoS for vehicles who has lower preferences towards this packet, i.e., causing large multi-hop dissemination delay.

**Challenge 3**: *The new dissemination protocol should be lightweight and fully distributed.* VANET operates in a distributed and highly dynamic environment. It is hard, if not infeasible, to design a centralized controller for safety data dissemination. We need to design a fully distributed and lightweight protocol so that safety data can be efficiently disseminated to vehicles.

To this end, we study how to quantify vehicles' data demand preference and propose the concept of packet value in Section IV. We then propose our new packet-value-based dissemination protocol in Section V.

## IV. QUANTIFYING DATA PREFERENCES

In this section, we present our solution to **Challenge 1** when incorporating the data preference of vehicle into safety data dissemination. In Section III, we have categorized data preferences of vehicle into spatial preference, temporal preference and type preference. Because data is encapsulated and transmitted in units of packets, we can quantify these data preferences on a per-packet level. To this end, we first propose the concept of *packet-value*.

*Definition 1:* Given a packet $p$, its **packet-value** $PV_v(p)$ for vehicle $v$ is a metric that reflects the spatial preference, temporal preference and type preference of $v$ on data contained in packet $p$.

We explore the modeling and computation of *packet-value* in the following. Given a vehicle $v$, we denote its location coordinates as $(x_v, y_v)$. For each packet $p$ in the network, we define it with a 5-tuple $\{x_p, y_p, RoI_p, t_p, type_p\}$. In this tuple, $(x_p, y_p)$ are the generation location coordinates of $p$. We assume that the region of interest of packet $p$ is bounded by a circle with a radius of $RoI_p$, which is centered at $(x_p, y_p)$. All vehicles within this region that move towards the center are interested in receiving $p$. In a typical highway scenario, this region can be approximated as a rectangle. An example of region of interest is shown in Figure 2. In this example, $p$ is generated by $A$ that is moving to the west. Vehicles $B$ and $C$ are interested in receiving $p$. Vehicle $D$ and $E$ are not interested because $D$ is moving away from the center and $E$ is out of the region of interest. Attribute $t_p$ is the generation time of $p$. We use $type_p$ to denote the type of safety data in $p$. Similar as EDCA, we also define two types of safety data. The first one is emergency safety data, which is generated when accident and sudden change of driving status happen. The second type is routine safety data, which is generated periodically at each vehicle. We use $emer$ and $rout$ to denote these two types, respectively.

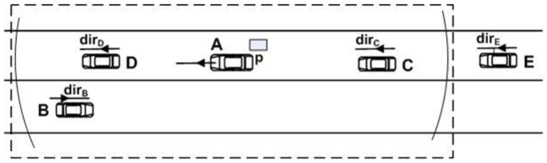


Fig. 2: Example of region of interest

The packet-value of any packet is decided by not only its original properties, i.e., the 5-tuple, but also its current status, i.e., current location and time. Given a packet $p$, its 5-tuple represents its original properties. As $p$ is disseminated through the network, its actual value to vehicles will change both spatially and temporally. This change of value will then affect the data preferences of vehicles towards data in $p$. The computation of packet-value should include all three classes of data demand preference. Therefore, the packet-value of packet $p$ at location $(x_p^c, y_p^c)$ and time instance $t_c$ for vehicle $v$ can be expressed as:

$$PV_v(p) = S_v(p) \cdot T_v(p) \cdot W_p. \tag{1}$$

In Equation 1, $S_v(p)$ is the *spatial-value* function of packet $p$'s generation location, current location $(x_p^c, y_p^c)$ and radius of range of interest, whose value reflects the spatial preference of vehicle $v$ towards data in $p$. $T_v(p)$ is the *temporal-value* function of packet $p$'s generation time and current time $t_c$, whose value quantifies the temporal preference of $v$ towards data in $p$. And $W_p$ is a *type-value* weight function of the data type in $p$ corresponding to the type preference on data in $p$. The product of function $S_v(p)$, $T_v(p)$ and $W_p$ integrates all three different data preferences into the single expression of packet-value. In the following, we discuss how to define these three functions to precisely capture the corresponding data preferences of vehicle, respectively.

**Spatial-value function.** In a typical road scenario, given a packet $p$, it draws interest only from vehicles that are within the region of interest and move towards the packet generation location. Other vehicles have no interest in receiving this packet. We denote $d_{pc} = \sqrt{(x_p - x_p^c)^2 + (y_p - y_p^c)^2}$ as the distance from the current location to the generation location of $p$, and denote $d_{pv} = \sqrt{(x_p - x_v)^2 + (y_p - y_v)^2}$ as the distance between the generation location and the location of $v$. The spatial-value function $S_v(p)$ has the following properties:

- $S_v(p) = 0$ if $v$ is moving away from $(x_p, y_p)$;
- $S_v(p) = 0$ if $d_{pv} > RoI_p$;
- $S_v(p)$ decreases as $d_{pc}$ increases;
- $S_v(p) \geq 0$ when $d_{pc} \leq RoI_p$;
- $S_v(p) = 0$ when $d_{pc} > RoI_p$;

From these properties, we propose the following formula to quantify a packet's spatial-value:

$$S_v(p) = \begin{cases} max(\alpha - \beta\sqrt{(x_p - x_p^c)^2 + (y_p - y_p^c)^2}, 0) \\ \qquad\qquad \text{if vehicle } v \text{ moves towards } (x_p, y_p) \\ \qquad\qquad\qquad\qquad \text{and } d_{pv} \leq RoI_p \\ 0 \qquad\qquad\qquad\qquad\qquad \text{otherwise.} \end{cases} \tag{2}$$

In Equation 2, we define $\beta = \frac{\alpha}{RoI_p}$. It is easy to see that this function satisfies all the properties of spatial-value listed above. From this equation we can also see that the spatial value of a packet decreases linearly as the distance from the generation location increases and becomes zero after reaching the end of region of interest. In existing farthest-first data dissemination protocol such as [27] [11], Equation 2 is usually used to realize farthest-first relay-node selection. In these protocols, the farther a vehicle receives a packet from the source location, the more likely this vehicle would be selected to further disseminate this packet. However, as we already show in Figure 1(a), this strategy cannot satisfy the spatial data preference of vehicle.

**Temporal-value function.** Vehicles rely on collecting real-time data to ensure their safety and efficiency. Therefore they have a higher preference on recent data than older one. As a result, the temporal value of a packet decreases rapidly at the beginning. Different from the spatial value, which becomes zero when the packet is disseminated out of a certain range from the source, old data has a low but still greater than zero temporal value because it might still be useful for safety applications to perform statistic analysis. This implies the decrease speed of temporal value gets slower as $t_c$ increases. Furthermore, vehicles have a higher temporal preference on emergency safety data than routine safety data even when they are generated at the same time. From these observations, we summarize the properties a temporal-value function should possess:

- $T_v(p) > 0$, $\frac{dT_v(p)}{dt_c} < 0$ and $\frac{d^2T_v(p)}{dt_c^2} > 0$ ;
- The temporal value of emergency safety data decreases

slower than the temporal value of routine safety data.

Through these properties, we propose the following formula to quantify a packet's temporal-value:

$$T_v(p) = e^{-\mu_{type_p}(t_c - t_p)}, \tag{3}$$

where $\mu_{type_p} > 0$ is the temporal-value fading factor depending on the type of safety data. And we have $\mu_{rout} > \mu_{emer} > 0$ since the temporal-value of emergency packets decreases slower than that of routine safety packets. Equation 3 satisfies all the properties of temporal-value listed above. It differentiates packets generated at different time, e.g., Figure 1(b), so that they can be assigned different priority for broadcast dissemination.

**Type-value function** Safety data in VANET already has the highest priority for transmission compared to non-safety data, e.g., multimedia data. Nevertheless, safety data packets should be further differentiated based on the information it contains when studying the data preferences of vehicle. Other than affecting the fading speed of temporal-value as in Equation 3, the type of safety data also affects the initial value of a packet when it is generated. Therefore, we propose to assign different weights to different types of safety data packets:

$$W_p = W_{type_p}, \text{where } type_p \in \{emer, rout\}, \tag{4}$$

in which we define $W_{emer} > W_{rout} > 0$ to indicate that vehicles have a higher preference to emergency safety data over routine safety data.

Combining Equation 2, 3 and 4 into Equation 1, we can get the complete expression of packet-value:

$$PV_p = \begin{cases} max(\alpha - \beta\sqrt{(x_p - x_p^c)^2 + (y_p - y_p^c)^2}, 0) \\ \cdot e^{-\mu_{type_p}(t_c - t_p)} \cdot W_{type_p} \\ \qquad \text{if vehicle } v \text{ moves towards } (x_p, y_p) \\ \qquad\qquad \text{and } d_{pv} \le RoI_p \\ 0 \qquad\qquad \text{otherwise.} \end{cases} \tag{5}$$

Having built the model to compute packet-value in Equation 5, we are able to use the following packet-value preference to represent all the data preferences of vehicle:

**Packet-value data preference:** Given any two packets $p_1$ and $p_2$ with, vehicle $v$ always has a higher data preference to $p_1$ over $p_2$ if $PV_v(p_1) > PV_v(p_2)$.

The packet-value data preference integrates all three classes of data preferences, i.e., the spatial preference, the temporal preference and the type preference. Therefore, it helps us address **Challenge 1** listed in Section III.

## V. PVCAST: A PACKET-VALUE-BASED DISSEMINATION PROTOCOL

Having proposed the packet-value preference to quantify the data preferences of vehicle towards a packet, we move on to explore the feasibility and benefits in designing an efficient safety data dissemination protocol. This protocol aims to satisfy the data preferences of all the vehicles in the network. To this end, we propose **PVCast**, a packet-value-based data dissemination protocol.

### A. PVCast in a nutshell

Figure 3 shows the architecture of PVCast. The control flow responds to packet reception. The basic idea of PVCast is to assign higher transmission priority to packets that can satisfy the data preferences of more vehicles through dissemination. Whenever a new packet $p$ arrives at the current vehicle $A$, $A$ updates $PV_A(p)$ using Equation 5. Then $A$ computes $edc_A(p)$, the *effective dissemination coverage* and $u_A(p)$, the *one-hop dissemination utility*, using Equation 7 and 8. Details on deriving these two equations will be shown in the next subsection. PVCast then performs forwarding probability test using $u_A(p)$ to decide if packet $p$ should be continue disseminating. After $p$ passes this test, PVCast assigns the minimum contention window (CW) size for broadcasting $p$ using $u_A(p)$ as well.

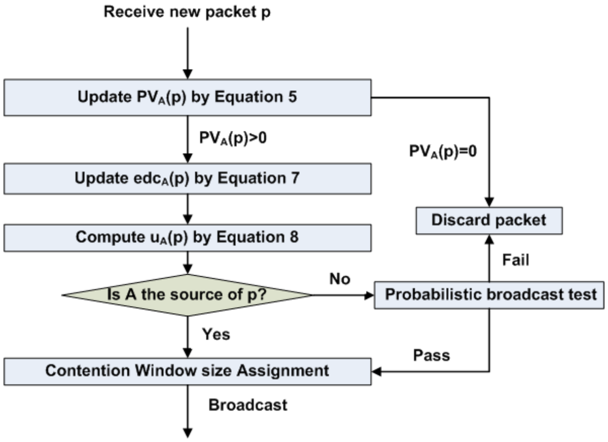


Fig. 3: **PVCast's architecture.** The figure shows the flow chart of PVCast.

PVCast is a lightweight and fully distributed dissemination protocol, which only needs local information to make dissemination decisions for each packet $p$. Therefore PVCast is successful in addressing **Challenge 3**. In the next few subsections, we will discuss the details of kernel modules of PVCast, including the computation of effective dissemination coverage and one-hop dissemination utility, the process of forwarding probability test, the process of minimum CW size assignment and the design philosophy behind them.

### B. One-hop dissemination utility

Packet-value is a metric to measure the actual value of data and quantify the data preferences of vehicle. When a packet $p$ is at vehicle $A$, however, $A$ can only compute $PV_A(p)$, the data value on $p$ at location $(x_A, y_A)$. Because our objective is to satisfy the data preferences of all the vehicles in the network, we need measure the potential satisfaction brought by $A$ rebroadcasting $p$ before making any dissemination decision. To this end, we propose the concept of one-hop dissemination utility:

*Definition 2:* Given a packet $p$ at vehicle $A$, the **one-hop dissemination utility** $u_A(p)$ is the sum of data preference of safety applications in vehicles that can be satisfied by $A$ rebroadcasting $p$, but not by the sender of $p$.

In order to compute $u_A(p)$, we need not only the packet-value $PV_A(p)$, but also $\rho_A$, the vehicle density within the transmission range of $A$. In PVCast, we use an EWMA traffic density estimator to estimate $\rho_A$. In every short period, e.g., 10 seconds, PVCast records the number of vehicles that $A$ is able to hear. Then we can estimate $\rho_A$ at the $T$th period as

$$\hat{\rho_A}[T] = (1 - W) \cdot \hat{\rho_A}[T-1] + W \cdot h_A[T], \tag{6}$$

where $h_A[T]$ represents the number of vehicles $A$ is able to hear in the $T$th period, and $W$ is a weight between 0 and 1. After getting the estimation of vehicle density, we can estimate the *effective dissemination coverage* of packet $p$ at vehicle $A$.

*Definition 3:* Given a packet $p$ sent by vehicle $U$ and received by vehicle $A$, the **effective dissemination coverage** $edc_A(p)$ is the cardinality of vehicle set $N_A$, where any vehicle $n_i \in N_A$ is out of the transmission range of $U$ but in both the transmission range of $A$ and the region of interest of $p$, and has $PV_{n_i}(p) > 0$.

In a typical road scenario, the width of road, e.g., 25m, is much smaller than the transmission range, e.g., 300m, and the radius of range of interest, e.g., 1200m. We then approximate both the transmission range of vehicle and the region of interest of a packet as rectangular bounded by the road as we showed in Figure 2 before. We can estimate $edc_A(p)$ as

$$edc_A(p) = \begin{cases} \frac{\hat{\rho_A}}{2} & \text{when } A \text{ is the source of } p \\ \frac{\hat{\rho_A}}{2} \frac{R_A + d_{UA} - R_U}{R_A} & \text{when } R_A + d_{UA} > R_U \\ & \text{and } RoI_p - d_{pA} \geq R_A \\ \frac{\hat{\rho_A}}{2} \frac{RoI_p - d_{pA} + d_{UA} - R_U}{R_A} & \text{when } R_A + d_{UA} > R_U \\ & \text{and } R_U - d_{UA} < RoI_p - d_{pA} < R_A \\ 0 & \text{otherwise,} \end{cases} \tag{7}$$

where $R_A$, $R_U$ are the predefined transmission range of $A$ and $U$, and $d_{pA}$ is the distance from the generation location of $p$ to the location of $A$. The derivation of Equation 7 involves some simple geometry approximation and the details are omitted due the constraint of space. Having the approximation of $edc_A(p)$, we can compute $u_A(p)$ as

$$u_A(p) = PV_A(p) \cdot edc_A(p). \tag{8}$$

From this equation, we can see that $u_A(p)$ is determined not only by the packet-value of $p$, but also by the extra vehicle broadcast coverage of $A$. This utility represents the extra data preferences of the whole network that can be satisfied if $A$ broadcast $p$. Using this utility, we will be able to make efficient dissemination decisions for rebroadcasting.

### C. Probabilistic broadcast test

After computing the one-hop dissemination utility, the first dissemination decision vehicle $A$ needs to make is *whether to broadcast* $p$. If $p$ is generated by $A$, the answer to this question is obviously positive. If $p$ is generated by some other vehicle, we design a probabilistic forwarding test module in PVCast to help vehicle make this decision. In this module, vehicle $A$ generates a random number $r$ between 0 and 1. Then $r$ is compared with a passing threshold $Pass_A(p)$. If $r$ is greater than the passing threshold, $A$ will start the CW size assignment module and broadcast this packet. Otherwise packet $p$ will be discarded. The passing threshold is decided by $u_A(p)$ in Equation 10

$$Pass_A(p) = \begin{cases} P_1 & \text{if } u_A(p) \geq \bar{U_1} \\ P_2 & \text{if } \bar{U_2} \leq u_A(p) \leq \bar{U_1} \\ P_3 & \text{otherwise.} \end{cases} \tag{9}$$

In this equation, we predefine $0 < P_1 < P_2 < P_3 < 1$. We also define $\bar{U_1} > \bar{U_2} > 0$ to categorize packets with different one-hop dissemination utilities into different utility levels. The rational behind this module is that the network can discard packets with a certain probability to reduce the broadcast storm. The higher expected dissemination utility of broadcasting a packet would bring, the lower chance this packet should be discard. In this way, PVCast is able to satisfy the data preference of vehicles in the whole network and alleviate the broadcast storm phenomenon.

### D. CW size assignment module

After the probabilistic broadcast test, the second dissemination decision $A$ needs to make is *what priority it should assign to packet* p to fulfill its one-hop dissemination utility while not interfering other broadcast in the network. In PVCast we make this decision by assigning different minimum CW size of the backoff procedure in MAC layer for broadcasting $p$ based on the priority level of $u_A(p)$, as shown in the following:

$$CW^A_{min}(p) = \begin{cases} CW_1 & \text{if } u_A(p) \geq \bar{U_1} \\ CW_2 & \text{if } \bar{U_2} \leq u_A(p) \leq \bar{U_1} \\ CW_3 & \text{otherwise.} \end{cases} \tag{10}$$

In this process, we predefine positive integers $CW_1 < CW_2 < CW_3$. The higher $u_A(p)$ is, the higher priority $A$ should have to access wireless channel to broadcast $p$. Therefore a smaller minimum CW size of would be assigned to $p$. In this way, PVCast enables adaptive CW size assignment for vehicle to access the channel, which reduces the probability of contention and collision in the network.

After both dissemination decisions are made, PVCast will send the packet and the corresponding minimal CW size to the MAC layer for actual transmission. PVCast make both dissemination decisions with the objective to satisfy the data preferences of all the vehicles in the transmission range of current vehicle. Through adaptive probabilistic broadcast and CW size adjustment, the satisfaction of vehicles within the one-hop range would lead to the satisfaction of vehicles in the whole network. Thus PVCast addresses **Challenge 2** when designing an efficient safety data dissemination protocol in vehicle networks.

## VI. PERFORMANCE EVALUATION

To characterize the feasibility and benefits of incorporating vehicles' data preferences in data dissemination, we implement PVCast on the ns-2 simulation platform and evaluate its performance in a typical highway scenario. In this section, we first present our evaluation methodology. Then we present and discuss the simulation results.

### A. Methodology

We implement PVCast in the ns-2 simulation platform. PVCast is encapsulated as a middle-layer protocol between IEEE-802.11p MAC protocol and upper layer applications. When deciding to broadcast a packet, the assigned minimum CW size of this packet is passed from PVCast to MAC layer in the packet header. In this way, we avoid any intrusive change to IEEE-802.11p protocol stack and ensure the portability of PVCast into different VANET protocol stacks.

| **Description** | **Value** |
|---|---|
| Highway scale | 2000 meters × 30 meters |
| Lanes per direction | 4 |
| Speed limit | 100 km/hour |
| Total number of vehicles | $N \in \{20, 40, 60, 80, 100\}$ |

TABLE I: Settings for the bi-directional highway

**Highway scenario** We use the Simulation of Urban MObility (SUMO) simulator, a microscopic and continuous road traffic simulation tool [1], to generate the trace for a typical bi-directional highway traffic scenario. This highway section is of west-east orientation with a length of 2000 meters and a width of 30 meters. There are four lanes at each direction. Along each direction there are two entries, one at the beginning of highway and the other at the 1-kilometer spot on the highway. Vehicles enter the highway through all four entries and drive with a speed limit of 100 kilometers per hour. Once arriving at the end of one direction, vehicles take the exit and enter the highway at the beginning entrance of the other direction. Table I summarizes the settings for this highway scenario.

| **Description** | **Value** |
|---|---|
| Transmission range | 300 meters |
| Radius of region of interest | 1200 meters |
| Packet size | 300 bytes |
| Routine safety data generation period | 0.1 second |
| Emergency safety data generation range | (1500, 2000) |
| Transmission power | 6dBm |
| CSThresh | -85dBm |
| Noise floor | -99dBm |

TABLE II: Settings for vehicles

**Vehicle settings** In our simulation, the movement of each vehicle is based on the trace file generated by SUMO. We assume every vehicle has a same transmission range of 300 meters. Each vehicle periodically generates one packet containing routine safety data every 0.1 second. When vehicles are within the $(1500, 2000)$ region at the east of highway, every second it has a probability of 50% to generate one packet containing emergency safety data. The radius of region of interest for every safety packet is 1200 meters. Table II summarizes the settings for vehicles in the simulation.

**Protocol studied** To understand the importance of considering vehicles' data preferences in increasing the efficiency of safety data dissemination in VANET, we comparatively study the following protocols:

- *CBD* A counter-based dissemination protocol. CBD assigns a waiting period with a random length for each packet. During this period, if the same packet is received over $C$ times, the vehicle will discard this packet. Otherwise, it will broadcast this packet at the end of the waiting period. This dissemination strategy was first proposed in MANET [24] and later adapted for VANET [23].

- *FARTHEST* A farthest-first dissemination protocol. It assigns a waiting period at a length inverse proportional to the distance between current vehicle and the sender for every packet. If a duplicate packet is not received, the vehicle will broadcast this packet after the end of this period. This strategy was first proposed in [24] and later adapted to VANET. It serves as the basic principle of many distance-based data dissemination protocol[11][15][12].

- *slottedP* A probabilistic dissemination protocol proposed in [27]. It uses the farthest-first strategy to assign waiting period for every packet as FARTHEST does. After the waiting period ends, the vehicle randomly decide to broadcast or discard the packet with a 50%-50% probability if there is no duplication reception.

- *PVCast* The packet-value-based dissemination protocol we propose in Section V, which adjusts the broadcast probability and contention window size on a per-packet level based on the one-hop dissemination utility. In simulation, we set $\alpha = 10$ in the spatial-value function, assign the type weight of safety data as $W_{emer} = 3$ and $W_{rout} = 1$, and set the temporal value fading factor of safety data as $\mu_{emer} = 0.8$ and $\mu_{rout} = 1$. Furthermore, we assign minimum contention window and broadcast probability of packet $p$ at vehicle $v$ based on the utility level in Table III

| **minimum CW** | **broadcast probability** | utility $u_v(p)$ |
|---|---|---|
| 3 | 0.5 | $[25, \infty)$ |
| 7 | 0.4 | $[20, 25)$ |
| 15 | 0.3 | $(0, 20)$ |

TABLE III: Parameter settings for PVCast

CBD, FARTHEST and slottedP represent the most common design principles of safety data dissemination protocols in VANET and have served as benchmarks for quite a few studies in VANET data dissemination, e.g., [12][29][21]. In our simulation, we set the maximal waiting period of all three protocols to be $25ms$ and the counter threshold $C$ in CBD to be 2. By comparing the performance of PVCast with these protocols, we will be able to get a better understanding on the feasibility and benefits of incorporating vehicles' data preferences into safety data dissemination protocols.

**Performance metrics** We evaluate each protocol's behavior based on the following metrics:

- *Per-vehicle throughput*: The number of unique packets with non-zero packet-value each vehicle receives every second;
- *Broadcast rate*: The total number of broadcast in the network every second;
- *Broadcast efficiency*: The sum of all vehicles' per-vehicle throughput divided by the broadcast rate;
- *Per-packet delivery delay*: The time difference between reception time and packet generation time when a packet is received at a vehicle,;
- *Per-packet vehicle coverage*: The number of vehicles each packet $p$ is disseminated to during simulation;
- *Per-vehicle emergency throughput*: The number of unique emergency packets with non-zero packet-value each vehicle receives every second;

### B. Simulation results

In what follows, we present the results of our simulation study. The length of each simulation is 100 seconds. Figure 4 shows the median of per-vehicle throughput of different protocols under different total number of vehicles. When there are only 20 vehicles on the highway, the per-vehicle throughput of all protocols are low because the network is sparse. As the number of vehicles increases, slottedP reaches its maximal per-vehicle throughput at 40 vehicles while PVCast, CBD and FARTHEST reaches their maximal per-vehicle throughput at 60 vehicles. In all scenarios, PVCast significantly outperforms CBD, FARTHEST and slottedP with a 20% - 120% higher throughput than slottedP, the second best protocol. Figure 5 shows that PVCast has the smallest broadcast rate compared to all other three protocols. We also plot the broadcast efficiency of each protocol in Figure 6. From this figure we see that the transmission efficiency of PVCast is 2x-5x times higher than the second best one. PVCast achieves its highest broadcast efficiency when there are 40 vehicles due to the sparseness of 20-vehicle case. Then the efficiency decreases as the vehicle number increases. Figure 4-6 show that the excessive number of broadcast in CBD, FARTHEST and slottedP causes severe broadcast storm, leading to significant degrading in per-vehicle throughput. On the contrary, PVCast effectively controls the broadcast rate by adaptively adjusting the broadcast probability and minimal contention window of each packet based on its one-hop utility. This leads to a great reduction in collision occurred during the broadcast, which improves the efficiency of broadcast in PVCast. The direct output of this efficiency increase is the significant improvement on per-vehicle throughput. Therefore, PVCast mitigates the broadcast storm problem in VANET and is efficient in disseminating safety data.

It is interesting to find in Figure 5 and 6 that 1) as the number of vehicles increases, the broadcast rate of PVCast also increases but the increase speed gets slower; and 2) the broadcast efficiency with 100 vehicles is slightly higher than that with 80 vehicles. The reason is as follows. When the vehicle density is low, i.e., 40-80, packet-value is the main factor affecting one-hop dissemination utility. Under these cases, PVCast satisfies the data preference of vehicles by increasing the broadcast rate moderately. However, when the vehicle density gets very high, the effect of density on one-hop dissemination utility gets more significant than packet-value. Under this case, PVCast satisfies the data preferences of vehicles mainly by delivering a packet to more vehicles. These observations show that PVCast is adaptive in making dissemination decisions to satisfy the data preferences of all the vehicles in VANET under various densities.

We then study the delay and coverage performance of PVCast. Figure 7 shows the median of per-packet delivery delay of all protocols. We see that it increases with the number of vehicles because there are more and more vehicles competing the channel for broadcasting. However, the increase of per-packet delay in PVCast is much smaller than the other three protocols. The high per-packet delivery delay in CBD, FARTHEST and slottedP comes from 1) the waiting period for each incoming packet before broadcasting, and 2) the high channel contention in the network. On the contrary, PVCast assigns different CW sizes to packets with higher dissemination utilities. As a result, the contention caused by multiple vehicles competing the same channel access is reduced and hence the per-packet delivery delay. Therefore, PVCast enables fast dissemination such that the temporal data preferences of all the vehicles can be satisfied.

We then show the median of per-packet vehicle coverage in Figure 8. From this figure we see that when the number of vehicles is small, i.e., 20, the median number of vehicles covered by a packet of PVCast is the same as slottedP and higher than CBD and FARTHEST. As the number of vehicles increases, the median of per-packet vehicle coverage in PVCast reaches its peak at 13 when there are 40 and 60 vehicles in the network. Though the per-packet vehicle coverage of PVCast decreases when there are 80 and 100 vehicles on the highway, it still outperforms the second best protocol by at least 80%. PVCast achieves this high per-packet vehicle coverage because it adjusts the priority of different packets based on the one-hop dissemination utility. The computation of utility integrates both both packet-value and the number of vehicles whose data preferences can be satisfied. In this way, PVCast achieves not only high per-vehicle throughput, but also *high vehicle coverage* of safety data.

It is worth noting that when there are 60, 80 and 100 vehicles on the highway, the per-packet vehicle coverage of slottedP is worse than FARTHEST. Meanwhile, the per-packet delay of slottedP is also larger than that of FARTHEST. Combined with the high vehicle coverage and low delay of PVCast, these observations show that fixing the broadcast probability for all packets is ineffective for disseminating a packet to a large number of vehicles. It is therefore necessary and beneficial to adaptively adjust the broadcast probability based on the one-hop dissemination utility as PVCast does.

Furthermore, we compare the per-vehicle emergency data throughput of different protocols in Figure 9. When the network is sparse, i.e., 20 vehicles, all protocols have low per-vehicle emergency throughput. As the number of vehicles in the network increases, however, vehicles in PVCast have a 2 to 3 times higher emergency data throughput than the second best protocol. This improvement is much higher than that of per-vehicle throughput for all the safety data in Figure 4. This observation demonstrates that PVCast can effectively differentiate different types of safety data by assigning a higher transmission priority for emergency safety data. In this way, PVCast can delivery more high-value data to vehicles so that vehicles' type data preference can be satisfied. On the contrary, CBD, FARTHEST and slottedP treat emergency safety data and routine safety data as equally important, which causes their low emergency data throughput in all cases.

In summary, we demonstrate the feasibility and effectiveness of comprehensively considering the data preferences of vehicle in safety data dissemination through simulation on a typical highway scenario. Compared to three representative dissemination strategies in VANET, PVCast yields a higher per-vehicle throughput, a higher vehicle coverage while incur a smaller per-packet delay. It also provides a high per-vehicle emergency throughput. Therefore, PVCast is efficient in satisfying the data preferences of all the vehicles in the network.

## VII. CONCLUDING REMARKS

In this paper, we systematically study the data preferences of vehicle in VANET. We propose the concept of packet-value to quantify all three classes of data preferences, i.e., spatial preference, temporal preference and type preference. We design PVCast, a packet-value-based safety data dissemination protocol, which aims to satisfy the data preferences of all the vehicles in the network. PVCast makes dissemination decision for each packet based on its one-hop dissemination utility. We compare the performance of PVCAST with three representative safety data dissemination protocols through ns-2 simulation. Simulation results in a typical highway scenario show that PVCast provides a significant improvement on per-vehicle throughput with a higher dissemination coverage while incurring a much lower dissemination delay. Our findings shed

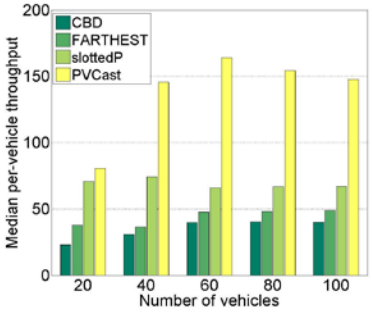


Fig. 4: Per-vehicle throughput (pkts/sec)

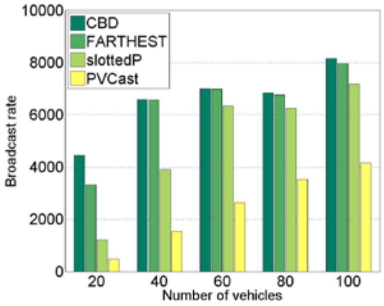


Fig. 5: Broadcast rate

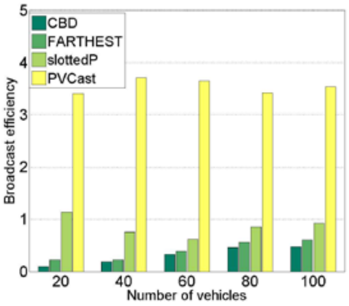


Fig. 6: Broadcast efficiency

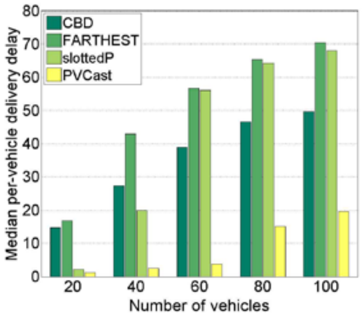


Fig. 7: Per-packet delivery delay (ms)

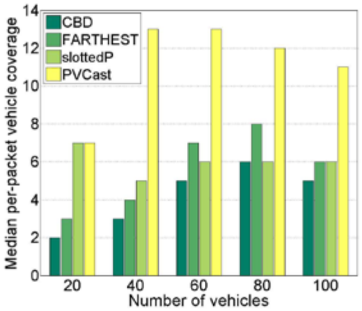


Fig. 8: Per-packet vehicle coverage

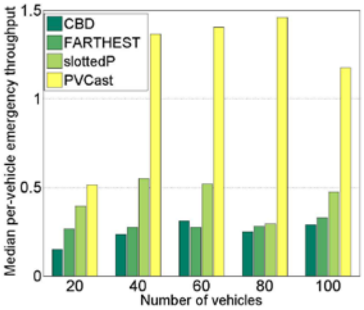


Fig. 9: Vehicle emergency throughput (pkts/sec)

light on how to incorporate the data preferences of vehicle into the design of an efficient safety data dissemination protocol for VANET. Future work along this direction includes designing data-preference-based power and rate control strategies to further improve the efficiency of safety data dissemination.

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