**Saudi Journal of Engineering and Technology (SJEAT)**
Scholars Middle East Publishers
Dubai, United Arab Emirates
Website: http://scholarsmepub.com/

**ISSN 2415-6272 (Print)**
**ISSN 2415-6264 (Online)**

# Survey: The Reliability of VANETs for Safety Applications

**Wenfeng Li*, Qiang Lu, Wuli Song, Xuehui Jiang, Juan Tian**
College of Information & Engineering, Taishan Medical University, Taian, China

**Original Research Article**

***Corresponding author**
*Wenfeng Li*

**Article History**
*Received: 12.01.2018*
*Accepted: 22.01.2018*
*Published: 30.01.2018*

**DOI:**
10.21276/sjeat.2018.3.1.5

**Abstract:** Vehicular ad hoc networks (VANETs) have become a hot research area over the past few years. The main purpose of VANETs is to improve traffic safety, traffic efficiency, and driving comfort. Particularly, traffic safety attracts the great attention of government, academia, and industry, because it is the most critical aspect of VANETs related to human lives. Therefore, many safety applications in VANETs have been proposed and investigated. However, how to guarantee the reliability of safety applications in VANETs is a big challenge, considering its natures of vehicle mobility and ad-hoc connection. In this paper, we provide an overview of VANETs for safety applications. Then, we discuss the specific reliability requirements in VANETs and the corresponding quality of service (QoS) metrics. Furthermore, based on these requirements and metrics, we analyse and evaluate whether or not current VANETs are able to support safety applications with stringent reliability requirements. New insights into potential enhancements from perspective of both new dynamic QoS requirements and radio resource sharing are provided and discussed. Finally, we illustrate future research directions to improve the reliability of VANETs for safety applications.

**Keywords:** VANET safety applications, vehicular communication, reliability, quality of service (QoS).

## INTRODUCTION

Vehicle brought to people not only lots of benefits, but also many problems with high societal costs: traffic congestion, fatcilities, and injuries.

In order to deal with these problems, many safety devices have been equipped into vehicles to improve safety and efficiency of road utilization, such as seat belts, airbags, parking radars, cameras, sensors, and anti-locking braking systems (ABS). However, the United States still suffered about 1.5 million traffic accidents and 32,675 road traffic fatalities in 2014 [1]. At the same time, the traffic safety situation is also not optimistic in developing countries with their economic development. For example, in China, over 100 million vehicles has been increased in last decade; more than 200 thousand traffic accidents happened; and 59,997 persons died in 2012 [2]. In addition, excessive vehicles led to traffic congestion, especially in the cities without sufficient transportation infrastructure.

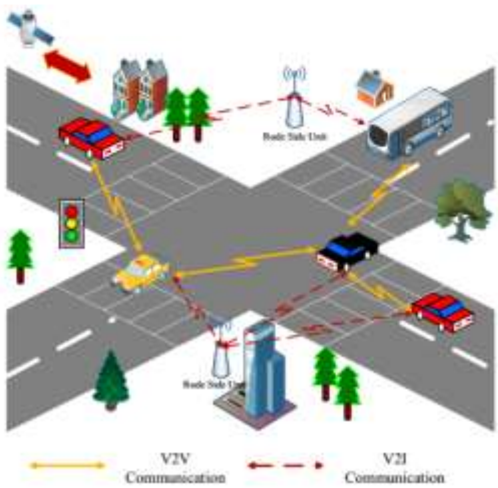


**Fig-1: Typical VANET scenario**

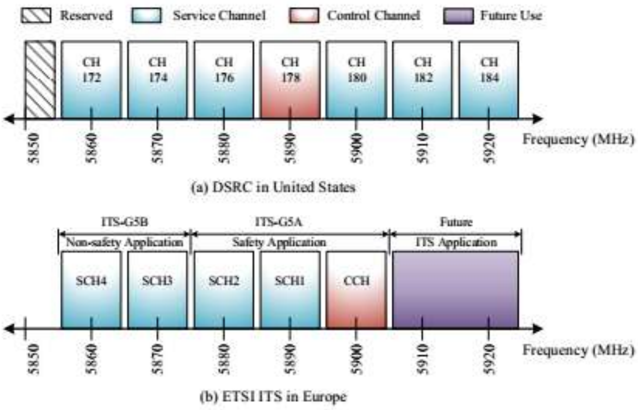


**Fig-2: Spectrum allocation in the IEEE and ETSI**

To improve road safety, traffic efficiency and driving comfort, governments have been investing research on Intelligent Transportation System (ITS) and enhancing infrastructure construction. Recent technical breakthroughs in electronics, computing, sensing, and wireless communications have been promoting ITS development significantly [3]. Vehicular ad hoc network (VANET), which is a sub-class of mobile ad hoc network (MANET), is one of the key enabling components in ITS [4]. The primary objective of VANET is to establish wireless communications among a large number of vehicles in an ad hoc manner without central control. Vehicles can communicate with each other directly, which is termed as Vehicle to Vehicle (V2V) communication. Besides, communication between a vehicle and an infrastructure such as a Road Side Unit (RSU) is called Vehicle-to-Infrastructure (V2I)[5]. Fig. 1 shows a typical VANET scenario. The U. S. Department of Transportation (DOT) estimated that VANET can avoid 81% of unimpaired light vehicles crashes in the United States [6]. In addition to improving transportation safety and traffic efficiency, VANET can also support infotainment applications to improve driving comforts [7].

In recent years, VANETs have attracted big interest from automotive industries, academia, and governments in many countries. An intelligent transportation project, Vehicle Infrastructure Integration (VII) [8], was proposed by the US Department of Transportation in 2004. In addition, the similar projects include Fleenet (Europe) [9], Car-2-Car Communications Consortium (C2CCC) [10], Network on Wheels project (Germany) [11], and Advanced Safety Vehicle project (Japan) [12] have been initiated and developed in recent years. A novel communication system known as Dedicate Short Range Communications (DSRC) is designed to support low-latency V2V and V2I communications. Each vehicle in DSRC is equipped with a set of wireless sensors, *e.g.*, On Board Units (OBUs), GPS, microprocessors, and wireless communication equipment, so that they can collect and exchange safety information such as position, speed, acceleration, brake, *etc.* with surrounding vehicles periodically. DSRC systems can increase the drivers' awareness range and alert drivers to avoid potential accidents, which is essentially about frequent exchanging the safety messages among nearby vehicles. One-hop broadcasting fashion is much suitable for sharing safety messages to all nearby vehicles due to the highly dynamic topology of the networks and the stringent delay requirements [13, 14].

Thus, highly reliable and timely broadcasting is an essential requirement in disseminating safety messages to all nearby vehicles. The mean beacon transmission delay is defined as duration from an information packet generation is generated to this packet is successfully received by other vehicles within the transmission range of the source vehicle. The requirement of the mean beacon delay for safety applications in VANETs should be less than 100*ms* [15]. The works in [13, 16] show that the mean beacon transmission delays are very low and can satisfy the delay requirement for safety applications in a typical DSRC system. However, there are still challenges to reliably and efficiently deliver the beacon in VANETs, *e.g.*, the hidden terminal problem, concurrent collisions and channel fading.

Therefore, we will concentrate on the one-hop broadcasting reliability for safety applications based on DSRC in this paper. We will at first introduce the medium access control layer (MAC-layer) and application layer (APP-layer) reliability metrics for safety-related applications in DSRC systems. Then, we will analyse the factors that affect the reliability of delivering messages in DSRC systems and the reliability of APP-layer for safety applications. Finally, we will discuss future research directions to enhance reliabilities of APP-layer for safety-related applications in VANETs.

**VANET Standards for Safety Applications**

As an important part of ITS, Dedicated Short-Range Communications (DSRC) is to support various VANET safety applications for V2V and V2I communications. The DSRC standardization is coordinated by a variety of research entities. In this section, the overview of two main DSRC standards is presented, which are made in the United States and Europe, respectively. Furthermore, safety applications and their performance and QoS requirements are briefly introduced.

**United States Standard**

DSRC, which is also called Wireless Access in Vehicular Environment (WAVE), is standardized by the IEEE 802.11p work group and 1609 work group in the United States [17]. As the name implies, DSRC/WAVE should be allocated a specified spectrum to transmit messages with high data rate. A licensed spectrum with 75 *MHz* bandwidth from 5.850*GHz* to 5.925*GHz* has been allocated for DSRC communication by the U.S. Federal Communications Commission (FCC).

DSRC/WAVE is working on multiple channels. As illustrated in Fig. 2, the 75*MHz* licensed spectrum is divided into seven 10 *MHz* channels with 5MHz guard band. Each channel has its index number, *e.g.*, channel-172. The channel-178 is Control Channel (CCH) and the other six channels are Service Channels (SCH). In DSRC/WAVE standard, control messages and public safety messages are transmitted on CCH; and the other six SCHs are used to transmit commercial or infotainment messages. In the latest version of DSRC/WAVE, only control messages are exchanged on CCH and channel-172 is dedicated to transmit safety messages, which avoids the possible congestion of control and safety messages.

The layered architecture of DSRC includes four layers: PHY, Data Link (including MAC), Network/Transport and Application layer [17]. DSRC/WAVE is a suite of standard and protocol stack. Different protocols are conceived and deployed at various layers. IEEE 802.11p is employed at the PHY and MAC layers. At higher layers, a set of IEEE 1609 standard family is employed based on IEEE 802.11p for security service, network and transport layer service, and multichannel coordination. Additionally, IPv6, UDP, TCP are also supported by DSRC.

**European Standard**

In Europe, the DSRC refers to ETSI ITS station standardized by the European Telecommunications Standards Institute (ETSI), which has many similarities with the DSRC/WAVE standard in United States.

ETSI allocates 50*MHz* bandwidth in the 5.9*GHz* spectrum to ITS communication, 30*MHz* spectrum is reserved to ITS-G5A band dedicated to safety applications, and the remainder 20*MHz* spectrum is called ITS-G5B band dedicated to non-safety services [18]. Hence, there are five channel in ITS-G5 including one control channel and four service channels SCH1-SCH4 as depicted in Fig.2. The differences between ETSI standard and DSRC/WAVE are 1) ETSI CCH is the service channel 180 in DSRC/WAVE; and 2) the channel 178 in DSRC/WAVE is SCH1 in ETSI standard.

The ETSI ITS station protocol stack is a layered architecture that is divided into four layers from bottom to top: Access Technologies, Networking/Transport, Facility, and Application layer. In Access Technologies layer, ETSI ITS station adopts access technology named as ITS-G5, which is based on IEEE 802.11p. The Networking/Transport layer and facilities layer has the similar functions as in IEEE 1609.3 and 1609.4 standards. Application message formats are specified by ETSI in application layer.

**Safety Requirement Specification**

The main purpose of VANETs based on DSRC is to enhance transportation safety, improve traffic efficiency and driving comfort. These applications can be classified into safety and non-safety applications according to their purpose.

**Table-1: Description of safety applications requirements**

| Application Name | Message type | Communication | Delivered frequency | Communication range | Latency |
|---|---|---|---|---|---|
| Cooperative forward collision warning | Beacon, Event-driven | V2V | 10*Hz* | 150*m* | <100*ms* |
| Intersection collision warning | Beacon | V2V, V2I | 10*Hz* | 300*m* | <100*ms* |
| Lane change assistance | Beacon | V2V | 10*Hz* | 150*m* | <100*ms* |
| Rear-end collision warning | Beacon | V2V | 10*Hz* | 150*m* | <20*ms* |
| Stationary vehicle warning | Beacon | V2V | 2*Hz* | 50*m* | <100*ms* |
| Traffic signal violation warning | Event-driven | V2I | 10*Hz* | 250*m* | <100*ms* |

Safety applications are primarily employed to decrease the probability of traffic accidents and casualties [19]. Safety applications can track position and movement of surrounding vehicles and alert drivers to take action to prevent potential collisions via exchanging Basic Safety Messages (BSM) between surrounding vehicles or from vehicles to RSU. A list of representative safety DSRC applications which have been identified by VSC is chosen and described in literature [20]. These safety applications can be classified in two categories: BSM based safety applications (*e.g.* Cooperative collision warning) and event-driven safety applications (*e.g.* Emergency electronic brake lights) from perspective of safety messages transmission mode. Event-driven messages are transmitted occasionally in case of dangerous situations on road, such as hard braking, icy surface, in order to alert nearby vehicles about it before it is too late [21]. BSMs are broadcasted periodically to keep drivers informed with status of nearby vehicles such as location, heading, speed, acceleration and other mobility information. Moreover, event-driven messages are more critical and should be disseminated with higher priority than beacon messages, because the triggered event is emergent or already happened.

Obviously, safety-critical applications are time-sensitive and require high reliability. Thus, a periodic one-hop broadcast manner is suggested by the VSC for DSRC based safety applications, which is to disseminate safety messages to all nearby vehicles. These safety applications have their own system performance requirements, respectively. For example, the beacon for most safety applications are required to be delivered at high updating rate 10*Hz* [22], and the latency for periodic message broadcast of most safety applications requires less than 100*ms*. Even safety applications such as pre-crash sensing require more critical latency (less than 20*ms*) [19]. The QoS requirements for several typical safety applications are summarized in Table I. In addition, the safety message delivery ratio in DSRC should be required greater than 0.99 as stated in [23] in order to guarantee safety messages being delivered reliably.

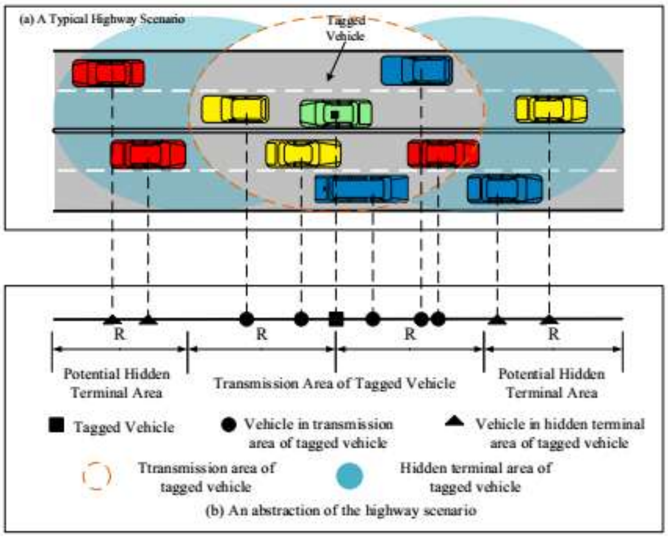


**Fig-3: Road topology abstraction: 2-Dimensional to 1-Dimensinoal**

There are two major factors of VANET that bring the challenges to achieve the desired QoS in safety applications. At first, IEEE 802.11p is employed as MAC protocol in VANETs. One feature of IEEE 802.11p is that its broadcast mechanism employing the distributed coordination function (DCF) without handshaking and acknowledgement mechanisms [24]. The transmitter cannot detect the failure of packages reception due to contentions and collisions at the MAC level, so that the transmitter will not retransmit these packages. Thus, collisions have a significant impact on the reliability of broadcast, particularly in dense road traffic scenarios. Secondly, the hidden terminal problem [25] greatly degrades the reliability of broadcast in VANET because IEEE 802.11p broadcast only adopts physical carrier sensing to reduce collisions without retransmissions. Thus, the hidden terminal problem in IEEE 802.11p broadcast can be significantly more complex and severe than that of IEEE 802.11p unicast. The potential hidden terminal areas of tagged vehicle can be seen in Fig. 3(a). Additionally, high vehicles' mobility and radio channel fading also affect reliability of beacon transmission in VANET.

**Reliability Metrics and QoS Requirements**

Reliability in the context of VANET is defined as the probability of all intended vehicles to receive the broadcast beacons within the specified time window [16], which is the most important aspect of safety applications in DSRC. The reliability for DSRC safety applications can be divided into two categories: MAC-level reliability and application-level (APP-level) reliability [26], which will be specified in detail later. Several commonly used reliability metrics and QoS requirements at MAC-level and APP-level are depicted in this section.

**MAC-Level Reliability Metrics and QoS Requirements**

MAC-level reliability represents the reliability of DSRC wireless communication itself. It is concerned with how reliable a data packet is successfully received by a receiver during a specific transmission. MAC-level reliability metrics are usually used to illustrate the fundamental features of DSRC wireless communication reliability itself, which is of most interest to researchers and engineers. Four metrics are commonly used to evaluate MAC-level reliability of safety applications based on DSRC.

- *Packet delivery ratio* (*PDR*) is defined as probability that a packet is received successfully by all potential receivers after this packet is delivered by a sender (or tagged vehicle), which is first introduced by Bai [26]. Given a time window, the *PDR* can be calculated as the ratio of the number of data packets successfully received to the total transmitted data packets within the time window.
- *Packet reception ratio* (*PRR*) is first introduced by Moreno *et al.* in [14] for VANET. It is defined as the percentage of receivers that successfully receive a packet from the sender among all the receivers being inspected when this packet is sent by sender.
- *Successful packet delivery probability* (*PDP*) is defined as the probability that a receiver successfully receives a packet from the sender. It can be simply calculated as the ratio of the number of packets received by a receiver to the total number of packets sent to this receiver by sender within a certain time window.
- *Effective Range* (*ER*) is defined as the maximum range from sender which the pre-defined QoS requirements for safety-related applications can be satisfied or achieved. For instance, we pre-defined a threshold of *PDR* is 0.99, then the ER of one safety-related application is a maximum distance from sender where the value of *PDR* is larger than threshold. It was introduced for evaluating safety applications in VANETs by Yousefi [27].

The *PDR* is a sender-oriented, point-to-all broadcasting reliability metric. *PRR* is a receiver-oriented reliability metric for evaluating how a packet from a sender (or tagged node) is received by all receivers in the context of network. *PDP* is concerned more about how an individual vehicle receives the packet from the tagged vehicle at a specific distance, which is a point-to-point communication metric. In other words, *PDR* can be measured or evaluated from derivation of *PDP* in most cases. These metrics are derived as the functions of the distance from receivers to the sender using analytical model, which allows us to evaluate the MAC-level reliability more conveniently and efficiently than field test.

### APP-Level Reliability Metrics and QoS Requirements

Different from MAC-level reliability, which cares about how reliable DSRC wireless communication is, APP-level reliability is more concerned about whether the reliable application services can be provided by safety applications based on DSRC. In safety oriented VSC communications, each newly generated beacon with fresh information can overwrite the previous beacon with outdated information, which is different from data transfer in traditional network applications like Internet HTTP or FTP service. Thus, APP-level reliability of safety applications may be satisfied even though a few old packets are lost in MAC layer as long as more than one packets are successfully received within a given duration time. The APP-level reliabilities should be greater than or equal to 99%, which is reasonably high enough to satisfy the reliability requirement [28]. Meanwhile, there is a certain relationship between MAC-level and APP-level reliability metrics. This relationship can be illustrated by an analytical model. Recently, two APP-level reliability metrics are proposed to evaluate the reliability of safety applications based on DSRC. These metrics can be derived by MAC-level reliability metrics such as *PDP*.

- *T-window reliability* (*TWR*) is defined as the probability of successfully receiving at least one of multiple consecutive packets from broadcast vehicles at distance *d* within the tolerance time window. An analytical model relating *TWR* with *PDP* can be written as

  $$P_{app}(d) = 1 - (1 - P_{MAC}(d))^{\lfloor T/t \rfloor} \qquad (1)$$

  Where $P_{app}(d)$ is *TWR* at distance *d*, $P_{MAC}(d)$ denotes *PDP* at distance *d*, *t* is the beacon generation interval, T is the tolerance time window. TWR is first defined as an application level reliability metric in [26]. Then, it was employed by Yousefi [13], Sepulcre [29] to evaluate the performance of VSC safety applications.

- *Awareness Probability* is defined by a *et al.* in [28] as the probability of successfully receiving at least *n* (*n*>0) of multiple consecutive packets from broadcast vehicle at distance *d* within the tolerance time window *T*. It can be expressed by

  $$P_A(\mathrm{d}, n) = \sum_{k=n}^{\lfloor T/t \rfloor} \binom{\lfloor T/t \rfloor}{n} P_{MAC}(d)^k (1 - P_{MAC}(d))^{\lfloor T/t \rfloor - k} \qquad (2)$$

  where *d* is the distance between transmitter vehicle and receiver vehicle, $P_{MAC}(d)$ is *PDP* at distance *d*, *t* is the beacon message interval and *T* is tolerance time window. It is noted that the awareness probability $P_A(d, n)$ becomes the *TWR* $P_{app}(d)$ as *n* is equal to 1.

The MAC-level reliability is of most interest to researchers and engineers, however APP-level reliability is more important since it determines whether safety applications based on DSRC is reliable and trustable.

### Evaluation of VANET QoS

### DSRC Performance Analysis

In order to evaluate the reliability metrics depicted in section III, three techniques can be employed: field operation testing (FOT), simulation, and analytic modelling. In general, FOT is expensive and unsafe. Simulation usually takes extensive computation time since VANETs may have large scale networks. Analytic modelling has the advantage of safe, low-cost, and computational-efficient among these three evaluation methods. Thus, analytic modelling can provide the valuable references and guidance for the design and analysis of VANETs. In the following of this section, we will discuss analytical modelling of VANETs.

To build a reasonable and extendable analytic model, some assumptions should be made because real-world radio networks are influenced by many factors. Figure 3 illustrates how a typical highway topology is abstracted into a one-dimensional VANET. This abstraction is affordable when the network size is very large and mobile nodes are placed with certain finite network density [30].

Under the assumption of the Poisson packet arrival process and using the discrete-time Markov chain, an analytic model is constructed by Ma *et al.* in [31] to characterize the operation of the broadcasting in IEEE 802.11p with respect to VANET. The closed-form solution is provided to obtain the *PDR*. Subsequently, more accurate analytical models [32-24] are improved based on Markov chain with the *M/G/1* queuing in their series works, which is used for deriving the MAC-level and APP-level reliability metrics in the context of different VANET applications.

An empirical model [35] was proposed to derive the reliability metrics and present the MAC-level metrics *PRR* and *PDP* in comparison to the corresponding APP-level metrics *TWR* and awareness probabilities in Fig.4. The model is taking into account the more impacting factors into account such as IEEE 802.11 CSMA, hidden terminal problem, channel fading following *Nakagami-m* distribution with fading factor *m* = 3, concurrent collisions. This analysis is conducted under a highway scenario with a given network parameter settings: Transmission range is 500*m*, Tolerance time window *T* is 1*s*, Data rate is 24 *Mbps*, Beacon generation rate is 10 *packets/s*, the length of beacon is 200 *bytes* and Vehicle density is 200 *vehicles/km*. Fig.4 shows that the *PRR*s and *PDP*s fail to meet reliability requirement (*i.e.*, they should be greater than 0.99) for DSRC safety-critical messaging from MAC-level perspective when vehicular density is up to *200vehicles/km*, *i.e.*, current DSRC cannot satisfy the reliability and QoS requirements from MAC-level prospect.

However, it is observed that the *TWR* and awareness probability (*n*=2, *i.e.*, at least two beacons of 10 broadcasted beacons are received successfully during the life time of message (1 *second*)) are close to 100% as transmission distance is less than 400*m*, which can ensure the reliability of the applications even though the MAC-level reliabilities are not high enough. Awareness probabilities with the increased requirements on numbers of received packets (*n*=3 and *n*=5) decreased rapidly as transmission distance is farther than 400*m*. In the recent analysis [36], these metrics were derived under the challenging highway scenario including the highest vehicle density, the maximum length of beacon, and the worst channel conditions, *etc*. Numerical results illustrate that not only *PRR* and *PDP* decrease, but also *TWR* and awareness probabilities reduce when traffic density increases. It means that the current DSRC may fail to meet the APP-level reliability and QoS requirement for all safety applications under heavy vehicle density scenarios.

To ensure the current DSRC systems to meet the APP-level reliability and QoS requirements for all safety applications, improving the reliability of DSRC itself is undoubtedly a direct way. However, we noticed that the existing APP-level QoS requirements for safety applications are too general to reflect the real constraints for reliable message communications in some situations. The QoS requirements for each safety application should be different because it has its own characteristics under different vehicular communication environments at different time. So we reconsider the QoS requirements for different safety applications.

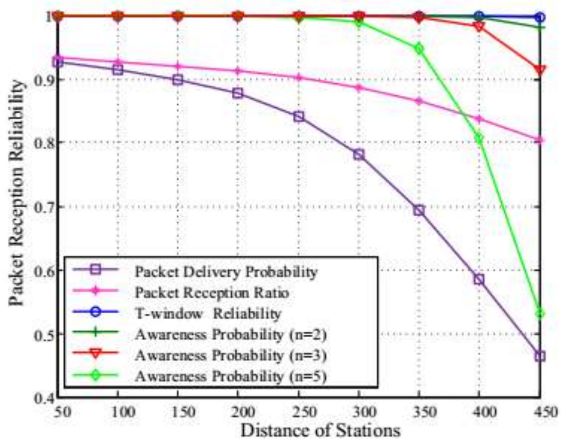


**Fig-4: MAC-level and APP-level reliability of DSRC broadcast with different parameters. Vehicular density is 200v/km, beacon transmission rate is 10 packets/s**

**QoS Evaluation**

Taking the characteristics of various safety applications of DSRC-based VANET and traffic flow into account, we reconsider the APP-level QoS requirements for various safety applications. The QoS requirements should be dynamically changed depending on types of safety applications and different communication situations, which is addressed as the following aspects.

**Different Region of Interest**

The Region of Interest (*ROI*) is the region or maximum effective range surveilled by vehicles associated with a safety application [37]. The range is enough to cover all vehicles related to the safety event and ensure normal operation of this application. Different safety applications should have different *ROI* sizes. For some safety applications, vehicles need to know the status of nearby vehicles, *e.g.*, in rear-end collision warning (*RCW*) application, all the vehicles within 50 meters from the tagged vehicle receive safety message packages sent by tagged vehicle successfully in a tolerance time window might be sufficient. In other words, the *ROI* of *RCW* might be set as 50*m*. This area is smaller than the transmission range of DSRC. However in other safety applications vehicles need to know the status of vehicles far ahead (*e.g.*, *ROI* of cooperation collision warning is up to 400*m*).

The above APP-level QoS metrics can be applied to evaluate DSRC VANET for safety applications via setting the requirements of *ROI*, probability, and APP-level metrics [28]. Therefore, three typical safety applications are chosen to analyse their QoS requirements. The APP-level QoS requirement for *RCW* can be specified as the probability that a vehicle at distance 50*m* from source vehicle successfully receives at least 5 beacons is greater than 99.9%. Similarly, the QoS requirement for cooperation collision warning (*CCW*) is satisfied when the awareness probability that a vehicle successfully receives at least 1 packet is greater than 99.0% under *ROI*=400*m*. Slow vehicle indication (*SVI*) requires that the awareness probability is greater than 99.9% with *ROI* = 100*m* and receiving at least 3 beacons.

As seen from Fig. 4, the *TWR* and the awareness probability meet the QoS requirements of three safety applications in previous section with low vehicle density, respectively. However, the numerical results show that the current IEEE 802.11p is not strong enough to meet the QoS requirements of above three safety applications under heavy traffic situations.

**Uneven Packet Transmission Rates**

For safety applications based on disseminating beacon in DSRC, there are strict beacon transmission rate requirements. Most of safety applications such as *CCW* require 10 *packets/s*, whereas the pre-crash sensing application requires high transmission rate of 50 *packets/s* [38]. Since each kind of safety applications has different *ROI*, only small portion of vehicles within *ROI* requires high rate of packet transmission for reliable delivery of safety messages on time. The vehicles, in the other area that is not closely associated with the safety event, do not have to transmit messages at as high rate as those in the *ROI*. It will cause the possibility of uneven QoS requirements in different areas: high QoS requirements for vehicles in the “hot spot” area (Region where the safety-related event is taking place); and low QoS requirements for vehicles that are not close to the “hot spot” area. Furthermore, reducing the frequency of transmissions from the vehicles not in the “hot spot” area leads to the low interferences to the vehicles in the “hot spot” area. Therefore, the previous analytical assumption of identical transmission rates for all vehicles overestimates the interferences to each receiver in the *ROI*.

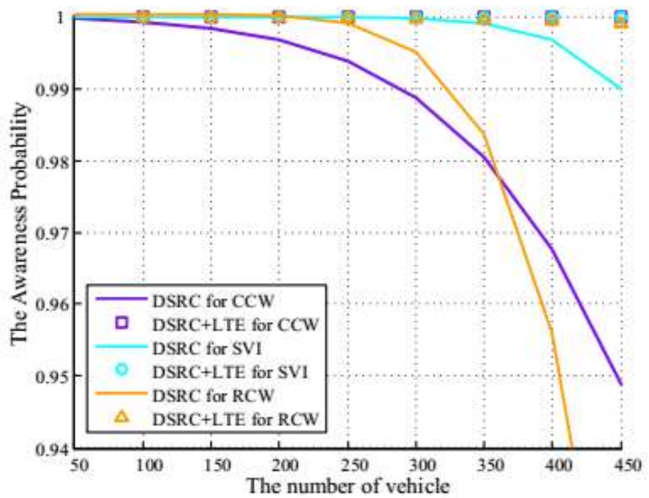


**Fig-5: The application level reliabilities of three safety applications that beacons are transmitted via DSRC alone and via joint DSRC-LTE over the different vehicle density**

**Vehicle Mobility**

Vehicles in VANET normally have high mobility since each individual vehicle has its own velocity and acceleration. Mobility has great impact on network topology in VANETs. The shorter distance between the communication vehicles is and the faster the vehicles move, the more critical QoSs are required. Therefore, the QoS requirements should be determined as a function of vehicle mobility such as vehicle speed and accelerates, driver's reaction time, mutual distances between vehicles, *etc*. For example, in the tolerance time window (T-window) $T_a$, one or serval BSM must be correctly received by a vehicle in a lane-change warning (or blind spot) application. A vehicle is considered having enough fresh information if each associated vehicle has more up-to-date information about its neighbours than the driver. Thus, it can warn the driver if he/she makes any mistake. Given two successive vehicles, $T_a$ must satisfy the following inequality: $T_a(d, V)\leq(d- A_d)/ V$ , where $d$ stands for the inter-vehicle distance, $A_d$ stands for the blind spot radius within which collisions are most likely unavoidable, and $V$ is relative speed. It is obvious that $T_a$ is a dynamic function of communication distance and vehicle relative velocity.

**Correlation between Vehicle Density and Speed**

The typical analyses of VANET QoS and capacity in the context of safety applications assume that high speed of vehicles can take place on road with arbitrary densities of vehicles. Actually, it is unrealistic that vehicles keep high speed with high vehicle density. Drivers will decelerate their vehicles to ensure the driving safety with increasing vehicle density. Vehicles will be stopped when inter-vehicle distance reduces to a certain distance to avoid collision in reality. That means vehicle density depends on speed of vehicles. For example, Greenshields model [36] can be used to describe the relationship between the vehicles' speed and density. This model is expressed as

$$V = V_f\ (1 - K/ K_j) \qquad (3)$$

Where $V$ is the instantaneous speed, $V_f$ denotes the free flow speed, $K$ is the current density, and $K_j$ is the maximum density.

According to the Greenshields model, the vehicles' speed decreases when vehicle density increase, *i.e.* inter-vehicle distance reduces. On the other hand, the braking distance is calculated as

$$Distance = V^2/2a \qquad (4)$$

Where $V$ represents the vehicles speed in *m/s* and $a$ is their acceleration in $m/s^2$. Thus, there is more T-window time at lower speed and higher density. It will allow more safety message packets to be transmitted/received in a T-window time without increasing packet generation rate.

Therefore, taking velocity, density, and time into account, the key parameter of APP-level reliability metrics, T-window time $T_a$, depends on vehicle densities, which can be prolonged in a proper way with increasing densities. As stated in [36], more packets are transmitted/received in the tolerance time window without increasing packet generation rate that would add congestions and collisions in the network, so that the QoS and reliability requirements for safety applications under the worst-case conditions can be satisfied.

**LTE-Assisted DSRC**

As mentioned above, the current DSRC cannot meet QoS requirements for safety applications under heavy vehicle density. The protocol and communication settings of current DSRC may be revised to improve reliability of transmitting/ receiving beacons via DSRC VANET. However, the limited capacity of DSRC system still cannot meet the strict QoS requirements under some situations, where both vehicle traffic and data flow are very heavy.

So, borrowing radio resource of other wireless communication systems for transmitting beacons when dense traffic occurs is proposed to improve reliability of transmitting/receiving beacons in VANET. Obviously, the 3GPP Long Term Evolution (LTE) is an ideal alternative wireless communication system. Analytical model [39] has been proposed to evaluate how many idle radio resource LTE can support to DSRC to transmit beacons. When the DSRC cannot guarantee its reliability due to increasing vehicle density, part of beacons can be transmitted via LTE and the other beacons can still be broadcasted via DSRC in a T-window time, which is called LTE-Assisted DSRC. Fig. 5 shows the APP-level reliabilities of three safety applications (CCW, SVI, RCW) where beacons are transmitted via DSRC alone and via LTE-Assisted DSRC over the different vehicle density. It is obvious that transmitting beacons via DSRC alone fails to meet the QoS requirements of all three applications in previous section when the number of vehicles is greater than 250 *vehicles/km*. Let each vehicle transmit 5 beacons via DSRC and 5 beacons via LTE per second, respectively. A beacon successfully received via LTE is set 0.85. The numerical results indicate the application level reliability of three safety-related applications satisfy their respective QoS requirements even if the number of vehicles is up to 450 *vehicles/km*, which reliability has been significantly improved compared with DSRC alone. But it is worth noting that awareness probability of SVI will be less than 99.9% with same parameters setting when number of vehicle is greater than 450 *vehicles/km*.

Additionally, Huang *et al.* [40] introduce cognitive radio to detect possible other idle spectrum for assisting DSRC to transmission BSMs timely. It provides a new way to improve the reliability of DSRC.

### Future Research

Many researches have manifested that the current DSRC system is away from meeting the required QoS for all potential safety applications under heavy traffic. Therefore, improving the reliability of current VANET to ensure reliable delivery of safety-related messages within diverse traffic conditions and communication environments is one of the future research trends.

At First, improving current DSRC system, designing adaptive and robust broadcast protocol for safety messaging channels in VANET, dynamically optimizing and adjusting network parameters for diverse traffic conditions are possible approaches.

Secondly, reliability metrics and QoS requirements should be reconsidered under heavy traffic flow. Dynamic QoS requirements for individual safety application should be identified, investigated and re-specified in a more accurate way.

Moreover, how to make DSRC work together with LTE seamlessly is our research in the future. We also consider the impact of 5G communication on VANET. Finally, designing cloud structure and cognitive protocol to combine the current DSRC based VANET and other wireless communication systems for safety applications would be also one of the future work.

## CONCLUSION

VANET is the enabling technology that will support many safety applications. In this paper, we first survey and introduce VANETs' safety applications supported by different standards. We then discuss the reliability metrics and QoS requirements for safety applications. VANETs can meet App-level reliability requirements for most safety applications even though MAC-level reliability is not good enough under normal traffic conditions. However, VANETs may not satisfy the reliability requirements of all safety applications in some heavy traffic conditions.

Thus, we suggest specifying the QoS requirements properly and dynamically depending on application types, communication status, and traffic situations. This proposed QoS requirement specification will help derive the optimal parameters using the analytical model. Moreover, we also propose to combine the IEEE 802.11p and other wireless communication systems like LTE, which can improve the VANETs' reliability in safety applications. Performance evaluation illustrates the benefits of LTE-Assisted DSRC, which leads to interesting research and development on VANETs for safety applications.

## ACKNOWLEDGEMENTS

The authors would like to thank the Tai'an Science and Technology Development Plan (guide plan) under Grant 201730338.

## REFERENCES

1. National Highway Traffic Safety Administration. (2014). Traffic Safety Facts, 2010 Data: Young Drivers. *Annals of emergency medicine*, *64*(4), 413.
2. Yearbook, C. S. (2005). China statistics press. *Beijing, China*.
3. Papadimitratos, P., De La Fortelle, A., Evenssen, K., Brignolo, R., & Cosenza, S. (2009). Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation. *IEEE communications magazine*, *47*(11).
4. Ma, X., Yin, X., & Trivedi, K. S. (2012). On the Reliability of Safety Applications in VANETs. *International Journal of Performability Engineering*, *8*(2).
5. UR Rehman, S., Khan, M. A., Zia, T. A., & Zheng, L. (2013). Vehicular Ad-Hoc Networks (VANETs)-An Overview and Challenges. *Journal of Wireless Networking and Communications*, *3*(3), 29-38.
6. Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., & Wang, J. (2014). *Vehicle-to-vehicle communications: Readiness of V2V technology for application* (No. DOT HS 812 014).
7. Das, S., Nandan, A., & Pau, G. (2004, October). Spawn: a swarming protocol for vehicular ad-hoc wireless networks. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks* (pp. 93-94). ACM.
8. Amanna, A. (2009). Overview of IntelliDrive/Vehicle Infrastructure Integration (VII). *VriginiaTech Transportation Institute*.
9. Enkelmann, W. (2003, June). Fleetnet-applications for inter-vehicle communication. In *Intelligent Vehicles Symposium, 2003. Proceedings. IEEE* (pp. 162-167). IEEE.
10. Reichardt, D., Miglietta, M., Moretti, L., Morsink, P., & Schulz, W. (2002, June). CarTALK 2000: Safe and comfortable driving based upon inter-vehicle-communication. In *Intelligent Vehicle Symposium, 2002. IEEE* (Vol. 2, pp. 545-550). IEEE.
11. Festag, A., Noecker, G., Strassberger, M., Lübke, A., Bochow, B., Torrent-Moreno, M., & Kunisch, J. (2008). 'NoW–Network on Wheels': Project objectives, technology and achievements.
12. Takahashi, A., & Asanuma, N. (2000). Introduction of Honda ASV-2 (advanced safety vehicle-phase 2). In *Intelligent Vehicles Symposium, 2000. IV 2000. Proceedings of the IEEE*(pp. 694-701). IEEE.

13. Yousefi, S., Fathy, M., & Benslimane, A. (2007). Performance of beacon safety message dissemination in Vehicular Ad hoc NETworks (VANETs). *Journal of Zhejiang University-Science A*, *8*(12), 1990-2004.
14. Torrent-Moreno, M., Jiang, D., & Hartenstein, H. (2004, October). Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks* (pp. 10-18). ACM.
15. CAMP Vehicle Safety Communications Consortium. (2005). Vehicle safety communications project: Task 3 final report: identify intelligent vehicle safety applications enabled by DSRC. *National Highway Traffic Safety Administration, US Department of Transportation, Washington DC*.
16. Ma, X., Zhang, J., & Wu, T. (2011). Reliability analysis of one-hop safety-critical broadcast services in VANETs. *IEEE transactions on vehicular technology*, *60*(8), 3933-3946.
17. Kenney, J. B. (2011). Dedicated short-range communications (DSRC) standards in the United States. *Proceedings of the IEEE*, *99*(7), 1162-1182.
18. ETSI, E. 300 674-1 v1. 2.1 (2004-08) Electromagnetic compatibility and Radio spectrum Matters (ERM). *Road Transport and Traffic Telematics (RTTT)*.
19. Karagiannis, G., Altintas, O., Ekici, E., Heijenk, G., Jarupan, B., Lin, K., & Weil, T. (2011). Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *IEEE communications surveys & tutorials*, *13*(4), 584-616.
20. Chen, R., Jin, W. L., & Regan, A. (2010). Broadcasting safety information in vehicular networks: issues and approaches. *IEEE network*, *24*(1).
21. Sepulcre, M., Mittag, J., Santi, P., Hartenstein, H., & Gozalvez, J. (2011). Congestion and awareness control in cooperative vehicular systems. *Proceedings of the IEEE*, *99*(7), 1260-1279.
22. Vinel, A., Koucheryavy, Y., Andreev, S., & Staehle, D. (2009, June). Estimation of a successful beacon reception probability in vehicular ad-hoc networks. In *Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing: Connecting the World Wirelessly* (pp. 416-420). ACM.
23. Xu, Q., Mak, T., Ko, J., & Sengupta, R. (2004, October). Vehicle-to-vehicle safety messaging in DSRC. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks* (pp. 19-28). ACM.
24. Uzcátegui, R. A., De Sucre, A. J., & Acosta-Marum, G. (2009). Wave: A tutorial. *IEEE Communications magazine*, *47*(5).
25. Hafeez, K. A., Zhao, L., Ma, B., & Mark, J. W. (2013). Performance analysis and enhancement of the DSRC for VANET's safety applications. *IEEE Transactions on Vehicular Technology*, *62*(7), 3069-3083.
26. Bai, F., & Krishnan, H. (2006, September). Reliability analysis of DSRC wireless communication for vehicle safety applications. In *Intelligent Transportation Systems Conference, 2006. ITSC'06. IEEE* (pp. 355-362). IEEE.
27. Yousefi, S., & Fathy, M. (2008). Metrics for performance evaluation of safety applications in vehicular ad hoc networks. *Transport*, *23*(4), 291-298.
28. An, N., Gaugel, T., & Hartenstein, H. (2011, August). VANET: Is 95% probability of packet reception safe?. In *ITS Telecommunications (ITST), 2011 11th International Conference on* (pp. 113-119). IEEE.
29. Sepulcre, M., & Gozalvez, J. (2011, January). On the importance of application requirements in cooperative vehicular communications. In *Wireless On-Demand Network Systems and Services (WONS), 2011 Eighth International Conference on* (pp. 124-131). IEEE.
30. Chen, X., Refai, H. H., & Ma, X. (2007, November). A quantitative approach to evaluate DSRC highway inter-vehicle safety communication. In *Global Telecommunications Conference, 2007. GLOBECOM'07. IEEE* (pp. 151-155). IEEE.
31. Ma, X., & Chen, X. (2007). Saturation performance of IEEE 802.11 broadcast networks. *IEEE Communications Letters*, *11*(8).
32. Ma, X., Chen, X., & Refai, H. H. (2008, November). On the broadcast packet reception rates in one-dimensional MANETs. In *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE* (pp. 1-5). IEEE.
33. Ma, X., & Chen, X. (2007, May). Delay and broadcast reception rates of highway safety applications in vehicular ad hoc networks. In *2007 Mobile networking for vehicular environments* (pp. 85-90). IEEE.
34. Yin, X., Ma, X., Trivedi, K. S., & Vinel, A. (2014). Performance and reliability evaluation of BSM broadcasting in DSRC with multi-channel schemes. *IEEE Transactions on Computers*, *63*(12), 3101-3113.
35. Ma, X., Yin, X., Wilson, M., & Trivedi, K. S. (2013, January). MAC and application-level broadcast reliability in vanets with channel fading. In *Computing, Networking and Communications (ICNC), 2013 International Conference on* (pp. 756-761). IEEE.
36. Li, W., Wu, J., Ma, X., & Zhang, Z. (2014, June). On reliability requirement for BSM broadcast for safety applications in DSRC system. In *Intelligent Vehicles Symposium Proceedings, 2014 IEEE* (pp. 946-950). IEEE.

37. Bai, F., Elbatt, T., Hollan, G., Krishnan, H., & Sadekar, V. (2006, December). Towards characterizing and classifying communication-based automotive applications from a wireless networking perspective. In *Proceedings of IEEE Workshop on Automotive Networking and Applications (AutoNet)* (pp. 1-25).
38. Park, Y., & Kim, H. (2013). Collision control of periodic safety messages with strict messaging frequency requirements. *IEEE transactions on vehicular technology*, *62*(2), 843-852.
39. Li, W., Ma, X., Wu, J., Trivedi, K. S., Huang, X. L., & Liu, Q. (2017). Analytical model and performance evaluation of long-term evolution for vehicle safety services. *IEEE Transactions on Vehicular Technology*, *66*(3), 1926-1939.
40. Huang, X. L., Wu, J., Li, W., Zhang, Z., Zhu, F., & Wu, M. (2016). Historical spectrum sensing data mining for cognitive radio enabled vehicular ad-hoc networks. *IEEE Transactions on Dependable and Secure Computing*, *13*(1), 59-70.