A Runtime Integrity Monitoring Framework for Real-time Relative Positioning Systems Based on GPS and DSRC

Keyvan Ansari, Yanming Feng and Maolin Tang, *Senior Member, IEEE*

***Abstract*—This paper provides a three-layered framework to monitor the positioning performance requirements of Real-time Relative Positioning (RRP) systems of the Cooperative Intelligent Transport Systems (C-ITS) that support Cooperative Collision Warning (CCW) applications. These applications exploit state data of surrounding vehicles obtained solely from the Global Positioning System (GPS) and Dedicated Short-Range Communications (DSRC) units without using other sensors. To this end, the paper argues the need for the GPS/DSRC-based RRP systems to have an autonomous monitoring mechanism, since the operation of CCW applications is meant to augment safety on roads. The advantages of autonomous integrity monitoring are essential and integral to any safety-of-life system. The autonomous integrity monitoring framework proposed necessitates the RRP systems to detect/predict the unavailability of their sub-systems and of the integrity monitoring module itself, and, if available, to account for effects of data link delays and breakages of DSRC links, as well as of faulty measurement sources of GPS and/or integrated augmentation positioning systems, before the information used for safety warnings/alarms becomes unavailable, unreliable, inaccurate or misleading. Hence, a monitoring framework using a tight integration and correlation approach is proposed for instantaneous reliability assessment of the RRP systems. Ultimately, using the proposed framework, the RRP systems will provide timely alerts to users when the RRP solutions cannot be trusted or used for the intended operation.**

***Index Terms*— DSRC; NTRIP; Relative-Positioning; RTCM; RTK; V2I; V2V**

I. Introduction

INTELLIGENT TRANSPORTATION SYSTEMS (ITS) attract remarkable investment flows from industry, academia and governments, for the development of safety and traffic management applications to be used by cooperative vehicles and road infrastructure, over and above autonomous systems. Several onboard autonomous systems such as radar and ultrasound ranging sensors, as well as imaging and video processing technologies, are already integrated within the architectures of ITS. In addition to these stand-alone technologies, Cooperative ITS (C-ITS) utilize a wide range of international standards and technologies for navigation, communications and networking, and computation to support safety-of-life applications. The fundamental enabling technology of C-ITS services is the Vehicular Ad-hoc Networks (VANETs) which facilitate inter-vehicle wireless communications and networking. C-ITS include technologies such as satellite positioning (e.g. Global Positioning System – Real-Time Kinematic (GPS – RTK)), cellular communications (e.g. 3G and 4G), and Wireless Access in Vehicular Environments (WAVE) communications (e.g. 5.9 GHz Dedicated Short Range Communications–DSRC).

C-ITS utilize combined communications-and-positioning units, On-Board Units (OBUs) and Road-Side Units (RSUs), which may participate in Vehicle-to-Vehicle (V2V) and/or Vehicle-to-Infrastructure (V2I) communications, since users of C-ITS form VANETs where OBUs and RSUs communicate directly with one another within their radio coverage ranges. Although direct V2V and V2I (termed V2X together) communications improve the communications latency experienced by safety messages, the multi-radio multi-band DSRC technology is designed in such a way as to further meet the latency requirements of safety applications. Nonetheless, C-ITS face a set of engineering challenges fundamentally different to autonomous ITS. A critical challenge is to enable Cooperative Collision Warning (CCW) systems between fast-moving vehicles using the C-ITS technologies, while maintaining a high level of system integrity in all traffic situations, particularly in abnormal scenarios where collisions are more likely to happen.

The Real-time Relative Positioning (RRP) system studied in [1] is an instance of C-ITS, which facilitates CCWs that require a standard deviation (STD) of about 50 cm positioning accuracy [2]. The RRP system provides in-lane-level position accuracy by exchanging GPS raw observation data through Basic Safety Messages (BSMs) of the SAE-J2735 standard. The RRP system consists of various sub-systems, such as V2X DSRC, GPS navigation, RTK using the Networked Transport of RTCM via IP (NTRIP) protocol, and cellular communications, to access positioning correction data from Continuously Operating Reference Stations (CORS). The positioning solutions provided by the RRP system can be

Manuscript received MMMM DD, 2013. This work was supported by the Commonwealth of Australia through the Cooperative Research Centre for Advanced Automotive Technology (AutoCRC) project C3-23. The first author (K. Ansari) is grateful to Queensland University of Technology (QUT) for the financial support through a postgraduate scholarship for his PhD study.

K. Ansari, Y. Feng and M. Tang are with the School of Electrical Engineering and Computer Science, Queensland University of Technology (QUT), Brisbane QLD 4000 Australia (e-mail: k.ansari@qut.edu.au; y.feng@qut.edu.au; m.tang@qut.edu.au).

calculated based on two separate data sources: (1) positioning using the V2V communications channel between pairs of vehicles that particularly uses V2V DSRC and GPS receivers; (2) positioning using V2I communications through either V2I DSRC or terrestrial communications (e.g. 3G/4G), and GPS receivers. The second type of positioning solutions may also benefit from Satellite Based Augmentation Systems (SBAS), but this is not the focus of this study as Australia currently does not have access to any SBAS. The system may further utilize built-in on-board sensors, such as odometers, gyros, radars and vision sensors, to either bridge certain GNSS outage conditions or assist in determining the relative positioning of vehicles. Each epoch positioning solutions achieved from both positioning data streams, if any, will be eventually converged into a single solution.

The RRP systems may face abnormal conditions due to malfunction of their sub-systems. The V2X DSRC sub-system, for instance, may encounter fast fading (especially shadow fading) and Doppler shift, both contributing to packet loss. Similarly, the GPS sub-system is susceptible to unintentional disruptions like signal blockage from buildings which degrade the accuracy of the positioning solutions, while RTK fixed solutions may not be available or reliable at certain circumstances. Other wireless communications technologies integrated into a RRP system, such as Wi-Fi and/or 3G/4G, may face previously unknown problems introducing some levels of uncertainty in position measurements. Each of these sub-systems may underperform for various reasons, leading to overall system failure as they are adopted for highly dynamic environments. Therefore, a major challenge in utilizing the GPS/DSRC-based CCW systems is to adequately evaluate the performance of these mission-critical systems in real time by assessing the performance of both the communications and positioning sub-systems of the RRP system using V2V communications and of the RRP system using V2I communications. If the performance of the positioning solutions does not meet the required performance for expected V2V or V2I safety applications, the safety system must warn the drivers to remove the dependence on the safety system. This is about the integrity of the positioning sub-system, which has not been seriously addressed in the existing literature on V2X safety applications.

The rest of this paper is organized as follows. Section 2 reviews positioning performance requirements of the RRP systems. An overview of the factors degrading the performance of the RRP systems is presented in Section 3. Section 4 provides the results of a series of field experiments using the RRP system, developed by Ansari et al. [1], to analyze the performance of the DSRC sub-system from which the Probability of Message Reception Failure (PMRF) is formulated. PMRF provides the likelihood in which any subject vehicle fails to correctly receive or decode a randomly chosen BSM within a given time frame in various traffic scenarios. The performance of the RTK sub-system of RRP is analyzed in Section 5. Section 6 introduces a novel framework to determine the failure risk of the RRP systems in delivering the required (relative) positioning accuracy. Section 7 concludes this study.

II. Performance Metrics of RRP Systems

A vital capability of all safety systems supporting V2X applications is to estimate the position of a given user with reference to other users. Essentially the RRP systems must provide robust positioning solutions satisfying a benchmark level of consistency, since their failure may lead to collisions. However, no proprietary performance standards have been established for positioning sub-systems of C-ITS used for vehicle safety purposes. One of the efforts in this regard was the suggestion of adopting the Required Navigation Performance (RNP) parameters used in aviation as a starting point [3], although conditions of roads and aviation are very different, due to essentials of signal-in-space performance.

The aviation RNP parameters include accuracy, integrity, continuity and availability, each of which may be differently interpreted by the C-ITS community. The work in [3] also introduced two additional parameters: interoperability and timeliness. However, the most relevant parameters related to integrity are accuracy and availability. In the following subsections, we discuss the concepts of three performance parameters in the RRP context which are offered by RTK approaches.

A. RRP Accuracy

RRP accuracy refers to the degree of conformance of an estimated/measured real-time relative position to a defined reference value at a given time. The typical accuracy requirement for relative V2I lane-level positioning with 95% confidence level is 1.1 meters or better as identified in the Vehicle Safety Communications – Applications (VSC-A) project of the US DOT [4-6]. However, there are safety applications requiring V2V lane-level positioning precision which corresponds to 1 meter or better, with a 95% confidence level, or 0.50 m Root Mean Square (RMS). More generally, 50 cm positioning accuracy is required in both absolute and relative senses in order to support the V2V and V2I lane level safety applications.

Consequently, positioning precision provided by stand-alone GPS receivers and/or most of the augmentation techniques such as Differential GPS is inadequate for cooperative vehicular

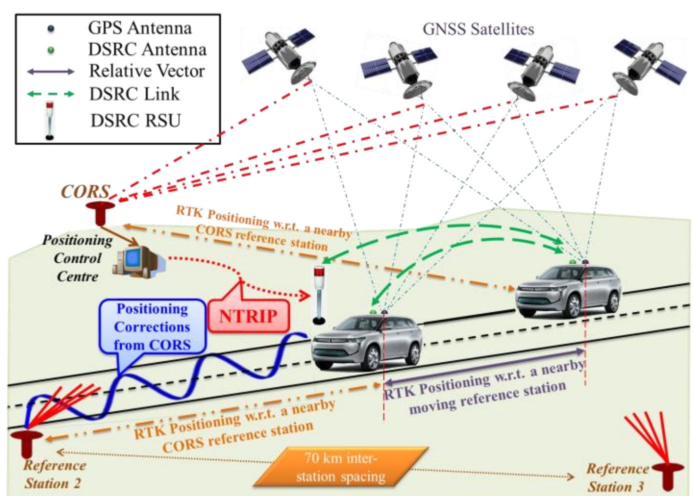

Fig. 1. Concepts of RTK positioning (not to scale)

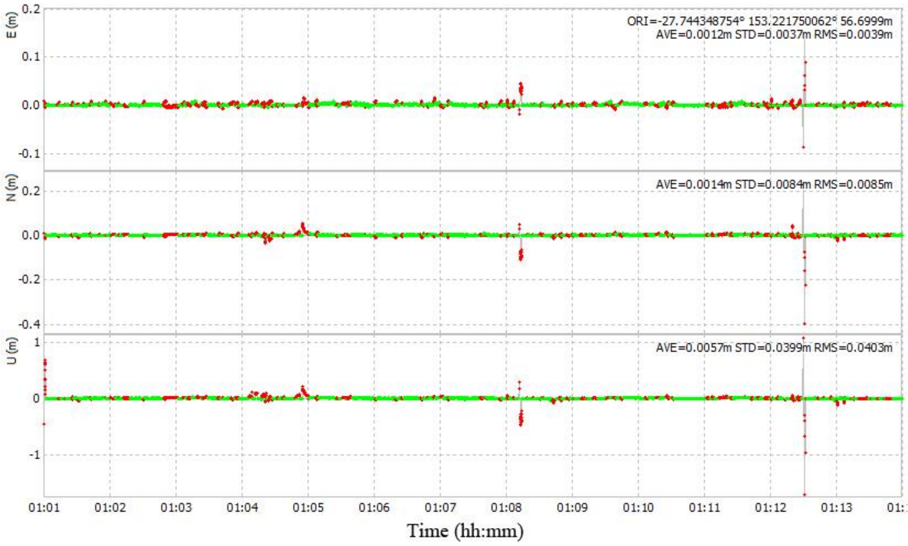

Fig. 2. Forward RTK positioning using a nearby CORS station (green dots represent fixed solutions – red dots represent float solutions)

environments. A range of precise positioning techniques have been used in the USA and Europe to support C-ITS, including Satellite Based Augmentation Systems (SBAS), network RTK systems and V2V RTK positioning. SBAS can marginally meet the lane-level V2X applications in the USA and Europe. But worldwide the network-RTK techniques are more widely available; the network-RTK techniques seem to be the choice to meet the positioning accuracy of road users. Therefore, the RRP in this context is based on RTK techniques. There are two RTK positioning modes available in the vehicular environment: (1) RTK with respect to a CORS receiver which can be a virtual station of the network or a single–base receiver located nearby; (2) RTK with respect to a nearby vehicle receiver as a moving reference station. Fig. 1 (not to scale) represents the concepts of both RTK positioning modes.

We now examine the performance of RTK solutions through examples in both modes in terms of their accuracies. The post-processing RTK with forward and backward filters is used to provide a reference trajectory for evaluation of the forward RTK solutions from both modes, i.e. RTK positioning w.r.t. a nearby CORS station and RTK positioning w.r.t. a nearby vehicle as a moving reference station. The backward RTK solutions have shown good consistency with the integrated RTK and Inertial Navigation System (INS) solutions, and were available for this study to establish the reference trajectories of both vehicles. The data can be filtered forward to be convergent and then filtered backward to eliminate the convergence procedure, and eventually homogeneous high accuracy positioning results can be obtained.

As numerical examples, Fig. 2 reflects the results of RTK positioning using a nearby CORS reference station; Fig. 3 illustrates the positioning precision of RTK using a neighbor vehicle as a moving reference station (known as moving-based relative RTK). Based on the results concluded by Ansari et al. [1], Table I gives a comparison between the techniques of post-processing combined-RTK (forward and backward) with a nearby CORS reference station used as the benchmark solution versus real-time single-base RTK using the same CORS station. The results represented in Fig. 2, Fig. 3 and Table I were collected from experimental settings within which the CORS reference station used was located within 5 km of the road where the rovers travelled with dual-frequency receivers. This reference station is part of the QLD CORS network. Note that the solutions represented in Fig. 2 and Fig. 3 are only samples, which are selected to illustrate the possible difficulties in supporting the stringent positioning requirement of C-ITS applications. Also note that the positioning algorithms used may achieve slightly different accuracy levels; the difference, if commercial algorithms are used, is mostly not significant though.

Fig. 2 indeed shows the good consistency between the standard RTK solutions with respect to the benchmark RTK solutions. In the worst cases, the horizontal errors are confined within +/-50 centimeters. The problem is that the errors of RTK with a mobile reference station, as shown in Fig. 3, often exceed the range of +/-50 centimeters; this indicates that monitoring the faults of the solutions is a much more serious problem, although the availability of RRP solutions could be significantly improved through algorithm design.

B. RRP Availability

RRP availability includes the percentage of time during which both cooperative positioning solutions (RRP) at a certain accuracy level and DSRC data links between a host vehicle and a targeted neighbor vehicle are available. The availability of precise RRP solutions further depends on the availability of both GPS signals and RTK solutions in terms of accuracy and ambiguity resolution reliability. Referring to the RTK solutions

TABLE I
ACCURACY OF SINGLE-BASE FORWARD RTK PROCESSING USING A NEARBY CORS STATION (CORRESPONDING TO FIG. 2)

All RTK Solutions (Fixed and Float)	E-W Bias (m)	N-S Bias (m)
Average	0.0029	0.0025
STD	0.0157	0.0319
RMS	0.0160	0.0320

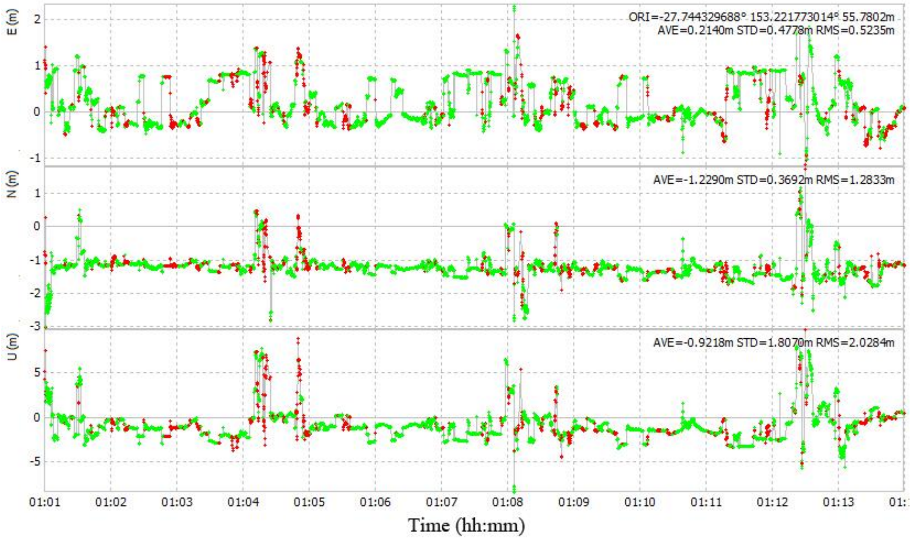

Fig. 3. Forward RTK positioning using a nearby vehicle as moving reference station (green dots represent fixed solutions – red dots represent float solutions)

shown in Fig. 2, the availability of forward RTK solutions at 0.05 m, 0.50 m and 1.0 m accuracies are 97.68%, 99.69% and 99.97% respectively for 2D positioning. Note that although the RRP solutions at required RMS accuracy of 0.50 m may not be available at 100% of the time (the availability of the moving-based RTK positioning at the require RMS accuracy is much lower than that of the RTK positioning using a CORS reference station), the RRP system will still be useful to the safety applications. This metric will be studied in more details for both DSRC and RTK positioning in Section 4 and Section 5 respectively.

C. RRP Integrity

RRP Integrity is related to the level of confidence in the information provided by the RRP system. The benchmark level of positioning consistency has to be determined, based on the type of applications supported by the safety systems; the integrity requirements of RRP solutions are different from a C-ITS application to another because different C-ITS applications require different positioning accuracy levels. Users must be provided with timely warnings when the overall performance of the system may be degraded and the obligatory positioning accuracy requisites cannot be met for the intended operation, such as when a given integrity risk threshold is met while the positioning error exceeds Horizontal/Vertical Protection Levels (HPL/VPL) within a predefined time to alert.

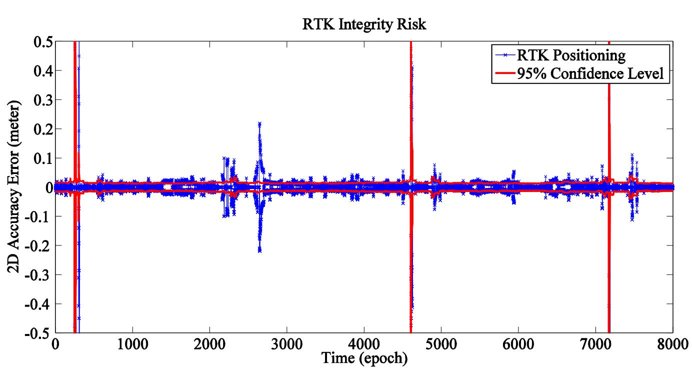

Fig. 4. Integrity risk involved in RTK positioning

Fig. 4 features the integrity risks and false alarms, which may not be detected if only the quality indications provided by positioning software are used. According to Table II, false alarms may happen when the 95% confidence level for a particular epoch is more than HPL (e.g. 0.1 m) but the actual positioning error does not exceed HPL. False alarms are not hazardous but need to be detected. On the other hand, integrity risks, which are hazardous to the safety of users, occur when the 95% confidence level for a particular epoch is less than both the actual calculated positioning accuracy error and HPL, and the positioning error exceeds HPL (e.g. 0.1 m). This is a serious problem and must be detected by safety systems. There are two other inconsistencies between the quality indications provided by positioning software and the actual positioning errors. Near-missed cases occur when the 95% confidence level for a particular epoch is determined less than the actual accuracy error and either HPL is greater than both the positioning error and the 95% confidence level for the same epoch (near-missed reliable solution), or HPL is less than both the positioning error and the 95% confidence level for the same epoch (near-missed error detected solution). The existence of the near-missed cases may represent the inherent behavior of the system in generating false alarms and/or not detecting errors (integrity risk).

Improving the accuracy and availability of RRP solutions, as a research and engineering task, is never out of date. For the safety-of-life applications, it is most important that the

TABLE II
STATES OF POSITIONING SOLUTIONS

PE vs CL	**PE vs HPL**	**CL vs HPL**	**Positioning Solution Status**
PE < CL	PE < HPL	CL < HPL	Reliable
		CL > HPL	False Alarm
PE < CL	PE > HPL	CL > HPL	Error detected
PE > CL	PE < HPL	CL < HPL	Reliable (near-miss)
PE > CL	PE > HPL	CL < HPL	Integrity Risk (error not detected)
		CL > HPL	Error detected (near-miss)
PE = Positioning Error, **CL** = 95% Confidence Level, **HPL**= Horizontal Protection Level			

positioning system be able to inform drivers when the positioning solutions must not be used for safety operation. This is what the integrity is about and what this manuscript is interested in. Integrity monitoring of the RPP solutions is more generally to identify circumstances in which the system should not be used for certain safety operations. An integrity monitoring framework for the RRP systems can be implemented as a three-level process. (1) If the service is considered unavailable (no precise position solution can be determined), integrity monitoring is unnecessary as the system will announce its unavailability for service and no risk associated with the system operation is involved. (2) If the service is claimed to be available, the system must ensure the availability of the integrity monitoring mechanism, such as Receiver Autonomous Integrity Monitoring (RAIM). (3) If the integrity monitoring module is available (more than five satellites are required in order for RAIM to provide service), the module must monitor the integrity requirements in terms of positioning accuracy and report any risk associated with the use of these systems.

Section 6 provides details about the proposed monitoring framework; but before doing so, in the following, the paper conducts a quantitative study of the service availability of 5.9 GHz DSRC affected by necessities of the RRP systems, such as the inclusion of RTCM-1004 binary messages into BSMs, as well as DSRC radio parameters and environment in real driving situations. It also explores the service availability of the absolute RTK positioning (RTK w.r.t. a CORS station delivering corrections via NTRIP or other methods) only, as the availability of moving-based relative RTK of the RRP systems is the same as the availability of the DSRC sub-system. The integrity monitoring framework will use probability propagation algorithms to determine the availability of the system by considering the individual availability of the V2V communications module, the V2I communications module, the positioning module and the RAIM module. For instance, the availability of the positioning sub-system in every epoch is equal to the sum of the availabilities of modules providing positioning solutions (e.g. RTK positioning module, relative RTK positioning module and built-in sensors) within which the sum of the probabilities of reliable solutions, of false alarms, of solutions with detected errors and of solutions with undetected errors must add to 1. Exploring the service availabilities of both communications and positioning sub-systems requires the knowledge of factors degrading the reliability of each sub-system. The following section provides this required knowledge. Regarding the quantitative study, a series of field experiments under various road and environmental conditions where light traffic was present has been conducted using a fleet of cars equipped with the RRP system as per in [1]. The utilized OBUs and RSUs were developed based on the DSRC protocol stack, including the IEEE 802.11p, IEEE 1609.4, IEEE 1609.3 and SAE-J2735 standards, while using a dual-antenna diversity configuration to quantify 5.9 GHz DSRC link quality of the RRP systems using the Message Delivery Ratio (MDR) factor from the perspective of the application layer.

III. Factors Affecting the Performance of RRP Systems

The reliability of each and every GPS/DSRC-based safety system, such as the RRP systems, heavily depends on various characteristics of the DSRC and GPS sub-systems. Therefore, this section studies various factors which challenge each of these sub-systems.

A. *Factors Degrading the Reliability of V2X DSRC Systems*

The DSRC radios used for this study are prototyped based on the common channel arrangements allocated in the US: 7 channels of 10 MHz in the 5.9 GHz frequency band, supporting the DSRC WAVE Short Message (WSM) protocol stack including the IEEE 802.11p standard. IEEE 802.11p adopts Orthogonal Frequency Division Multiplexing (OFDM) modulation technique similar to IEEE 802.11a. Although DSRC implements 48 data subcarriers (plus 4 subcarriers dedicated to carry pilot symbols) [7] as part of its specifications for parallel transmissions, considered adequate for zero-interference links in ideal environments [8], three channel impairment factors commonly destroy the orthogonality of adjacent sub-carries and therefore degrade the reliability of DSRC’s OFDM technique. These include [7, 9]:

- Environmental multipath fading – attenuation
- Environmental Electro-Magnetic Interference (EMI)
- Mobility-related Doppler spread

The presence of large numbers of mobile and stationary objects, including DSRC terminal platforms themselves, such as OBUs and RSUs, within the communications range of WAVE systems creates multiple duplications of a transmitted signal across multiple signal paths. This is known as DSRC multipath propagation [9]. DSRC multipath fading affects individual subcarriers by causing Inter-Symbol Interference (ISI) between successive OFDM symbols. To avoid residual ISI, OFDM considers a Cyclic Prefix (CP) as part of the symbol interval (doubled in 10-MHz DSRC OFDM compared to 20-MHz OFDM PHY) to avoid the overlapping of two successive symbols with each other. Although the extended CP interval of IEEE 802.11p, 1.6 μs, is effective in ISI restoration due to the multipath [9], it introduces some levels of spectrum inefficiency. Although DSRC attenuation (path loss) is not critical to the RRP systems, since their critical range does not exceed 100 m, EMI is another factor affecting DSRC waves in addition to multipath fading. Vehicle velocity introduces frequency shifts in observed wireless signals, the so-called Doppler spread effect, which also affects the sub-carrier orthogonality feature of the OFDM scheme by causing Inter-Carrier Interference (ICI) [10]. To cope with the higher Doppler spreads that exist in VANETs, the IEEE 802.11p subcarrier space, also known as the Guard Band (GB), is halved, compared to 20-MHz OFDM PHY [7].

Accordingly, one limitation of the RRP systems is that rovers may experience a temporary loss of DSRC signals since it is a ground-based communications system. Although the IEEE 802.11p standard (DSRC PHY and MAC) has been already characterized in the literature, this paper formulates the availability of 802.11p links through ample empirical studies by analyzing the performance of the application layer in the next section.

B. Factors Degrading the Performance of Positioning Systems

The GPS has been verified to be the most effective and fully operational navigation and positioning system yet; however the positioning inaccuracy, due to limitations (satellite-related, receiver-related and environment-introduced) that have been forced throughout the system, has to be considered seriously in safety applications. The integrity of any GPS-based safety system can be significantly degraded when used under non-ideal conditions. Various factors lessen the accuracy (closeness to truth) provided by GPS receivers [11]. For RRP over distance of less than 1 km, the key factors include:

- Geometric distribution of the observed satellites (Dilution Of Precision – DOP), including number of satellites
- Availability of DSRC data links
- Noise level of the observations, including multipath
- Positioning algorithms

Other factors such as satellite orbital errors, ionosphere and troposphere are not important for the RRP system. The most common method of GPS integrity monitoring for stand-alone receivers is RAIM, which is a software application embedded into aviation receivers providing integrity by detection and exclusion of GNSS faults [12, 13]. When the RAIM concept is adapted to the RRP solutions, the above factors will limit the RAIM capability. In other words, the RAIM could be unavailable. In this case, the RRP has also to warn the drivers about the system integrity.

IV. Availability of the DSRC Sub-System: Analyzing the Factors Degrading the Reliability

This section aims at deriving a relationship between the 802.11p controllable and environmental uncontrollable factors affecting the DSRC sub-system and the packet-drop probability of a receiving message. This is studied by first analyzing the data collections of BSMs exchanged in various road test experiments using DSRC radios. Through formulation of the affecting factors on DSRC, mathematical expressions and a model are provided for PMRF measure. PMRF computation is derived, based on correlation functions using Joint Probability Distribution (JPD), to determine the availability of the RRP systems in real time. Note that the default values of the transmission power and data rate were set to 20 dBm and 6 Mbps during the field data collection campaigns reflected in this paper, unless stated otherwise.

A. Particular Observations of DSRC Performance

Of the DSRC field test data collection runs, two types of results attract attention. The first is the maximum MDR difference experienced by the leader and follower vehicles

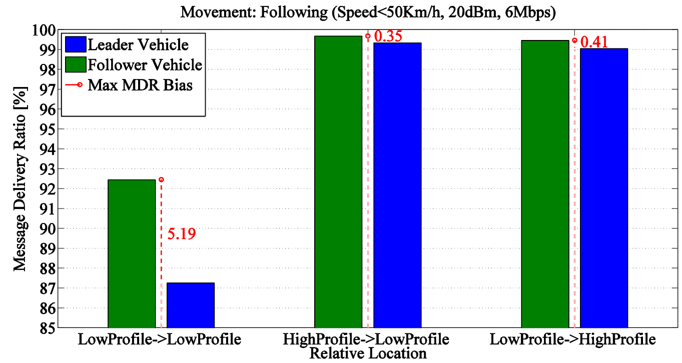

Fig. 5. Max BSM Delivery Ratio Bias at Leading and Following Vehicles (Concurrent Exchange at Straight Road) – (Separation Distance up to 50 m)

traveled on a straight road of almost 400 m long, with a roundabout at each end, with one of the participants a high-profile SUV and the other a low-profile sedan, in comparison with the scenario which both communicating vehicles were low-profile sedans (Fig. 5). Secondly, the maximum MDR difference at the leader and follower vehicles traveled on a curved road where both of the vehicles were low-profile sedans (Fig. 6).

Fig. 5 reveals that the maximum MDR difference at leader and follower vehicles where (1) both vehicles were low-profile sedans, (2) the leader vehicle was a low-profile sedan and the follower was a high-profile SUV and (3) the leader vehicle was a high-profile SUV and follower was a low-profile sedan. The results are concluded from a set of data collected at the same time in the same environmental situations where all the conditions of the road, weather and traffic were identical. Fig. 5 confirms that the MDR at leader vehicles is always lower than at the follower vehicles in scenarios of following movement regardless of the type of vehicles involved in the message exchange setting. This is due to the ICI in 802.11p OFDM of OBUs as carrier synchronization errors and Doppler frequency shifts affect the Bit Error Rate (BER) of the received signals extremely [10]. However, the MDR difference experienced by both parties is at least improved by 4.78% when a high-profile SUV was involved, which means involvement of a high-profile vehicle improves the distribution fairness of BSMs in bidirectional DSRC among two vehicles. One reason for this improvement is that higher antenna elevation increases the effective range of DSRC links. As a general rule of thumb, involvement of a high-profile vehicle results in higher MDR in

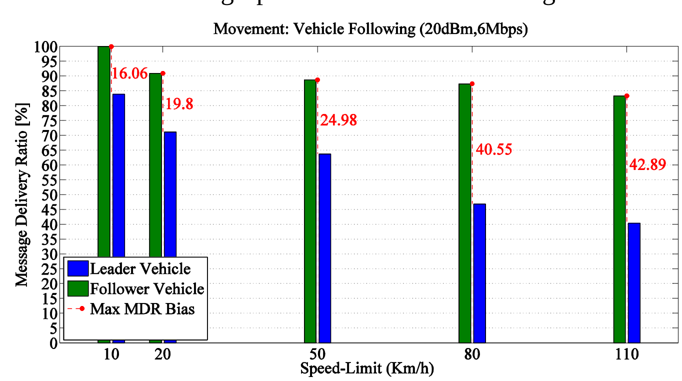

Fig. 6. Max BSM Delivery Ratio Bias at Leading and Following Vehicles (Concurrent Exchange at Curved Road) – (Separation Distance up to 300 m)

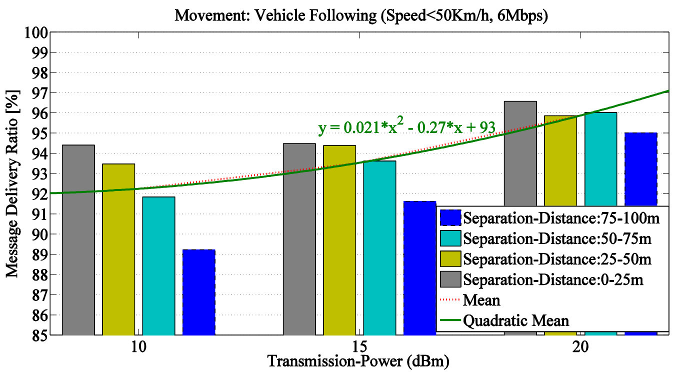

Fig. 7. BSM Delivery Ratio vs. Transmission Power (The quadratic mean model represented here is only illustrative and should not be regarded as final and conclusive.)

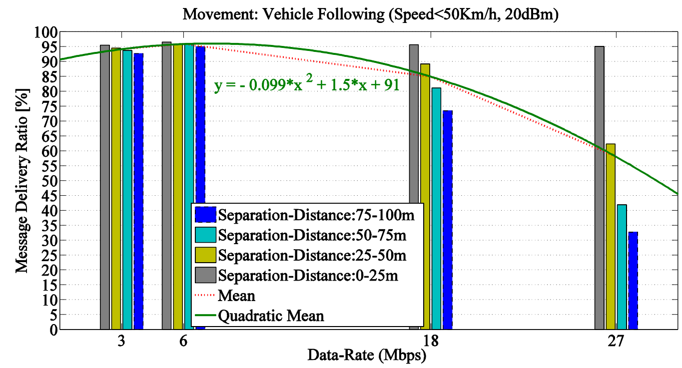

Fig. 8. BSM Delivery Ratio vs. Data Rate (The quadratic mean model represented here is only illustrative and should not be regarded as final and conclusive.)

TABLE III
DIFFERENCE RATIO OF DSRC MDR FOR VARIOUS RADIO POWERS

Transceiver Power	10dBm vs. 15dBm	10dBm vs. 20dBm	15dBm vs. 20dBm
Separation: 0-25m	-0.08%	-2.25%	-2.17%
Separation: 25-50m	-0.97%	-2.49%	-1.53%
Separation: 50-75m	-1.90%	-4.35%	-2.50%
Separation: 75-100m	-2.60%	-6.08%	-3.57%

TABLE IV
DIFFERENCE RATIO OF DSRC MDR FOR VARIOUS DATA RATES

Data Rate	3Mbps vs. 6Mbps	18Mbps vs. 6Mbps	27Mbps vs. 6Mbps
Modulation	BPSK vs. QPSK	16-QAM vs. QPSK	64-QAM vs. QPSK
Separation: 0-25m	-1.14%	-0.93%	-1.51%
Separation: 25-50m	-1.43%	-6.95%	-34.99%
Separation: 50-75m	-2.45%	-15.52%	-56.43%
Separation: 75-100m	-2.43%	-22.70%	-65.60%

comparison with the cases where no high-profile vehicle was involved.

Then again, Fig. 6 confirms that the MDR at leader vehicles are lower than that experienced at the follower vehicle for concurrent exchange periods. One reason for this, other than the channel impairment factors studied above, could be the antenna placement on the vehicles themselves, which requires further research investigation. It is also understood from Fig. 6 that as the road speed limit increases, the maximum gap between the MDR at leader and follower vehicles increases. This is because higher movement speeds make the sub-carrier spacing more sensitive on the Doppler spread. Moreover, the comparison between Fig. 5 and Fig. 6 confirms that both road curvature and separation distance impose some degrees of message loss, though their impact on the leader vehicle is greater. It is argued here that the separation distance is the most affecting factor on Message Error Rate (MER) in safety applications with the 100 m effective range. Therefore, the graphs illustrated in the following subsections have been prepared based on the separation distance factor except for the curvature study where the relative location of vehicles has more influence on MER.

B. DSRC Controllable Factors

This subsection examines the effect of two frequently discussed 802.11p radio configuration parameters, namely transmission power and data modulation rate, on DSRC links of up to 100 m, to derive a statistical model for their effects on the medium. Although both of these parameters are controllable, they affect the characteristics of DSRC links, as some adoptive applications may vary the values of these parameters during the execution of both safety and non-safety applications. To statistically study the effects of DSRC radio transmission power adoption on MDR, controlled experiments were run modifying the amount of radio transmission power value, varying between 10 dBm, 15 dBm and 20 dBm, while the measurement is done for various separation distances between two vehicles driving on rural roads with two lanes.

Fig. 7 demonstrates the MDR factor versus various radio transmission powers studied on the basis of the separation distance between the two vehicles. Although the transmission power ranges from 0 to 33 dBm in increments of 1 dBm, only the three most common values were tested. Two general trends are observable. Firstly, as the power increases towards 20dBm the MDR factor improves, as represented in Table III, however all three power levels can maintain an acceptable level of MDR (more than 90%) for the RRP systems. Secondly, as the separation distance increases the MDR factor decreases due to decrement of the effective range of DSRC radios and Signal-to-Noise Ratio (SNR) loss. Fig. 7 also represents the trend for the mean values of various separation distances, best represented by a quadratic formula, as shown in the figure. The general MDR model of the DSRC Radio Powers (RP) for various separation distances (d) can be represented as $MDR_d^{RP} = a_d^{RP} * RP^2 + b_d^{RP} * RP + c_d^{RP}$.

Fig. 8 demonstrates the MDR factor versus various data rates supported by 802.11p, studied on the basis of the separation distance between the two vehicles. Although 802.11p supports 8 levels of transmission speeds ranging from 3 to 27 Mbps, only four of the common values, including the industry-wide use 6 Mbps, were tested. The results of 3, 18 and 27 Mbps are compared with the result of the 6 Mbps selection in Table IV. The reason why 6 Mbps outperforms both 18 Mbps and 27 Mbps is that QPSK is less vulnerable to noise than both 16- and 64-QAM modulation techniques [9]. Although 6 Mbps

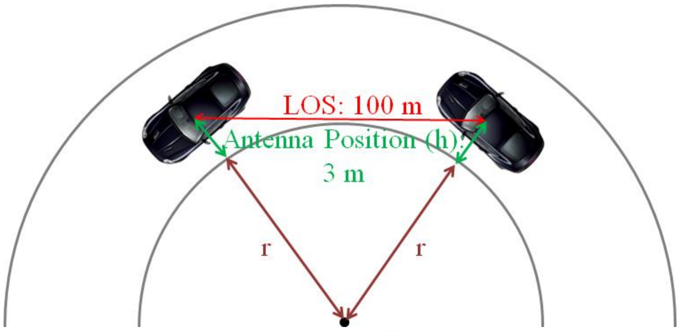

Fig. 9. Road Curvature Affects DSRC LOS

transmission delivers a higher MDR than the 3 Mbps option, the maximum MDR difference between them is less than 2.35% of MDR. As this is already the default data transmission rate, the figure testifies that the 6 Mbps rate delivers the optimum performance. Fig. 8 also represents the trend for the mean values of various separation distances, which most likely is best represented by a quadratic formula as shown in the figure, although the study does not cover all the possible data rates. The general MDR model of the DSRC Data Rates (DR) for various separation distances (d) can be represented as $MDR_{d}^{DR} = a_{d}^{DR} * DR^{2} + b_{d}^{DR} * DR + c_{d}^{DR}$.

C. DSRC Uncontrollable Factors

This subsection examines the effect of three different uncontrollable parameters on DSRC links imposed by road limitations and traffic conditions such as road speed limit and curvature, separation distance of vehicles, and V2V relative speed. The line-of-sight (LOS) distance available to DSRC radios is affected by road geometry. DSRC sight distance must be adequate for individual systems to effectively exchange safety messages before the LOS is blocked by any obstruction on the inside of a horizontal curve. The integrity of the RRP systems is adversely affected by insufficient DSRC sight distance on curved roads. Hence, it is vital to determine the radius ranges of curved roads where their side furniture may cut the longest LOS distance, 100 m, required by the RRP system.

It is assumed that vehicles traveling on curved roads employ DSRC antennas located at least 3 meters away from the road shoulder (h), as shown in Fig. 9. For the configuration shown in the figure, the following formula is used to calculate the upper limit of the radius range that may disturb the necessary LOS distance of the RRP system:

$$(h+r)^{2} = \left(\frac{LOS}{2}\right)^{2} + r^{2}$$

Therefore, if the Curvature Radius (CR) of any road be less than 415.16 m, the DSRC LOS distance of up to 100 m may not be maintained regardless of the road speed. The RRP system has been tested on four different curved roads with up to 400 m CR. The results of the message delivery ratio factor are shown in Fig. 10 for the leader vehicle versus follower vehicle. While testing MDR on the curved road with 20 m radius, two low-profile vehicles traveled at a speed of less than 30 Km/h, whereas the speed of the vehicles slightly exceeded 50 Km/h for the other three tests. Each set of the four tests has been run for at least 10 minutes while the RRP system of each vehicle

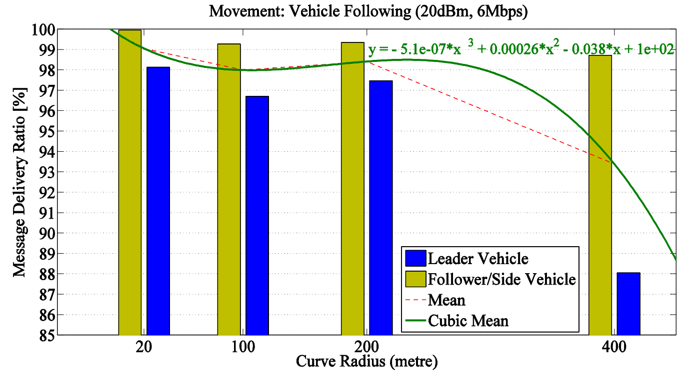

Fig. 10. BSM Delivery Ratio vs. Curve Radius (The cubic mean model represented here is only illustrative and should not be regarded as final and conclusive.)

logged both Tx and Rx BSMs, along with a time stamp for every message.

The red line shown in Fig. 10 corresponds to the trend for the mean values of MDR at leader and follower, which is best represented by a cubic trend, as shown in the figure by the green line and formula. Accordingly, the general MDR model of curved roads with various Curvature Radius (CR) for different relative locations (l) can be represented as $MDR_{l}^{CR} = a_{l}^{CR} * CR^{3} + b_{l}^{CR} * CR^{2} + c_{l}^{CR} * CR + d_{l}^{CR}$.

Fig. 10 emphasizes the fact that MER at the leader vehicle is higher than at the follower vehicle, while the CR may also further increases MER at the leader vehicle. The maximum separation spaces between the two vehicles were 10 m, 40 m, 50 m and 80 m for roads with CR of 20, 100, 200 and 400 meters, respectively.

The maximum LOS available to a pair of DSRC equipped vehicles on roads with CR of 20, 100, 200 and 400 meters are 22.7, 49.3, 69.5 and 98.1 meters, respectively. Therefore, the RRP system has to actively compute the maximum LOS available to the host vehicle and its pairs, based on the current road geometry curvature, while monitoring the relative distance between pairs of vehicles to immediately report any possibility of DSRC link breakage due to road curvature. This mechanism has to be implemented as part of the preliminary checks of PMRF calculation.

Since the road speed-limit factor affects the DSRC Doppler spread, and the relative velocity factor of a Subject Vehicle (SV), compared with those of its pairs ($\vec{V}_{Rltv} = \left|\vec{V}_{SV} - \vec{V}_{Pair}\right|$),

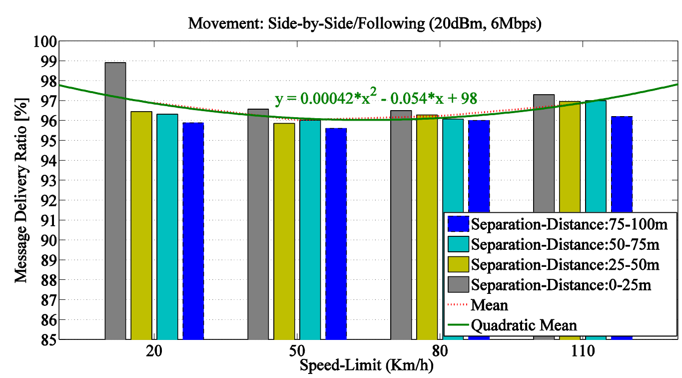

Fig. 11. BSM Delivery Ratio vs. Road Speed Limit (The quadratic mean model represented here is only illustrative and should not be regarded as final and conclusive.)

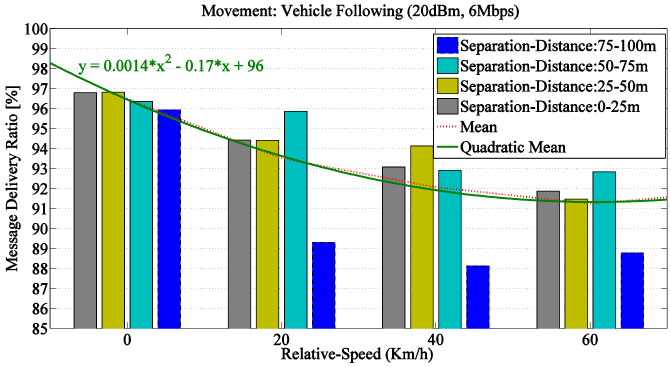

Fig. 12. BSM Delivery Ratio vs. Vehicle Relative Speed (The quadratic mean model represented here is only illustrative and should not be regarded as final and conclusive.)

influences DSRC Doppler shift [8], both factors are considered in calculation of PMRF. Therefore, Fig. 11 plots the MDR of the sample data as a function of absolute speed while Fig. 12 maps MDR as a function of relative speed of a pair of vehicles traveling in the same direction, considering their separation distances. The data samples used in Fig. 11 were selected from measurement campaigns where the environmental and traffic conditions were chosen to be as similar as possible, because the tests were carried out on different roads (with different speeds) and the presented results might be slightly influenced by dissimilar environmental factors.

Fig. 11 and Fig. 12 suggest there are quadratic correlations between MDR and both absolute Speed (SP) and Relative Speed (RS) factors. Unlike the declaration made by Bai et al. [9] that "PDRs of DSRC radios are insensitive to relative velocity for any given separation distance", the results in this study reveal that not only is DSRC MDR affected by vehicles' relative speed (up to 8% loss difference in MDR), but also, as the separation distance between a pair of vehicles with increasing relative speed increases, the DSRC MER increases as well.

The general correlation functions existing between DSRC MDR and Road Speed (SP), as well as Relative Speeds (RS) of vehicles for various separation distances (d) can be respectively represented as $MDR_d^{SP} = a_d^{SP} * SP^2 + b_d^{SP} * SP + c_d^{SP}$ and $MDR_d^{RS} = a_d^{RS} * RS^2 + b_d^{RS} * RS + c_d^{RS}$.

It is worth noting that Fig. 12 represents only data sampled from vehicles traveling in the same direction car-following manner. Therefore, the correlation between MDR and the relative speed of the opposing vehicles cannot be derived from these data samples, as the Doppler shift effect would be different from the case represented here. Yet, studying the recent stated correlation deserves further research attention.

D. Probability of BSM Reception Failure (PMRF): JPD of DSRC Degrading Factors

Since the default radio power and data rate of DSRC units were fixed to 20 dBm and 6 Mbps respectively when DSRC uncontrollable factors were tested, the PMRF measure has to account for only the MER ratio of the in-use parameters, rather than the default parameters, to minimize the effects of the redundant factors. Therefore, the ratio of the in-use radio-power and data-rate values, compared with the MDR values of the cases with the default parameters used ($\frac{MDR_d^{RP}}{MDR_d^{20dBm}}$ and $\frac{MDR_d^{DR}}{MDR_d^{6Mbps}}$), is considered in calculation of the PMRF measure. Hence, **If** CR<415 m:

$$PMRF(RP, DR, CR, SP, RS | d_{Rltv} = d, l_{Rltv} = l) =$$
$$1 - \left(\frac{MDR_d^{RP}}{MDR_d^{20dBm}} * \frac{MDR_d^{DR}}{MDR_d^{6Mbps}} * MDR_l^{CR} * MDR_d^{SP} * MDR_d^{RS} * 10^{-6}\right)$$

where 10<RP<20; DR=3, 4.5, 6, 9, 12, 18, 24 and 27; 20<CR<400; 10<SP<100; 0<RS<60.

Else, **If** CR≥415 m:

$$PMRF(RP, DR, SP, RS | d_{Rltv} = d) =$$
$$1 - \left(\frac{MDR_d^{RP}}{MDR_d^{20dBm}} * \frac{MDR_d^{DR}}{MDR_d^{6Mbps}} * MDR_d^{SP} * MDR_d^{RS} * 10^{-4}\right)$$

where 10<RP<20; DR=3, 4.5, 6, 9, 12, 18, 24 and 27; 10<SP<100; 0<RS<60.

Ultimately the risk evaluation framework, presented in Section 6, utilizes PMRF at time t to calculate the risk for movement of a pair of vehicles at t+1.

V. Availability of the RTK Positioning Sub-System: Analyzing the Factors Degrading the Performance

This section turns the attention of the paper towards the availability of precise positioning to C-ITS using the RTK positioning technique. Because the relative RTK positioning makes use of the communications links established between pairs of vehicles and the raw GPS observations to perform relative positioning, the availability of relative RTK is heavily correlated to that of DSRC (assuming vehicles have unobstructed views to sufficient numbers of GPS satellites). Hence, the focus of this section is only on the availability of the so-called absolute RTK positioning.

High-precision GNSS positioning solutions can be obtained through RTK positioning using carrier phase measurements, once the carrier phase ambiguity of integer cycles has been successfully resolved. GPS as a dual-frequency system had had much attention during the past two decades regarding instantaneous and precise positioning. Nevertheless, the GPS modernization initiative, as well as the advent of GLONASS (and BeiDou), have collectively led to a harmonized multi-frequency GNSS and multi-constellation RTK [14, 15]. As a remarkable result, the multi GNSS constellations have significantly enhanced the resolution of the carrier phase ambiguities [16]. The Ambiguity Resolution (AR) success rate is therefore defined as the probability that an AR model or method (AR processing procedure) successfully fixes the carrier phase ambiguities to their correct integer values [17]. Integer carrier phase AR is fundamental for fast-acquisition and high-precision GNSS positioning [18]. Theoretically, after an AR processing procedure is developed, the success rate of AR can be predicated to assess the strength or the performance of the procedure [19].

Reliable integer AR is crucial to RTK positioning and its applications in the context of C-ITS, because largely biased positioning solutions may be achieved using incorrect ambiguity fixing [19]. In this regard, RTK availability can be assessed based on two principles [20]: (1) RTK availability in terms of the accuracy of position solutions, and (2) RTK availability in terms of the reliability of AR. The first availability principle is referred to as the percentage of time during which the RTK solutions of certain accuracy are available using the ambiguity-fixed and/or ambiguity-float phase measurements. The second availability principle, given all the ambiguity-fixed solutions will provide the required accuracy, is referred to as the percentage of time in which position estimations are all based on the phase measurements to which integers have been correctly fixed at each epoch.

A. RTK Availability in terms of Position Accuracy

An assessment for the performance of the commercial network RTK services over three various triangle networks with long inter-station distances (mean of 69 km, 118 km and 166 km) has been carried out by Wang et al. [21]. The results indicate that RTK positioning accuracy and availability, in terms of accuracy of position solutions, depend on the type of RTK approach being used. For instance, Virtual Reference Station (VRS)-based approaches can perform well under shorter triangle distanced networks (dense CORS networks) but the RTK uncertainty of the VRS systems increases as the distances among the stations increase, resulting in higher position errors of up to 2.5 meters. The potential outliers in RTK positions can be detected using the Coordinate Quality (CQ) values, although over-optimistic values are often provided. If the CQ value is considered 10 times worse than the provided CQ value, the actual 3D position errors will be within the worst CQ value range in (average) 97.52% of times [21]. This probability is increased as the distances between the reference stations decrease. Hence, solutions with CQ values greater than a limit, such as above 100 mm in height and 50 mm in horizontal distance, can be rejected and regarded as unavailable to C-ITS users. The results of the same study revealed that if the VRS method is used with a short distanced network (e.g. mean of 69 km between stations), at least 99% of 3D solutions are correctly estimated within 15 cm of the true position. The 1% failure to meet the threshold is most likely because of unstable floating ambiguity solutions or incorrectly fixed ambiguities.

B. RTK Availability in terms of AR Reliability

An AR processing procedure includes acceptance tests in addition to integer estimation. The so-called ratio-test is a widely held acceptance test. However, it is argued in [18] that the correctness of the integer least-squares solution cannot be tested using the ratio-test with a fixed critical value. Alternatively, the ratio-test is recommended to be used with the fixed failure rate approach [18]. This approach ensures that the AR risk (the probability that an ambiguity is incorrectly fixed to an integer) does not exceed a user-defined value. This approach provides users with control over the failure rate.

C. Monitoring Accuracy of RTK Solutions

This article proposes a measure to be deployed by taking advantage of the flexibility offered by the RRP system introduced in [1]. Since the cooperative vehicles can exchange their raw GNSS data, the relative RTK solutions between vehicles can be obtained. In case fixed-reference RTK solutions are available to the cooperative vehicles, both RTK solutions can verify each other. Timely warnings can be issued if the inconsistency between the two RTK solutions, fixed-base and moving-base, at each epoch of observation reaches an alert limit. One practical implementation issue with this approach, though, is how to provide rovers with truly independent observation data sets for AR verifications.

Using this approach, absolute RTK position solutions with more than 0.5 m error in E-W and/or N-S directions can be detected, and consequently adequate warnings can be issued to drivers. Fig. 13 contains a few number of wrong RTK solutions due to AR, which are inaccurate for V2V lane-level positioning and are identified by numbers 1 to 6; the figure represents the results of absolute RTK w.r.t. a nearby CORS reference station compared to the results of post-processing combined-RTK (forward and backward) using the same CORS station used as the benchmark solution. Any RTK solution having a bias of more than 0.5 m, if not detected, is an integrity risk to the overall system performance. The tests conducted in this study show that the wrong solutions inaccurate for V2V lane-level positioning (possible integrity risks) can be detected in real-time if both RTK solutions (fixed-base and moving-base) are compared against each other and if the differences of E-W and/or N-S components are greater than 2 m (see Fig. 14).

VI. INTEGRITY MONITORING FRAMEWORK FOR THE RRP SYSTEM

As the RRP integrity is a first-order design constraint, this section determines the necessities of a reliable RRP system first and then provides a three-layered integrity monitoring framework, shown in Fig. 15, for continuous RRP operation. The framework aims at monitoring the integrity of the RRP systems during the availability of DSRC and RTK solutions with the required accuracy. To this end, the framework identifies the effects of wrong positioning solutions and concurrently provides timely and valid warnings to users. The integrity requirement parameters can be represented as a quality indicator that includes a pre-defined alert limit, a time to alert and the integrity risk. The development of a fault detection and exclusion mechanism using an Extended Kalman Filter (EKF), along with an integrity risk determination mechanism, dedicated to the GPS/DSRC-based positioning systems is among our future research plans.

A. The Fundamentals of Safety Messaging for Reliable RRP

A high-speed vehicle moves almost 2 meters along its lane within 50 msec, which is not considered a significant movement in high speed roads. BSMs transmitted faster than 20 Hz (every 50 msec) can hardly provide fresh effective information within such a short period, but channel congestion is increased. On the other hand, since the reaction time of

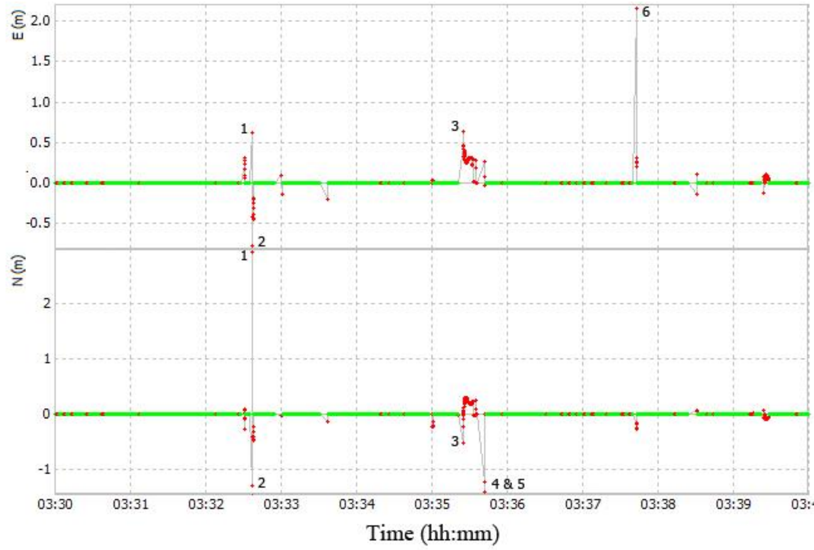

Fig. 13. RTK Positioning: Wrong solutions having a bias of more than 0.5 m are inaccurate for V2V lane-level positioning (green dots represent fixed solutions – red dots represent float solutions)

drivers to any stimuli, such as brake lights, is about 700 msec or longer, any reception interval of BSMs longer than 500 msec would characterize the safety system as being not effective and reliable [22]. Hence, the transmission interval between BSMs must be between 50 msec and 500 msec. A 100 msec mean delay between the transmissions of BSMs (10 Hz) has been agreed by the C-ITS community to be the minimal essential for accurate cooperative (relative) positioning. In this context, accuracy is referred to as a measure of bias that reflects the closeness of a position solution provided by the total system to a reference (true) value. Likewise, integrity is referred to as a measure of trust that reflects the correctness of a position solution provided by the total system.

B. Reliability Monitoring

Statistical quality control of C-ITS, the theory supporting this quality control, and its applications are key research topics in the field of CCW systems, but are as yet under-discussed. An integrity risk assessment model for C-ITS performance quality control can be developed based on the present situation and dynamics of vehicles. Each one of the vehicles traveling together within a certain separation distance (e.g. 100 m) must firstly ensure the availability of the subsystems of its RRP system; for instance, they calculate the risk level (probability) of not receiving BSMs or messages essential to perform relative RTK positioning from the surrounding vehicles. Employing PMRF, introduced in Section 4, for real-time DSRC characterization as a multi-layer media helps to account for all parameters of the various communications layers affecting the overall medium performance. This employment is in the layer monitoring the 'system availability' in Fig. 15. The effects of receiving imprecise measurements from the surrounding vehicles, or AR state change, or wrong AR, can be detected using the RTK cross-check approach introduced in Section 5. However, this mechanism can only detect biased solutions and ensure the availability of RTK positioning in terms of accuracy

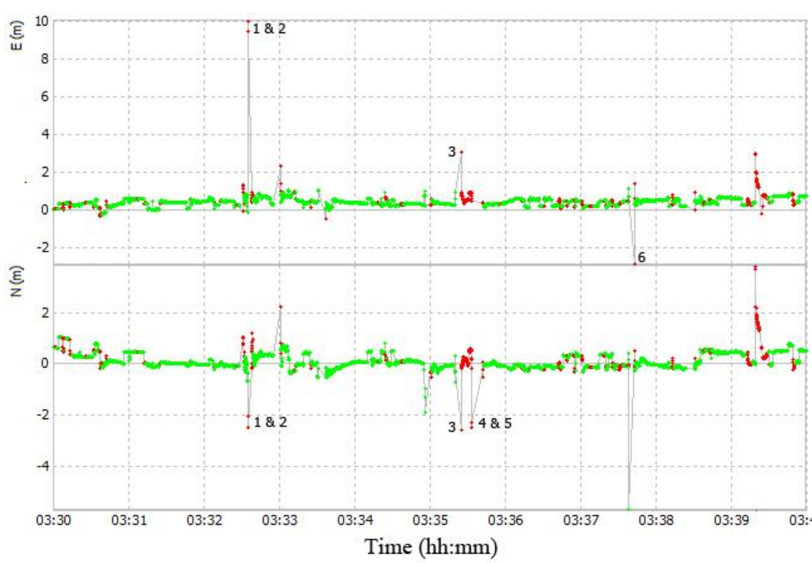

Fig. 14. RTK Positioning: Detection of wrong solutions inaccurate for V2V lane-level positioning in real-time (green dots represent fixed solutions – red dots represent float solutions)

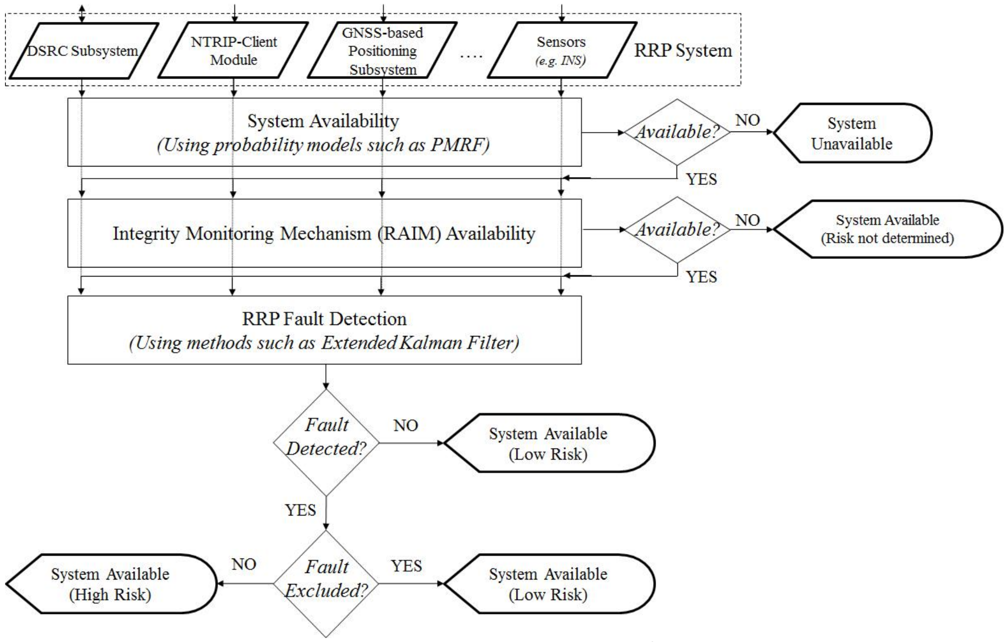

Fig. 15. Integrity Monitoring Framework for RRP

(within the 'system availability' layer), but it cannot detect the source of the errors and cannot exclude the faults. Although the RRP systems have various input modules, such as DSRC radios, NTRIP-Client, GNSS receivers and Inertial Navigation System (INS) sensors, not the unavailability of each and every of them may result in the unavailability of the entire system. For instance, if the DSRC, NTRIP-Client and GNSS receiver modules are available, except the INS sensors, the RRP service may still be available to the users. If the overall system is not available, the system will announce its unavailability for service, and no integrity risk is associated with the system operation. Secondly, if the RRP service is available, the system must ensure the availability of the integrity monitoring mechanism within the second layer in Fig. 15. This mechanism may not be available if less than a certain number of satellites are visible to the system. If the integrity monitoring mechanism is not available, the risk associated with the system use cannot be determined, so the user must be notified. Note that even if the risk is not determined, most of the solutions are not faulty and the system can be used by drivers. Thirdly, if the integrity monitoring mechanism, while is available, detects any fault in the solutions provided by the system, and cannot exclude the fault, using the system involves high risks.

The quality assessment is actively updated as new information is received, or at a fixed rate (e.g. every 50 msec), to detect any integrity risk by comparing the quality value to a given system failure threshold (alert limit). This model can be deployed as an advisory system only when the current risk assessment value exceeds the pre-defined alert limit. Accordingly, the user will be notified about the existence of uncertainty in the overall system performance. The proposed model does not enforce any type of action to be taken by the user, although it is advisable for users not to rely on the system for the determined periods including uncertainty.

VII. Conclusions

The Real-time Relative Positioning (RRP) systems improve the precision of DSRC-based safety warnings to drivers by adopting the 5.9 GHz DSRC technology to distribute positioning correction data and GPS raw observation data in order to attain a RRP map of neighbors in real-time. The major contribution of this paper in the improvement of the RRP systems is twofold: (1) the introduction of a runtime integrity monitoring framework for the RRP Systems; (2) the development of a probability model for inter-vehicles message reception (DSRC availability monitoring) based on actual communications data from measurement campaigns, and of an availability (in terms of accuracy) monitoring mechanism for RTK positioning.

The integrity monitoring framework for the RRP systems is proposed as a three-layered process. (1) Monitoring the availability of sub-systems using the developed DSRC/RTK availability monitoring mechanisms. (2) Monitoring the availability of the integrity monitoring mechanism, RAIM, itself. (3) Monitoring the integrity requirements in terms of the positioning accuracy using RAIM and report any risk associated with the system use. Through empirical measurements by which about one hundred thousand BSMs were collected using the RRP systems, this paper analyzed the impacts of a number of radio parameters and environmental factors on DSRC characteristics in order to establish a system integrity monitoring framework for C-ITS. While careful attention has been paid to ensure that the scenario design, data collections and sample selections are as comprehensive, systematic and independent as possible, it can be stated that some incontrollable and/or redundant factors play roles in the correlations established between DSRC MDR and the determined DSRC affecting factors. It is obvious that, under crowded/saturated vehicular conditions, the reception probability of BSMs is lessened, this reduction rate is not yet experimentally studied in real-world scenarios based on the separation distances between vehicles (e.g. up to 100 m). Hence the PMRF has essentially to consider the network busy ratio where some priority access control or radio power adjusting measures may also be utilized for topology control purposes. The RTK cross-check approach used in this study has proven to be sufficiently effective in detecting imprecise solutions for C-ITS safety applications; however, using other validation techniques is also suggested.

REFERENCES

1. Ansari, K., et al. *Vehicle-to-Vehicle Real-Time Relative Positioning Using 5.9 GHz DSRC Media*. in *Proceedings of IEEE 78th Vehicular Technology Conference, VTC 2013-Fall*. 2013. Las Vegas, USA: IEEE.
2. Shladover, S.E. and S.-K. Tan, *Analysis of Vehicle Positioning Accuracy Requirements for Communication-Based Cooperative Collision Warning.* Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 2006. **10**(3): p. 131-140.
3. ARRB-Project-Team, *Vehicle Positioning for C-ITS in Australia (Background Document)*, in *Austroads Research Report*, D. Green, et al., Editors. 2013, Austroads Ltd. Austroads Project No. NT1632, Austroads Publication No. APR431-13. p. 88.
4. Basnayake, C., *Positioning for Driver Assistance: Communication on the Road.* GPS World, 2009. **20**(4): p. 28-36.
5. Basnayake, C., G. Lachapelle, and J. Bancroft. *Relative Positioning for Vehicle-to-Vehicle Communications-Enabled Vehicle Safety Applications*. in *Proceedings of The 18th ITS World Congress*. 2011. Orlando, Florida.
6. Basnayake, C., et al., *Can GNSS Drive V2X?* GPS World, 2010. **21**: p. 35-43.
7. Li, Y.J., *An Overview of the DSRC/WAVE Technology*, in *Quality, Reliability, Security and Robustness in Heterogeneous Networks*, X. Zhang and D. Qiao, Editors. 2012, Springer Berlin Heidelberg. p. 544 - 558
8. Cheng, L., et al., *A Measurement Study of Time-Scaled 802.11a Waveforms Over The Mobile-to-Mobile Vehicular Channel at 5.9 GHz.* IEEE Communications Magazine, 2008. **46**(5): p. 84-91.
9. Bai, F., D.D. Stancil, and H. Krishnan, *Toward understanding characteristics of dedicated short range communications (DSRC) from a perspective of vehicular network engineers*, in *Proceedings of the sixteenth annual international conference on Mobile computing and networking, MobiCom '10.* 2010, ACM Chicago, Illinois, USA. p. 329 - 340.
10. Zhao, Y. and S.G. Haggman, *Sensitivity to Doppler shift and carrier frequency errors in OFDM systems-the consequences and solutions*, in *The 46th IEEE Vehicular Technology Conference, Mobile Technology for the Human Race.* 1996. p. 1564-1568.
11. Chrzanowski, A. and Y.Q. Chen, *Modeling of GPS systematic errors in monitoring and control surveys.* Journal of Surveying Engineering 1994. **120**(4): p. 145 - 155.
12. Hewitson, S. and J. Wang, *GNSS receiver autonomous integrity monitoring (RAIM) performance analysis.* GPS Solut, 2006. **10**(3): p. 155 – 170.
13. Civil-Aviation-Safety-Authority, *Navigation using Global Navigation Satellite Systems (GNSS)*. 2006, Civil Aviation Advisory Publication.
14. He, H., et al., *Performance assessment of single- and dual-frequency BeiDou/GPS single-epoch kinematic positioning.* GPS Solutions, 2014. **18**(3): p. 393-403.
15. Carcanague, S., *Low-cost GPS/GLONASS Precise Positioning in Constrained Environment* 2013, Institut National Polytechnique de Toulouse.
16. Verhagen, S., P. Teunissen, and D. Odijk, *Carrier-phase Ambiguity Success Rates for Integrated GPS-Galileo Satellite Navigation*, in *Proceedings Space, Aeronautical and Navigational Electronics Symposium, SANE2007*. 2007: Japan: Institute of Electronics, Information and Communication Engineers (IEICE). p. 139-144.
17. Feng, Y. and J. Wang, *Computed success rates of various carrier phase integer estimation solutions and their comparison with statistical success rates.* Journal of Geodesy, 2011. **85**(2): p. 93-103.
18. Teunissen, P.J.G. and S. Verhagen, *The GNSS ambiguity ratio-test revisited: a better way of using it.* Survey Review, 2009. **41**(312): p. 138-151.
19. Wang, J. and Y. Feng, *Reliability of partial ambiguity fixing with multiple GNSS constellations.* Journal of Geodesy, 2013. **87**(1): p. 1-14.
20. Feng, Y. and J. Wang, *GPS RTK Performance Characteristics and Analysis.* Journal of Global Positioning Systems, 2008. **7**(1): p. 1-8.
21. Wang, C., et al., *Assessment of commercial network RTK user positioning performance over long inter-station distances.* Journal of Global Positioning Systems, 2010. **9**(1): p. 78-89.
22. Xu, Q., et al., *Vehicle-to-Vehicle Safety Messaging in DSRC* in *Proceedings of the 1st ACM Workshop on Vehicular Ad hoc Networks (VANET '04)*. 2004, ACM: Philadelphia, PA, USA. p. 19-28.

Keyvan Ansari is an associate lecturer at the School of Electrical Engineering and Computer Science, Queensland University of Technology (QUT), Australia. He earned his PhD degree in Computer Science at QUT in 2014 and received his Master of Information Technology (Honors) degree from the University of Newcastle, Australia, in 2009 and his Bachelor of Computer Engineering degree from Sadjad University of Technology, Iran, in 2006. His current research interests include inter-vehicle communications and positioning techniques, integrated systems for intelligent transport safety applications, and requirements engineering and management, as well as multimedia data mining. He has served on the technical program committees for several international conferences and as a reviewer for a number of international journals and magazines.

This manuscript is a part of his doctoral study in vehicular positioning using Dedicated Short Range Communications (DSRC) at QUT. His PhD study was under the financial support of the Australian Cooperative Research Centre for Advanced Automotive Technology (AutoCRC), project C3-23.

Yanming Feng received his PhD degree in satellite geodesy from Wuhan Technical University of Surveying and Mapping (merged into Wuhan University in 2000), China. He is currently a Professor in Global Navigation Satellite Systems at the School of Electrical Engineering and Computer Science, Queensland University of Technology, Australia. He has served as a project leader within Cooperative Research Centre for Spatial Information and Cooperative Research Centre for Automotive Technologies. His active research interests have included satellite orbit determination, wide area GNSS positioning, GNSS integrity determination, multiple GNSS data processing algorithms, and Dedicated Short-Range Communications for road safety applications. He is the Editor-in-Chief for The Journal of Global Positioning Systems.

Maolin Tang is a senior lecturer at the School of Electrical Engineering and Computer Science, Queensland University of Technology, Australia. He has a PhD in Computer Systems Engineering from Edith Cowan University, Australia, a Master of Computer Science from Chongqing University, China, and a Bachelor of Computer Science from Huazhong University of Science and Technology, China. His current major research interests include Evolutionary Computation and Cloud Computing, in particular Applications of Evolutionary Computation in Cloud Computing. He has published many refereed papers in prestigious journals and international conference proceedings. He has been a reviewer for a number of international journals, a program committee member for many international conferences, and a senior member of IEEE.