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Design of an Integration Platform for V2X Wireless Communications and Positioning Supporting C-ITS Safety Applications

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Abstract

In this paper, an integrated inter-vehicles wireless communications and positioning system supporting alternate positioning techniques is proposed to meet the requirements of safety applications of Cooperative Intelligent Transportation Systems (C-ITS). Recent advances have repeatedly demonstrated that road safety problems can be to a large extent addressed via a range of technologies including wireless communications and positioning in vehicular environments. The novel communication stack utilizing a dedicated frequency spectrum (e.g. at 5.9 GHz band), known as Dedicated Short-Range Communications (DSRC), has been particularly designed for Wireless Access in Vehicular Environments (WAVE) to support safety applications in highly dynamic environments. Global Navigation Satellite Systems (GNSS) is another essential enabler to support safety on rail and roads. Although current vehicle navigation systems such as single frequency Global Positioning System (GPS) receivers can provide route guidance with 5-10 meters (road-level) position accuracy, positioning systems utilized in C-ITS must provide position solutions with lane-level and even in-lane-level accuracies based on the requirements of safety applications. This article reviews the issues and technical approaches that are involved in designing a vehicular safety communications and positioning architecture; it also provides technological solutions to further improve vehicular safety by integrating the DSRC and GNSS-based positioning technologies.

Keywords: Communications Architecture, Cooperative Systems, DSRC, GPS, IEEE 802.11p, Positioning Architecture, Vehicle-to-Vehicle Communications, Vehicle-to-Infrastructure Communications

1. Introduction and Motivation

Road crashes all over the globe have continued to cause drastic numbers of deaths and dire economic losses each year. During the past decade, the concept of 'Vision Zero' has been promoted in many countries such as Sweden regarding road/rail fatalities, congestion and emissions by utilizing Intelligent Transportation Systems (ITS) and their underlying technologies (Cook, Kolmanovsky, McNamara, Nelson, & Prasad, 2007; Elvik, 1999). In this regard, Cooperative ITS (C-ITS) employ Vehicular Ad-hoc Networks (VANETs), Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications (together known as V2X), along with vehicle navigation/positioning systems. C-ITS connect and locate vehicles, terrestrial travelers and the transport infrastructure together to address safety and congestion problems. A consistent V2X wireless communications technology for C-ITS architecture is (5.9 GHz) Dedicated Short-Range Communications (DSRC). In addition, V2X positioning is supported by Global Navigation Satellite Systems (GNSS) and non-GNSS techniques. Precise digital road maps are another vital technology for efficient C-ITS functions, since a wide range of V2X safety applications requires geometry preview of the road and location information of road entities. Map matching algorithms can also assist vehicle positioning by using high accuracy road maps.

Various nationally and internationally defined projects, such as FleetNet ("FleetNet", 2000) and its successor Network On Wheels ("NOW", 2004) in Germany, European projects PReVENT and the Car-to-Car Communication Consortium ("Mission-&-Objectives", n.d.), as well as the Vehicle Safety Communication Consortium (VSCC) of the United States (VSCC, 2005), have operated so far to address vehicular safety concerns. Some of the projects include specific safety applications such as Emergency Electronic Brake Light (EEBL) and Forward Collision Warning (FCW). Although not all of the safety applications such as FCW require a sophisticated communications architecture to exchange safety messages, the fully operational C-ITS platform has to support all types of applications, which may cover a substantial number of vehicles on roads. Therefore, a scalable platform is a must to meet the demands of each individual safety application. The platform also needs to support commercial non-safety applications such as toll collection to make C-ITS more attractive for deployment.

A set of standards, such as IEEE 802.11p based on the Wi-Fi family of standards, has been established as the DSRC protocol stack by IEEE and SAE working groups to support Wireless Access in Vehicular Environments (WAVE). Since VANETs significantly differ from low-velocity and sparse infrastructure-based Wi-Fi deployments, there are many challenges in the reliable operation of DSRC in highly mobile and often densely populated environments where Line-of-Sight (LOS) is not often available. Although some mechanisms such as channel switching, a key prerequisite for DSRC media to maintain non-safety communications on segregated channels, have been addressed throughout the standards, none of these activities specifically addresses the safety demands of C-ITS in detail. In this regard, the existing mechanisms do not address issues such as achieving the most optimized non-safety communications without jeopardizing safety. Furthermore, the channel characteristics of DSRC require functionalities that increase the probability of the reception of safety messages. The main reason for DSRC to be not real-time is the adoption of CSMA/CA by the WAVE MAC, which delivers nondeterministic channel access.

A well-integrated precise vehicle positioning architecture is the other key requirement beyond the communications architecture, for any C-ITS platform to support safety-of-life applications. Although the standard mass market grade GNSS equipments have been widely used for navigation, traffic control and fleet management, the limited standalone positioning accuracy can support only a small proportion of safety applications. GNSS augmentation techniques such as Differential GPS (DGPS), Real-Time Kinematic (RTK), and Satellite-Based Augmentation Systems (SBAS) have to be considered to meet the required sub-meter or higher positioning accuracy for safety purposes. On the other hand, the current digital road maps are produced basically for road navigation purposes. The accuracy of road maps in most segments is not high enough to exactly identify the lane in which the vehicle is driven or to precisely represent the road geometry.

The high technical requirements of V2X communications and positioning for C-ITS safety applications motivate this work, which proposes a more efficient, versatile and advanced architecture for V2X systems. To this end, this article studies the concepts that have to be taken into consideration while a robust vehicular-safety communications and positioning architecture is designed. This is accomplished through the identification of the options available for the must-have communications and precise positioning building blocks of the V2X platform to meet the demanding nature of safety applications; non-safety applications can be also supported. Section 2 examines the V2X communications technology available to support C-ITS, which necessitate a series of positioning and networking requirements that are studied in Section 3. Section 4 and 5 examine the positioning techniques suitable for C-ITS and the data access methods to support RTK positioning in C-ITS, respectively. Finally, Section 6 provides a schematic top plan representation of the building blocks of a V2X communications and positioning system. The study is concluded in Section 7.

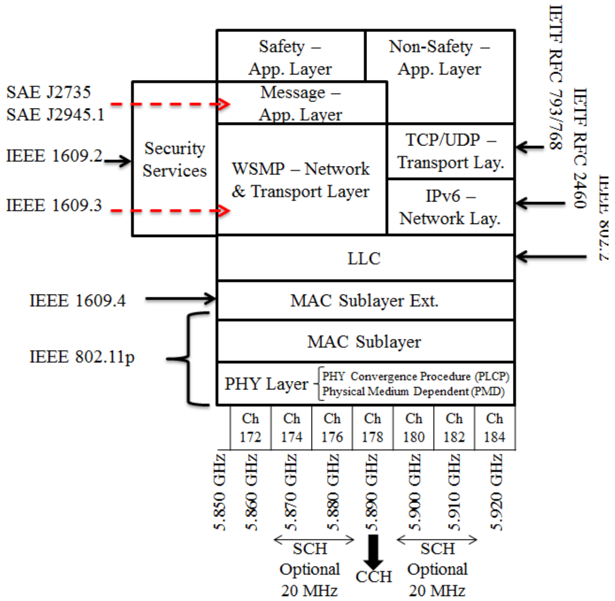
2. V2X Communications Enabler Capable of Satisfying the Safety Requirements of C-ITS

In late 1999, the 75 MHz spectrum at 5.9 GHz band was allocated by the US Federal Communication Commission (FCC) for WAVE. The Australian Communications and Media Authority (ACMA) has placed a similar frequency spectrum embargo at 5.850-5.925 GHz in Australia for ITS purpose since April 2008. V2X communications have been enabled via the DSRC protocol stack as the WAVE common model in order to achieve the safety, mobility and commercial applications promised by ITS.

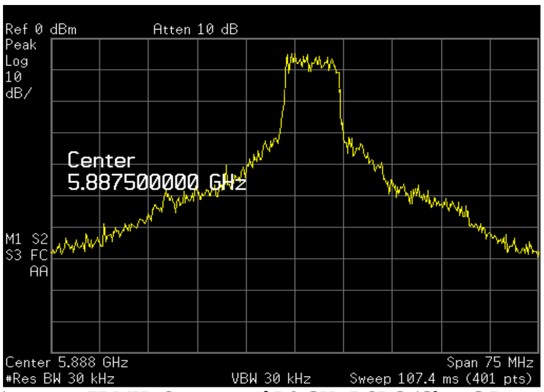
DSRC is designed to provide the interoperability required between the services supported by VANETs for C-ITS. In this regard, the common DSRC protocol stack enforces interoperability as one of its fundamental supports through assigning seamless standards to various layers of the stack. The PHY layer of the WAVE system has been optimized from IEEE 802.11 and 802.11a to support highly mobile environments and the nondeterministic characteristic of the channels. The PHY defined in IEEE 802.11p supports a Control Channel (CCH), four Service Channels (SCH), a dedicated channel for safety of life (Ch 172) and channel 184 for high-power/long-range applications. Additionally, the High-Availability Low-Latency (HALL) communication type is supported by DSRC-enabled safety systems as a unique requirement of vehicle safety applications such as cooperative collision avoidance.

Four classes of DSRC devices, each with specific maximum transmit power and a desired communication range, have been defined by the FCC as A, B, C, and D. The maximum communication range of DSRC-based systems is generally considered to be less than 1 Km LOS as per the specifications of the Class D devices with maximum output power of 28.8 dBm. Class C devices with 20 dBm output power are generally considered suitable for V2V safety applications. These Class C devices are expected to cover an area about 400 meters wide, which is extensive enough to support V2V safety-of-life applications. The IEEE 802.11p standard defines a transmit spectral mask for each device class to limit the out-of-band energy of a transmitter. Once a higher maximum transmit power is allowed by a class of devices, a tighter spectral mask is enforced by that class to protect adjacent channels (Kenney, 2011).

Fig. 1(a) represents the DSRC protocol stack and associated standards, along with the channel arrangement. The overall DSRC communication stack is mostly (being) standardized by the IEEE and SAE working groups. Since WAVE is a multi-channel system, IEEE 1609.4 enhances the IEEE 802.11 MAC to define the MAC sub-layer at the DSRC stack. These enhancements provide mechanisms to prioritize data transmission, channel coordination, and channel routing tasks (Kenney, 2011; SAE-DSRC-Committee, 2009). Fig. 1(b), on the other hand, represents the spectral emission of IEEE 802.11p (Class C), which is typically measured to ensure that DSRC units do not influence devices operating in adjacent channels.



(a) The DSRC Protocol Stack and Channel Arrangement



(b) 75 MHz Spectrum of 5.9 GHz DSRC (Class C Device)

Figure 1: 5.9 GHz DSRC

2.1 DSRC channel characteristics and capacity

Communication signals of IEEE 802.11p based systems are generated based on the principles of the Orthogonal Frequency Division Multiplexing (OFDM) technique. Various channel impairments – path loss, and time- and frequency-selective fading – degrade the reception probability of a signal in wireless communication channels. Path loss is referred to as the decay of the signal strength in accordance with the distance to the sender. The range in which a signal can be received varies greatly in fast moving environments like VANETs because the signal attenuation depends on numerous factors such as the length of the signal propagation path, the direction of signal propagation, receiver location and the LOS available between sender and receiver. Additionally, constructive and destructive interferences due to multipath propagation, as well as changes (even minor) in the environment as the medium, cause the fading effect.

Therefore, the nondeterministic characteristic of DSRC is caused by various factors such as path loss, Doppler shift and fading, which all depend on the current environment in which DSRC messages are being exchanged. For instance, the Doppler spread depends on the effective speed, operating frequency and distance between communicating nodes. Various channel measurements revealed that as the distance between two communicating nodes increases from a short distance of several meters to a long distance of hundreds of meters, the fading becomes more severe, from a near-Rician fading to a pre-Rayleigh fading (Qu, Wang, & Yang, 2010). Therefore, the knowledge of channel characteristics is essential for designing IEEE 802.11p based transceivers and evaluating their performance.

Concurrent disseminations of messages from different stations in VANETs may result in data collision if the dissemination ranges of the transmitting nodes overlap. This includes the hidden terminal problem. Several Decentralized Congestion Control (DCC) mechanisms, such as LIMERIC (Kenney, Bansal, & Rohrs, 2011) and Distributed Coordination Function (DCF) schemes for MAC, have been proposed to alleviate/eliminate over the air collisions caused by multi-station medium access contentions. Most of the proposed DCF mechanisms lessen the probability of a collision if the transmitting stations are in the sensing range of each other; these do not address the hidden terminal problem.

MAC provides channel access mechanisms which authorize a station to utilize the channel in a distributed manner by sensing the channel at periodic intervals. DSRC may enjoy DCF mechanisms that provide high priority messages with fast access to the channel such as the Enhanced DCF (EDCF) of IEEE 802.11e. EDCF adjusts the values of the Arbitration Inter-Frame Space

Duration (AIFSD), and the Contention Window (CW) size based on the priority level of each frame. A prioritized frame is more likely to acquire the channel access over lower priority frames if smaller AIFSD and CW sizes are selected when they are being transmitted.

Fig. 2 represents the reception probability of DSRC packets when the CW size is varied in different VANETs with dissimilar sizes, based on the model studied by Wang and Hassan (Wang & Hassan, 2009). The message reception probability can be obtained using:

$$R = \frac{P_t . P_s}{n . b_0}$$

where R is the probability that a message transmitted in a randomly selected time slot does not collide with any other message. Variable n indicates the number of nodes in the study. b_0 is the probability that the back-off counter of a given node has reached 0, which is calculated based on the CW value. P_t is the probability that at least one node transmits in the selected time slot, which is:

$$P_t = 1 - (1 - b_0)^n$$

P_s indicates the probability that a successful transmission takes place in the selected time slot, which is:

$$P_s = \frac{n . b_0 . (1 - b_0)^{n-1}}{P_t}$$

As for the results shown in Fig. 2, it was assumed that all communicating nodes try to broadcast Basic Safety Messages (BSM) once the channel allows. However, the standard identifies post-back-off specifications in which a back-off time is scheduled for each node to be triggered after transmitting each message, even though another message is ready to be transmitted. Therefore, the transmit-back-off pattern is basically repeated in a continuous loop. A back-off counter value is randomly selected from 0 to (CW −1) in each back-off process and is decremented until it reaches 0. The transmission range of every node is also assumed to be sufficient enough to cover all the nodes in the study. Additionally, the

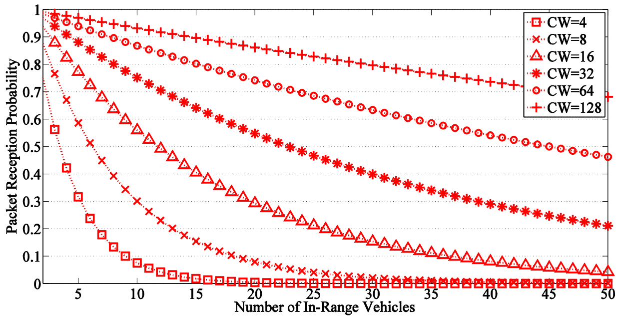


Figure 2: DSRC Packet Reception Probability

transmissions are considered to not involve "power capture"; consequently messages engaged in collisions are destroyed. Therefore, the channel load must be kept unsaturated all the time to limit the number of packet collisions. However, some of the applications necessitate a certain level of message density to be sent/received in order for C-ITS to provide the safest possible operation. Hence, a compromise between the throughput and reliability provided by DSRC has to be reached.

It is rather challenging to provide a numerical specification for the capacity of channels, such as those expressed for channel occupation time and bandwidth, since the channel capacity is influenced by various elements. These influencing elements take account of the message length, the CW value, the back-off slot time, and the transmission delay; this delay includes the transmission time for the PHY header, MAC header and payload, and DIFS time plus the Over-the-Air (OTA) propagation delay. The message throughput, which can be seen as a factor of the channel capacity, may be calculated as the average number of successfully transmitted messages (with no collision) in a randomly selected time slot by a node, over the average length of slot time (Wang & Hassan, 2009).

Fig. 3 represents the reception rate of BSMs exchanged at 10 Hz rate between a pair of DSRC units obtained from a real-world measurement campaign. It is understood from the figure that although DSRC tends to behave in a symmetric manner, the channel impairments disrupt the performance of cooperative links. The figure further confirms the nondeterministic characteristic of the DSRC channels.

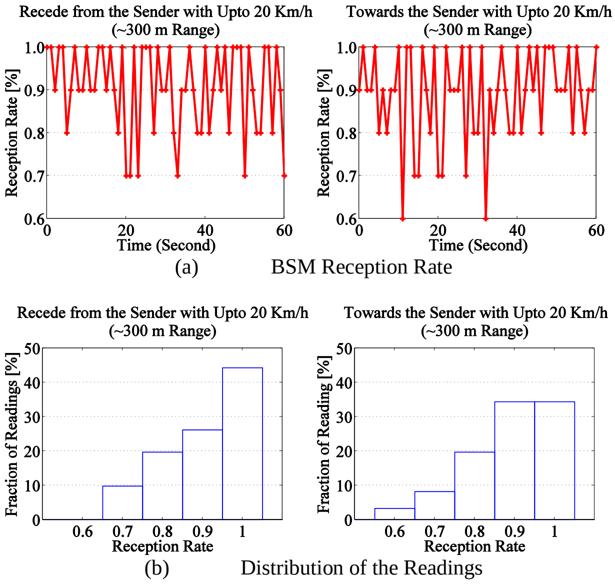


Figure 3: Vehicle-to-Infrastructure DSRC

2.2 Situational challenges for DSRC

The fact that WAVE must seamlessly work under diverse conditions that are mostly harsh, due to the movement of vehicles and the nature of outdoor radio channels, is the major challenge for DSRC. The multipath of the channel impairments and the mobility of the communicating nodes are the dominant challenges, since their combination results in doubly selective fading (time-varying frequency-selective fading). Hence, the DSRC technology still has many challenges at its PHY and MAC about addressing the safety needs of the vehicular communication environment. For instance, although the 1600 ns of OFDM guard interval of IEEE 802.11p PHY is much greater than 700 ns measured as the maximum delay spread, the measurements of joint Doppler-delay Power Spectrum Density (PSD) significantly vary in different scenarios. Most of the measurements are rather dissimilar to the Gaussian-shaped PSD of Rayleigh fading channels (Qu, et al., 2010). Therefore, the introduction of a universal statistical channel model supporting various scenarios is not a straight-forward process, requiring more research efforts to be devoted to characterizing the relationship that exists between the channel statistics and V2X scenarios.

Various traffic scenarios exist which challenge the DSRC radios. As an example, consider the intersection shown in Fig. 4, with an obstructing building on the northeast corner. Vehicle A travels on the North-South road with a green light while from the West-East and East-West roads both Vehicle B and C respectively approach the intersection with red lights, where both must stop at the stop lines. What will happen if Vehicle B or Vehicle C cannot manage to stop in time? The answer is very clear: Vehicle A may collide with any vehicles which cannot stop at the stop line. Therefore, in this case the earlier the driver of Vehicle A is warned about the danger, the more likely the crash can be prevented. This particular application of DSRC is known as 'Intersection Movement Assist' (IMA).

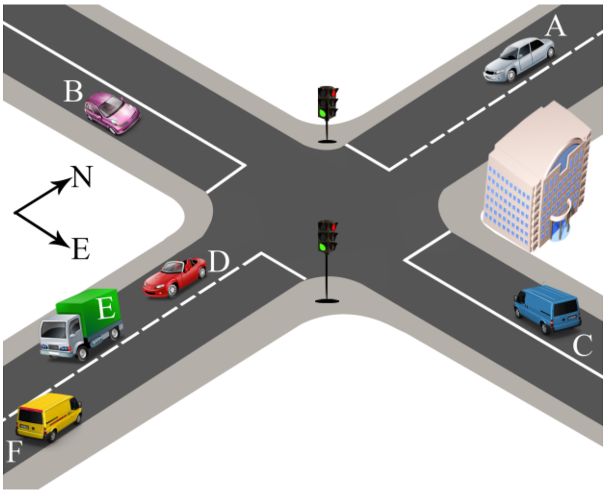


Figure 4: Scenarios Challenging DSRC:
Intersection Movement Assist + Do Not Pass Warning

The delay-spread of the multipath channel between Vehicle A and Vehicle B of Fig. 4 will be low since the northwest intersection is open, although even IMA may not be necessary to avoid the collision because the visual contact to Vehicle B is available to the driver of Vehicle A. Conversely, a combination of simultaneous multipath and mobility exists in the communication channel between Vehicle A and Vehicle C due to the surrounding buildings. The DSRC radios used for the latter scenario must be able to close the communication link as quickly as possible and to provide warnings to drivers within a limited time frame to stop them from colliding.

Now consider the other side of the intersection shown in Fig 4, where Vehicle D, E, and F are presented. The driver of Vehicle D may attempt to overtake when it is not safe to do so if the full view of the approaching traffic is blocked to the driver of Vehicle D by the front vehicle. However, the driver of Vehicle D can be warned about the existence of Vehicle F if Vehicle D and Vehicle F utilize DSRC units before an attempt to overtake is made. This particular application of the DSRC technology is referred to as 'Do Not Pass Warning' (DNPW). Similar to IMA, the adverse conditions of simultaneous multipath and mobility challenge DNPW application. Various V2X safety applications are proposed where each of them enforces a set of challenges to C-ITS. Section 3 introduces the six most crucial safety applications of C-ITS.

2.3 A Key resolution to the DSRC challenges

In addition to the measures promoting the throughput and reliability of DSRC, which can be taken through the upper PHY stack, such as the message dissemination frequency controller introduced in (Ansari, Wang, & Feng, 2013), the radios at PHY can be designed in such a way to enhance the performance of DSRC. In this regard, using multiple antennas in VANETs provides C-ITS with numerous benefits. The DSRC radios may utilize the Multiple Input Multiple Output (MIMO) technology, which increases spectral efficiency to lessen the challenges enforced by the traffic scenarios. The benefits that C-ITS may receive from the employment of the MIMO technology include the increment of the communication range through beamforming, the improvement of the communication reliability through spatial diversity, the increment of the network throughput through spatial multiplexing, and the easier management of multiuser interferences due to the existence of multiple DSRC terminals in range (El-Keyi, ElBatt, Bai, & Saraydar, 2012).

The MIMO technique can overcome channel fading while maintaining high rates of data transmission as well as low rates of bit error (Shan, Kam, & Nallanathan, 2004; Tarokh, Jafarkhani, & Calderbank, 1999). Multiple-antenna enabled systems can provide more reliable transmissions than conventional systems employing a single antenna if spatial multiplexing and space-time coding techniques are used by the MIMO encoder. A set of measurement campaigns were carried out in this study using a pair of DSRC transceivers with two radios used in both the Single Input Multiple Output (SIMO) (which is a special case of MIMO) and the single antenna configurations to compare the Packet Error Rate (PER) of the MIMO configuration and that of the conventional systems. Depending on the scenarios where the systems were tested, the PER of the single antenna system was greater than the PER of the MIMO configuration:

$$(1-PER)^{MIMO} = a.(1-PER)^{Conventional}$$

where $1.02 \le a \le 1.1$. This means the MIMO technology can increase the reception rate of BSM by 10%.

3. V2X Supported Safety Applications and their Positioning and Networking Requirements

3.1 V2X supported safety applications

V2X communications and positioning systems can support tens of safety applications and each of them can correspond to various scenarios. However, in the United States the focus of most of the safety projects has been on the development of six vital V2V safety applications (ARRB-Project-Team, 2013; Kenney, 2011), which are:

- Extended/Emergency Electronic Brake Light (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Blind Spot Warning + Lane Change Warning (BSW + LCW)
- Do Not Pass Warning (DNPW)
- Control Loss Warning (CLW)

These applications are considered to have the greatest influence on road/rail safety improvements in the near future. Both the IMA and LCW applications were discussed in the previous section. This section briefly presents the concept of the EEBL application as a representative of the applications demanding precise positioning and lane-level navigation.

There might be situations in which drivers do not have a clear sight of the brake lights of the vehicles in front, such as when they travel on a curved road or when adverse weather conditions exist. In such driving conditions, in which a driver cannot maintain the view of their front vehicles (not essentially the immediate leader), the EEBL application can exchange warning messages with vehicles traveling behind the vehicle encountering a hard brake. The information of EEBL can also be integrated into adaptive cruise control systems. Considering the benefits of EEBL, not every received EEBL warning has to be responded to, since they might not be relevant to every vehicle traveling behind the sender of the EEBL warning. For instance, other than vehicles which have passed the sender or have travelled in the opposite direction, vehicles traveling on other lanes must not reveal the EEBL warning to their drivers.

Taking the requirements of safety applications into consideration, the success of almost all V2V safety applications and of a number of V2I applications depends on accurate relative positioning, and occasionally on the intelligence about the surrounding environment and roads; these both imply robust communication links among vehicles and roadside units. Hence, the V2X safety platform must provide precise positioning services to both DSRC On-Board Units (OBU) and Road-Side Units (RSU) using low overhead networking and effective routing strategies, in order to fully satisfy the requirements of V2X safety applications. The precise positioning is possible using sophisticated positioning techniques, and the intelligence about the road geometry is achievable via local digital maps.

3.2 Positioning accuracy requirements of V2X safety applications

Three levels of accuracy requirements have been considered for C-ITS safety applications, namely road-level, lane-level and where-in-lane-level (EDMap-Consortium, 2004), which correspond to meter-level, sub-meter-level and decimeter-level positioning respectively (ARRB-Project-Team, 2013). The horizontal positioning accuracy requirements of emerging V2X safety applications are 5.0 m for road-level, 1.1 m for lane-level and 0.7 m for where-in-lane-level positioning at the 95th percentile confidence level (ARRB-Project-Team, 2013). As the requirements of safety applications shift towards higher order positioning capabilities, the cooperative positioning update rates have to become more frequent, from about 1 Hz for meter-level positioning to 10 Hz or higher for safety applications with lane-level and/or where-in-lane-level positioning requirements. Hence, DCC mechanisms have to be employed by V2X platforms to avoid DSRC channel saturation caused by the cooperative V2V positioning techniques. No performance standards for C-ITS with respect to positioning have been established. In addition to accuracy, however, the recent report (ARRB-Project-Team, 2013) introduces several more required parameters, including continuity and availability, plus the following three critical parameters:

- **Integrity** – the ability of the positioning system to identify when a pre-defined alert limit has been exceeded, and to then provide timely and valid warnings to drivers. It is acceptable for the positioning system to provide the required performance most of the time, such as 95%, but the positioning system has to inform the drivers when the system cannot offer safety functionality.
- **Interoperability** – the ability of different vehicle positioning systems with different absolute positioning capabilities to be used on the road network, and still meet the required performance.
- **Timeliness** – the ability of the system to update absolute and relative position solutions at the required rates or on an event basis.

For road safety applications, vehicle positioning accuracy, integrity, interoperability and timeliness must all be considered.

3.3 Networking and routing requirements of V2X safety applications

A key issue with cooperative V2X positioning is the latency effect of VANETs on the positioning timeliness performance, due to deficiencies of communication links. Therefore, efficient strategies of cooperative positioning must be developed to meet the high rate demand of positioning computational updates in the C-ITS environment. This requirement will be studied in depth through the following two sections. Additionally, V2X platforms have to adopt efficient vehicular routing and networking strategies to adequately support high timeliness requirements of cooperative positioning, particularly when the traffic is spread out sparsely. Incidentally, even though most of the V2X safety applications employ single-hop broadcasting as their effective method of message dissemination, which eventually has the greatest safety potentials, there are traffic scenarios which necessitate the use of multi-hop message exchange mechanisms.

Reducing broadcast flooding of the safety messages is vital to the optimal performance of vehicular networks and the reliability of message disseminations. Considering the challenging requirements of various V2X safety applications, several routing strategies initially proposed for Mobile Ad-hoc Networks (MANETs) may be adopted by V2X platforms of VANETs in conjunction with traffic-based methods to improve the overall reliability of the shared DSRC channel. A few MANET-specific routing strategies which can be effective in VANETs for reduction of redundancy, contention and collision by preventing some hosts from rebroadcasting include probabilistic, distance-based, hop-based, location-based and cluster-based schemes (Tseng, Ni, Chen, & Sheu, 2002).

The probabilistic-based methods broadcast messages with a given probability (p) which is in many cases calculated based on the back-off counter of the sender. Distance-based and hop-based methods broadcast messages by considering the positional distances and hop counts existing between the transmitting node and intended receivers. Location-based methods broadcast messages to intended vehicles based on their position information. In spite of the stated schemes which are based on statistical and/or geometric modeling, cluster-based methods use graph modeling to broadcast messages to vehicle groups.

Taking everything into account, the characteristics of VANETs and their application requirements have necessitated the adoption of networking protocols other than broadcasting. Therefore, since VANETs enable wireless multi-hop techniques and geographical addressing using V2X DSRC, geocast has been adopted in the platform, designed as an alternative class of vehicular networking strategy. Geocast networking is not only a promising mechanism for a range of C-ITS safety applications coping with VANET-specific characteristics such as highly dynamic topology changes, but also can promote V2X safety while the DSRC technology is gradually introduced into the marketplace. Hence, the support of geographical flooding by any preliminary V2X platform being widely employed is necessary to the reliability of safety VANETs.

The architecture will support geo-networking over both the WSMP and IPv6 stacks of the DSRC protocol stack (referred to as WSMP geo-networking and IPv6 geo-networking respectively) in order to be versatile for various communication settings dictated by the traffic and/or infrastructure. Unlike WSMP geo-networking, which is only supported through the V2X DSRC, IPv6 geo-networking can be supported using Internet-based communication modes in addition to the V2X DSRC. The application data is encapsulated in either the WSMP header or the IPv6 header and then, depending on the medium to be used, the encapsulated packet is further encapsulated in a header of 802.11p or the medium used for the Internet connection.

Although the J2735 message set standardizes 16 different types of messages (using 73 different data frames which themselves use 149 different data elements) (SAE-DSRC-Committee, 2009), no message type has been specifically standardized for geographical flooding purposes. Hence, once the data vital to the geocast schemes is identified, the rest of this section proposes a message type by utilizing the flexibilities offered by the J2735 message set through using the data items already specified in the SAE standard; this message can be adopted for geocasting.

It often matters to most safety applications to know “where” the recipients are located with regard to the sender, but it rarely matters to them to identify “who” is receiving the data. Having said that, it usually matters to applications supported through geocast mechanisms to identify the sender (originator/forwarder) while they also require making sure that the intended flooding regions receive the message. Therefore, a geocasting message has to include the IDs and geographic locations of both the originator and last sender, and the geographic location(s) of the region(s) of interest. Three types of regions can be supported, namely circular (a point and radius), polygons (wide area enclosed regions) and shape points (short road segments). Additionally, as the geocast strategies are usually supported through multi-hop communications, some types of stop mechanisms such as Time-to-Live (TTL), Distance-to-Live (DTL) and/or hop limits have to be implemented to avoid the broadcast storm problem. So any geocast message, such as Receiver-Based Geo-Multicast (RBGM) introduced in (Ansari, Feng, & Singh, 2013), has to include fields for the TTL, DTL and/or hop counters. In case the geocast stop mechanism uses the TTL parameter, the message has to also carry the timestamp of the originator (DSRC units are synchronized to the GPS time).

The SAE J2735 standard includes the message sets supporting C-ITS V2X messaging. The standard represents the message structures in ASN.1 and XML syntaxes. Among the 16 types of messages standardized in J2735, Ala Carte Message (ACM) offers the flexibility to include and carry any combination of the data frames and/or data elements defined in the standard. As reflected in Fig. 5, the ACM includes a data frame named AllInclusive (DF_AllInclusive) which productively makes the combination of any data frames and data elements possible. Table I represents the data items which can be included in the DF_AllInclusive of any MSG_A_la_Carte to support geocasting. The actual content of geocast messages is determined by the requirements of geocasting applications. For instance DE_EventFlags may be used if the application requires disseminating additional information.

Table 1: J2735 Data Item Candidates for Geocast Messages

J2735 Data Item	Description
DF_VehicleIdent	Used to identify public fleet vehicles
DE_VINstring	A legal VIN or a shorter value to provide an identity of the vehicle
DF_FullPositionVector	A complete set of time, position, speed and heading
DF_Position3D	Position values (lat, long, elevation)
DF_ValidRegion	Used to identify applicable regions of use, field of view (heading), and the spatial distance over which the message applies and should be presented to the driver
DE_TermDistance	Used to terminate management process based on Distance-to-Live
DE_TermTime	Used to terminate management process based on Time-to-Live

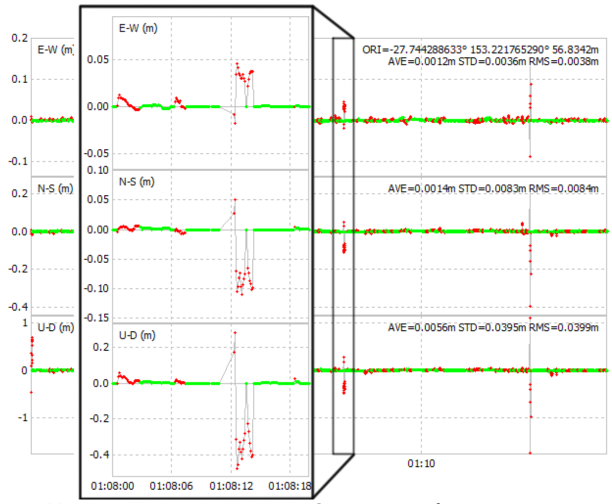
```
-- MSG_A_la_Carte (ACM) (Desc Name) Record 1
AlaCarte   ::=        SEQUENCE {
           msgID      DSRCmsgID,
                      -- the message type
           data       AllInclusive,
                      -- any possible set of data items here
           crc        MsgCRC    OPTIONAL,
           ... -- # LOCAL_CONTENT
}
```

Figure 5: ASN.1 Source Code of SAE J2735 ACM (Candidate for Geocasting) (SAE-DSRC-Committee, 2010)

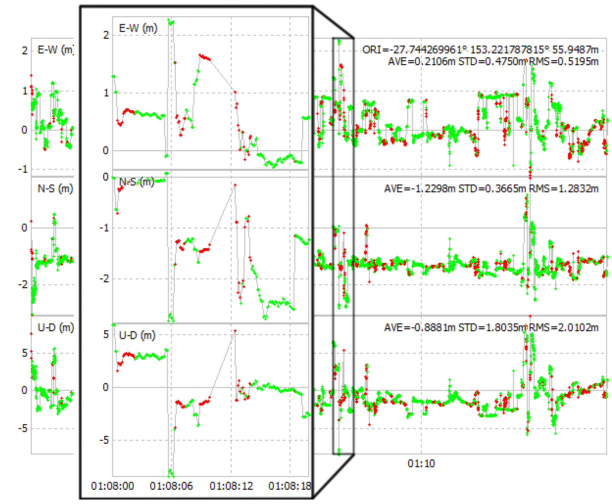
4. Positioning Techniques Available for C-ITS Safety Application

Positioning techniques suitable for vehicle positioning are grouped into two classes: GNSS-based techniques and non-GNSS techniques. Global Navigation Satellite Systems (GNSS) is a generic term for all satellite navigation systems such as the US GPS, Russian Glonass, European Galileo, and China’s Beidou systems. These and their augmentation systems provide positioning services all over the globe. Space-Based Augmentation Systems (SBAS), mainly including Wide Area Augmentation Systems (WAAS) and European Geostaionary Navigation Overlay System (EGNOS), are also regarded as components of GNSS.

GNSS based techniques developed predominantly based on GPS that have been tested in the existing prototype vehicle positioning systems include (1) Single Point Positioning (SPP) with GNSS and/or SBAS signals, (2) Differential GNSS (DGNSS), (3) Real Time Kinematic (RTK) positioning and (4) Relative RTK positioning between vehicles. SPP is a standalone positioning mode which uses a minimum of four pseudorange measurements to estimate user location epoch by epoch without knowledge of vehicle dynamics. The problem is that the SPP mode can only give the positioning accuracy of several meters with GPS signals. SPP accuracy with multiple GNSS signals can be improved to the level of a few meters, but still cannot meet most of the safety requirements. SPP users in USA and Europe can enjoy a slightly higher level of positioning accuracy using WAAS or EGNOS augmented signals, typically sub-meter to 2 meters horizontal accuracy. This accuracy can marginally meet the requirements for some safety applications requiring lane-level positioning accuracy. But, unlike the USA and Europe, no SBAS service is available in Australia and many other nations. The pseudo-range code based differential GNSS technique is thus the alternative to SBAS and available almost anywhere needed. Again the positioning accuracy is also in the range of 1 to a few meters. DGNSS services require communication connection between the vehicle and a reference network server. The RTK technique, on the other hand, uses carrier phase measurements and corrections from nearby Continuous Operating Reference Stations (CORS) to achieve centimeter-level position accuracies. This accuracy can sufficiently meet all types of V2X safety applications. The limiting factors in using RTK technique for V2X safety applications are twofold. Firstly, the RTK solutions may suffer from effects of unpredicted biases in the order of decimeters to meters, due to incorrectly fixed ambiguity solutions. Fig. 6 shows examples of such effects on each component. Multi-constellation GNSS receivers offer the potential to improve the accuracy and reliability of position solutions. Secondly, RTK algorithms generate more robust solutions with dual-frequency carrier phase measurements; however the hardware may not be



(a) RTK Positioning with a CORS Reference Station



(b) Relative RTK Positioning with a Rover Reference Station

Figure 6: Samples of Real-Time Kinematic (RTK) Positioning Technique

affordable for vehicle users. Similarly to DGNSS, RTK rely on continuous data links between vehicles and infrastructure. The latency of correction data imposed by data encoding/decoding, and transmission mechanisms, from reference stations to vehicles is still an error source. If this latency usually ranges from 100 ms to few seconds, as shown in (El-Mowafy & Al-Musawa, 2009), the effects on RTK solution are insignificant.

In a conventional RTK mode the reference receiver(s) are placed in fixed stations. In the Relative RTK mode, each vehicle plays both reference and rover receiver roles. In other words, vehicles within a certain range exchange their raw measurements every epoch and perform RTK data processing with respect to other vehicles, which are acting as moving reference stations. The relative RTK processing algorithm is similar to conventional RTK, except that the varying baseline between vehicles is usually very short and the onboard computational load is much heavier if the RTK processing has to be performed with respect to several target vehicles in the range. The relative RTK has a few more limitations as well. As the raw data from each moving vehicle is not predictable, delay of data delivery or loss of signals at a vehicle will lead to loss of the relative position states. In other words, the solutions are dependent on quality and availability of signals from other vehicles in addition to their own situations. Fig. 6(b) shows the examples of relative RTK suffering from signal outages. Using onboard sensing data with respect to other vehicles can to a certain degree overcome the solution outage problem. Nevertheless the relative RTK capability neither depends on communication links to the infrastructure nor requires extra hardware.

As discussed earlier, C-ITS necessitate vehicles to broadcast their positions as reference points known as “dropping breadcrumbs” in order for cooperative vehicles to keep track of the locations of their surrounding vehicles. If the cooperative vehicles offer only SPP solutions, the accuracy is inadequate for many safety-of-life applications. If the cooperative vehicles can also provide their raw GNSS data, the relative RTK solutions between vehicles can be obtained. As a result, additional V2V safety applications can be implemented. In case the cooperative vehicles offer fixed-reference RTK solutions, the relative RTK solutions are also desirable, because both RTK solutions can verify each other. Timely warning can be issued if the inconsistency reaches an alert limit. Both RTK solutions, which are much better than the SPP solutions, would be helpful for integrity monitoring. In general, both absolute and relative RTK positioning algorithms should be implemented at each vehicle positioning system to address the required performance to the greatest extent.

5. GNSS Data Access and Exchanges for (Relative) RTK Positioning

Efficient transmissions of GPS correction data depend highly on the format and content of data exchanged between the CORS station and rovers. The format of GNSS data specifies the structure of the message, while exchange mechanisms identify the encoding methods used to represent both the observation and correction information. Also, the content of a message determines the minimum bandwidth required to transmit the information. The transmission latency plays a critical role in the increment or decrement of positioning errors since the timeliness requirement of positioning data varies among the different positioning accuracy levels (ARRB-Project-Team, 2013). Therefore, the size of the messages and the medium (bandwidth) available to the mechanisms distributing correction data to rovers are vitally important in achieving an efficient, reliable and integral performance.

Most positioning modules support various formats of GNSS data. Two general categories of standards are used for exchanging GNSS data. These include public formats standardized by nonprofit organizations such as the Radio Technical Commission for Maritime Services (RTCM), and proprietary formats such as the Compact Measurement Record (CMR) developed by Trimble Navigation Ltd as a GNSS manufacturer, to be used with licensed Software or Hardware. The common data formats used in transmission of GPS data include Receiver Independent Exchange Format (RINEX), the National Marine Electronics Association (NMEA) standards and the RTCM standards. RINEX is a format used for data processing and archiving raw GPS data. Also, NMEA is the standard used for communicating GPS positioning data among marine electronic devices as well as between a GPS receiver and other devices providing positioning services (e.g. GPS receiver to PDA). NMEA standards are used for real-time positioning processing. Data standards recommended by RTCM SC-104 (Special Committee 104) are used for the transmission of GPS correction data from GPS reference stations to GPS rovers in the RTK positioning technique.

5.1 The RTCM SC-104 standards

The RTCM is an independent international nonprofit organization which standardizes radio communications. Standards for various radio communication services and applications have been developed by a number of special committees within the organization. Special committee 104 focuses on Differential GNSS (DGNSS) to recommend standards for both maritime and terrestrial practices. The committee recently developed the RTCM V3.1 standard in addition to the second version of the Networked Transport of RTCM via Internet Protocol (NTRIP) protocol. The 2nd version of RTCM SC-104, initiated more than 10 years ago, increasingly received complaints about its data format and parity scheme. Additionally, the growing uses of DGNSS required new standards and protocols to quickly support new GNSS (e.g. Galileo), new signals (e.g. L2C & L5) and new applications (e.g. Network RTK). The fresh version 3 of the standard has been designed to address the problems of version 2, as well as to integrate the new requirements (Lin, 2005). Fig. 7 represents the evolution of the RTCM SC-104 standard to the current version (RTCM V3.1) (Zinas, 2010).

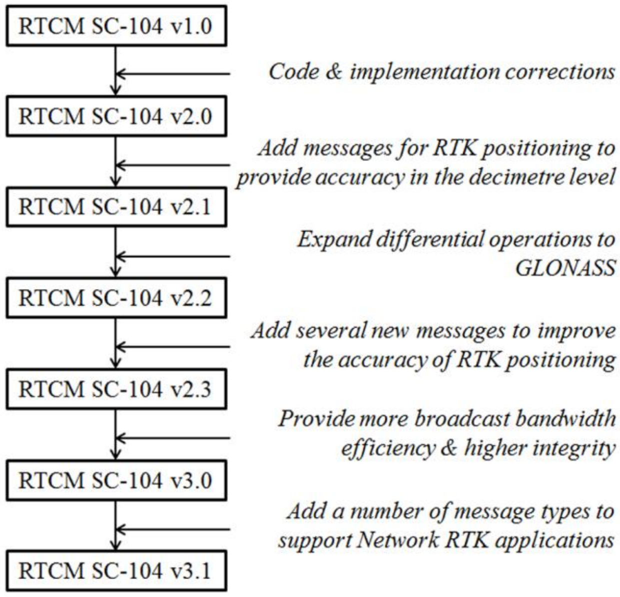


Figure 7: Evolution of the RTCM SC-104 Standards

The releases 2.2 and 2.3 of the RTCM SC-104 format are considered to provide centimeter level accuracy for rovers using RTK mechanisms. As already discussed, RTK positioning is possible by means of two forms of correction data generated at reference stations: pre-processed correction data, and raw observations of the reference station. Therefore, different message types are considered in each version of the RTCM SC-104 standard for the purpose of differential positioning. For instance, the Type 18 and 19 messages of the RTCM V2.3 standard are the most widely used messages to contain raw carrier phase measurements and raw pseudo-rage measurements, respectively (Qu, 2012). The message types used in each version of the standard for specific purposes are described in RTCM 10403.1, Differential GNSS Services – Version 3 and RTCM 10402.3 RTCM Recommended Standards for Differential GNSS Service, Version 2.3 standard documentations (Radio-Technical-Commission-For-Maritime-Services, 2001, 2006).

The version 3.0 release of RTCM has been developed to provide more broadcast bandwidth efficiency as well as higher integrity. Types 1001 to 1013 messages were included in the first release of version 3 to support traditional single station RTK and differential operations. These message types, which reduce the transmission bandwidth required by version 2.3 for the same use, are categorized in four groups, namely observations, station coordinates, antenna description and auxiliary operation information. The 'odd' messages (1001, 1003, 1005, 1007, 1009 and 1011) contain the minimum information required to provide the service; additional information was included in the format of the 'even' messages (1002, 1004, 1006, 1008, 1010 and 1012) to enhance the performance of differential services. For instance, both the Type 1003 and 1004 messages of the RTCM V3.0 include pseudo-range and phase-range measurements of L1 and L2 frequencies, while the satellite carrier-to-noise (CNR) is supported only by the Type 1004 message as measured by the reference station (Radio-Technical-Commission-For-Maritime-Services, 2006). As reflected in Fig. 7, no message supporting Network RTK was included in the RTCM SC-104 V3.0 standard. RTCM V3.1 was later introduced to support Network RTK applications with a number of new message types (Lin, 2005).

5.2 Data exchange for V2X RTK positioning

The message type and number of visible satellites are the two key parameters determining the amount of data to be transmitted to users of either single-base or Network RTK[1]. For instance, a bandwidth of 4800 bits per second (bps) is required if the RTCM V2.3 standard is employed to broadcast observation corrections or dual-frequency code and carrier-phase observations of 12 satellites. Conversely, 1800 bps bandwidth is required if the same information content is sent using the RTCM V3.0 standard (Wegener & Wanninger, 2005). As per the RTCM 10403.1 standard (Radio-Technical-Commission-For-Maritime-Services, 2006), for instance, the size of the Type 1003 and 1004 messages in Bytes are as follows:

$$Bytes_{1003} = 8.00 + 12.625 * N_s$$

$$Bytes_{1004} = 8.00 + 15.625 * N_s$$

where Ns represents the number of visible satellites.

Positioning augmentation systems utilize radio data links and/or the Internet to broadcast correction data in the form of RTCM SC-104 messages from single or networked reference stations to improve the position accuracy provided by real-time positioning systems. Therefore, the performance of real-time positioning systems highly depends upon the data link established between rovers and reference stations. Various principal criteria, including range and coverage of service, bandwidth of the communication channel and communication costs, may be considered when the conventional and modern distribution methods of correction data are compared. The current distribution methods include UHF/VHF radio broadcasting, satellite broadcasting and mobile Internet.

Utilizing radio transmissions in the UHF band (or sometimes VHF) at bandwidth of up to 9600 bps is the most common distribution method used in the single-base RTK method. This method may only cover a few tens of kilometers of open areas due to power restrictions. However, cellular based technologies such as GSM, EDGE and 3G are the most preferred methods in recent years for transmissions of Network RTK corrections, since the service providers make data communications available on dial-in access servers (Wegener & Wanninger, 2005). These cellular-based technologies have become important as they can facilitate Internet Protocol (IP) based communications used for real-time data exchange. Following this concept, the application-level NTRIP protocol was designed to stream GNSS data such as differential correction data to users (rovers) over the Internet (Radio-Technical-Commission-For-Maritime-Services, 2004, 2011).

1) Streaming RTK Data to Internet-Enabled DSRC OBU/RSU

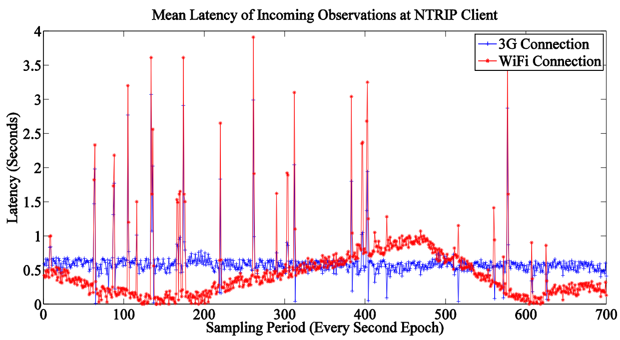
The stateless NTRIP protocol was designed based on the Hypertext Transfer Protocol (HTTP/1.1), in which the HTTP server program is referred to as the NTRIP Caster and the HTTP client applications are known as NTRIP Clients. Other than the NTRIP Clients, who are fixed or mobile users, and the NTRIP Caster, which is the link between the data sources and data receivers, the NTRIP protocol has two other components, namely NTRIP Sources and NTRIP Servers. NTRIP Sources are GNSS receivers providing continuous observation data, in reference to a known location, to NTRIP Servers, which transfer the received data streams to the NTRIP Caster.

The nature of NTRIP is sufficiently versatile to be adapted in the C-ITS architecture of RSUs and OBUs since the NTRIP protocol version 2.0, which supports User Datagram Protocol (UDP) connectivity, can handle thousands of simultaneous connections to an NTRIP Caster. The NTRIP's transport option of unicast UDP reduces the latency of the network through the reduction of communication traffic by dropping the delayed data packets and requiring no handshaking dialogues to exchange data. Fig. 8 represents samples of the latency experienced by the NTRIP Clients, where in Fig. 8(a) the two NTRIP Clients concurrently received correction data

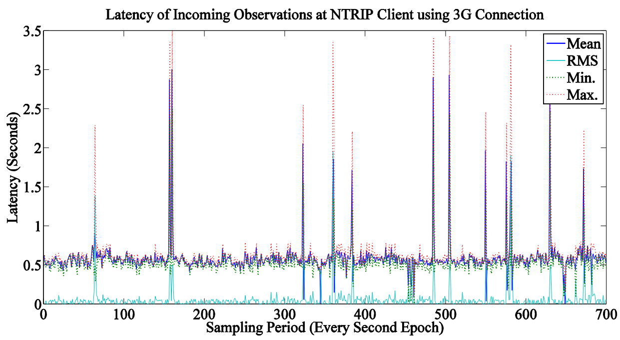
[1] The communication bandwidth required to transmit Network RTK corrections in the form of observations of a Virtual Reference Station (VRS) is identical to what is required in case of single-base RTK.

from the same mount-point. It is shown in (Yan, 2007) that UDP connections may reduce the network latency by 30% in comparison with Transmission Control Protocol (TCP) connections where the data loss rate is not greater than 0.04%.

The average latencies per stream shown in Fig. 8(a) were computed over every two epochs of GPS time. It is understood from Fig. 8 that the mobile Internet connection technologies may impose higher data latency to the NTRIP mechanism, although, in the case of the Local Area Network (LAN), the traffic condition of the WLAN being presented determines the data latency experienced by NTRIP Clients. Modern mobile Internet technologies such as 3G employed in this study, subject to network availability and coverage, have the capacity to fulfill the requirements of RTK positioning using NTRIP mechanism. This competency is because the maximum delay experienced by the mobile NTRIP Client using a 3G connection during the measurement campaigns was less than 3.5 seconds while, as stated in (Qu, 2012), the NTRIP correction data of up to 20 seconds old can improve the positioning accuracy to the centimeter level. The internal clock of a DSRC unit being either OBU or RSU, hosting an NTRIP Client has to be properly synchronized to GPS time in order to correctly compute latencies.



(a) Different Internet Connections: WiFi vs. 3G



(b) Mobile 3G Performance (with speed of up to 80 Km/h)

Figure 8: NTRIP Data Latency from Caster to Clients

2) Streaming RTK Data to Non-Internet-Enabled DSRC OBU/RSU

Maintaining wireless connections to a CORS data server is a must for C-ITS road users, who are mostly in moving vehicles in order to perform RTK positioning which can result in absolute position accuracy of decimeter to centimeter levels. The users' GPS equipment of choice, being low-end single-frequency receivers or high-end dual-frequency receivers, determines the accuracy of positioning solutions. As discussed above, the mobile internet connection through the 3G/4G cellular networks is the most current technique to receive CORS corrections using NTRIP. This technique requires all vehicles to have cellular data connectivity which imposes on-going data charges to C-ITS users. Additionally, not all road networks are covered by cellular services in many countries such as Australia.

Cooperative V2X communications can be used as emerging wireless data connection links between an NTRIP Caster and moving vehicles. In this regard, DSRC RSUs can be connected to an NTRIP Caster using either LAN connections or cellular networks to concurrently receive the corrections and broadcast them to vehicles moving within the RSU coverage range of hundreds of meters. The SAE-J2735 message set can support this application in two ways. First, the SAE-J2735 BSM Part-II is capable of carrying RTCM V3.0 messages as required to be exchanged among RSUs and OBUs. Second, the SAE-J2735 data dictionary defines a message type known as MSG_RTCM_Corrections to unambiguously support RTCM data transmissions among RSUs and OBUs. Therefore, exchanging RTCM correction data (received from an NTRIP Caster) from a RSU to vehicles' OBUs allows vehicles equipped with DSRC OBUs to compute their position states while accessing the corrections without direct cellular connections. Hence, on-going cellular data charges do not apply to users of V2X DSRC platforms.

The above proposed setting may encounter a problem because (1) vehicles may lose DSRC links to RSUs connected to the Internet as soon as they travel outside of the transmission range of the DSRC RSUs, or (2) the Internet-enabled RSUs lose their connections to online CORS data servers (no CORS correction data is available at RSU). Two measures can be taken to address the identified deficiencies. Firstly, a large number of Internet-enabled DSRC RSUs can be installed throughout road networks and monitored continuously. This solution imposes huge infrastructural and operational costs to service providers and perhaps the users of the service. Alternatively, vehicles can perform Relative RTK positioning by exchanging their raw GPS observations using RTCM data V3.0, such as RTCM-

1004 binary message, wherever NTRIP data is not accessible for RTK processing from in-range RSUs.

6. Integrated Building Blocks of V2X Communications and Positioning Processing Units

The common base for effective developments and operations of a variety of C-ITS applications is a platform employing the DSRC protocol stack and GNSS positioning mechanisms. The platform shall facilitate the addition and modification of applications aiming at safety applicability, while at the same time promoting non-safety uses of C-ITS. The DSRC/GNSS platform is seen as a middleware (interface) providing WAVE to multiple applications. Fig. 9 summarizes the building blocks of C-ITS units enhanced from that represented in (Alexander, Haley, & Grant, 2011).

A typical V2X unit usually consists of a collection of the following modules, depending on their being an OBU or a RSU:

- Human-Machine Interface (HMI)
- Cooperative Applications
  - V2X Safety/Non-Safety Applications
  - NTRIP Services
  - Geo-routing Services
- Positioning and Sensing
  - Digital Map Database
  - Map Matching
  - Onboard sensors
  - GNSS receiver
  - Precise positioning computation
- Internet Communication Access
  - TCP and/or UDP Connections
  - IPv4 and/or IPv6 Connections
- V2X Wireless Communication
  - Ingress/Egress Interface (WSMP or IPv6 over 802.11p DSRC)

OBUs and RSUs are the most vital parts of any C-ITS. The basic hardware structures of OBUs and RSUs are similar except for the CAN interface being provided by OBUs to access the real-time data of the host vehicle. The HMI component can be used to promote the control of units and to show the status of current applications. The V2X units must combine reliable low-latency wireless communication with precise positioning to allow direct communication links and relative positioning vectors between vehicles and roadside equipment. Other than the standards and specifications of the DSRC radios, whether HW or SW implemented, as per Fig. 1, V2X units require a daemon for positioning and timing such as gpsd to obtain data from the onboard GPS receiver and provide the desired data to safety applications. This requirement is due to the essential role of positioning and timing in all aspects of C-ITS. In this

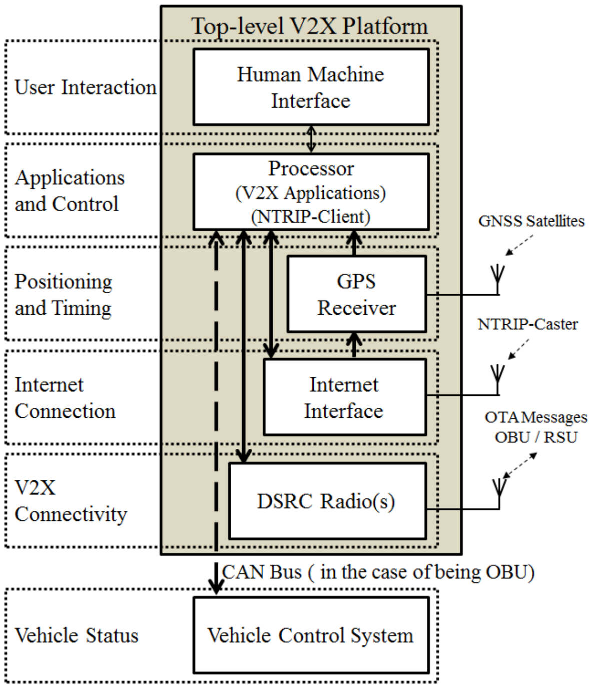


Figure 9: Building Blocks of V2X Communications/Positioning Units

context, the inclusion of the "Internet Connection" component, along with an NTRIP-Client application into V2X units, provides RSUs and OBUs with ubiquitous access to real-time GNSS corrections.

NTRIP Clients are programs which handle HTTP communications to receive data streams of desired NTRIP Sources from an NTRIP Caster and write the data to a serial port or an IP port. The NTRIP Client has to send the correct request message to the NTRIP Caster in order to be accepted and receive data. The NTRIP Client may receive the source-table from the NTRIP Caster after sending the first correct request message. The source-table can be stored in memory or a new source-table may be requested by the NTRIP Client before an NTRIP Source is requested. The NTRIP Client has to determine the mount-point of the NTRIP Source that the desired data stream belongs to. For RSUs, the desired NTRIP-Source/mount-point can be manually selected as the best available mount-point stays unchanged. In the case of OBUs, the NTRIP-Client application has to automatically select the desired mount-point, based on the current position of the user, the required format of data and the type of GNSS in use.

Since the proposed V2X unit architecture employs the complementary characteristics of DSRC, GNSS, and wireless mobile Internet communication, it has the potential to revolutionize the vehicle positioning and navigation systems of C-ITS while providing opportunities for revenue generation. The intelligence about the precise location of mobile users can enhance a wide range of mobile services, from navigation and positioning to location-based services. Non-safety services of C-ITS are forecast to significantly enhance the market for service innovation and value added mobile services of DSRC.

7. Conclusion

A tight V2X wireless communications and positioning integration approach considering the networking and positioning accuracy requirements of C-ITS safety applications is presented. The results of a series of V2X communication and relative positioning measurement campaigns have been reported, and based on these results a number of improvements and amendments to the current architecture of V2X systems have been suggested. Discussion shows that the employment of MIMO technology, along with enhanced channel estimation and tracking mechanisms, provides highly reliable communications links. However, DSRC channel modeling of special safety scenarios, such as those involving Non-Line-Of-Sight (NLOS) conditions, requires further research attentions. Also discussed is that a precise (lane-level) positioning mechanism is an inseparable component of any V2X system. Therefore, the employment of the RTK positioning technique using the NTRIP protocol has been suggested where the results of the field trials have proved that this is a deserved inclusion to any cooperative safety systems. Though, the performance of the proposed integration approach is dependent on the number of GNSS satellites in view as well as the availability of Internet access.

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Biography

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