# Cars Talk to Phones: A DSRC Based Vehicle-Pedestrian Safety System


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***Abstract*—The prevalence of smartphones presents a unique opportunity to develop a system that can have a significant impact on reducing the annual 400,000 fatalities from pedestrian traffic accidents. This system gives 360 degrees, extended range, NLOS view where both the driver and the pedestrian are warned of a possible collision. This, the first of its kind, system was developed from a two year collaborative research effort between Honda and Qualcomm to leverage DSRC so vehicles can communicate with smartphones to preempt a possible collision between a pedestrian (with a smartphone) and an approaching vehicle. This paper describes the pedestrian and vehicle-based algorithms and gives an overview of how this system warns both the driver and the pedestrian so they can take evasive action and prevent a collision. We present the results from our field tests where we demonstrate several pedestrian safety scenarios and present the over-the-air performance data collected in the field tests. Finally, we discuss remaining challenges and present possible approaches to reducing false positives, minimizing spectrum and channel congestion and improving security and localization.**


## I. Introduction

Over the last decade, the U.S. government and the automobile industry have been working on on a technology called DSRC (Dedicated Short-Range Communications) [1] enabling vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications for safety. The U.S. Department of Transportation (USDOT) has estimated that V2V communications based on DSRC can address up to 82% of all crash types involving unimpaired drivers in the U.S. and approximately 40% of all crashes occurring at intersections [2]. These statistics point to the huge potential for this technology to reduce crashes and improve safety for the driving public. The recently concluded USDOT Connected Vehicle Safety Pilot [3] has collected data that demonstrates the readiness and effectiveness of DSRC-based V2V communications for collision prevention. The results in the safety pilot were used to support the NHTSA decision announced in February, 2014 to move towards mandating DSRC for all new light vehicles in the near future.

Over the last two years, Qualcomm and Honda researchers have been jointly working to extend the DSRC safety benefits to pedestrians by enabling DSRC in smartphones and vehicle to pedestrian (V2P) communications [4], [5]. This technology works alongside V2V and V2I applications currently supported by DSRC. The motivation is clear: pedestrian fatalities and injuries are especially problematic and addressing them is an ever-growing focus for traffic safety. According to NHTSA, pedestrians account for $14\%$ of US road fatalities with over $4400$ annual fatalities [6]. Moreover, $69,000$ pedestrians are injured annually. Over 73% of pedestrian fatalities are in urban areas, and over 70% are not at intersections. Older pedestrians are particularly vulnerable, as the fatality rate trends up with age to the point where pedestrians over $75$ years of age have a fatality rate of nearly $1.5$ the general population. The financial impact is also substantive; conservative estimates place the financial burden at over $\$15$ billion a year [7]. Globally, pedestrian fatalities inflict a more burdensome impact, as there is an estimated $400,000$ annual pedestrian fatalities with a disproportionate number occurring in developing countries [8].

Current pedestrian protection systems (PPS) belong to a class of advanced driver assistance systems (ADAS) where onboard sensors are employed to detect the presence of pedestrians that could potentially intersect the vehicle's path. PPS sensors provide awareness and can trigger active measures such as steering, braking, or external airbag deployment. There is no one single method that can prevent pedestrian traffic accident in all conditions. Current PPS systems mitigate crashes with pedestrians by employing a wide array of sensor combinations such as cameras, radar, ultrasonic and LIDAR to overcome fog, rain, darkness, shadows and contrast. All these sensors require a clear line of sight (LOS). This LOS requirement limits the effectiveness of PPS sensors restricting them to a limited range and narrow field of view. Current PPS systems can not detect a pedestrian occluded by obstacles such as trees, street signs, parked cars or buildings. Additionally, variations in pedestrian clothing and physical disparity combined with the dynamic and cluttered backgrounds present a difficult environment for detection when combined with the variable angles of approach and the fact that nearly 70% of US pedestrian traffic accidents occur at night [2] further limiting some of these systems' robustness.

Smartphones are becoming prevalent within all age groups where they are carried and likely in use by a distracted pedestrian walking along the road, crossing at mid-block or walking behind a car. DSRC is a reliable, non line of sight

(NLOS), relatively long range and low latency communication between vehicles and pedestrians and presents an appealing solution to preventing pedestrian accidents when a smartphone is included as part of the solution to the pedestrian safety equation. In this paper, we make the case that a smartphone-based PPS offers value over existing systems. We detail our system design, beginning with the smartphone components and progressing to the vehicle components. The key enabling components start with the implementation of a DSRC stack within the Wi-Fi chipset on the smartphone and leveraging the phone's GPS and inertial system. Our system also includes a smartphone-based pedestrian distraction monitor and a motion state classifier which can provide additional information in the Basic Safety Message (BSM) sent to the vehicle. The vehicle system is based on a V2V safety system design, customized for V2P applications with a specialized target classification system for a pedestrian path prediction algorithm that interacts with the host vehicle path prediction module where both systems are expressly designed to work in concert to suppress false alarms.

For both the vehicle and pedestrian-based applications, customized HMI were developed for warning modalities and scenarios. We describe these pedestrian safety scenarios and detail the accompanying and promising over-the-air performance data collected in the field. Finally, we give an overview of remaining challenges and discuss next steps.

## II. Overview of Current V2P Platform

In this section, we discuss the system that we developed and present our field experiment results.

### A. Smartphone system design

The V2P prototype was developed on Android smartphones equipped with Qualcomm Wi-Fi solutions. The design goal was to provide an *always-on*, *highly accurate* and *low latency* pedestrian collision warning system, without introducing significant hardware or processing overhead to the smartphone. Towards this end, different modules were implemented at different layers of the smartphone software stacks, as shown in Fig. 1. In particular, the lower layer is the firmware and driver layer, which mainly deals with I/O operations on the data arriving from communication links and sensors. Our main effort in this layer was to enable the DSRC radio using the Wi-Fi chip. The middle layer is the service layer which implements three necessary components required for a V2P system:

1) Context Awareness: This module is used to gate the DSRC operation for power saving and channel congestion control.
2) DSRC Manager: This module includes the DSRC upper layer stack and queues the incoming or outgoing BSM messages.
3) Safety Service: This module implements the collision detecion algorithm.

The upper layer is the application layer where we implemented the main demo application with the Human-Machine-Interface (HMI) to the pedestrian.

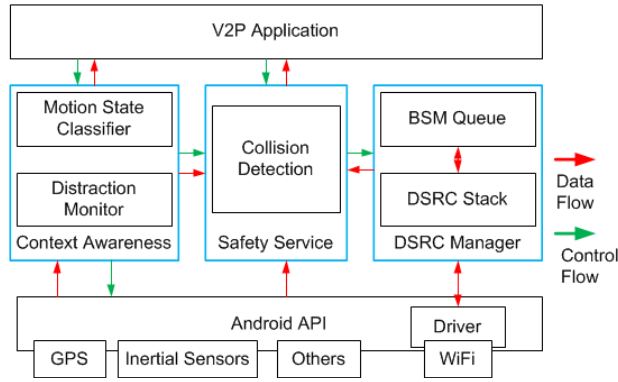



Fig. 1: V2P system design in smartphone

*1) Firmware and driver modifications:* One of the key challenges for this effort is to enable DSRC operation without adding new hardware to existing smartphones. The DSRC band is in the range of $5.85$GHz to $5.925$GHz. Since this band is adjacent to the legacy 5GHz Wi-Fi band, no hardware modification is required in the RF front end. However, modifications were needed in the firmware and driver for the current generation of Qualcomm Wi-Fi chipset to tune to the DSRC band. The firmware modifications involved the inclusion of the DSRC band operation as well as enabling the reception of broadcast packets by setting the interface to operate in *promiscuous* mode. Transmission of broadcast packets were already available in the current firmware design. Enabling the functionality of broadcast packets is a key component to the DSRC solution since there is no Wi-Fi association in the system architecture. The driver was also modified to process these broadcast packets without Wi-Fi association. The broadcast packet consist of a BSM data encapsulated as Wave Short Message (WSM) protocol as defined by IEEE P1609.3 [9]. Once DSRC operation is enabled, the driver will instruct the firmware to tune the RF front-end to operate in the DSRC band. Data packets received from over the air will be inspected by the driver and passed to the upper layer software if it is classified as a WSM packet. The upper layer software will decode the WSM packet further to process the information contained in the BSM. Data packets received from the upper layer will be modified by the driver to be WSM compliant frames and sent over the air as broadcast packets. Again, no hardware changes to the Qualcomm Wi-Fi chipset were required to enable the DSRC functionality.

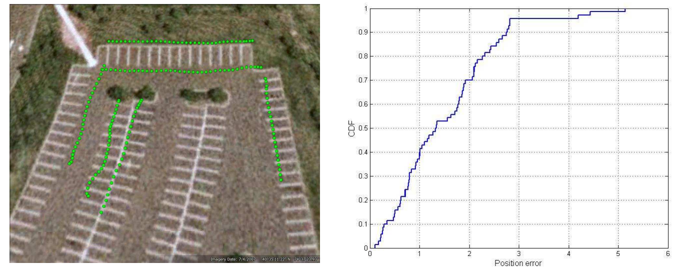
*2) Services:* In this layer, we implemented several key enabling modules for efficient DSRC operation.

First, we implemented a *context awareness* module to gate the DSRC operation. In particular, we incorporated a *motion classifier* [10] that detects if the pedestrian is stationary, walking or running. The system turns on/off DSRC operation based on the motion state of the pedestrian. The motion classifier uses three-dimensional accelerometer data from the smartphone with *minimal* power consumption. Typically, the battery drain from accelerometers is as small as 1mA. This compares with a 30mA battery drain for Wi-Fi and 15mA for GPS. In the prototype implementation, reception of BSM and GPS signal is completely shut off if a pedestrian is determined to be stationary. If a person cumulatively walks for 2 hours a day, the total power consumption will be roughly 100mAh, a reasonably small amount compared to the typical smartphone battery capacity of over 1500mAh. Hence, the context awareness module is a key to reducing battery drain speed and makes *always-on* V2P capability possible in smartphones.

The motion classifier we employed in our experiments showcases the feasibility of using power-efficient sensors to gate the transmission of BSM and enable operation of other hardware blocks. Certainly, to improve performance, we can fuse the output from other sensors to further optimize power usage. Examples include, using the GPS and audio to detect if a person is indoor or outdoor; or using a precise map and camera to detect if a person is walking alongside or on a street. This context awareness enables the transmission of a BSM only when *necessary*. This also avoids a large number of V2P BSM packets introduced by pedestrians using our smartphone safety applications and thus reduces channel congestion in DSRC channels.

Additionally, the distraction monitor runs as part of our context awareness service. This module detects whether the pedestrian is engaged in potentially distracting activities such as texting, listening to music or talking to the phone. Such information is sent over to the vehicle side as part of the BSM message information, which can be used by vehicles to adjust the safety algorithm threshold and even trigger different warning messages to the driver, depending on the pedestrian distraction type, e.g. driver needs extra caution if the pedestrian is detected to be texting and crossing the street.

The safety service runs the collision detection algorithm based on the pedestrian location and received vehicle location and trajectory via a BSM. Designing reliable collision detection algorithms for V2P is much more challenging than designing V2V algorithms because a vehicle moves in a more predictable, kinematic manner than pedestrians. The uncertainties of pedestrian motion mainly arise from two sources: GPS positioning error and changes to movement trajectories. In order to understand the GPS performance, field measurements were conducted as shown in Fig. 2a. The GPS error is measured by calculating the difference between the GPS fixes and the landmarks on Google earth. The plot of the error CDF is shown in Fig. 2b where, with over 95% probability, the GPS error is within 3m and the mean of the error is 1.5m. To deal with uncertainty of pedestrian location and trajectory, the collision detection algorithm is constructed on a probabilistic model. The probability of collision is assumed to be proportional to the intersection area between the predicted trajectories of the pedestrian and vehicle. Warning is triggered if the collision probability is above a threshold. The algorithm works well in the test scenarios presented in Section II-C.




(a) GPS traces

(b) GPS error CDF

Fig. 2: GPS field measurement


(a) Demo App (b) Collision (c) Backing vehicle

Fig. 3: Demo App and HMI

The DSRC manager implements the full stack of DSRC protocol enabling the communication of the smartphone with any standard DSRC devices.

*3) Demo App and HMI:* Visual and audio signals were designed to deliver alerts and warnings to pedestrians in a most effective fashion. As shown in Fig. 3, the visual alerts are presented in bright yellow color and pop up to occupy the full screen to immediately grab the pedestrian's attention. The audio alerts are designed to mimic the natural warning sound from vehicles where the audio signal is a sequence of loud car horns in a "'collision warning"' and a sequence of short high-pitch beeps in a "'backing-up"' warning.

### *B. Vehicle system design*

Vehicle installation consists of processing, communicating, and positioning hardware also known as On Board Equipment (OBE). Fig. 4 shows overview of the functional blocks that comprise vehicle installation. Inputs to the OBE include signals from the host vehicle's Controller Area Network (CAN), GPS, and DSRC receiver. In our system, the OBE outputs audio and visual warnings to the driver. Additionally, OBE broadcast vehicle awareness messages used by pedestrians equipped with DSRC smartphones. To compute a vehicle's path, the V2P system uses the vehicle's yaw-rate, speed and location. The onboard system also calculates the path of the pedestrian via the awareness message received from the smartphone. After vehicle and pedestrian path predictions are computed, the system classifies the collision threat level, then determines if the vehicle is on the collision path with a pedestrian. If there are multiple targets, a threat arbitration process selects the target that represents the highest likelihood of collision. Consequently, the Human Machine Interface (HMI) Notifier modifies the warning state for this highest collision threat. Visual warnings are displayed via transparent Heads-Up Display (HUD) and audio warnings are produced through the vehicle's speakers. In order to alert pedestrians to the vehicle's location, speed, and state, the OBE periodically sends a BSM over the DSRC channel.

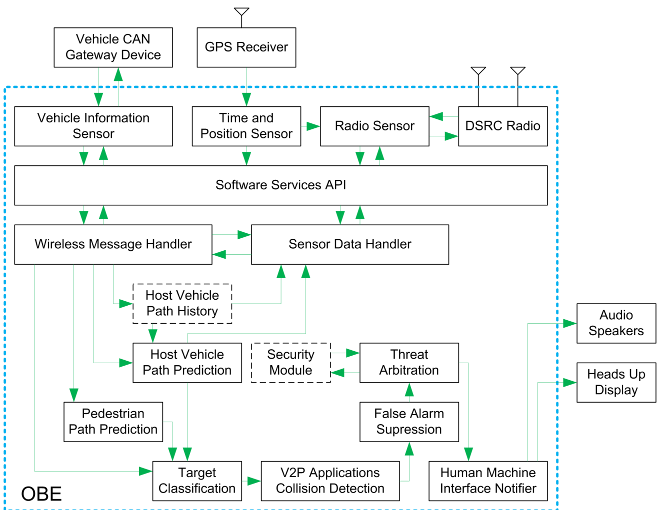



Fig. 4: V2P vehicle functional blocks

*1) Vehicle warning strategy:* Fig. 5 shows an overview of the V2P cooperative system. The vehicle calculates relative position and direction of a pedestrian. In our system pedestrians may be located either ahead or behind the vehicle. For vehicles traveling forward, only pedestrians classified as ahead are of interest. Depending on the distance and vehicle speed, pedestrians can be further classified to be within INFORM, WARN or WARN_BRAKE zones. Each zone's warnings or alert is displayed on the HUD shown in the lower left corner of Fig. 5. For example, if a pedestrian is in the INFORM zone and his/her direction of travel is from left to right, a static "INFORM Image" will be presented to the driver. Furthermore, through the smartphone's context sensing described in the prior section, it is determined whether the pedestrian is distracted. This distracted state information is then incorporated into the awareness message that the smartphone is continuously broadcasting. The vehicle reads the pedestrian distraction state information and presents an appropriate warning image to the driver when the pedestrian is in the WARN_ZONE. If the driver fails to react to the warnings, a more intense audio and visual warning is issued. Finally, when the pedestrian is in the WARN_BRAKE zone, a flashing "BRAKE" image is presented to the driver on the HUD. Conversely, when a vehicle is backing out of a parking slot with a pedestrian and smartphone in its path, the vehicle informs the driver using audible beeps that vary in frequency based on the distance from the pedestrian. Once the driver acts on any of the warnings and applies the brakes, V2P

| - | Value |
|---|---|
| Data Rate | 6 Mb/s |
| Bandwidth | 20MHz |
| Communication Channel | CH181 |
| Pedestrian packet size | 97 bytes |
| Standards | IEEE 802.11p |
| Transmission Rate | 10 Hz |

TABLE I: Specification of the DSRC devices

warnings disappear. All the parameters in the V2P system are customizable and are currently being evaluated for optimal configurations.

State information on distracted pedestrians can be have value future use in a more matures system. For example, if a pedestrian is listening to music through headphones, flashing of headlights may be a better option than sounding a horn. On the other hand, if a pedestrian is texting, using the horn may be appropriate.

A vehicle traveling in heavy pedestrian traffic may generate unnecessary warnings to the driver. In this case, the V2P system recognizes that there are too many pedestrians ahead and displays a general pedestrian zone image on HUD, as shown in the lower right corner of Fig. 5.

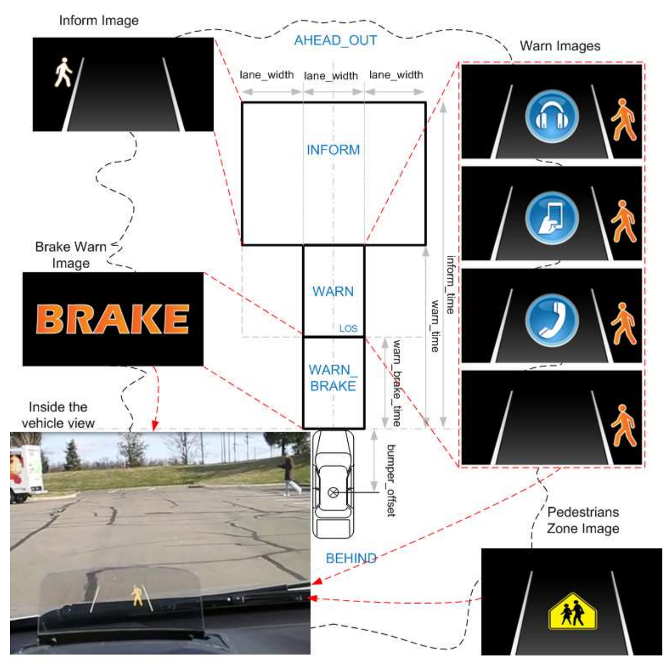



Fig. 5: Vehicle Warning Strategy

## C. Test scenarios

To verify the communication robustness of our system in a real-world setting, we examined the characteristics of DSRC at an intersection located within a residential district. The specification of the DSRC devices we employed are shown in Table I. The first scenario was NLOS as shown in Fig. 6 where a building and a large vehicle were partially

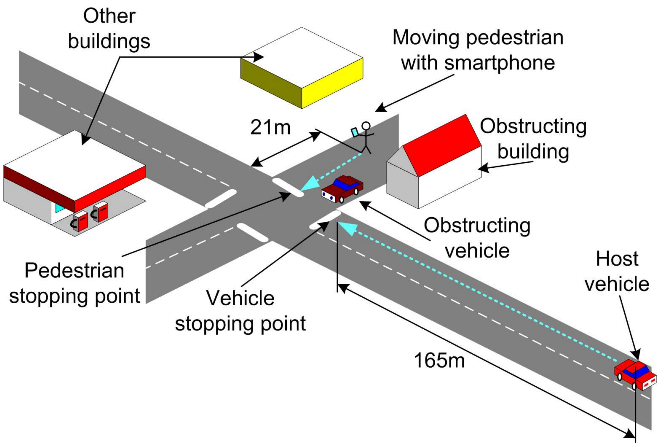



Fig. 6: NLOS test setup

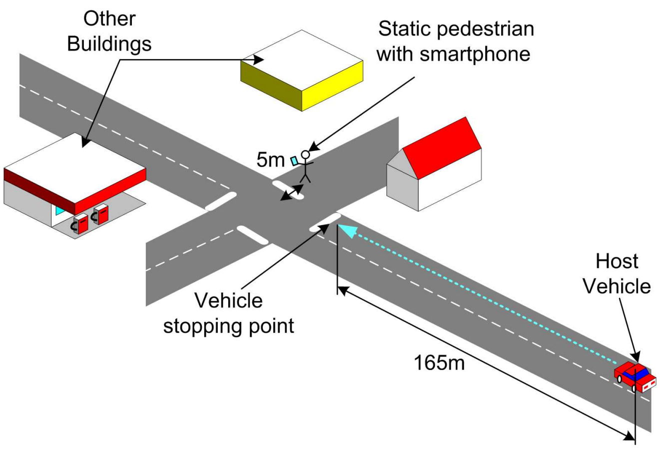



Fig. 7: LOS test setup

obstructing direct LOS between the vehicle and the pedestrian. In our experiment, the vehicle started driving 165m from the intersection and at the same time the pedestrian began walking from a point 25m away from that intersection. The vehicle then accelerated to 12.5m/s, and started braking approximately 45m before the intersection. The pedestrian walking speed was 1.5m/s. Finally, the vehicle and pedestrian came to a full stop as indicated in the figure. The second scenario was the LOS, scenario depicted in Fig. 7. The vehicle maneuver was the same as in the NLOS scenario while the pedestrian was standing 5m from the intersection.

We used Inter Packet Gap (IPG) and Received Signal Strength Indicator (RSSI) as communication performance metrics. IPG is defined as the time between successive successful receptions of messages sent by a specific transmitter. RSSI is an indication of the power level being received by the antenna. The higher the RSSI number, the stronger the signal. In general, RSSI is relative measure of the power and is typically posed in arbitrary units. For this experiment, the receiver was tuned to output RSSI measurements in dBm.

The maximum relative speed between a pedestrian and a vehicle is typically lower than maximum relative speed between two vehicles. Therefore, the communication range requirement for V2P system is shorter than for V2V cooperative systems. In all our tests, the vehicle was traveling between 10 to 20m/s. The corresponding V2P communication range of 150m allows vehicle to become aware of a standing pedestrian anywhere from 7.5 to 15 seconds in advance. In most scenarios, this Time to Collision (TTC) is sufficient to warn the driver of impeding collision with a pedestrian.

### *D. Field measured data*

Fig. 8 and Fig. 9 show RSSI and IPG values for the NLOS and LOS scenarios respectively. These figures are superimposed results of three runs. As expected, power values of the received signals for the NLOS are lower than LOS scenario. However, the vehicle receiver was able to decode most of the messages as indicated in low IPG values. IPG values are typically between 100 and 150ms for these scenarios. In both cases IPG values indicate that there is no significant loss of communication for the distances bellow 160m.

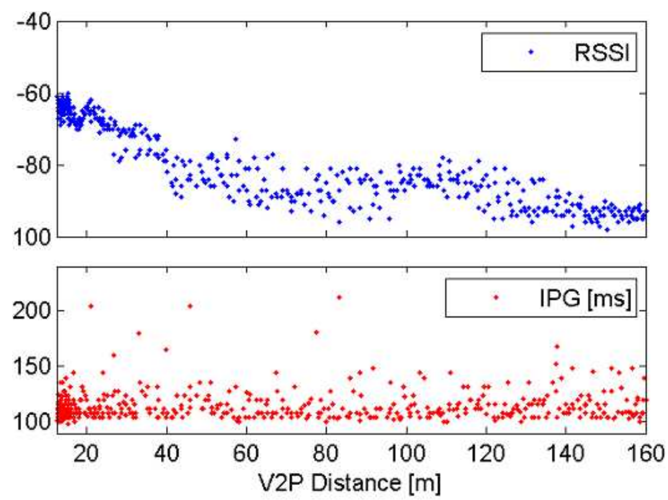



Fig. 8: NLOS: RSSI and IPG results

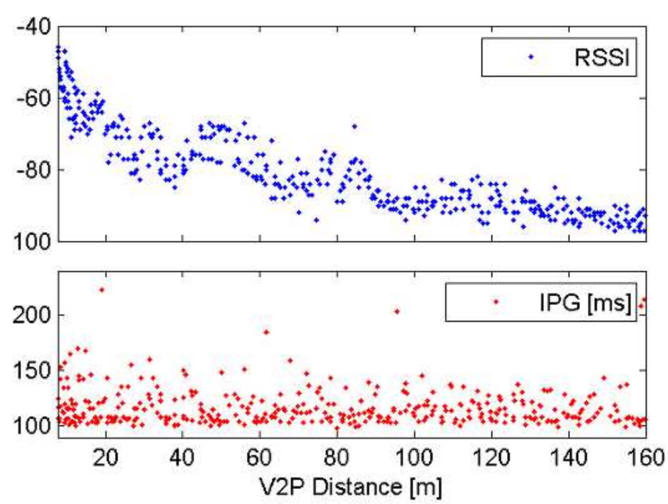



Fig. 9: LOS: RSSI and IPG results

## III. Further Challenges and Next Steps

In the previous section, we validated that the our systems has an acceptable performance for both radio transmission range and also positioning accuracy. We also demonstrated that by introducing a situational awareness capability, the power consumption of a DSRC smartphone is manageable. However, this is a first step and to realize the vision of having phones talk to cars and protect vulnerable road users from crashes, there are many challenges and obstacles that the industry has to work together to address. In this section, we discuss some of the key challenges which have not been addressed in our system. We also present possible solutions to address these challenges so researchers can make the V2P concept a standard option in mobile and automotive applications.

### A. Spectrum and channel congestion

Channel 172 (5.855GHz – 5.865GHz) of the DSRC spectrum is currently assigned for V2V safety applications. With the potential of thousands of vehicles in the 300m DSRC transmission range, channel congestion has been a key issue of investigation over the last few years in the U.S. and Europe [11]–[13]. Enabling billions of potential transmitters from mobile devices in Channel 172 can certainly complicate the congestion issues. We discuss a few mitigation schemes to eliminate or reduce channel congestion in the critical safety channel across the different operation modes of the smartphones.

(1) *Receive-only mode:* Mobiles are *only* allowed to receive in the critical safety channel thus creating no additional burden to the safety channel's bandwidth. In this case, the safety alerts are dependent on safety applications running on the mobile phones. A device receives BSMs from neighboring vehicles and calculates the imminent threat of collisions. In this case, a warning will be triggered only on the pedestrian smartphones and not on the vehicles. There are non-safety critical benefits such operation mode can bring to consumers where users can use phones to receive information from DSRC-enabled infrastructure and other devices (e.g. signal phase and timing information (SPAT) from the traffic signal [14].

(2) *Allow transmission in service channels:* Mobiles are allowed to transmit in another DSRC channel, instead of Channel 172 :. Similar to option (1), this allows the existing V2V system using Channel 172 to not be affected by the introduction of DSRC-equipped smartphones. Industry and regulating agencies, i.e., the Federal Communications Commission would have to agree on assigning one service channel to be available for pedestrian use of DSRC. Vehicles may want to listen in the V2P channel to take advantage of the pedestrian transmissions and improve pedestrian detection functionality, which may add cost on the vehicle side as a secondary DSRC radio would be required. Furthermore, it is likely that a congestion control protocol for smartphones would be required within the V2P channel. Clearly, this option does not exclude option (1) above, i.e. a mobile device can send its beacon in one of the service channels and yet listen to surrounding vehicles in Channel 172.

(3) *Allow smartphone transmission in channel 172:* In this scenario, smartphones are allowed to transmit in the critical safety channel, in addition to the receiving capability. Certain restrictions have to be applied on the mobile side to reduce channel congestion. To start with, mobile devices may be limited to transmit at lower power and lower duty cycle compared to the OBE transmission. This may be natural since pedestrians move at slower rates than vehicles. For safety applications to be effective, lower power and lower duty cycles may be sufficient. For example, mobile devices might only transmit at 10 dBm maximum power (instead of 20dBm,) with a periodicity of 1Hz (instead of 10Hz). This combination of reduced power and periodicity can reduce the air interface congestion from a mobile device by a factor of 40, as compared to an OBE, potentially mitigating congestion issues. In addition, situational awareness would have to be enforced in smartphones so DSRC signals are only transmitted when needed, e.g., when the devices detect the owner is walking near or along a street.

In summary, there are different ways to introduce mobile devices to DSRC with minimal impact to channel congestion in the critical safety channel. However, industry and standards groups must work closely together to enable this. New standards, performance requirements and subsequent certification may be required to specify the role of mobile devices in the DSRC eco-system.

### B. Mobile positioning accuracy

Effective DSRC operation between vehicles requires good relative positioning accuracy. Inaccurate GPS positions can cause false positives and missed detections for V2V safety applications. GPS and positioning technology is expected to improve thus enhancing a DSRC system's effectiveness. Compared to an in-vehicle implementation, a smartphone has a limited form factor and power budget for GPS. Hence, smartphones may exhibit worse positioning accuracy under comparable conditions. To further improve the positioning accuracy on phones is certainly a key step towards making V2P safety systems a reality. One key enhancement might come from ranging capability embedded in Wi-Fi. With 160MHz channelization, Wi-Fi based ranging, as defined in IEEE802.11mc [15], is expected to reach sub-meter accuracy. With the large-scale penetration of Wi-Fi technologies into both phones and cars, this capability will aid the GPS-based positioning approach to obtain much better relative positioning accuracy.

### C. Security design

Vehicle security is envisioned to be based on the public-key infrastructure and applied at four stages: bootstrapping, certificate provisioning, misbehavior reporting and revocation [16]. A vehicle may not necessarily have a permanent connection to the infrastructure. However, it is assumed, once powered, that smartphones are always connected to the infrastructure, allowing for an easier security management. Nevertheless, smartphone security must be compatible with the vehicle security design.

Security will also depend on the smartphones' operation mode. For example, there will be no need for certificate provisioning to the phone if the phone is in receive-only mode. On the other hand, if the smartphone transmits awareness messages then certificates can be provisioned through infrastructure.

### *D. Certification process*

Certification of a DSRC-enabled smartphones is contingent on development of performance requirements and objective tests. We observe that while on the one hand the V2P safety application is an important outgrowth of the safety proposition offered by V2V, that certification of communications and application performance should be an outgrowth as well. Is the smartphone's V2P function a supplemental alert or is it a safety-critical warning? Answers to the such questions will dictate the certification process. We realize that while certifications are important, over certifying may prevent the introduction of a smartphone into what might be the largest portion of the DSRC ecosystem. Therefore, to what extent V2P applications are certified will be an important future consideration.

## IV. Conclusions

In this paper, we described a joint prototype effort between Honda R&D and Qualcomm Research to build a DSRC based collaborative pedestrian safety system consisting of pedestrian and in-vehicle components. The key enabling components begin with implementation in firmware and software of DSRC stack within the Wi-Fi chipset on the smartphone, utilizing the smartphone GPS capability for positioning. Context awareness is another important element in the smartphone DSRC implementation to lower power consumption and reduce channel congestion. The vehicle system has at its core target classification and false alarm suppression algorithms developed specifically for pedestrian-vehicle conflict scenarios. Customized HMI were developed for different warning modalities and scenarios. Our over-the-air wireless performance is shown to be sufficient where RSSI and IPG metrics for both NLOS and LOS demonstrated that a communication distances of at least 160m is attainable, allowing the warning applications we have developed to have a an extensive range.

We established practicality and instantiated our work with complete experiments, firmware and algorithms. We performed real-world use field tests with Honda vehicles communicating with Qualcomm-developed DSRC smartphones. We highlighted and outlined remaining challenges and next steps including issues relating to spectrum and channel congestion. These challenges are significant, and we describe approaches for addressing spectrum and channel congestion with several operational concepts that may include a smartphone receive-only mode, allowing transmission in DSRC service channels only or by allowing smartphone DSRC in Channel 172 with reduced transmission power and rate. Other challenges are perhaps more straightforward, as we can expect Wi-Fi ranging to allow sub-meter relative accuracy between a vehicle and a pedestrian. Security design and certification will progress alongside V2V security systems.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