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V2PSense: Enabling Cellular-based V2P Collision Warning Service Through Mobile Sensing

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***Abstract*—The C-V2X (Cellular Vehicle-to-Everything) technology is developing in full swing. One of its mainstream services can be the Vehicle-to-Pedestrian (V2P) service. It can protect pedestrians who are mostly vulnerable on the road. In this work, we seek to enable a V2P service that can identify which pedestrians may be nearby a dangerous driving event and then notify them of warning messages. To enable this V2P service, there are two major challenges. First, a low-latency V2P message transport is required for this infrastructure-based service. Second, the pedestrian's smartphone requires an energy-efficient outdoor positioning method instead of power-hungry GPS due to its limited battery life. We thus propose a novel solution, V2PSense, which trades off positioning precision for energy savings while achieving low-latency message transport with LTE high-priority bearers. It does a coarse-grained positioning by leveraging intermittent GPS information and mobile sensing data, which includes step count from the pedometer and cellular signal strength changes. Though the V2PSense's positioning is not as precise as the GPS, it can still ensure that all the pedestrians nearby dangerous spots can be notified. Our results show that it can achieve the average precision ratio 92.6% for estimating where the pedestrian is while saving 20.8% energy, compared with the GPS always-on case.**

***Index Terms*—V2X, V2P, Cellular network, Mobile sensing**

I. Introduction

The cellular-connected vehicle is forecasted to be a mainstream reality [22]. Its key technology, C-V2X (Cellular Vehicle-to-Everything), enables heterogeneous connectivity and on-device intelligence on the vehicle. One of the visions is to improve road safety. A major focus can be the safety of vulnerable road users, which include pedestrians, cyclists and motorcyclists. In recent years, they take nearly half (49%) of the people who die on the world's roads [28]. It calls for Vehicle-to-Pedestrian (V2P) safety services built on top of the C-V2X.

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We here focus on a cellular-based V2P warning service that pedestrians can be notified once any dangerous driving behaviors (e.g., exceeding a speed limit, wandering, etc.) nearby are detected. This cellular-based V2P solution is motivated by two major factors. First, the coverage of cellular networks is pervasive, so vehicles and pedestrians in most areas can be connected. It can complement most current V2X solutions based on the DSRC (Dedicated Short-Range Communications) technology [8], the performance of which can be largely constrained by its market penetration due to its short transmission range [24]. Second, most car-connected devices and pedestrians' smartphones have been cellular-connected, so drivers and pedestrians do not need extra devices.

The pedestrian who wants to enable the V2P service needs to install a V2P application on his/her smartphone. Once any dangerous event is reported from a vehicle, a V2P server, which can be deployed at the edge or in the core network, will send a safety warning message to the pedestrians nearby the locations where the vehicle is approaching. When receiving warning notifications, V2P applications may warn their pedestrians with sound or vibration. Note that dangerous events can be monitored by some detectors (e.g., speed limit and alcohol detectors) or sensors (e.g., vehicle track and tire damage sensors) in V2X-enabled ADAS (Advanced Driver Assistance Systems) devices, which can communicate with the V2P server through cellular network connectivity.

There are two major challenges. First, a low-latency V2P message transport is required, but this infrastructure-based service can result in larger latency than the one based on direct communication between two ends. Specifically, a maximum latency of 100 ms for the V2P message transport is stipulated in the 3GPP standard [2]. Second, the phone's V2P application needs to have an energy-efficient outdoor positioning method, which is required to report the pedestrian's position, due to the phone's limited battery life. Current outdoor positioning methods including the GPS (Global Positioning System) and cellular-based techniques may not be applicable. keeping the GPS module always-on can be too energy-intensive for the phone (see Figure 3). Moreover, the cellular-based methods can be classified into network-based [4] and client-based [9], [10], [13], [21], [29] solutions. The former is not scalable, whereas the latter is not applicable to temporal/device diversity (see Figures 4 and 5).

We propose a novel solution, V2PSense, which enables an energy-efficiency positioning method while achieving low-latency V2P message transfer. In the former, our major idea is to trade off precision for energy savings on the smartphone. It is because the warning service does not need to know precisely where each pedestrian is, but only identify all the pedestrians possibly running into dangerous spots (e.g., intersections). It saves energy by using both intermittent GPS information and mobile sensing data instead of continuous GPS service. The mobile sensing data includes *step count* from the phone's pedometer functionality and *signal strength changes* over time with respect to each observed base-station cell. In the latter, it utilizes LTE high-priority bearers, which are used by the VoLTE (Voice over LTE) signaling [17] and offered maximum 100 ms delay of message transfer. V2PSense keeps track of a potential arrival area (PAA) for each pedestrian. Once a pedestrian's PAA overlaps any dangerous spots, it represents that the pedestrian is close to dangerous events and s(he) will be notified.

We implement and evaluate V2PSense using an LTE test bed and several Android phones. The V2P service involves three main entities: a V2P application server, the vehicle's ADAS device, and the pedestrian's smartphone. The server is deployed in the LTE core network. The vehicle's ADAS device emulated by an Android phone is responsible for only generating safety messages with dangerous events. The smartphone has a V2PSense application to be installed. We here focus on whether the estimated PAA area of a pedestrian can really cover his/her actual position or not, and how much energy-saving can be gained compared with the GPS always-on case. Our results show that V2PSense can achieve 92.6% precision ratio with 20.8% energy saving.

The rest of the paper is structured as follows. Section II presents related work. In Section III, we enable the LTE-based V2P service and present the limitations of current outdoor positioning. We design and evaluate the V2PSense solution in Sections IV and V, respectively. Section VI concludes the paper and presents our future work.

II. Related Work

In this section, we examine current studies of cellular V2X/V2P and outdoor positioning solutions.

Cellular V2X/V2P Solutions. Both the 3GPP standard and the research community have started to undertake the development of V2X solutions [11]. The former has completed an initial version of the cellular V2X standard [1]. It mainly focuses on communication and data/resource scheduling mechanisms on top of the existing cellular infrastructure. In the latter, there have been several research studies [5], [7], [18], [19], [25]–[27]. Most of them examine the performance of V2X communication over the LTE network in terms of different aspects. They respectively consider the leverage of a beamforming technique in the communication [19], study network coverage with respect to maximum number of supported vehicles [18], compare the V2X with the IEEE 802.11p [14] regarding cooperative awareness [7], and investigate vehicular safety applications in terms of LTE device-to-device (D2D) communication [26] and LTE resource scheduling [27].

Several studies [6], [12], [20] have been proposed to address various V2P issues. Specifically, Begheri et al. proposed a solution for direct communication between vehicles and pedestrians [12], and leveraged both the perception system formed by embedded sensors and the V2P communication to achieve pedestrian safety [20]. The other [6] study seeks to save energy on the pedestrians' mobile devices by adapting the frequency of V2P safety messages.

Our work differs from them in two major aspects. First, we focus on an LTE-based V2P solution that can enable energy-efficient collision warning service on the pedestrian's battery-constrained smartphone. It reduces the usage time of power-hungry GPS module to save energy by leveraging mobile sensor information to update the pedestrian's location. Second, we design and evaluate our solution based on a real test bed including both LTE networks and smartphones.

Outdoor Positioning. Several mechanisms [4], [9], [10], [13], [15], [16], [21], [29] have been proposed as alternatives to the GPS for outdoor positioning. Each of them has some limitations that can thwart V2P services. Specifically, the WiFi-based approach [16] does not work without dense deployment of WiFi access points. The approaches based on cellular signal fingerprints [9], [10], [13], [21], [29] are not reliable since the fingerprints may vary with times, locations, and mobile devices. Another solution [15] based on cellular network Cell-ID can provide only coarse-grained positioning. In the 3GPP standard [4], the outdoor positioning can be offered based on 3G/4G Location Service, but it requires mobile devices to closely collaborate with location servers deployed by carriers. When a large number of pedestrians require this service, heavy loads can be imposed on the network infrastructure. However, our solution neither has these limitations nor requires support from location servers.

III. Enabling LTE-based V2P Service

We deploy a V2P application server in the LTE core network to provide an LTE-based V2P service, as shown in Figure 1. The vehicle's on-board ADAS device and the pedestrian's smartphone, which are UEs (User Entity), attach to the LTE network through the LTE base station, eNB (evolved NodeB). In the core network, the LTE gateways are responsible for forwarding data packets between the eNB and the Internet or the server. Both of the ADAS system and the V2P application on the smartphone connect to the server, since they subscribe to the V2P service. Note that the connection between the smartphone and the server is active only when the pedestrian is staying outdoors.

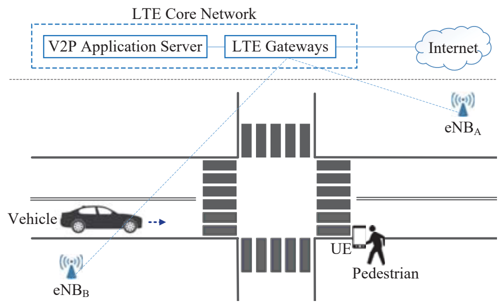


Fig. 1. An example scenario that enables the LTE-based V2P service.

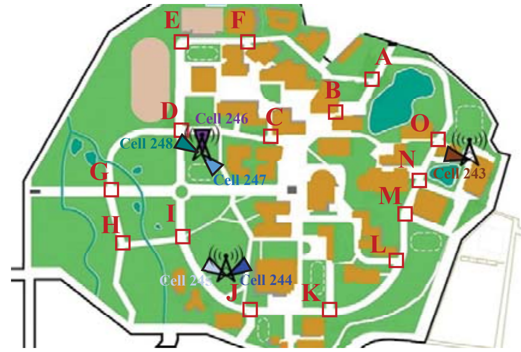


Fig. 2. The map of the campus where an LTE test bed with three eNBs is deployed. The eNBs contain different numbers of cells. Each square represents a forked road or an intersection.

We focus on pedestrian safety around intersections, where most traffic accidents happen. When a vehicle with any dangerous driving events approaches an intersection, all the pedestrians around or approaching it will be warned of potential dangers. To this end, the V2P application server needs to keep track of connected UEs' locations and monitor driving events. The connected vehicles and pedestrians are thus required to periodically update their location information to the server. According to the 3GPP V2X requirement [2], the update interval and the maximum delay of V2X message transfers between the UE and the server are both considered to be 100 ms.

There are two assumptions in this work. First, dangerous events can be monitored by some detectors (e.g., speed limit and alcohol detectors) or sensors (e.g., vehicle track and tire damage sensors), and each event is reported to the V2P server together with the corresponding vehicle's GPS coordinate. These can be easily done by the ADAS system. Second, the V2P server can collect the GPS coordinates of all the concerned intersections from the Google Map. As a result, once the positions of both vehicles and pedestrians can be obtained, the server can identify which pedestrians are around the intersections with dangerous events.

A. Experimental Setting

We conduct experiments using an LTE test bed deployed in our campus. As shown in Figure 2, there are three LTE eNBs, which contain different numbers of cells. We deploy a V2P application server in the core network connecting to these eNBs. Our test UEs, where our developed V2P application is installed, communicate with the server through the eNBs without reaching the Internet. They include three phone models: ASUS ZenFone 3 Deluxe, SONY Xperia Z5, and HTC U Play. Their Android versions are 7.0, 7.0, and 6.0, respectively. In the positioning tests, we test 15 forked roads or intersections as represented by small squares in the figure.

For the message delivery between the UEs and the application server, the message format follows the SAE (Society of Automotive Engineers) J2735 message set [23], which is designed for the DSRC V2V applications. We mainly use the BSM (Basic Safety Message) message type, so its encoder/decoder modules are required at the server and the UEs' applications.

B. Low-latency V2P Message Transfers

In order to achieve the maximum 100 m latency, we do V2P message transfers over the LTE network's high priority bearers. They are designed for LTE services which require different performance guarantees [3]. The LTE bearers can be classified into two types, guaranteed bit rate (GBR) and non-GBR. The former is used for the sessions which deliver real-time multimedia data with guaranteed performance demands, whereas the latter is for the other services, such application signaling, mobile data service, etc. We then choose the non-GBR bearer with the highest priority, since it has maximum delay support, 100 ms, specified in the standard. Note that the bearer has `QCI=5`, where QCI stands for QoS Class of Identifier, different from mobile data service with `QCI=9`.

C. Outdoor Positioning on Smartphone

The smartphone can do outdoor positioning using its GPS module, but keeping it always-on can drain battery very fast. It is thus too energy-intensive for the smartphone to consume a V2P service with always-on GPS. To address this issue, some cellular-based methods [9], [10], [13], [21], [29] have been proposed in the literature. Most of them rely on the relationship between the signal strengths (i.e., RSRP (Reference Signal Received Power)) observed on the smartphone with respect to nearby base stations, and its locations. They assume that the smartphone's location can be identified based on its observed RSRP values according to their relationship in the history. However, they are not applicable to temporal and device diversity.

We next show the drawbacks of these GPS-based and RSRP-based positioning methods with our test bed.

GPS-based Positioning. We compare two smartphone settings, GPS always-on and GPS off, in terms of how much energy is consumed over time. We run each test for 32 hours. Figure 3 shows the battery level decreasing over time for those two cases of the HTC phone. After the 32-hour test, they have 28% and 65% remaining battery levels, respectively. The former case drains battery two times faster than the latter.

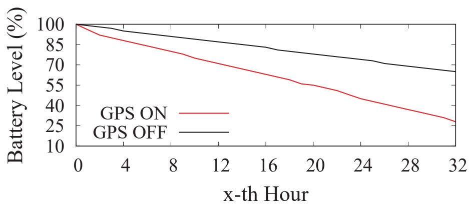
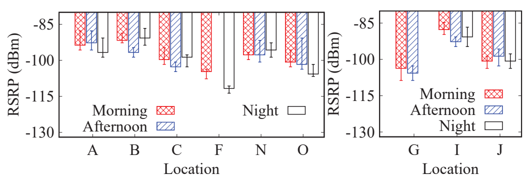


Fig. 3. Smartphone's battery level decreases over time for two cases, GPS always-on and GPS off.



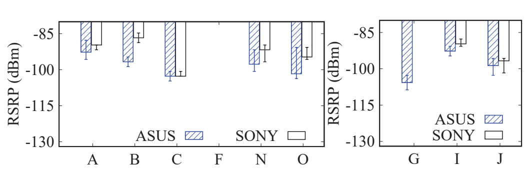
(a) Cell-243 (b) Cell-244

Fig. 4. Smartphone's RSRP values (ASUS phone) vary with times (morning, afternoon, night) with respect to Cells 243 and 244.

We here show the results of only one phone, which leads to the greatest difference of energy consumption between those two settings. The same trend that the GPS always-on case consumes much more energy is also observed on the other two phones. Note that the V2P application will be employed by many pedestrians with various phone models, so its design should be generally lightweight to most phones.

RSRP-based Positioning. The RSRP values observed at one position with respect to an eNB cell may vary with times and phone models. To validate it, we conduct experiments at various locations by measuring RSRP values of their nearby cells at different times (i.e., morning, afternoon, and night) using three phone models. We collect the data over a week and get 10 RSRP samples for each test, where one location is considered with one phone at a time.

Figures 4 and 5 respectively show that the ASUS phone's RSRP values vary with times by considering Cells 243 and 244, and they are different from the SONY phone's in the afternoon. Note that the other results show the same trend and are thus omitted. As a result, the RSRP-based positioning needs to collect RSRP data at different times for various locations and device models. It is almost impossible to accommodate these temporal and device diversities.



(a) Cell-243 (b) Cell-244

Fig. 5. Smartphone's RSRP values vary with phone models (ASUS and SNOY) with respect to Cells 243 and 244.

IV. V2PSense Design

Our goal is to identify which pedestrians may be in danger due to a dangerous driving event and then notify them. The notification can be generated by our developed V2P application, which is installed on pedestrians' smartphones, through sound or vibration. Due to smartphones' limited battery life, the design should be lightweight in terms of energy consumption. To this end, we trade off positioning precision for energy savings on the smartphones. We argue that a coarse-grained positioning method is sufficient for the V2P warning service, since it does not need to know precisely where each pedestrian is, but only ensure that all the pedestrians possibly running into dangerous spots (e.g., intersections) can be notified.

We thus propose a solution, V2PSense, to identify the pedestrians being possibly dangerous based on a coarse-grained, yet energy-efficient, positioning method. It consists of an application server in the LTE core and an application installed on the smartphone of each pedestrian registering the service. Instead of keeping the GPS module always-on, it employs both mobile sensing data and intermittent GPS information to estimate a potential arrival area, named as PAA, for each pedestrian. The PAA indicates the area which the pedestrian may enter. The V2PSense server can then determine whether s(he) is possibly in danger by checking whether the PAA overlaps dangerous intersections or roads. Since it only needs to intermittently activate the GPS, it can save energy.

We set the activation frequency of the GPS to be a configurable parameter, say α minutes, so each pedestrian can adjust positioning granularity based on his/her smartphone's energy life. For each pedestrian, the PAA is set to the GPS coordinate whenever it is updated. Afterwards, the PAA is estimated based on the latest GPS coordinate and the updated mobile sensing data. This set of information is periodically sent to the server every 100 ms by the smartphone. The sensing data includes *step count* over time from the smartphone's pedometer functionality and *RSRP changes* over time with respect to nearby cells.

A. PAA Estimation

The V2PSense server estimates a pedestrian's PAA whenever his/her periodical information update is received. The estimation consists of two steps. First, the V2PSense server uses the increased step count (say, r) which happens after the time of getting the latest GPS coordinate, say O, to estimate how far the pedestrian may have walked away from location O. It can then determine a circle area, an initial PAA, which covers all of his/her possible positions with a center O and a radius of r. Second, it uses the RSRP changes over time to sense the pedestrian's moving direction, thereby narrowing down the initial PAA. The area can be greatly shrunk by the RSRP information of multiple cells [1] observed by the smartphone. By considering one cell's RSRP value observed

[1]The multiple cells observed by a smartphone include a main cell and one or more neighboring cells. The main cell is the one to which the smartphone attaches, whereas the neighboring ones are those whose signals can be observed from it.

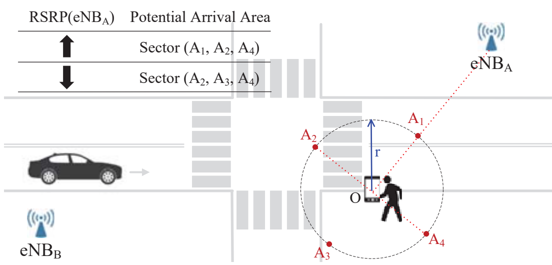


Fig. 6. Illustration of the V2PSense design by considering the RSRP of only main cell, eNB_A.

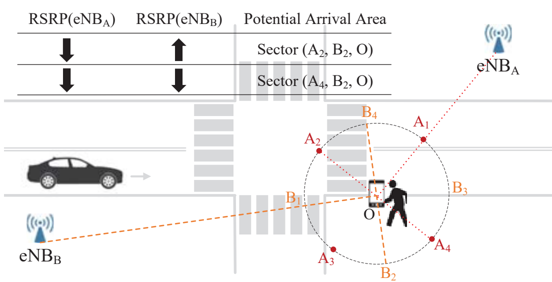


Fig. 7. Illustration of the V2PSense design by considering the RSRP of both main cell, eNB_A, and one neighboring cell, eNB_B.

by the smartphone at some time, if it increases from the one observed at the time of the latest GPS update, the smartphone is considered to be moving towards the cell's position with respect to the latest GPS coordinate. If it decreases, the smartphone is moving away from the cell. Based on this simple hint, the initial PAA can be curtailed iteratively by considering the observed cells one by one. In order to ignore the normal variations of RSRP values, only the RSRP changes larger than a threshold (say, θ) are considered. Note that this approach, which is based on the relative changes of RSRP values over time, is different from conventional RSRP-based positioning methods, which consider the mapping between RSRP values and locations.

B. An Illustrative Example

We illustrate the V2PSense design by considering an example where a pedestrian's smartphone can observe its attached main cell and one neighboring cell, which belong to eNBs eNB_A and eNB_B, respectively. Figure 6 shows this scenario. Assume that the latest GPS coordinate, which is Position O, is obtained at time t_1. At some time t_2, which is smaller than $t_1+\alpha$, the V2PSense application gets the step number counted during the time from t_1 to t_2. It is thus able to estimate the radius r of the initial PAA, as represented by the dotted circle in the figure. By considering the eNB_A's RSRP values change from t_1 to t_2, it divides the initial PAA into two semicircle areas by the diameter $\overline{A_2A_4}$, which is perpendicular to the line connecting Position O and the eNB_A. As shown in the table of the figure, if the RSRP change is an increase, the new PAA is the sector formed by A_1, A_2, and A_4. If it is a decrease, the new PAA is the other semicircle. If no RSRP changes are detected, the new PAA is the same as the initial one.

After considering the main cell, the V2PSense application starts to curtail the new PAA with the neighboring cell information. The new PAA is the sector (A_2, A_3, A_4) by assuming that the decrease of eNB_A's RSRP values is observed. By considering the eNB_B's RSRP change, it divides the new PAA into two sectors by the line $\overline{B_2B_4}$, as shown in Figure 7. When the change is an increase or a decrease, the final PAA is the sector (A_2, B_2, O) or (A_4, B_2, O), respectively.

If the intersection shown in the figure has a potential danger coming from the vehicle approaching it, the V2PSense server considers the pedestrian with the final PAA (A_2, B_2, O) to be dangerous and then notifies him/her. It is because the overlap between the PAA and the intersection area indicates that the pedestrian may be inside the intersection area at time t_2. On the other hand, if the final PAA is the sector (A_4, B_2, O), the pedestrian is anticipated to be safe at the time.

V. Performance Evaluation

In this section, we evaluate our V2PSense design in terms of energy efficiency on smartphones and the precision of PAA estimation. We implement it with 3 dBm threshold (θ) of RSRP changes and 5-second (β) update frequency of the PAA. Two cases, 1 and 5 minutes, are considered to be the frequencies of GPS activation (α). In terms of the energy efficiency, the GPS always-on case, which is used by most V2X solutions, is used for the comparison. Assume that the real-time GPS information reported by a pedestrian's smartphone is his/her accurate position. It is thus considered as the pedestrian's position when the precision performance is examined. Note that the V2PSense application is designed to be a background service, so pedestrians do not need to keep their phones active. Moreover, the notification does not need to be visible, since it can be sound or vibration.

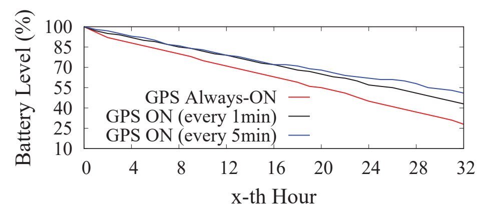


Fig. 8. Smartphone's battery level decreases over time for three cases, GPS always-on, and the 1-min ($\alpha = 1$) and 5-min ($\alpha = 5$) frequencies of GPS activation.

Energy Efficiency. We compare two frequencies of GPS activation, 1 and 5 minutes, with the GPS always-on case in terms of energy consumption. As shown in Figure 8, they respectively have 43%, 51%, and 28% remaining battery life after a 32-hour test. The 1-min and 5-min cases can save energy by 20.8% and 31.9%, respectively.

Precision Ratio. We evaluate the PAA estimation precision by checking whether each PAA update can cover the current pedestrian's position. In order to do the check, we keep the