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***Abstract*—The existing R&D efforts for protecting vulnerable road users (VRU) are mainly based on perception techniques, which aim to detect VRUs utilizing vehicle embedded sensors. The efficiency of such a technique is largely affected by the sensor's visibility condition. Vehicle-to-Pedestrian (V2P) communication can also contribute to the VRU safety by allowing vehicles and pedestrians to exchange information. This solution is, however, largely affected by the reliability of the exchanged information, which most generally is the GPS data. Since perception and communication have complementary features, we can expect that a combination of such approaches can be a solution to the VRU safety. This is the motivation of the current work. We develop theoretical models to present the characteristics of perception and communications systems. Experimental studies are conducted to compare the performances of these techniques in real-world environments. Our results show that the perception system reliably detects pedestrians and other objects within 50 m of range in the line-of-sight (LOS) condition. In contrast, the V2P communication coverage is approximately 340 and 200 meters in LOS and non-LOS (NLOS) conditions, respectively. However, the communication-based system fails to correctly position the VRU w.r.t the vehicle, preventing the system from meeting the safety requirement. Finally, we propose a cooperative system that combines the outputs of the communication and perception systems.**

I. Introduction

According to the road statistics [1], traffic accidents cause more than 3000 deaths worldwide per day, among which half are VRUs (pedestrians, cyclists, and etc.), showing a strong need for solutions to protect VRUs. Computer vision is the most active research domain for pedestrian safety and a great number of perception techniques to detect pedestrians based on vehicle on-board sensors are developed [2]. Such techniques, however, are not applicable if an obstacle exists between the vehicle and the pedestrian. Moreover, the detection coverage is limited by tens of meters and it can largely degrades at night or bad-weather conditions.

Thanks to the widespread usage of mobile phones, it is possible to build a vehicular ad hoc network, where vehicles and VRUs communicate to avoid possible accidents. A common solution to protect VRUs using wireless communication is that vehicles' on-board and pedestrians' handheld devices exchange information regarding their position and trajectory, determine the risk of collision, and warn the human user if necessary [3]–[6]. This approach "detects"

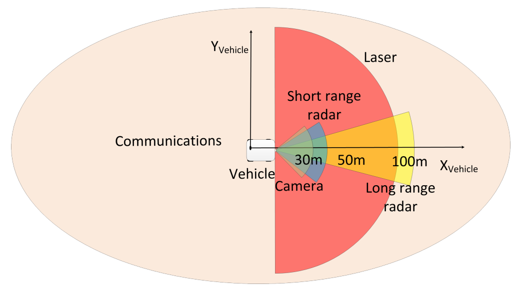


Fig. 1: Field of View of vehicular sensors in comparison with a radio communication range.

pedestrians in a much larger geographical zone compared to the perception techniques. Indeed, the communication range of the Wi-Fi technology is typically several hundred meters; this is much longer compared to the field of view (FOV) of vehicle embedded sensors, which is shorter than 100 m as illustrated in Fig. 1. Communication-based approaches have also weaknesses in contrast to the perception-based techniques. One of the weaknesses is that the exchanged GPS data can be often inaccurate (the position can have 5 m of error in a "good" weather condition) that can result in an over- or under-estimation of collision risk [3]. The error is significantly poorer compared to the precision of some vehicle on-board sensors, such as lasers, which can provide centimeter order of accuracy.

To summarize, it is clear that perception and communication approaches have complementary features, and hence their combination can be an efficient solution for the VRU safety. To the best of our knowledge, WATCH-OVER [7] and Ko-TAG [8] projects are the only existing efforts that look at both the communication and perception domains for protection of VRUs. In WATCH-OVER, the radio signal emitted from a pedestrian device is measured at a vehicle to estimate its location; then a vision technique is used to validate the presence of the pedestrian. Ko-TAG proposes different cooperative localization techniques based on radio signals measurements [9]. It is clear that in both the projects, communication is used for signal measurements but not for information delivery.

We are interested in combining perception and communication techniques by exploiting the capabilities of object detection of a laser-based perception mechanism and information delivery of Wi-Fi based V2P communication. In our approach, a vehicle detects obstacles (including pedestrians) using laser sensors and sends cooperative awareness messages (CAM) to a destination area, which is determined by the obstacle detection module. On the other hand, upon reception of a CAM, the pedestrian acknowledges its existence by a P2V packet. The contributions of this work are:

- definition of a metric to jointly evaluate the performance of the combined perception and communication system,
- performance evaluation of perception and communication systems in real world scenarios,
- proposal of a novel pedestrian protection system based on perception and communication for both the LOS and NLOS scenarios.

The rest of the paper is organized as follows. Section II highlights the related work. Section III presents theoretical models of pedestrian detection and localization characteristics of the perception and communication techniques. Section IV proposes a combined perception and communication system for pedestrian safety, which is evaluated in Section V. Finally, Section VI concludes our paper.

II. Related Work

In the automotive industry, moving obstacle detection has been an important topic for many years and has mainly been tackled with solutions based on vehicle sensors (e.g. camera, laser, and radar) and computer vision technologies. Active sensors such as laser and radar provide data about position and speed of objects. Hence, these sensors have been used to detect and track pedestrians [10], [11]. In [11], the authors defined various scores for detection, recognition and tracking of pedestrians in laser and vision data in order to distinguish pedestrians and non pedestrians, showing the feasibility of a fast sensor based pedestrian detection algorithm in a complex urban environment. However, this approach does not consider scenarios, where pedestrians might be hidden behind an obstacle. Passive sensors such as cameras provide rich information about the environment. Hence, the computer vision field has been very active over the last years to extract the maximum content from images and detect pedestrians in different situations [12]. The survey conducted in [12] evaluates 16 vision based pedestrian detectors for different pedestrian scales (near, medium and far) and LOS/NLOS conditions (no/partially/severe occlusion). The study shows that even in the most favourable conditions (near scale and no occlusion), the performance of pedestrian detection is far from being perfect and degrades sharply when the visibility condition becomes worse. In the cases of heavy occlusion, nearly all pedestrians are missed. As mentioned in [11], [12], an enhanced pedestrian detection can be achieved by combining different sensors (e.g. laser and camera). In [13], obstacles are detected by a laser, which enables establishing a region of interest for camera images so that partially occluded pedestrians are detected by a vision technique. As a result, the perception system can deal with partial occlusions. However, detection of pedestrians in the cases of severe occlusions as well as for the zones that are beyond the sensor coverage area remain an issue.

As mentioned earlier, WATCH-OVER [7] and Ko-TAG [8] are the only efforts that use wireless communication in addition to vehicle on-board sensors for VRU protection. However, these projects concentrated their effort on measurement of radio signal in order to improve the quality of the perception systems. In contrast, we are interested in using communication for information dissemination among vehicles and pedestrians.

The V2P communication and the application requirements for the VRU safety are studied in [3], [4]. [4] compared the cellular and ad-hoc Wi-Fi technologies for V2P and showed that ad-hoc communication is preferable due to the strict delay requirement. In [3], we showed that the Wi-Fi communication satisfies the application's requirement for up to 80 km/h of vehicle's speed in the LOS condition. We also showed that while GPS's position update is typically 1 Hz, to meet the safety requirement, the V2P information exchange should be made at much higher frequency. Finally, an android application, V2ProVu, which receives information from vehicles, calculates collision risk, and displays the danger level to the pedestrian is introduced. The current work provides additional contributions for pedestrian safety including, sensor based obstacle detection, transmission of CAMs to a geographical dissemination zone in occluded areas, and acknowledgement from the pedestrians using the P2V communication.

III. Modelling characteristics of perception and communication techniques

As perception and communication systems are very different, standard metrics such as object state estimation error used in perception or packet delivery ratio (PDR) used in communication are not sufficient to evaluate a combined system. Therefore, in this section, we first define a metric that jointly evaluates the characteristics of the two systems especially their pedestrian detection and localisation capabilities. We then provide theoretical models of pedestrian detection probability and relative positioning uncertainty for perception and communication techniques.

A. Performance metric for VRU protection systems

A road safety system must be able to detect the risk and the location of a potential accident and alert the human users. This requires not only to detect VRUs but also to correctly estimate their locations. Inspired by multi-target tracking, we introduce a metric to measure the performance of the system by considering pedestrian detection and positioning errors.

Multi-target tracking aims at jointly estimating the number of targets and the locations of each target. In this field, *miss-distance* is a metric that calculates the "difference" between the reference multi-object state and the estimated multi-object state. Letting $S=\{s_1, ..., s_m\}$ and $G=\{g_1, ..., g_n\}$ be the estimated and reference multi-object states, respectively, Schuhmacher *et al.* introduced Optimal SubPattern Assignment (OSPA) metric, $\bar{d}_p^{(c)}(S, G)$, as a miss-distance that can consistently evaluate a multi-target filter by considering errors in estimating the number of targets and their locations [14]. OSPA has two parameters, p and c, where p controls the influence of each distance between a reference and an estimated state and c is the cut-off distance, which acts as a penalty for not finding a match between an estimated object and a reference one. c has typically the size of the observation window [14].

In this paper, we are interested in the ability of a VRU protection system in detecting the presence and estimating the location of a pedestrian. In this case, the OSPA distance $\bar{d}_p^{(c)}(S^k, G^k)$ at time k can be simplified in two terms as (1).

$$\bar{d}_p^{(c)}(S^k, G^k) = (\min(c, d(S^k, G^k))^p + c^p * \Delta(k))^{\frac{1}{p}} \quad , \quad (1)$$

where

$$\Delta(k) = \begin{cases} 0, & \text{if detection at time k} \\ 1, & \text{otherwise} \end{cases} . \quad (2)$$

The first term represents the positioning error as the distance between estimated pedestrian location S^k and the ground-truth location G^k. Here, the cut-off distance, c, penalizes the case where S^k=$\emptyset$, *i.e.*, the pedestrian is not detected. The second term is the missed detection error calculated by multiplying $\Delta(k)$ with c.

Since the application aims to detect and locate pedestrians over multiple trials, the application error can be calculated as the mean of $d_p^{(c)}(S^k, G^k)$. Specifically, letting MPE and P^d be the mean positioning error and pedestrian detection probability, respectively, the application performance can be defined as

$$E_{app} = MPE + 2 \times c \times (1 - P^d) \quad , \quad (3)$$

where

$$MPE = \frac{1}{T \times P^d} \sum_{\substack{1 \leq k \leq T, \\ \Delta(k)=0}} d(S^k, G^k) \quad . \quad (4)$$

In the following subsections, we provide theoretical models to evaluate the perception and communication systems.

B. Pedestrian detection probability

A perception system may detect an obstacle (pedestrian in our case), if the obstacle is in the sensor's FOV. As illustrated in Fig. 1, since the FOV angle is 180 degrees for laser-based perception systems, the system may detect an obstacle if the distance to the obstacle, d, is less than the sensor coverage, d_m:

$$P_{per}^d(d) = \begin{cases} 1 - Q(\frac{w_{min} - \mu(d)}{\sigma_c}), & \text{if } d \leq d_m \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

The upper equation of (5) indicates that the detection probability can be smaller than 1 for the range shorter than the FOV, if the mean obstacle width, $\mu(d)$, is smaller than the minimum requirement, i.e., the width of the impact cluster w_{min}. Specifically, standard method for obstacle detection is to gather consecutive laser impacts and select representative clusters containing more than Nb_{min} points. Hence, assuming that cluster width w_c follows a Gaussian distribution $\mathcal{N}(\mu(d), \sigma_c^2)$, we find $\mu(d)$ in (5) as follows

$$\mu(d) = \theta \times Nb_{min} \times d \quad (6)$$

Here θ is the laser angular resolution.

For the communication system, we can consider that a pedestrian is "detected" if the vehicle receives a packet from the pedestrian. Therefore, the pedestrian detection of the communication system is expressed by the successful packet reception probability. Assuming that bit error rate (BER) for individual bits of a packet are equal, the pedestrian detection probability for the communication system is

$$P_{com}^d = 1 - (1 - BER)^L \quad (7)$$

Here, L is the packet length. BER is a function of the SNR (signal to noise ratio), which can be calculated as follows for BPSK and QPSK modulators.

$$BER = Q(\sqrt{2SNR}) \quad (8)$$

It should be noted that (5) and (7) can be evaluated by counting the number of detection over the number of time instants in an experiment.

C. Relative positioning uncertainty

The relative position of an obstacle is estimated from sensor measurements by the perception system in the vehicle's coordinates. In parallel, absolute positions are exchanged between vehicles and pedestrians through the communication system. Then, the following statements can be put regarding the vehicle-pedestrian distance:

- The perception system estimates the relative location of the pedestrian (w.r.t the vehicle): $L_{per}^r(x_P, y_P)$, is estimated with an uncertainty Σ_{per}^r by the laser-based detection system.
- The global positioning system, e.g., GPS, provides the absolute vehicle (resp. pedestrian) location, $L^a(x_V, y_V)$ (resp. $L^a(x_P, y_P)$), with an uncertainty Σ_V^a (resp. Σ_P^a). As a result of the V2P communication, the relative location of the pedestrian can be calculated, $L_{com}^r(x_P$-x_V,y_P-$y_V)$ with uncertainty Σ_V^a+Σ_P^a.

If the absolute positioning is based on only the typical GPS receivers, Σ_P^a and Σ_V^a can be as large as 5 m [3]. If the vehicle has an advanced localization system, such as SLAM and map-matching, it is possible to reduce Σ_V^a down to few centimeters [15].

Since laser sensors can measure the distance to an obstacle at centimeter accuracy, MPE can be neglected (null) for the perception system. Using this distance (obtained from the laser) as the ground truth, the MPE for the communication system can be evaluated from the absolute vehicle and pedestrian positions.

IV. Proposal

In [3], we introduced the *V2ProVu* application that aims at protecting vulnerable users from road hazards. Specifically, in the previous work, *V2ProVu* allowed vehicles to broadcast CAMs and pedestrians to calculate the collision risk. However, there was no perception involved in [3]. In the current work,

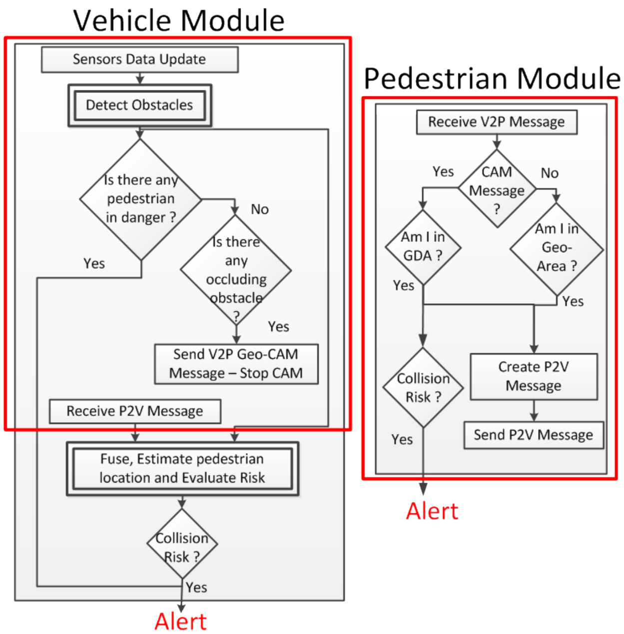


Fig. 2: Flow chart for cooperative pedestrian safety application.

we extend *V2ProVu* with perception capabilities as detailed in Fig. 2. We focus here on the functions inside red rectangles, leaving the fusion step as future work.

On the vehicle side, when a new sensor measurement is available, obstacle detection and classification is made using laser impacts segmentation. This approach allows the system to detect obstacles and classify pedestrians and non-pedestrian objects. Interested readers should refer to [11]. Then, as shown in Fig. 2, an alert is raised to the vehicle if a pedestrian is in a dangerous situation (e.g. immediate risk of collision). Otherwise, the system looks for occluding obstacles, which are close to the vehicle's path. If there is no such an obstacle, a CAM is broadcasted by the vehicle to pedestrians, else, a Geo-CAM, which contains the geographical coordinates of the zone of interest, i.e., the geographical area behind the obstacle is sent. While CAM is a single hop broadcast, Geo-CAM can be forwarded so that the packet reaches the occluded area.

On the pedestrian side, upon reception of a V2P message, it evaluates if the pedestrian is either in the geographical dissemination area specified by Geo-CAM, or in the geographical destination area (GDA) (see [3]) calculated from the vehicle dynamics using standard CAMs, as illustrated in Fig. 2. If the pedestrian is inside the destination area, it sends a unicast packet to the vehicle to inform about its position and to acknowledge the reception of the alert.

Finally, when a pedestrian-to-vehicle (P2V) message is received at the vehicle, its content is fused with detected obstacles and collision risk for this pedestrian is evaluated.

V. Evaluation

A. Experiment set-up

We evaluate our system for LOS and NLOS scenarios on the Inria Paris-Rocquencourt campus [3]. In the experiments, a vehicle approaches a pedestrian from 500 m of distance with the speed of appx. 4 m/s in the following two cases:

- no obstacle exists between the vehicle and the pedestrian (LOS),
- pedestrian stands behind a parked vehicle, with height of 2 m (NLOS).

Table I lists the functionalities, which are implemented in the vehicle and the pedestrian's hand-held device.

TABLE I: Experiment configuration

Vehicle	Laser based obstacle detection Camera based pedestrian recognition [11]
Pedestrian	V2ProVu application for pedestrian protection [3]
Common Features	Wi-Fi ad-hoc communication GPS-based positioning

On the vehicle side, laser measurements are provided at every 100 ms. Triggered by the measurement, the location of the vehicle is estimated. Furthermore, 200 Bytes of CAM packets are broadcasted every 100 ms at the transmission power of 24 dBm and data rate of 1 Mbps. On the pedestrian side, the procedures of "pedestrian module" in Fig. 2 are made. Each test is repeated more than four times for both LOS and NLOS conditions.

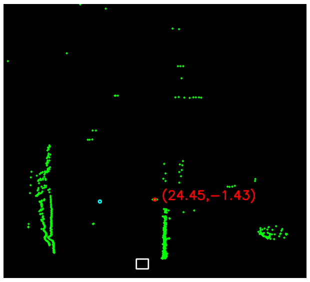
For performance investigation, distance between the vehicle and the pedestrian is split into 20 m of bins and the average performances (pedestrian detection and relative positioning) are evaluated for the individual bins. Furthermore, because the vehicle drove on a straight road at constant velocity, time-to-collision (TTC) is linear (indeed, the mean confidence interval of TTC was 0.06 s, which is a negligible variation). This allows us to calculate the average performances for both the LOS and NLOS scenarios using the results achieved from different tests.

B. Qualitative evaluation

In this section, we qualitatively and visually investigate the limitations of the perception and communication systems. Fig. 3 shows the capabilities and the limitations of the individual approaches in detecting a pedestrian for different scenarios. The white rectangular (Figs. 3a, 3c, 3d) illustrates the ego vehicle that tries to detect the pedestrian. The blue circle (Figs. 3a, 3c, 3d) is the pedestrian's position as announced by the P2V communication. The red (Fig. 3a) and the orange circles (Fig. 3d) are the positions of the pedestrian and an occluding obstacle, respectively, detected and recognized by the laser-and-camera based perception system.

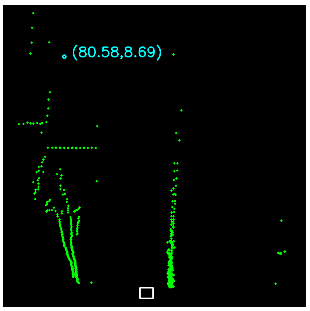
Figs. 3a and 3b illustrate the results of pedestrian detection by the presence of laser impacts and the recognition of a pedestrian body in the image in a LOS condition. As can be seen in Fig. 3a, while the pedestrian is detected in the front right side of the vehicle, the communication system announces his position as in front left of the vehicle. Since positioning of the laser system is very reliable, this is the case where, the communication system has an error due to the inaccuracy of the GPS data.

Fig. 3c shows the case, where the distance between the pedestrian and the vehicle is larger than 80 m. Here, the com-

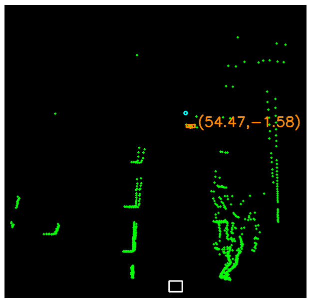


(a) Pedestrian detection in LOS.

(b) Camera based detection.



(c) V2P based detection at high range.



(d) Pedestrian detection in NLOS.

+ Laser points ○ Perception based detection
○ Communications based detection ○ Occluding object

Fig. 3: Obstacle detection in various conditions.

munication system announces the existence of the pedestrian, but the pedestrian system could not detect him because the laser impacts on the pedestrian were too sparse. Similarly, Fig. 3d shows the case, when the pedestrian is behind an obstacle. Here again, the communication system could ”detect” the pedestrian but the perception system could not. Nevertheless, the perception system could successfully detect the occluding obstacle.

To summarize, the limitations of the individual systems are:

- the reliability of the V2P communication system is degraded due to the inaccuracy of the GPS data (Fig. 3a),
- the ability to detect pedestrians is limited by FOV of the sensors of perception systems (Fig. 3c),
- the ability to detect pedestrians is limited for the perception system if an obstacle blocks the line-of-sight to the pedestrian (Fig. 3d).

C. Evaluation of pedestrian detection capabilities

This section investigates the pedestrian detection capabilities of the perception and communication systems. The results obtained from the experiments are compared for the LOS and NLOS scenarios. The packet delivery ratio (PDR) is used for the V2P communication. In addition, the theoretical curves obtained from the models in III-B (for the LOS scenario) are presented. Note that, to obtain SNR in (8), the path loss at a distance, d, is calculated using the two-ray ground model:

$$Loss(d)[dB] = \begin{cases} 20log_{10}(4\pi\frac{d}{\lambda}), & \text{if } d \leq d_c \\ 20log_{10}(\frac{d^2}{h_t h_r}), & \text{otherwise} \end{cases} \quad (9)$$

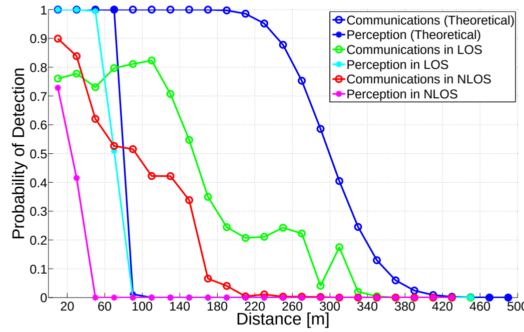
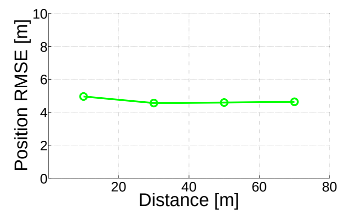
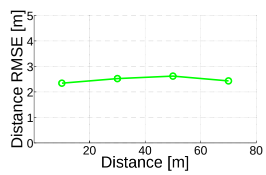


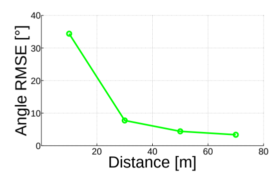
Fig. 4: Detection capabilities of perception and communication in LOS and NLOS conditions.



(a) Position RMSE.



(b) Relative distance RMSE.



(c) Relative angle RMSE.

Fig. 5: Relative vehicle-pedestrian positioning error.

Here, λ is the wave length, h_t and h_r are the transmitter's and receiver's antenna heights, respectively, and d_c is the cut-off distance.

Fig. 4 compares the capabilities of pedestrian detection. We notice that the detection probability of the perception system in LOS fits well to the theoretical curve. On the other hand, although the curves have similar shapes for the communication system, the gap between the experimental and theoretical curves are large due to the high packets loss experienced during the tests. We believe that this is due to the processing overhead of the software.

The detection capabilities are poorer in the NLOS scenario for both the communication and perception systems. This is especially significant for the perception system: the detection distance is reduced to 40 m and the probability of detection stays below 70% due to the occlusion. For the V2P communication, the performance is largely degraded for the distances farther than 60 m.

To summarize, the perception system excels in detecting a pedestrian for the distances smaller than 50 m, while the communication performs better for the distances larger than 80 m.

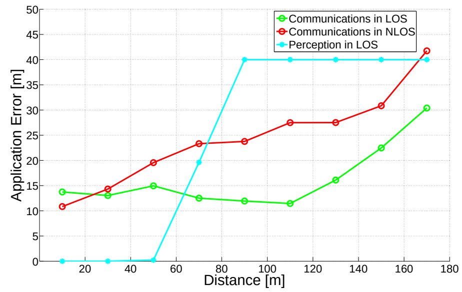


Fig. 6: Application error evaluation.

D. Evaluation of positioning uncertainty

Since laser sensors can accurately locate obstacles, having the laser measurements as the ground truth, we evaluate the positioning error of the communication system. Note that because it is not possible to get the ground truth value for the NLOS scenario, evaluation is made only for the LOS scenario.

Fig. 5a is the root mean square error (RMSE) of the relative position (i.e., the distance between L^r_{per} and L^r_{com} in III-C); this is the distance between the red and blue circles in Fig. 3a. As the result shows, the positioning error of the communication system is around 5 m without depending on the V2P distance.

Fig. 5b and 5c are the distance and angle errors in the polar coordinate, where the position of the vehicle is the pole. The distance and angle errors can be visualized in Fig. 3a as the length and angle differences of the vectors that are to the blue and the red circle (from the white rectangular). As can be seen in Fig. 5b, the distance error is constant 2.5 m. However, RMSE of the relative angle increases with the decrease of the V2P distance (see Fig. 5c). Conceivably, this is due to the inaccuracy of estimation of the vehicle orientation. This can be problematic for correctly assessing collision risk especially for short distances.

E. Evaluation of VRU protection system

Fig. 6 shows the application error defined in (4), where c is 20 m. As can be seen in the figure, for the distances above 80 m, the communication system performs better, obviously because the perception system is not able to detect any obstacle. For distances below 50 m, perception system could perfectly detect and locate the pedestrian, while the communication system shows error due to the positioning inaccuracy. For distances between 50 and 80 meters, non negligible errors are present in both the perception and communication systems. Hence, for this distance range, we believe that a mechanism that fuses data coming from the perception and communications systems has a potential to improve the reliability of the VRU protection system.

VI. Conclusion

This paper studied the characteristics of perception and communications systems for the VRU protection. Our theoretical models and experimental results showed that perception system can well detect and locate pedestrians and other obstacles in up to 50 m of range but it cannot detect the pedestrians which are far from the sensors or behind an obstacle. On the other hand, communication systems can provide extended pedestrian detection range even in NLOS conditions and its contribution is important for the V2P distances larger than 80 m. Finally, we proposed a combined VRU protection system that exploits the strengths of both the perception and communication mechanisms. Our future work includes 1) development of data fusion mechanisms that take account of information achieved from the perception and communication systems and 2) implementation of multi-hop communication in order to improve the system performance particularly, in NLOS conditions.

Acknowledgement

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