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RESEARCH ARTICLE

Implementation of a V2P-Based VRU Warning System With C-V2X Technology

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ABSTRACT Cellular vehicle-to-everything(C-V2X) technology can protect vulnerable road users(VRUs) in traffic accidents. Smartphones are the most common portable devices for VRUs, but they do not support direct communication between vehicles and pedestrians. To address this problem, we propose a vehicle-to-pedestrian collision warning system that includes a phone case designed for the smartphone. It allows VRUs to communicate directly with connected vehicles(CVs) through C-V2X. A collision warning method based on s-t-coordinates is proposed to help VRUs to avoid collision with CVs on both straight and curved roads. Firstly, the World Geodetic System-1984(WGS-84) coordinates of the VRU and CV are transformed to Universal Transverse Mercator(UTM) coordinates. Then the s-t-coordinates of the VRU and CV are calculated. The lateral and longitudinal distance between them is determined. Finally, the time-to-collision(TTC) is used to determine the time to alert the VRU and the driver. To verify the effectiveness of this system, we conduct experiments on communication, positioning, and scenario. The communication experiments show that the system can communicate effectively with low latency and its reliable communication range is more than 200 meters in different scenarios. The positioning experiments show that the average positioning accuracy of the phone case is 0.83 meters in the open-sky scenario, which satisfies the lane-level positioning requirement for VRU applications. The scenario experiments indicate that our method can alert the driver and VRU on both straight and curved roads. The comparative experiments illustrate that our method outperforms the conventional method(CM) and the existing pedestrian alert system(PAS).

INDEX TERMS C-V2X, VRU, smartphone, V2P, phone case, connected vehicle.

I. INTRODUCTION

The Road Safety Annual Report 2020 shows that the number of road deaths is decreasing. This is mainly attributable to safer roads and safer vehicles equipped with crash-preventing technology such as airbags, electronic stability control systems, and automatic emergency braking systems [1]. Compared with other traffic participants, vulnerable road users (VRUs) are much more likely to suffer from injuries or death in traffic accidents due to their lack of external protection. Therefore, it is necessary to design a system that can help drivers or VRUs to take preventive measures to avoid collisions.

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Vehicle-to-everything(V2X) technology has been rapidly developing in recent years. V2X communication, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N), has the characteristics of low latency and high reliability [2], [3]. Many V2V and V2I applications have been developed, such as cooperative platooning, intelligent parking lot, cooperative forward collision warning, and cooperative sensing [4], [5], [6], [7], [8], [9], [10]. V2P applications are mainly focused on vehicle-pedestrian collision warning and vehicle-rider collision warning [11]. These V2P applications alert drivers or VRUs in advance, which can prevent accidents between vehicles and VRUs.

There are two V2P system architectures: indirect communication and direct communication. In indirect communication architecture, vehicles and VRUs communicate with each other through infrastructure. In [12], [13], and [14], roadside sensors(Lidar, camera, radar) detect VRUs on the road and roadside units broadcast their information to connected vehicles(CVs). These methods can only alert drivers, not both drivers and VRUs simultaneously. Additionally, roadside infrastructures require high computing power in this architecture. Pedro et al. [15] proposed a multi-sensing and communication method to prevent accidents between vehicles and VRUs through LTE or 5G. Bagheri et al. [16] and Hussein et al. [17] proposed V2P collision avoidance methods with smartphone, cellular network, and cloud. However, these methods may result in high communication latency and low reliability [18] because they exchange messages through roadside infrastructures. This makes them unsuitable for safety applications.

In the direct communication architecture, vehicles and VRUs communicate directly with each other without any intermediate entity [18]. Wu et al. proposed a V2P system based on DSRC [19]. The firmware and driver of the Wi-Fi chipset on the smartphone are modified to support DSRC in this system. José. et al. [20] and Kaustubh et al. [21] introduced pedestrian protection applications that calculate risk, and provide hazard alerts for pedestrian using Wi-Fi. Andreas. et al. [22]designed a low power pedestrian protection system based on IEEE802.15.4 to alert the driver. These methods show that direct communication architecture is more efficient for V2P applications. However, they require the devices of VRUs and vehicles to support the same type communication technology.

There are several direct communication technologies between VRUs and CVs, such as Wi-Fi [20], [24], C-V2X [23], [25], DSRC/IEEE 802.11p [19], Bluetooth [26], and IEEE 802.15.4 [22]. Wi-Fi has a communication range of 100 meters to 150 meters. However, it takes a long time to establish a connection between the VRU and the CV. It shortens the time for the driver to avoid a collision in high-speed situations [24]. DSRC has the characteristics of low delay but suffers from a collision probability under higher traffic loads due to its random-access scheme, making it unsuitable for VRU applications in areas with high traffic loads, such as crossroads [27]. Bluetooth and IEEE 802.15.4 have a communication range of about 50 meters and 80 meters, respectively. These two technologies can only support short-range V2P applications [24]. Compared with the above technologies, C-V2X has a longer range [28] and higher reliability [27]. However, there is limited research about VRU applications based on C-V2X [11]. There is a lack of suitable VRU devices that can support direct communication and have a long communication range at present. While smartphones are the most common portable devices for VRUs, they do not support C-V2X direct communication, which means that VRUs cannot communicate directly with CVs through smartphones.

To address this problem, we propose a new V2P-based VRU collision warning system in this study. The main contributions of this research are as follows.

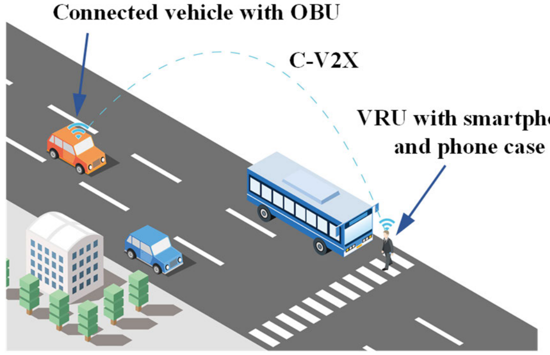

FIGURE 1. VRU collision warning system.

FIGURE 2. Smartphone and phone case.

1) A phone case is designed for a smartphone to help VRUs communicate directly with CVs through C-V2X. It can enhance the safety of VRUs and prevent collision between vehicles and VRUs.

2) VRU collision warning method based on s-t-coordinates is proposed and verified by field test. It is proved to be an effective method to alert the driver and VRU on both straight and curved roads.

3) We evaluate the performance of the V2P-based VRU warning system on reliable communication range, end-to-end latency, and localization accuracy.

The remainder of this paper is organized as follows. We introduce the hardware design scheme of the phone case, software architecture, and collision warning algorithm in Section II. We present the results of experiments and performance analysis in Section III. Finally, we summarize the conclusions in Section IV.

II. SYSTEM ARCHITECTURE

The proposed VRU collision warning system consists of an on-board unit(OBU) installed in a CV, a smartphone, and a phone case, as shown in Fig. 1. The phone case and the CV exchange real-time information, including position and motion status, through C-V2X. The V2P applications on the OBU and smartphone determine whether there is a risk of collision, respectively. If a risk of collision exists, they will alert the driver and VRU with sounds, icons, or vibrations.

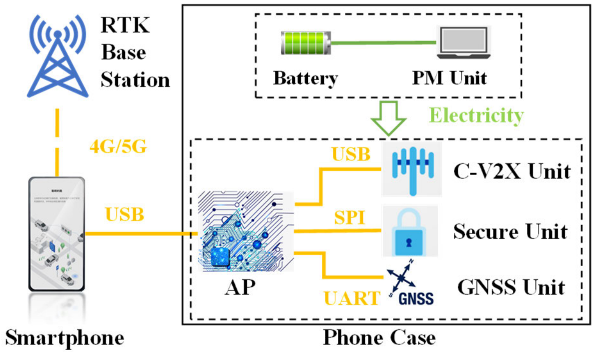

FIGURE 3. Hardware composition of the phone case.

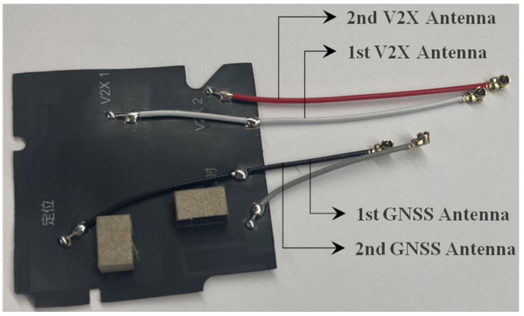

FIGURE 4. Antennas of the phone case.

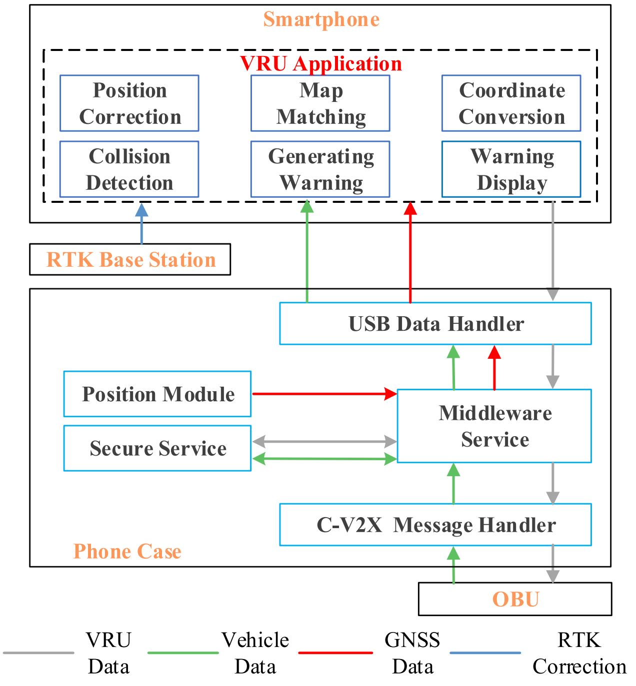

FIGURE 5. Data flow of VRU collision system.

A. HARDWARE DESIGN

In this study, we designed a phone case for the smartphone so that it can communicate directly with CVs. As shown in Fig. 2, the pictures on the left, middle, and right are the front side of the smartphone, the back side of the smartphone with the phone case installed, and the front side of the phone case, respectively. The phone case supports C-V2X communication without affecting the smartphone. It is installed on the back of the smartphone and is convenient for VRUs to carry.

The phone case consists of six components: a battery, a power management(PM) unit, an application processor(AP), a C-V2X unit, a security unit, and a global navigation satellite system(GNSS) positioning unit, as shown in Fig. 3. The phone case is charged with a USB-C charger. The battery and power management unit supply power to the whole device so that the phone case does not consume the power of the smartphone. The C-V2X unit is used to communicate with the CV. The security unit ensures information security during communication. The GNSS positioning unit provides positioning of the phone case. The AP obtains data from the other units and sends the information about the VRU and the CV to the smartphone. The smartphone's application combines this information and the real-time kinematic(RTK) corrections of the base station to obtain the high-precision position for the VRU. The high-precision position of the pedestrian is sent to the AP and broadcasted by the C-V2X unit finally. The AP connects the C-V2X unit, secure unit, GNSS unit, and smartphone with universal serial bus(USB), serial peripheral interface(SPI), universal asynchronous receiver-transmitter (UART), and USB, respectively. The smartphone communicates with the RTK base station using 4G or 5G networks.

There are four built-in antennas on the flexible printed circuit (FPC) board of the phone case, as shown in Fig. 4. These antennas include two V2X antennas and two GNSS antennas. The first V2X antenna is used to send and receive V2X data. The second V2X antenna is used to receive V2X data, which can enhance reception. The first GNSS antenna is an L1 single-frequency passive antenna for time synchronization. The second GNSS antenna is an L1/L5 dual-frequency antenna for high-precision positioning. The communication effectiveness is ensured by adjusting the antenna gain, efficiency, and radiation field shape. Shielding and absorbing measures are taken to reduce the interference between the antennas of the phone case and the antennas of the mobile phone.

B. SOFTWARE ARCHITECTURE

The data flow of the proposed VRU collision system is shown in Fig. 5. The algorithm of the VRU application is implemented on the smartphone. The input data of the smartphone include RTK correction data, GNSS data, and vehicle data.

The VRU application corrects the positioning of the VRU according to the input RTK correction data, then map matching and coordinate conversion are conducted. After that, the collision warning algorithm determines whether a risk of collision exists. If the risk of collision exists, the VRU application will alert the VRU through the smartphone. The middleware service module in the phone case receives encrypted vehicle data from the OBU and forwards it to the secure service module. The middleware service module obtains the decrypted vehicle data from the secure service module and then forwards it to the VRU application on the smartphone. The direction of VRU data flow is opposite to that of vehicle data flow.

C. COLLISION WARNING ALGORITHM

In the conventional VRU collision warning method, the lateral and longitudinal distance between the VRU and the CV is calculated using (1) [29]. Then, the time-to-collision(TTC) is calculated with (2). Finally, the VRU warning is determined according to the lateral distance and TTC. The pseudo-code of the conventional method(CM) is shown in Algorithm 1. When the CV is driving on a bumpy road or curved road, the lateral and longitudinal distance calculated with this method may be inconsistent with the actual situation.

$$\begin{cases} dist_{lon} = (x_{vru} - x_{veh})\cos\theta + (y_{vru} - y_{veh})\sin\theta \\ dist_{lat} = -(x_{vru} - x_{veh})\sin\theta + (y_{vru} - y_{veh})\cos\theta \end{cases} \tag{1}$$

$$TTC = \frac{dist_{lon}}{v} \tag{2}$$

where θ is the heading angle of CV, (x_{vru}, y_{vru}) and (x_{veh}, y_{veh}) are the Universal Transverse Mercator(UTM) coordinates of the VRU and CV, respectively. v is the velocity of CV.

Algorithm 1 Conventional Method (CM)

Input: lat_{veh}, lon_{veh}, v,θ
Output: $VRU_{warning}$
Initialization: $TTC_{threshold}$, $dist_{threshold}$
//receive the CV data with C-V2X communication
(lat_{vru},lon_{vru}) ←ReceiveCVData()
(x_{vru}, y_{vru}) ←ConvertLatLontoXY(lat_{vru},lon_{vru})
(x_{veh}, y_{veh}) ←ConvertLatLontoXY(lat_{veh},lon_{veh})
$(dist_{lon}, dist_{lat})$ ←$formula$(1)
if $|dist_{lat}| < dist_{threshold}$
  TTC← $formula$(2)
  if $0<TTC<TTC_{threshold}$ **then**
    $VRU_{warning} =$ **true**
  else
    $VRU_{warning} =$ **false**
  end if
end if
return $VRU_{warning}$

A collision warning method based on s-t-coordinate is proposed to solve the problem of CM. The pseudo-code of the s-t-coordinate method(STM) is shown in Algorithm 2. The ReceiveCVData module outputs the World Geodetic System-1984(WGS-84) coordinate of CV for the VRU through C-V2X communication. In the ConvertLatLontoXY module, we transform the WGS-84 coordinate to the UTM coordinate. The transformation can be found in reference [30]. In the FindReferencePath module, we obtain the reference path for the CV according to the road section where the vehicle is located.

Algorithm 2 s-t-coordinate method (STM)

Input: lat_{veh}, lon_{veh}, v
Output: $VRU_{warning}$
Initialization: $TTC_{threshold}$, $dist_{threshold}$
//receive the CV data with C-V2X communication
(lat_{vru},lon_{vru}) ←ReceiveCVData()
(x_{vru}, y_{vru}) ←ConvertLatLontoXY(lat_{vru},lon_{vru})
(x_{veh}, y_{veh}) ←ConvertLatLontoXY(lat_{veh},lon_{veh})
get the reference line of road from map according to the coordinate of vehicle
$referencePath_{lonlat}$ ←FindReferencePath(lat_{veh},lon_{veh})
$referencePath_{xy}$ ←ConvertLatLontoXY($referencePath_{lonlat}$)
(s_{veh}, t_{veh}) ←GetSTCoordinate(x_{veh}, y_{veh}, $referencePath_{xy}$)
(s_{vru}, t_{vru}) ←GetSTCoordinate(x_{vru}, y_{vru} , $referencePath_{xy}$)
$(dist_{lon}, dist_{lat})$ ← $(s_{vru}$- s_{veh}, t_{vru}- $t_{veh})$
if $|dist_{lat}| < dist_{threshold}$
  TTC←$formula$(2)
  if $0<TTC<TTC_{threshold}$ **then**
    $VRU_{warning} =$ **true**
  else
    $VRU_{warning} =$ **false**
  end if
end if
return $VRU_{warning}$

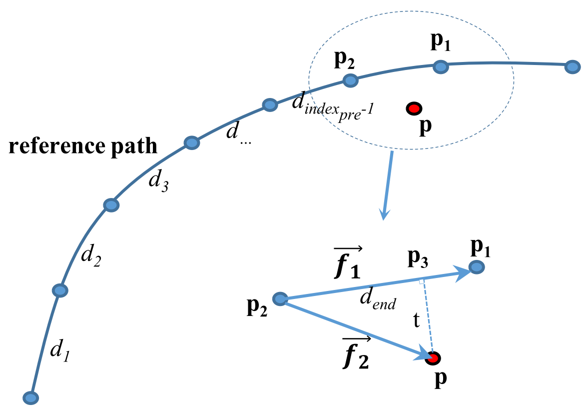

FIGURE 6. Schematic of calculating s-t-coordinate.

The main difference between STM and CM is the calculation of lateral and longitudinal distance. The OBU and smartphone can obtain map from the maps platform. The map contains the reference path of road that consists of a series of points along the road. The calculation of s-t-coordinates for the CV and the VRU is shown in Algorithm 3. In the GetST-Coordinate module, we obtain the s-t-coordinates relative to the reference path for the input position. The FindNearstPoint and Find2ndNearstPoint modules return the nearest point and the next nearest point for the input position in the reference path, respectively.

Algorithm 3 GetSTCoordinate

Input: x, y, $referencePath_{xy}$
Output: s, t
//find the nearest point **p1** of point(x,y) and it's index
$(x_{p1}, y_{p1}, index_1) \leftarrow$ FindNearstPoint($referencePath_{xy},_{x,y}$)
//find the next nearest point **p2** of point(x,y) and it's index
$(x_{p2}, y_{p2}, index_2) \leftarrow$ Find2ndNearstPoint($referencePath_{xy},_{x,y}$)
$index_{next} \leftarrow max(index_1, index_2)$
$index_{pre} \leftarrow min(index_1, index_2)$
//vector f1
$(xf1, yf1) \leftarrow (referencePathxy(indexnext) - referencePathxy(indexpre))$
//vector f2
$(xf2, yf2) \leftarrow ((x, y) - referencePathxy(indexpre))$
//the s-t coordinate of point(x,y)
$t \leftarrow formula$ (3)
$s \leftarrow formula$ (5)
return t, s

The nearest point p_1 and the next nearest point p_2 of point p can be found on the reference path, as shown in Fig. 6. The indexes of p_1 and p_2 in the point list are $index_1$, $index_2$, respectively. The vector from the point with the smaller index to the point with the larger index is $\vec{f_1} = (x_{f1}, y_{f1})$. The vector from the point with the smaller index to the point p is $\vec{f_2} = (x_{f2}, y_{f2})$. The lateral distance of point p is the vertical distance from point p to line segment p_2p_1, and the t coordinate of point p is calculated with (3). The distance d_{end} from the point with the smaller index to the perpendicular foot p_3 is calculated with (4). The s coordinate of point p is calculated with (5).

$$t = \begin{cases} \dfrac{|f_1 \times f_2|}{\left|\vec{f_1}\right|}, x_{f1}y_{f2} - x_{f2}y_{f1} \geq 0 \\ -\dfrac{\left|\vec{f_1} \times \vec{f_2}\right|}{\left|\vec{f_1}\right|}, x_{f1}y_{f2} - x_{f2}y_{f1} < 0 \end{cases} \tag{3}$$

$$d_{end} = \frac{\vec{f_1}\,\vec{f_2}}{\left|\vec{f_1}\right|} \tag{4}$$

$$s = d_{end} + \sum_{i=1} d_i \tag{5}$$

where d_i is the distance between the point with index i and the other point with index $i+1$ on the reference path. $index_{pre}$ is the minimum of $index_1$ and $index_2$.

The lateral and longitudinal distance between the CV and VRU can be calculated with (6). The collision warning algorithm proposed in this study can be implemented in the smartphone and OBU, which can alert the driver and VRU, respectively.

$$\begin{cases} dist_{lon} = s_{vru} - s_{veh} \\ dist_{lat} = t_{vru} - t_{veh} \end{cases} \tag{6}$$

TABLE 1. Specifications of the main devices.

Name	Specification
Smartphone	Xiaomi Mi 9
Phone case	CPU: iMX6ULL, Memory: 512MB, Storage: 8G, LTE-V module: ZM8350
OBU	CIDI OBU3.0 (CPU: iMX6, Memory: 512MB, Storage: 8G, LTE-V module: ZM8350)

III. EXPERIMENT AND VALIDATION

In this section, we designed experiments on communication, positioning, and scenario to illustrate the performance of the proposed VRU collision warning system. The reliable communication range, end-to-end latency, and positioning accuracy are used to measure the performance of the system [31].

A. COMMUNICATION EXPERIMENT

We designed experiments on an open road to verify the communication performance of our proposed VRU collision warning system. The specifications of the OBU, smartphone, and phone case are shown in Table 1. As the smartphone is often placed in hand or in the trouser pocket, the placement method may influence communication performance. Therefore, we designed the scenarios to study the impact of the placement of the smartphone on communication. LOS and NLOS scenarios are common scenarios to study communication performance. There are four combinations, as shown in Fig. 7. For each scenario, we designed four cases: OBU sending 100-byte messages, OBU sending 300-byte messages, phone case sending 100-byte messages, and phone case sending 300-byte messages. The message is sent 3000 times in each case. Fig. 8 shows the field experiment on Yuchi Avenue.

To study the influence of the smartphone in the trouser pocket, we designed scenario 2 and scenario 4 in which the smartphone and the phone case are placed in a bag. 100-byte packets and 300-byte packets are sent for each scenario to study the influence of the size of the message packet since 3GPP ETSI TS 122 185 requires periodic broadcast messages supporting V2X application with message payloads of 50 bytes to 300 bytes [33].

The reliable communication range, packet loss ratio(PLR), and end-to-end latency are used as performance metrics. End-to-end latency is the time that it takes to transfer a given piece of information from a source to a destination [34]. It is measured at the application level. The average end-to-end latency is calculated for each scenario. Packet loss ratio(PLR) is defined as the number of unsuccessfully received packets divided by the total number of transmitted packets. The PLR is usually used to estimate the reliable communication range [35]. The reliable communication range, which can be computed with the linear interpolation method, is defined as the range when the PLR is 10% [32].

The communication range of the proposed system is tested by selecting points every 60 meters along the road, starting from the position of the stationary CV. The PLR and latency

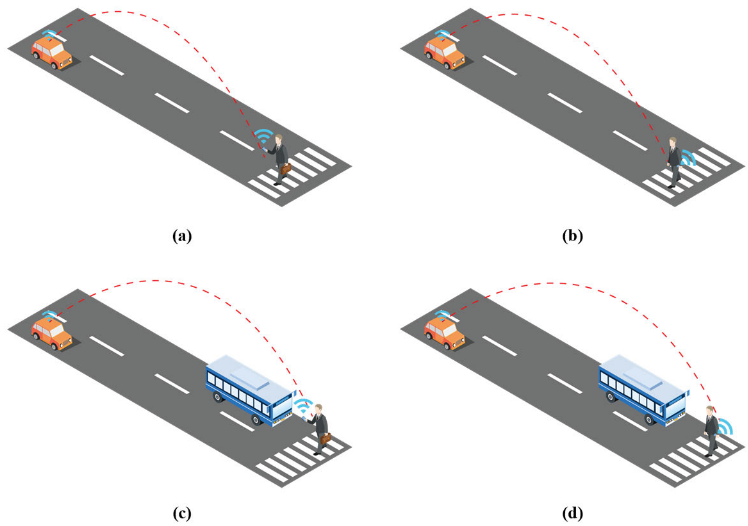

FIGURE 7. Test scenarios. (a) scenario 1:LOS scenario with smartphone in hand, (b) scenario 2: LOS scenario with smartphone in bag, (c) scenario 3: NLOS scenario with smartphone in hand, (d) scenario 4: NLOS scenario with smartphone in bag.

FIGURE 8. Field experiment.

TABLE 2. The reliable communication range for the measured scenarios.

Scenario	Message sending device	Range(m)	
		100 bytes	300 bytes
Scenario 1	OBU	>420	> 420
	phone case	> 420	> 420
Scenario 2	OBU	> 420	380
	phone case	> 420	378
Scenario 3	OBU	306	255
	phone case	306	258
Scenario 4	OBU	305	241
	phone case	309	249

of the system are shown in Fig. 9. Fig. 9(a) shows that the PLR is almost close to 0 in all scenarios when the communication distance is less than 180 meters. Fig. 9(b) shows that the end-to-end latency is between 14 ms and 27 ms in different scenarios. It is much less than 100 ms, which is the latency requirement of VRU applications in cooperative intelligent transport systems(C-ITS) [27]. The reliable communication range, as shown in Table 2, is calculated according to the PLR. The 200 meters communication range is sufficient to give the driver ample response time [27], [33]. According to Table 2, the reliable communication range of the system in different scenarios is far more than 200 meters, which meets the communication range requirement for VRU applications. The reliable communication range of our system is longer than that of Wi-Fi, Bluetooth, and IEEE 802.15.4. Fig. 10∼13 present the comparison of PLR in different cases.

Fig. 10 shows that the PLR is close to 0 when the communication distance is less than 240 meters in both LOS and NLOS scenarios. That illustrates that the proposed system can communicate effectively in both LOS and NLOS scenarios. The PLR of the NLOS scenario is greater than that of the LOS scenario when the distance is over 300 meters.

Fig. 11 illustrates that the PLR is also close to 0 when the communication distance is less than 240 meters, whether the size of messages is 100 bytes or 300 bytes. That means that the proposed system can communicate effectively whether the system sends small messages or large messages. The PLR of the 300-byte scenario is greater than that of the 100-byte scenario when the distance is over 300 meters.

Fig. 12 presents that the PLR is also close to 0 when the communication distance is less than 240 meters. The result shows that whether the smartphone is in the bag or in hand has little influence on C-V2X communication.

Fig. 13 shows that the PLR is close to 0 when the communication distance is less than 240 meters, whether the OBU or the phone case sends messages. That indicates that the phone case can successfully receive and send messages when the communication distance is less than 240 meters. Fig. 9∼13 indicate that the proposed VRU collision warning system can communicate effectively with low latency when the communication distance is less than 240 meters.

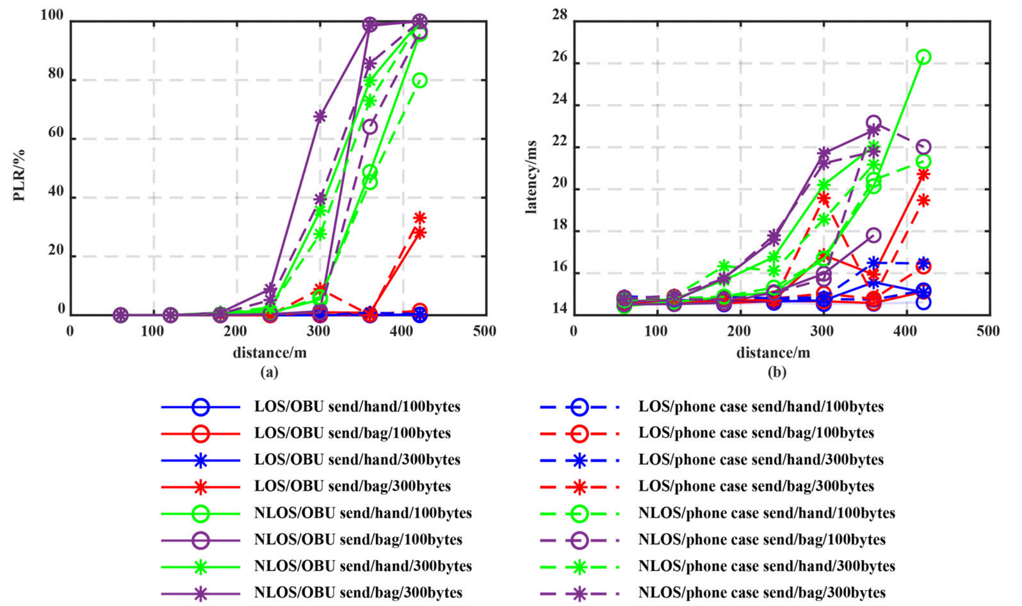

FIGURE 9. (a) PLR, (b) end-to-end latency. (The circle and star indicate the size of messages is 100 bytes and 300 bytes, respectively. The solid line and dotted line indicate OBU and phone case sending messages, respectively. The blue, red, green, and purple indicate scenario 1, scenario 2, scenario 3, and scenario 4, respectively).

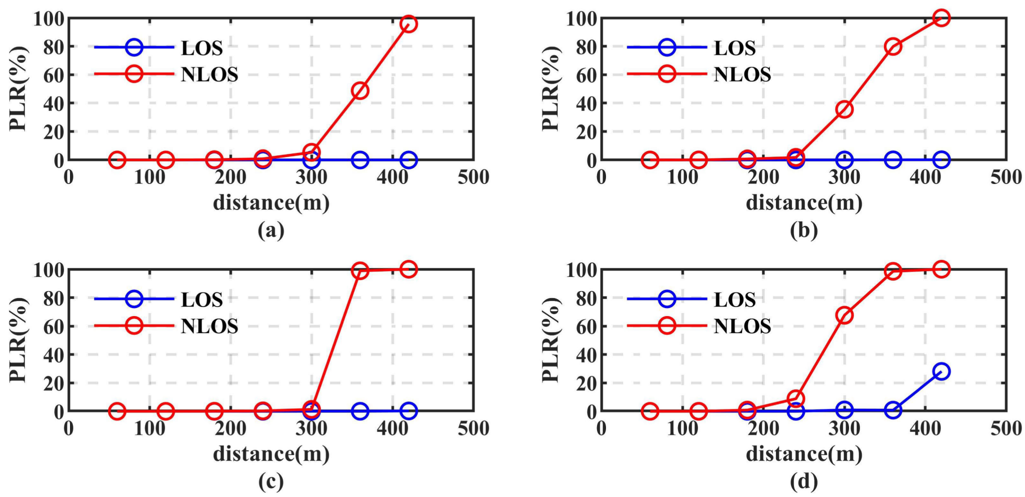

FIGURE 10. Comparison of PLR in LOS scenario and NLOS scenario. (a) scenario 1 and scenario 3 with message size of 100 bytes, (b) scenario 1 and scenario 3 with message size of 300 bytes, (c) scenario 2 and scenario 4 with message size of 100 bytes, (d) scenario 2 and scenario 4 with message size of 300 bytes.

B. POSITIONING EXPERIMENT

A commercial positioning device, the CGI-610 from CHC-NAV company, is used as a reference device to measure the positioning accuracy of the phone case. The CGI-610 device, which has a high-precision dual-antenna receiver, provides reliable and accurate positioning. It can output data up to 100 Hz and achieve horizontal accuracy of 2 cm with RTK [36]. The phone case and the antenna of the reference device are placed at the same position on the top of the vehicle. The distance between the WGS-84 coordinates output by the reference positioning device and the phone case can be determined using the Vincent formula [37]. This distance is used to measure the position accuracy of the phone case.

We chose an open-sky scenario and an urban scenario to test the position accuracy of the phone case, as shown in Fig. 14. Fig. 15 shows the trajectory of the phone case and reference device in the open-sky scenario and urban scenario, respectively. To quantitatively compute the positioning accuracy, cumulative distribution function (CDF) is used to describe the distance distribution between the phone case and the reference device. Table 3 and Fig. 16 show the positioning deviation between the phone case and the reference device.

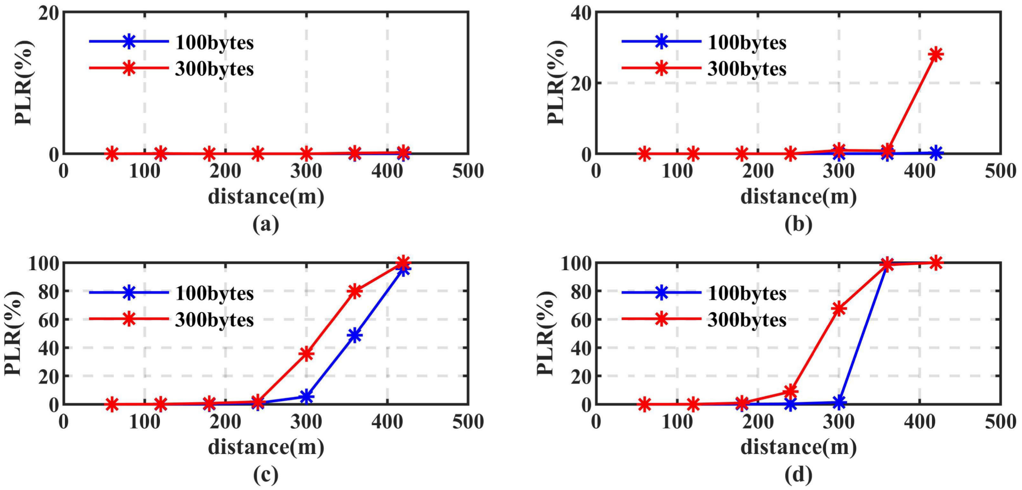

FIGURE 11. Comparison of PLR with different message size. (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4.

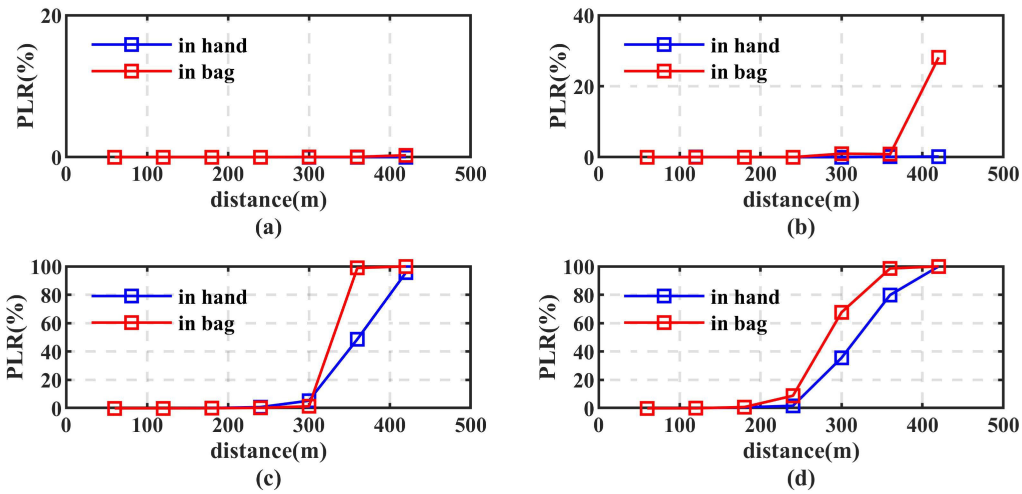

FIGURE 12. Comparison of PLR when the smartphone is in hand and in the bag. (a) LOS scenario with message size of 100 bytes, (b) LOS scenario with message size of 300 bytes, (c)NLOS scenario with message size of 100 bytes, (d) NLOS scenario with message size of 300 bytes.

TABLE 3. The positioning performance of phone case.

	open-sky scenario	urban scenario
Max value of distance (m)	1.62	6.90
Mean value of distance (m)	0.83	2.94
Percentage of points *s.t.* distance <1.5m	97.79%	25.08%

According to Fig. 16 and Table 3, in the open-sky scenario, the maximum positioning error is 1.62 meters and the average positioning error is 0.83 meters. The positioning error of 97.79% points is less than 1.5 meters. In the urban scenario, the maximum positioning error is 6.90 meters and the average positioning error is 2.94 meters. The positioning error of 25.08% points is less than 1.5 meters.

The positioning error in the urban scenario is greater than that in the open-sky scenario because of the multipath effect. The phone case is affected in the urban scenario and this may cause false positives and missed detection. The required positioning accuracy for VRU application is 1.5 meters [38], so the positioning accuracy cannot meet the requirement in urban scenario. As one of the future work, the authors will work with positioning module manufacturers to further improve the positioning accuracy in urban scenario.

C. SCENARIO EXPERIMENT

We designed experiments to verify the proposed method on a straight road and a curved road. The experiment sites are located at Yuchi Avenue and Yuchi Bridge in Changsha, Hunan Province, China, as shown in Fig. 17. The CV, as shown in Fig. 18, drives on the adjacent lane of VRU. The

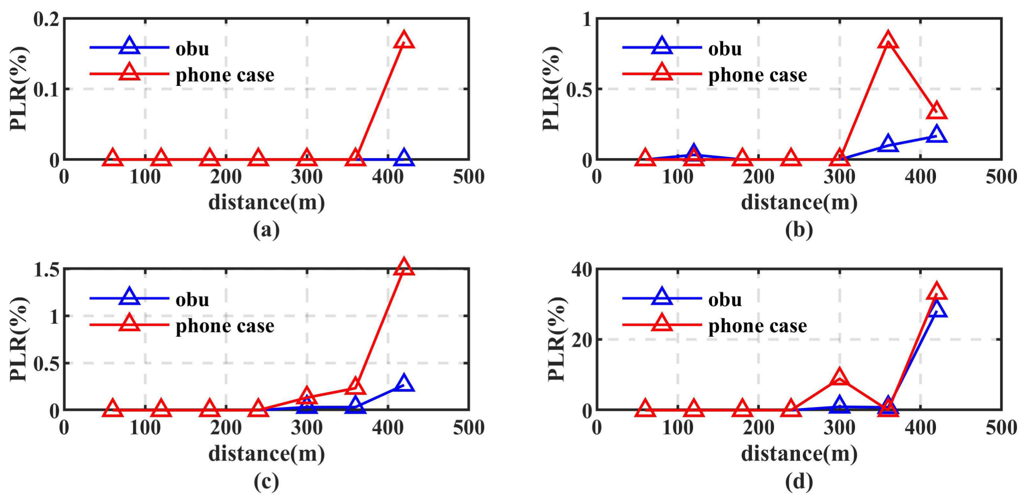

FIGURE 13. Comparison of PLR when OBU and phone case send messages. (a) scenario 1 with message size of 100 bytes, (b) scenario 1 with message size of 300 bytes, (c) scenario 2 with message size of 100 bytes, (d) scenario 2 with message size of 300 bytes.

(a) (b)

FIGURE 14. The field of positioning experiment. (a) open-sky scenario, (b)urban scenario.

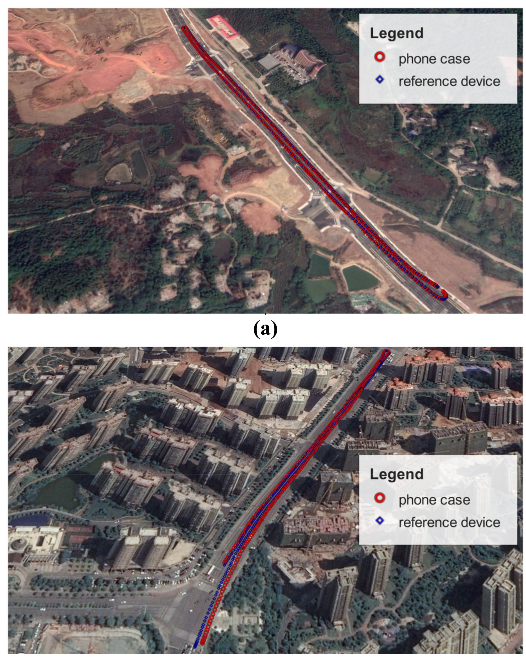

FIGURE 15. The trajectory of reference device and phone case on satellite map. (a) open-sky scenario, (b)urban scenario.

CV approaches the VRU at a speed of around 40 km/h. The OBU and the phone case broadcast messages every 100 ms. The thresholds of CM and STM are the same. The lateral distance threshold is 5.25 meters and the TTC threshold is 5.5 s. The TTC, the lateral distance, and the warning time are recorded during experiments. Fig. 19 and Fig. 20 show the results on the straight road and the curved road, respectively. We repeated the experiment several times to verify the proposed method. The results are shown in Table 4.

The warning time of STM and CM is the same when the CV drives on the straight road, as shown in Fig. 19(a). As shown in Fig. 19(b), the lateral distance of STM varies between 1.51 meters and 2.15 meters, while the lateral distance of CM varies between -1.30 meters and 7.73 meters. The lateral distance of STM changes more smoothly than that of CM. The TTC of STM is the same as the TTC of CM, as shown in Fig. 19(c).

The warning time of STM is 3.49 s earlier than that of CM when the CV drives on the curved road, as shown in Fig. 20(a). That enables the driver and VRU to have more time to take measures to avoid a collision. As shown in Fig. 20(b), the lateral distance of STM varies between 1.97 meters and 3.49 meters, and it also changes very smoothly. Although the lateral distance of CM gradually decreases when the CV approaches the VRU, it is still much greater than that of STM. The lateral distance of CM even exceeds 50 meters when the CV is far away from the VRU. The CV drives on the adjacent lane of VRU, therefore this result is inconsistent with reality. The TTC of CM is less than or equal to that of STM, but the

TABLE 4. Comparison between STM, CM, and PAS.

site	Run#	STM WT (s)	STM MD_{lat} (m)	STM SD_{lat} (m)	CM WT(s)	CM MD_{lat} (m)	CM SD_{lat} (m)	PAS WT(s)	STM vs. CM diff. of WT (s)	STM vs. CM Percentage	STM vs. PAS diff. of WT (s)	STM vs. PAS Percentage
Straight road	1	18.90	**1.96**	**0.29**	18.90	2.39	1.08	20.90	**0.00**	0.00%	**-2.00**	-10.58%
	2	19.11	**3.80**	**0.28**	19.11	4.00	1.31	19.51	**0.00**	0.00%	**-0.40**	-2.10%
	3	18.69	**2.71**	**0.25**	18.69	3.56	1.47	20.18	**0.00**	0.00%	**-1.49**	-7.99%
	4	16.19	**3.22**	**0.36**	16.19	4.34	1.64	18.10	**0.00**	0.00%	**-1.91**	-11.82%
	5	19.39	**1.81**	**0.17**	19.39	2.45	1.59	20.68	**0.00**	0.00%	**-1.29**	-6.66%
	6	16.71	**1.62**	**0.18**	16.71	2.17	1.19	16.30	**0.00**	0.00%	**0.41**	2.44%
Curved road	1	14.81	**4.38**	**0.59**	18.71	47.03	37.40	13.81	**-3.90**	-26.35%	**1.00**	6.74%
	2	16.52	**2.04**	**1.10**	19.80	58.25	40.74	15.60	**-3.28**	-19.85%	**0.92**	5.55%
	3	13.48	**3.25**	**0.89**	17.25	53.29	40.03	12.98	**-3.76**	-27.90%	**0.50**	3.74%
	4	14.27	**1.84**	**0.54**	17.37	53.31	38.29	13.79	**-3.10**	-21.71%	**0.48**	3.37%
	5	12.62	**2.40**	**0.42**	16.11	51.35	38.00	12.30	**-3.49**	-27.61%	**0.32**	2.57%

Note : WT indicates the time when a warning is first triggered, M_{lat} indicates the mean of lateral distance, SD_{lat} indicates the standard deviation of lateral distance.

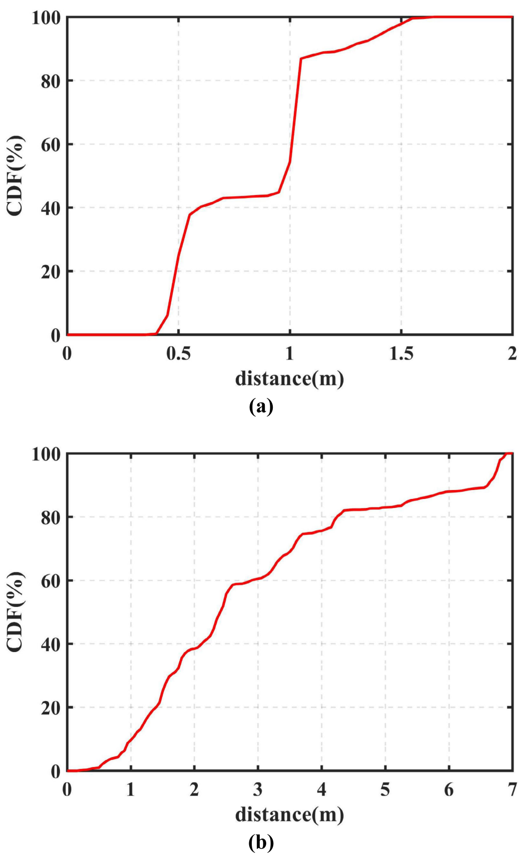

FIGURE 16. CDF of distance between phone case and reference positioning device. (a) open-sky scenario, (b) urban scenario.

FIGURE 17. Experiment sites. (a) Yuchi Avenue (b)Yuchi bridge.

FIGURE 18. The connected vehicle.

warning time of CM is later than that of STM because the lateral distance of CM is over the threshold.

According to Table 4, results show that the warning time of STM is the same as that of CM when the CV and VRU are on the straight road. The mean lateral distance for STM is less than that of CM, and the standard deviation of lateral distance for STM is less than that of CM. When the CV and VRU are on the curved road, the warning time of STM is 3.1 to 3.9 s earlier than that of CM. That indicates that the STM can alert the driver and VRU earlier than CM under the same condition so that the driver and VRU can have much more time to avoid a collision. The mean lateral distance ranges from 1.84 meters to 4.38 meters which is much smaller than that of CM by 37.4 to 40.74 meters. As the CV drives on the adjacent lane of VRU, the lateral distance computed by STM is much more

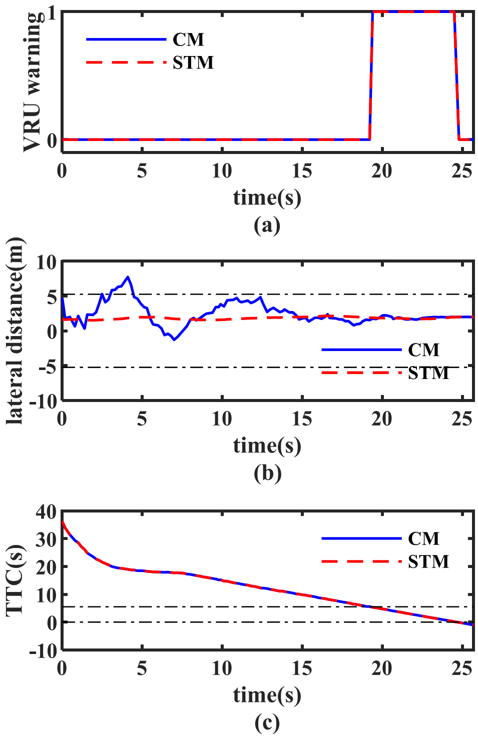

FIGURE 19. Comparison of STM and CM on the straight road.(The black dot lines indicate the thresholds of corresponding parameters).

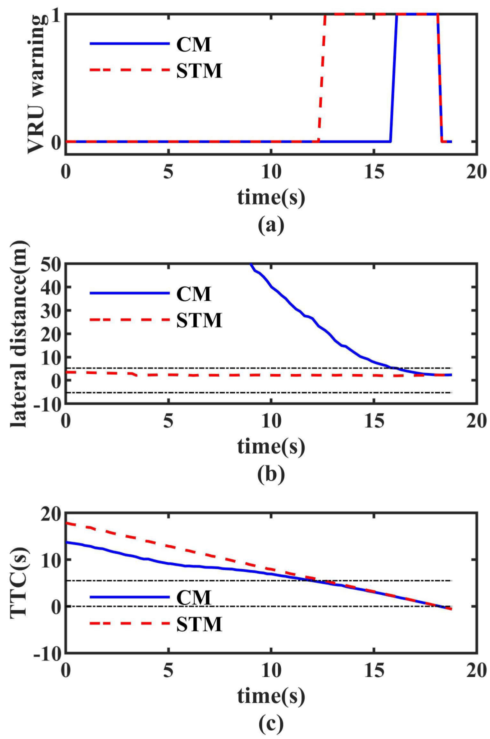

FIGURE 20. Comparison of STM and CM on the curved road. (the black dot lines indicate the thresholds of corresponding parameters).

consistent with the actual distance. The standard deviation of lateral distance for STM is much less than that of CM.

CM calculates the relative position by using the heading angle of the CV. However, this method is not very accurate when the CV is on bumpy roads or curved roads, as the heading angle can vary greatly in these conditions. Our method calculates the relative position using s-t-coordinates, which are based on the reference path of the road. This method is not affected by changes in the heading angle when the CV is on bumpy roads or curved roads.

We designed an experiment to compare our method with the pedestrian alert system (PAS) in [15] and [20], which calculates the TTC with vehicle speed, yaw rate, and pedestrian position in the vehicle coordinate system. We conducted eleven sets of comparative experiments, with six on straight roads and five on curved roads. Table 4 illustrates the comparison between STM and PAS. Fig. 21 shows the comparison of STM, CM, and PAS in terms of the warning time.

As shown in Table 4, when the CV and VRU are on the straight road, there are five sets of experiments that STM alerts the driver earlier than PAS. PSA only alerts the driver earlier than STM in one set of experiments. When the CV and VRU are on the curved road, PSA alerts the driver earlier than STM. The performance of PAS on the curved road is also shown in Fig. 21(b). PAS achieves slightly better performance than STM on the curved road. The warning system should alert the driver or the VRU from the time when a warning is first triggered until the vehicle passes the VRU. However, Fig. 21(a) shows that PAS misses some alerts on the straight road. This means that PAS does not always alert the driver when CV and VRU are on the straight road. This may mislead the driver and leave them with insufficient time to take measures to avoid a collision. STM and CM, on the other hand, can continuously alert the driver under the same condition. Therefore, STM and CM outperform PAS when CV and VRU are on the straight road.

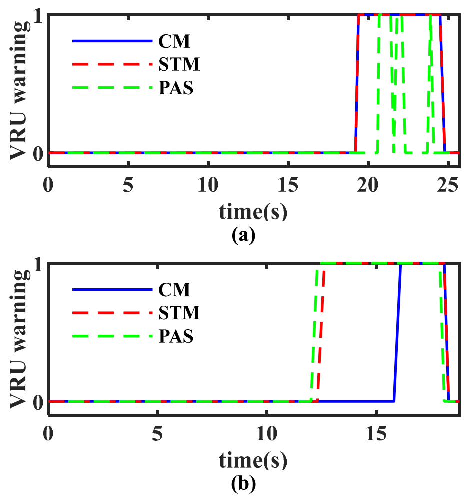

FIGURE 21. Comparison of STM, CM and PAS. (a) on the straight road (b) on the curved road.

IV. CONCLUSION

We proposes a V2P-based VRU collision warning system in which a phone case is designed to help VRUs communicate directly with CVs through C-V2X. The phone case is installed on the back of the smartphone and is suitable for VRUs to carry. The proposed STM can protect the VRUs on both straight roads and curved roads. The experiments show the reliable communication range and end-to-end latency meet the requirements of VRU applications in C-ITS. The positioning accuracy of the phone case meets the positioning requirements of VRU applications in the open-sky scenario. Comparative experiments show that the STM outperforms CM on the curved road and achieves the same performance on the straight road. PAS performs slightly better than STM on the curved road, but PAS misses some alerts on the straight road, whereas STM can continuously alert the driver.

The proposed VRU warning system may be extended in the following aspects in the future. 1) The phone case is constantly sending messages, which shortens battery life. The wake-up mechanism of C-V2X communication for the phone case can be considered to extend battery life while ensuring the safety of VRUs. 2) The authors will work with positioning module manufacturers to further improve positioning accuracy in urban scenarios. 3) The trajectory prediction for VRUs can be taken into consideration to improve safety.

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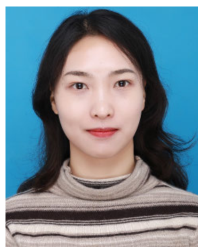

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