GPS-free Vehicular Localization System Using Roadside Units with Directional Antennas

Chia-Ho Ou, Bing-Yi Wu, and Lin Cai

Abstract: **The success of dedicated short-range communications (DSRC) applications depends on an accurate knowledge of the positions of vehicles within the network. At present, vehicle localization is generally performed using some form of vehicle-mounted global positioning system (GPS). However, GPS signals may not be always available. Various GPS-free vehicle localization techniques using the ranging information, the prior knowledge of the vehicle's position, or the special hardware have been proposed for enhancing the performance of traditional GPS-based methods. Different from the previous approaches, we propose a GPS-free vehicle localization system using roadside units (RSUs) with directional antennas without specific hardware support on the vehicle and the assumption of the prior knowledge of the vehicle. In the proposed approach, each vehicle determines its position using the information contained within beacon messages transmitted by neighboring RSUs deployed along the road only. The performance of the proposed localization scheme is evaluated by ns-2 simulations and is compared with those of recent GPS-free and GPS-assisted localization systems. The simulation results show that the proposed localization scheme achieves a higher positioning accuracy than the existing GPS-free and GPS-assisted schemes. The feasibility of the proposed system for practical applications is further investigated experimentally. The experimental results for the positioning accuracy are consistent with those obtained from the ns-2 simulations.**

Index Terms: **Directional antenna, GPS-free, localization, positioning, roadside unit.**

I. INTRODUCTION

WITH the advancement of telematics, modern vehicles can now use a variety of wireless technologies (e.g., WiFi, 3.5G and WiMAX) to communicate with one another. Of the various technologies available, dedicated short-range communications (DSRC) is promising for satisfying the application requirements of vehicular communication environments. DSRC vehicular networks generally contain two main types of device: On-board units (OBUs) installed within the vehicles and roadside units (RSUs) mounted at the roadside [1]–[4]. The success of DSRC-based applications depends on the OBUs having an accurate knowledge of the positions of vehicles in the network. Vehicle localization is commonly performed using some form of the global positioning system (GPS) [5] method.

GPS receivers typically have a localization accuracy (i.e., 5 to 10 m) [6]. Several enhanced GPS methods have been proposed with the ability to detect the vehicle position with a high degree of accuracy (e.g., differential GPS (DGPS) and assisted GPS (AGPS) [7]). However, GPS schemes suffer several inherent limitations, including an obstructed line of sight, sparse coverage, and so on. GPS receivers require at least three (for 2D) or four (for 3D) satellite signals to perform localization. Consequently, an insufficient number of satellite signals may be available for localization purposes. In practical vehicular networks, this problem can be overcome using a Dead Reckoning (DR) technique, in which the vehicles compute their current locations based on their last known positions, travel distances, and directions [8], [9]. However, the use of DR over an extended period of time is not recommended since the DR errors rapidly accumulate over both time and distance.

Many solutions have been proposed for overcoming the localization limitations of GPS by means of either GPS-assisted [10]–[17] or GPS-free techniques [18]–[24]. GPS-assisted cooperative positioning in vehicular networks utilizes vehicle-to-vehicle (V2V) communications among neighboring vehicles to share position and range information in order to improve the positioning estimates of each vehicle. However, the frequent and massive position and range information exchange over the shared DSRC control channel results in a significant message overhead. A minimum of three position-known neighboring vehicles (known as anchors) are required for trilateration or multilateration purposes, and thus localization of the vehicle of interest may not be possible. It was shown in GPS-free methods that this problem can be resolved by utilizing RSUs to assist in the position determination process. Most of the RSU-based localization schemes use ranging techniques (e.g., received signal strength (RSS), time of arrival (TOA), or time difference of arrival (TDOA) [25], [26]) to estimate the distance between the RSU and the vehicles [19]–[22]. While such techniques achieve a high degree of accuracy in static networks, their use in dynamic vehicular communication networks is far more challenging [17]. Moreover, existing RSU-based localization schemes require the prior knowledge of the vehicle's position (e.g., GPS position) to estimate the vehicle's current position [21], or the vehicle needs to equip with the special equipment, i.e., RFID reader [18] or antenna array [23], [24], to calibrate its current position or to estimate angle of arrival (AOA) of signals sent by RSUs respectively.

Manuscript received March 20, 2018; approved for publication by Berkan Dülek, Division II Editor, September 24, 2018.

This work was supported by the the Ministry of Science and Technology of Taiwan under Contracts 101-2221-E-251-004, 104-2221-E-153-004, and 105-2221-E-153-008.

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Digital Object Identifier: 10.1109/JCN.2019.000002

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Accordingly, the present study proposes a GPS-free vehicle localization scheme based on RSUs with directional antennas without specific hardware support on the vehicle and the assumption of the prior knowledge of the vehicle. Notably, the aim of the proposed scheme is to augment GPS-based localization methods and provide a GPS-free localization service to vehicles. In the proposed method, each pair of RSUs located along the roadside periodically broadcast their positions and antenna orientation information. While driving through the coverage area of the two antennas, each vehicle obtains the equations of two non-parallel straight lines from the information provided by the RSUs and then determines its current position by calculating the coordinates of the intersection point of these two lines using simple trigonometric theory.

The main contributions of this paper are five-fold:

1. We propose a vehicle localization system using RSUs with directional antennas. Based on the geometric analysis, we obtain an optimal antenna orientation angle and beam width for RSUs.
2. We propose a RSU deployment method for continuous vehicle localization and derive a fault tolerant mechanism to deal with RSU failures.
3. We analyze the theoretical localization error of the proposed scheme.
4. The performance of the proposed localization method is evaluated by means of a series of ns-2 simulation [27] and is compared to those of GPS-free and GPS-assisted vehicular localization schemes.
5. The practical feasibility of the proposed method is demonstrated by implementing the localization scheme on the WAVE/DSRC Communication Unit (IWCU) platform [28]–[30] designed and developed by the Industrial Technology Research Institute (ITRI) [31].

The rest of this paper is organized as follows. Section II describes related vehicle localization research. Section III presents the system model and localization algorithm proposed in the present study. Section IV examines the effect of moving vector measurements on the localization accuracy of the proposed method. Section V presents and discusses the simulation results. Section VI describes the implementation of the proposed system on the IWCU platform and presents the corresponding experimental results. Finally, concluding remarks and further research issues are given in Section VII.

II. RELATED LOCALIZATION RESEARCH

A. *GPS-Assisted Localization*

In the localization scheme proposed in [10], the positions of GPS-unequipped vehicles are determined using GPS-equipped vehicles as anchor points. Specifically, when a GPS-unequipped vehicle wishes to determine its location, it broadcasts a request message to all its neighbors. Any GPS-equipped vehicles receiving this message immediately transmit their coordinates to the GPS-unequipped vehicle. Having received three sets of coordinates and determined the corresponding range information, the GPS-unequipped vehicle computes its own position using a trilateration algorithm. In [11], [12], the positioning accuracy in vehicular networks is enhanced by means of a three-phase localization mechanism. In the first phase, every vehicle in the network estimates its distance from each of its neighbors and then shares this information with them. In the second phase, the kinematics information of the neighboring vehicles, the distance estimates among these vehicles, and road information are used to improve the accuracy of the initial position estimate. In the final phase, the operations of the second phase are repeated iteratively in order to maintain an up-to-date position estimate. To deal with the exponential error propagation problem of trilateration schemes, a grid-based localization mechanism has been proposed to compute the vehicle's location by using only addition operations [16]. With the proposed grid-based scheme, the vehicle calculates its position based on the different geometric relationship (i.e., patterns) of the three location-aware neighboring vehicles.

Drawil and Basir [13] proposed a cooperative localization scheme for mitigating multipath effects on the accuracy of GPS-based positioning schemes. In the proposed method, each vehicle measures the distance between itself and each of its neighbors and obtains an initial position estimate by means of an integrated GPS and Inertial Navigation System (INS). Each vehicle then exchanges its position estimate, the uncertainty of the position estimate, and the inter-vehicle distance information with all of its neighbors. On receiving this information, each vehicle selects the vehicles with the smallest uncertainty in their position estimates as anchor points to enhance the accuracy of its position estimate.

The authors in [14] proposed a cooperative positioning scheme based on the Doppler shift to enhance the GPS positioning accuracy. In performing localization, each vehicle sends its GPS position and travel speed to all its neighbors. On receiving this information, each vehicle measures the range-rate to its neighbors in accordance with the Doppler shifts of the received signals. The vehicles then use a data fusion technique based on their own position and speed, the positions and speeds of their neighbors, and the Doppler shifts of the received signals to improve their position estimates. The minimum speed difference between the vehicle and its neighbors has been assumed.

Existing cooperative localization schemes typically involve the frequent and massive exchange of positioning and range information. The resulting message overhead not only increases the possibility of packet collisions; thereby degrading the application performance, but also reduces the accuracy of the localization scheme itself. To address this problem, Yao *et al.* [15] proposed a range information exchange mechanism incorporating multiple techniques for reducing the message overhead, including information piggybacking, data compression, range information broadcast interval setting, and packet integration via network coding.

To eliminate the requirement of location-aware neighboring vehicles in cooperative positioning and assumption of the minimum speed difference in [14], Kaiwartya *et al.* propose a geometry-based vehicle localization scheme (GeoLV) for dealing with GPS outage in vehicular cyber physical systems [17]. The proposed scheme determines a vehicle's position based on the vehicle's past and present travel direction and distance and knowledge of road trajectories to provide a road-level positioning accuracy for the vehicles.

B. *GPS-Free Localization*

In [18], a radio frequency identification (RFID) assisted vehicular localization system is introduced for improving GPS accuracy based on the concept of DGPS. Similar to [10], some of the vehicles are equipped with GPS receivers. If vehicles are also equipped with RFID readers, they can estimate GPS error by comparing to the correct position information obtained from a RFID tag on the road and then broadcast GPS error to neighboring vehicles to help them refining their GPS positions. In a recent study, a localization method based on RSUs is presented in [19]. In the proposed approach, two RSUs facing one another on opposite sides of the road broadcast their position information to the vehicles as they pass through their respective coverage areas. On receiving this information, the vehicles use a ranging technique such as TOA or TDOA to measure their distance from each RSU. Based on the position and distance information, each vehicle constructs two intersecting circles and computes the corresponding intersection points. Since each vehicle knows the direction in which it is traveling, it is able to select the appropriate intersection point as its current position following the second round of RSU broadcasts. To reduce the required number of RSUs, ref [20] proposed a localization system using only a single RSU to determine a vehicle's position. The proposed two-way TOA packet handshake procedure is used to exchange control information between the vehicle and the RSU. The distance between the RSU and the vehicle can be measured. The proposed ranging technique estimates only one-dimensional position information (i.e., y-location) for the vehicle. X-location can be estimated and updated based on the motion model obtained from Inertial Navigation System (INS) [21] if the initial estimate of x-location is known in advance. Another single RSU-based localization method, RSU/INS-Aided Localization System (RIALS), is presented in [22]. In the proposed system, each vehicle measures its distance to the RSU using a ranging technique (e.g., TOA) and obtains vehicle kinetic information from INS within the interval of subsequent beacon broadcast. Based on distance and kinetic information, the vehicle forms a number of intersecting circles whose centers are displaced based on its kinetic information and the initial position of the RSU. The intersection among these circles is determined as the current position of the vehicle. A sufficient number of intersecting circles is required to achieve a desired localization accuracy.

A GPS-free vehicle localization method based on vehicle-to-roadside (V2R) communications and AOA estimation has been presented in [23]. Similar to the most of RSU-based schemes, the RSU periodically broadcasts the beacon message containing its own position information in the network. After receiving the message sent by the RSU, the vehicle with an equipped antenna array performs AOA estimation. With AOA estimates and the RSU's position, the vehicle measures its position using a weighted least square algorithm. The authors also integrate the proposed AOA-based localization scheme into cooperative positioning by considering V2V and V2R communications simultaneously to reduce the requirement of the number of location-aware neighbors and V2V communication overhead [24].

Several vehicular localization systems using directional antennas or antenna arrays have been proposed to identify vehicles in several applications [32]. In electronic toll collection (ETC) applications, a tag is attached to each vehicle and an RSU is equipped with a reader antenna array. The RSU detects which lane the vehicle is located based on its antenna array and simultaneously collects the toll. In parking lot applications, the RSU with an antenna array estimates the direction information of a vehicle when the vehicle transmits a signal to RSU. The direction information can be updated while the owner moves relative to the vehicle. These systems identify the lane location or direction rather than determining the vehicle's actual position. Different from the previous work, in this work, the RSUs with directional antennas are used to assist the vehicles estimating their current positions.

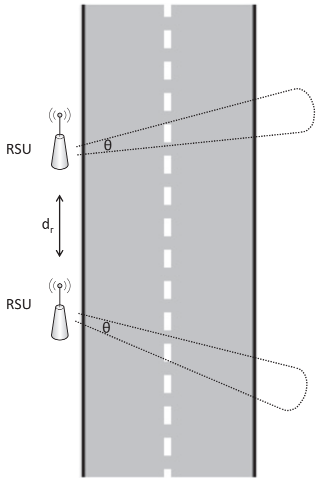

Fig. 1. System architecture.

III. RSU-BASED LOCALIZATION SYSTEM

A. *System Overview*

We proposes a localization scheme for vehicles traveling in a road segments based on RSUs with directional antennas. Fig. 1 presents the system architecture of the proposed approach. (Note that while we assume that the two RSUs are deployed on the same side of the road, the proposed scheme is easily extended to the case where they are deployed on opposite sides.) As in [33]–[35], the directional antenna model considered in the present study approximates the antenna pattern as a conical section with an apex angle (i.e., beam width) of θ, where $0 < \theta < \frac{\pi}{2}$. As shown in Fig. 1, the orientations of the two directional antennas of two RSUs are fixed and the distance between the two RSUs is set as d_r. Each vehicle traveling along the road is assumed to be equipped with an OBU device to receive the beacon messages broadcast by the RSUs, a digital compass to obtain its current direction of travel, and an odometer to calculate its travel distance. (Note that all three devices are fitted as standard in most modern vehicles.) The beacon messages broadcast by the RSUs contain both the absolute coordinates of the RSU and the orientation of the RSU's directional antenna. Having obtained two beacon messages from the RSUs (i.e., one message from each RSU), each vehicle computes its current position using the method described in the following section.

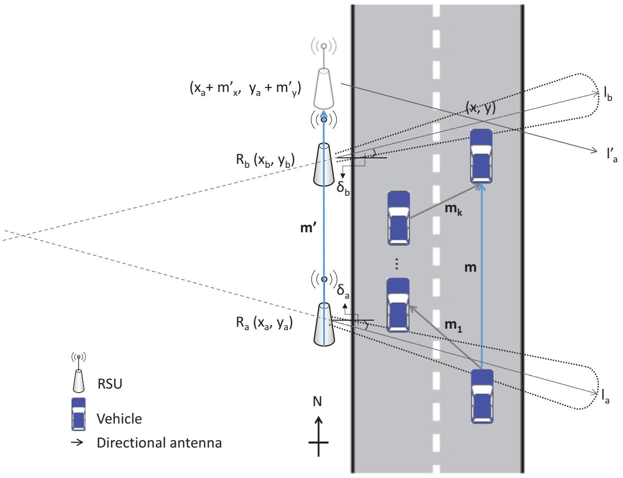

Fig. 2. Vehicle localization scheme.

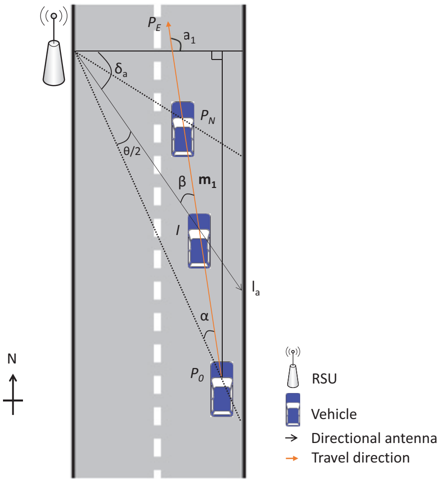

Fig. 3. Starting position selection of moving vector.

B. Vehicle Localization Scheme

Assume that two RSU (R_a and R_b) are located on the same side of the road. Furthermore, assume that the directional antennas of R_a and R_b are orientated at angles of δ_a and δ_b, respectively, relative to the east direction (see Fig. 2). Note that $0 < |\delta_a|, |\delta_b| < \frac{\pi}{2}$. A vehicle V driving along the road in the northward direction receives the first beacon message broadcast by R_a as it enters the coverage area of the directional antenna. On receiving this message, the vehicle records both the absolute position coordinates (x_a, y_a) [1] of R_a and the orientation of R_a's directional antenna (δ_a). As the vehicle proceeds along the road, it subsequently enters the coverage area of the directional antenna of R_b and receives the first corresponding beacon message. The vehicle then adds the absolute position of R_b (x_b, y_b) and the orientation of R_b's directional antenna (δ_b) to the position and orientation information already stored in its memory.

Based on the orientation and position information contained within the two beacon messages, two straight-line equations, i.e., l_a and l_b, can be computed by V. However, from Fig. 2, it is clear that the intersection of lines l_a and l_b does not lie on the road. Thus, to obtain the current coordinates of V, i.e., (x, y), the straight line l_a must be translated based on the vehicle's movement during the interval between the two beacon broadcasts. In practical environments, vehicles do not always travel continuously in a straight line parallel to the side of the road, but may in fact perform lane changes or overtaking maneuvers. Thus, in the proposed localization scheme, V utilizes both its digital compass and odometer to calculate all of its moving vectors formed by its moving direction and distance during the time between receiving the first beacon message from R_a and the first beacon message from R_b. To correctly translate the straight line l_a in order to estimate its current position, V must compute the overall displacement of all of the individual moving vectors generated during the corresponding period. Consider the case shown in Fig. 2. Assume that V performs k movements during the interval between the two beacon broadcasts and thus generates k moving vectors, i.e., $\mathbf{m}_j, j = 1, \cdots, k$. The overall displacement whose length is the shortest distance from the initial to the final position of V during the interval between the two beacon broadcasts can thus be computed as

$$\mathbf{m} = [m_x, m_y] = \sum_{j=1}^{k} \mathbf{m}_j = \left[\sum_{j=1}^{k} m_{j,x}, \sum_{j=1}^{k} m_{j,y} \right], \tag{1}$$

where $[m_x, m_y]$ denotes the vector $\mathbf{m}$ whose x component is m_x and y component is m_y.

The radio patterns of the directional antennas are not confined to a single straight line, but actually have a conical-like section. As a result, the position at which V receives the beacon message broadcast by R_a does not lie exactly on line l_a. In practice, vehicle V cannot select the location at which it first receives the beacon message from R_a (i.e., P_0, see Fig. 3) as the starting position of its first moving vector $\mathbf{m}_1$ since the straight line l_a cannot be translated correctly. Therefore, a starting position selection scheme for the first moving vector $\mathbf{m}_1$ is proposed to correctly calculate the moving vectors. Accordingly, on receiving a beacon message from R_a, V uses the information provided by its odometer and digital compass to update and record its current position P_l relative to P_0 in a location list for R_a, i.e., $Loc_{Ra} = \{P_l | l = 1, \cdots, N\}$, where N denotes the number of beacon messages received from R_a. The vehicle V then sets a timer and waits for the receipt of further beacon messages. If no message is received before the timer expires, the proposed selection scheme is used to determine the approximate coordinates at which vehicle V intersects line l_a, i.e., $P_s(x_s, y_s)$. The index s of Loc_{Ra} can be obtained as

$$s = N * \lceil \frac{\overline{IP_0}}{\overline{P_N P_0}} \rceil = N * \lceil \frac{sin(\alpha + \theta)}{2 * cos(\frac{\theta}{2}) sin(\beta)} \rceil, \tag{2}$$

where $\angle\alpha = \pi - a_1 - \delta - \frac{\theta}{2}$, $\angle\beta = \pi - a_1 - \delta$, and $a_1 = \arctan(\frac{m_{1,y}}{m_{1,x}})$ is the direction of the vehicle's first moving vector.

Based on the starting point selection method described above, the moving vector displacement can be approximated as follows:

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[1] (x_a, y_a) denotes the two-dimensional Cartesian coordinates of R_a whose abscissa is x_a and ordinate is y_a.

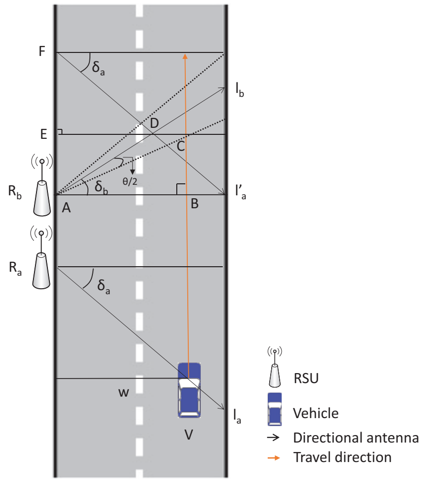

Fig. 4. Geometric error due to beam width.

$$\mathbf{m'} = [m'_x, m'_y] = \mathbf{m'}_1 + \sum_{j=2}^{k} \mathbf{m}_j, \tag{3}$$

where $\mathbf{m'}_1 = P_E - P_s = (x_E - x_s, y_E - y_s)$, and $P_E(x_E, y_E)$ is the final position of the vehicle's first moving vector. The vehicle V then computes two straight-line equations, i.e., l'_a and l_b (see Fig. 2), as follows:

$$y - y_a - m'_y = \tan(\delta_a)(x - x_a - m'_x) \tag{4}$$

$$y - y_b = \tan(\delta_b)(x - x_b). \tag{5}$$

Finally, the coordinates of vehicle V can be obtained as

$$x = \frac{y_a - y_b - \tan(\delta_a)x_a + \tan(\delta_b)x_b - \tan(\delta_a)m'_x + m'_y}{\tan(\delta_b) - \tan(\delta_a)} \tag{6}$$

$$y = y_b - \tan(\delta_b)x_b + \tan(\delta_b)x. \tag{7}$$

In real-world environments, most roads carry traffic traveling in two different directions. For reasons of space constraints, the discussions above consider the simple case in which the road carries traffic traveling in one direction only. However, the extension of the proposed localization scheme to the case of two opposing traffic flows can be easily realized.

C. Optimal Antenna Orientation Angle and Beam Width Determination

In practical environments, the transmission pattern of the directional antennas has the form of a narrow cone rather than a perfectly straight line. The effect on the localization performance of the geometric errors caused by the antenna orientation angle and beam width is shown in Fig. 4. Assume that the beam width of each RSU is equal to θ and the directional antennas of the corresponding RSUs in each set have the same orientation. Furthermore, for reasons of simplicity, assume that the vehicle V can obtain the approximate coordinate at which the vehicle intersect line l_a based on the proposed starting position selection mechanism, is located at a distance w from the left-hand-side of the road, and travels in a perfectly straight line along the road. After moving forward, V detects the beacon message broadcast by RSU R_b at point C. On detecting this message, V uses the coordinates of RSUs R_a and R_b and the corresponding direction antenna orientations ($-\delta$ and δ) to calculate the intersection point D between the two straight-lines l'_a and l_b, as its estimated position. However, V is in fact located at point C rather than point D. In other words, a localization error, $\overline{CD}$, exists. From basic trigonometric principles, the magnitude of $\overline{AC}$ in $\triangle ABC$ [2] can be computed as

$$\frac{\overline{AC}}{\sin(\frac{\pi}{2})} = \frac{\overline{AB}}{\sin\left(\frac{\pi}{2} - (\delta - \frac{\theta}{2})\right)} \tag{8a}$$

$$\overline{AC} = \frac{w}{\sin(\frac{\pi}{2} - \delta + \frac{\theta}{2})} \tag{8b}$$

$$= w \sec(\frac{\theta}{2} - \delta). \tag{8c}$$

It is obvious that both $\angle FDE$ [3] and $\angle EDA$ are equal to δ so that $\angle ADC = \pi - \angle FDA = \pi - 2\delta$. Thus, the magnitude of $\overline{CD}$ in $\triangle ACD$ can be obtained as

$$\frac{\overline{CD}}{\sin(\frac{\theta}{2})} = \frac{\overline{AC}}{\sin(\pi - 2\delta)} = \frac{\overline{AC}}{\sin(2\delta)} \tag{9a}$$

$$\overline{CD} = \frac{\overline{AC}\sin(\frac{\theta}{2})}{\sin(2\delta)} \tag{9b}$$

$$= w \sec(\frac{\theta}{2} - \delta)\sin(\frac{\theta}{2})\csc(2\delta). \tag{9c}$$

To minimize the localization error, $\overline{CD}$, an error optimization problem for determining the optimal antenna orientation angle and beam width is given by

$$\textbf{(P1)} \min_{\delta,\theta} \; f(\delta,\theta) = w \sec(\frac{\theta}{2} - \delta)\sin(\frac{\theta}{2})\csc(2\delta) \tag{10}$$

$$\text{subject to } \frac{\pi}{18} \leq \theta < \frac{\pi}{2}, \tag{11}$$

$$0 < \delta + \frac{\theta}{2} < \frac{\pi}{2}. \tag{12}$$

The objective of the error optimization problem is to minimize the geometric error caused by the antenna orientation angle and beam width as shown in (10). Constraint (11) state the beam width limits due to the road structure. Constraint (12) indicates that the coverage of the directional antenna cannot be over the surface of the road. Note that various manufacturers have produced directional antennas with a minimal horizontal beam width of around 10 degrees (i.e., $\pi/18$) [36]. Thus, the minimal value of θ was assigned a value of $\pi/18$ in Constraint (11).

It is observed that f is a monotonically increasing function given the antenna orientation angle δ, where $0 < \delta < \frac{\pi}{2}$. This is because

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[2] $\triangle ABC$ denotes a triangle with vertexes A, B, and C.

[3] $\angle FDE$ denotes an angle formed by two rays F and E sharing a common endpoint D.

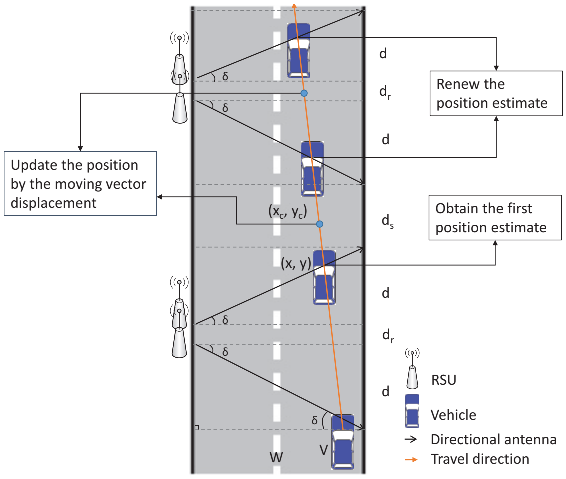

Fig. 5. RSU deployment.

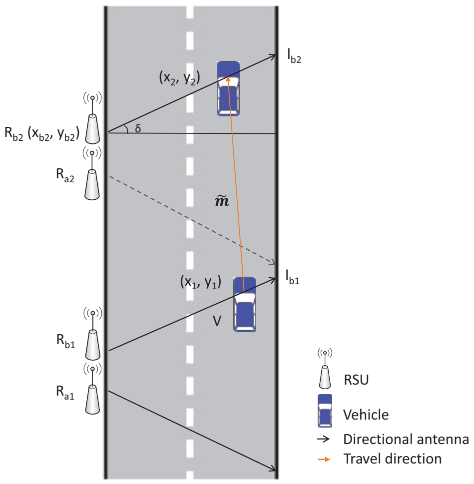

Fig. 6. Position update using single RSU.

$$\frac{\partial f}{\partial \theta} = \frac{1}{2\sin(\delta)\cos(\frac{\theta}{2}-\delta)^2} > 0, \tag{13}$$

where $\frac{\pi}{18} \leq \theta < \frac{\pi}{2}$. We can conclude that the value of f can be minimized by replacing θ as its minimal value.

Given θ, Problem P1 is thus transformed into the following problem:

$$(\mathbf{P2}) \min_{\delta} \quad f(\delta) = w\sec(\frac{\theta}{2}-\delta)\sin(\frac{\theta}{2})\csc(2\delta) \tag{14}$$

$$\text{subject to} \ \ 0 < \delta < \frac{\pi}{2} - \theta. \tag{15}$$

Constraint (15) is transformed from Constraint (12). Problem P2 is a convex optimization problem [37] since the objective function is convex with respect to δ while the constraint is linear. Therefore, Problem P2 can be efficiently solved by Newton's method [38].

D. RSU Deployment

Clearly, to maintain an up-to-date estimate of the vehicle's position as it travels along the road, more than two RSUs are required. However, in deploying the additional RSUs, a tradeoff must be achieved between the need to maintain the localization accuracy on the one hand and the need to minimize the deployment cost on the other. Accordingly, the present study proposes an efficient RSU deployment method designed to satisfy both objectives. Assume that the width of the road is denoted by W and the orientation of the RSU directional antennas is denoted by δ. Fig. 5 illustrates the proposed RSU deployment method, in which the first RSU is placed at a distance d from the beginning (i.e., bottom) of the road such that all of the vehicles which enter the road inevitably pass through its coverage area. In accordance with basic trigonometric principles, the value of d can be computed as

$$\frac{W}{\sin(\frac{\pi}{2}-\delta)} = \frac{d}{\sin\delta} \tag{16a}$$

$$d = \frac{W\sin\delta}{\sin(\frac{\pi}{2}-\delta)}. \tag{16b}$$

Having determined the position of the first RSU, the distance between neighboring RSUs (referred to as a RSU set) is set equal to d_r, as discussed in Section III.A. Moreover, the distance between neighboring RSU sets is set as d_s. Note that the value of d_s has a direct impact on the RSU deployment cost. In other words, for a smaller value of d_s, the total number of RSUs required to maintain accuracy along a road of a given length increases, and vice versa. Note that the optimal RSU deployment is to set $d_s = 0$ for achieving the best positioning accuracy.

As shown in Fig. 5, having deployed the RSUs, a vehicle V entering the road obtains its first position estimate (x, y) after receiving the beacon messages from the first two RSUs. The vehicle then starts to measure its moving vector displacement $\mathbf{m}_c = [m_{c,x}, m_{c,y}]$ and updates its current coordinates (x_c, y_c) in accordance with

$$(x_c, y_c) = \mathbf{m}_c \cdot (x, y) = (m_{c,x}x, m_{c,y}y). \tag{17}$$

When V receives the beacon message of the next RSU, it renews its position estimate using (6) and (7) of the proposed localization scheme. Thus, through the integration of the RSU deployment strategy and the proposed localization method, the vehicle can estimate its position continuously as it travels along the road.

E. Tolerance toward RSU Failures

In real-world environments, RSUs may malfunction or fail completely as a result of crashes, poor maintenance, severe weather conditions, and so on. RSU failures inevitably impact on the normal operation of the proposed localization scheme. Accordingly, this section presents a position update method for vehicles encountering a temporary RSU failure. Consider the scenario shown in Fig. 6, in which R_{a2} fails such that only R_{b2} functions properly. In such a situation, vehicle V estimates its current coordinates (x_1, y_1) based on the beacon messages received from R_{a1} and R_{b1}. As discussed in Section III.D, having renewed their position coordinates based on the beacon messages received from two RSUs, the vehicles update their positions continuously using (17) until they receive the beacon message from the next RSU. Thus, vehicle V can continue to update its position while moving between the radio patterns of R_{b1} and R_{b2} even though R_{a2} fails. However, when V receives the beacon message of R_{b2}, the localization method described in (6) and (7) cannot be performed correctly since the antenna orientations of R_{b1} and R_{b2} are identical. In other words, the position coordinates cannot be obtained using the proposed intersection-point method since for two parallel lines, no such point exists.

Accordingly, vehicle V estimates its new position, (x_2, y_2), based on its moving vector displacement $\tilde{\mathbf{m}} = [\tilde{m}_x, \tilde{m}_y]$ and the beacon message received from R_{b2}. In other words, the new position of V, (x_2, y_2), is computed by solving the intersection of the two straight-lines l_{b2} and $\tilde{\mathbf{m}}$, formulated respectively as

$$\begin{aligned} y - y_{b2} &= \tan(\delta)(x - x_{b2}) && (18) \\ y - y_1 &= \frac{\tilde{m}_y}{\tilde{m}_x}(x - x_1). && (19) \end{aligned}$$

IV. LOCALIZATION ERROR ANALYSIS

In the proposed localization scheme, positioning errors may arise as a result of inaccuracies in the moving vector measurement. As described in Section III.B, vehicle V computes its coordinates (x, y) based on the beacon messages transmitted by the RSUs and its own moving vector. Since both the coordinates of the RSUs along the roadside and the orientations of their directional antennas are absolutely and statically fixed (i.e., can be assumed to be accurate), localization errors of the proposed system result predominantly from inaccuracies in the moving vector measurement. This section presents a statistical analysis of the resulting localization error. With no loss of generality, assume that vehicle V performs k movements during the interval between receiving beacon messages from two neighboring RSUs, R_a and R_b. As stated in (1), the moving vector displacement is estimated as $\hat{\mathbf{v}} = (\hat{v}_x, \hat{v}_y) = \sum_{j=1}^{k} \hat{\mathbf{v}}_j = \sum_{j=1}^{k} (\mathbf{v}_j + \mathbf{e}_j)$, where $\mathbf{v}_j + \mathbf{e}_j = (v_{j,x} + e_{j,x}, v_{j,y} + e_{j,y})$, $\hat{v}_x = \sum_{j=1}^{k} (v_{j,x} + e_{j,x})$, $\hat{v}_y = \sum_{j=1}^{k} (v_{j,y} + e_{j,y})$ and $\mathbf{e}_j = (e_{j,x}, e_{j,y})$ denotes the measurement inaccuracies of the corresponding moving vectors, where $j = 1, \cdots, k$. Assume that $\mathbf{e}_j$ is distributed in accordance with a Bivariate Normal distribution, i.e., $N(\mu_{j,x}, \mu_{j,y}, \sigma_{j,x}^2, \sigma_{j,y}^2, \rho_j)$, where $j = 1, \cdots, k$. Assume also that $\mathbf{e}_j$ is independent, correlation of zero is between $e_{j,x}$ and $e_{j,y}$ (i.e., ρ_j = 0), and $\mu_{j,x}$ = $\mu_{j,y}$ = 0, where $j = 1, \cdots, k$. Finally, assume that R_a and R_b are located at $(0, 0)$ and $(0, d_r)$, respectively, where d_r denotes the distance between the two RSUs. Without loss of generality, let the orientations of the directional antennas of R_a and R_b be given as $-\delta$ and δ, respectively. The equations of the corresponding straight lines are expressed as

$$\begin{aligned} y - \hat{v}_y &= \tan(-\delta)(x - \hat{v}_x) && (20) \\ y - d_r &= \tan(\delta)x. && (21) \end{aligned}$$

Subtracting (20) from (21), x can be formulated as

$$x = \frac{\hat{v}_y + \tan(\delta)\hat{v}_x - d_r}{2\tan(\delta)}. \quad (22)$$

Meanwhile, from (21), y can be formulated as

$$y = d_r + \frac{1}{2}\big(\hat{v}_y + \tan(\delta)\hat{v}_x - d_r\big). \quad (23)$$

Since V estimates (rather than measures) the coordinates (x, y) when determining its position, the variances of x and y can be regarded as a measure of the localization error. Let $Var(A)$ denote the variance of a random variable A. The variance of x can be derived as

$$\begin{aligned} Var(x) &= Var\left(\frac{\tan(\delta)\hat{v}_x + \hat{v}_y - d_r}{2\tan(\delta)}\right) && (24a) \\ &= \frac{1}{4}\sum_{j=1}^{k}\sigma_{k,x}^2 + \frac{1}{4\tan^2(\delta)}\sum_{j=1}^{k}\sigma_{k,y}^2. && (24b) \end{aligned}$$

Similarly, the variance of y is given by

$$\begin{aligned} Var(y) &= Var\left[d_r + \frac{1}{2}(\hat{v}_y + \tan(\delta)\hat{v}_x - d_r)\right] && (25a) \\ &= \frac{\tan^2(\delta)}{4}\sum_{j=1}^{k}\sigma_{k,x}^2 + \frac{1}{4}\sum_{j=1}^{k}\sigma_{k,y}^2. && (25b) \end{aligned}$$

It is seen in the equations above, that the variance of both x and y depends on the individual variances of $\mathbf{e}_1, \mathbf{e}_2, \cdots, \mathbf{e}_k$. (Note that this finding is confirmed by the simulations results presented later in Section V.D.)

V. PERFORMANCE EVALUATION BY SIMULATION

The performance of the proposed localization system (namely RSUDA) was evaluated by means of a series of experiments based on an ns-2 simulator with improved IEEE 802.11 PHY and MAC modules [39] to support IEEE 802.11p based vehicular communication environments.

A. Methodology

The simulations used a typical road segment built using MOVE software [40]. Note that MOVE is based on the well-known road traffic simulator SUMO [41]. The road segment was assumed to have a length of d_s m (i.e., the distance between neighboring RSU sets) and to comprise four lanes (i.e., two lanes in each direction). The width of each lane was assumed to be 3 m. Moreover, the mobility patterns of the vehicles were generated automatically by MOVE. Finally, the vehicle speed for each vehicle was specified as v_s km/h.

In the RSUDA scheme, two RSU sets were all deployed on the left-hand-side of the road and at the beginning and the end of

Table 1. Simulation parameters.

Parameter	Value(s)
Distance between neighboring RSU sets d_s	(0.5), 1, 1.5, 2, 2.5 km
Beam width θ	(10), 12, 14, 16, 18 degrees
Vector estimation error e_v	(2%), 4%, 6%, 8%, 10%
Vehicle speed v_s	(60), 70, 80, 90, 100 km/h

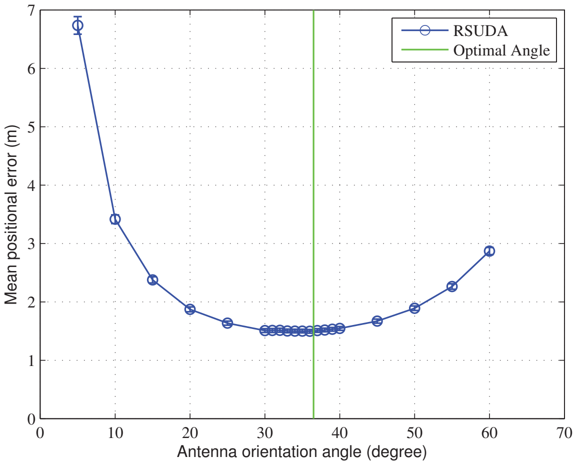

Fig. 7. Mean positional error vs. antenna orientation angle.

the road respectively. The distance between two RSUs, d_r, was set as 1 m based on experimental investigation of our testbed system. For all RSUs, the radio patterns of the directional antenna were assumed to have a conical-like section. The preliminary results showed that vehicles located very close to the RSUs (i.e., very close to the left-hand-side of the road) often failed to detect the beacon messages broadcast by the RSUs due to the very narrow width of the radio pattern and the given beacon interval. Thus, in the simulation setting, the RSUs were set to 10 m away from the left-hand-side of the road [4]. The directional antennas of the various RSUs all had a beam width of θ and were orientated in a direction of either $-\delta$ and $+\delta$. The beacon interval was set as 100 ms. The detailed parameter settings for the present simulations are summarized in Table 1. Note that default values in the simulations are indicated within the parentheses.

For each set of simulation conditions, 500 simulation runs were performed using different traffic patterns. The performance of the RSUDA localization method was then quantified in terms of the mean positional error of the corresponding localization results. The error bars in the following figures present a 95 % confidence interval but are often not visible because the interval is too small.

B. Impact of Antenna Orientation on Localization Performance

Fig. 7 shows the mean positional error of the proposed RSUDA localization scheme for different orientations of the directional antennas, i.e., from 5 to 60 degrees. It is seen that the mean localization error decreases from 6.74 m to 1.50 m as the orientation angle is increased from 5 to 36 degrees and increases from 1.50 m to 2.87 m as the orientation angle is increased from 37 to 60 degrees. The green line indicates the optimal orientation angle (i.e., about 36.45 degrees) obtained by solving the optimization problem P2 in Section III.C. It is noted that this result is consistent with the simulation result. The lowest localization error in the simulation is about 1.496 m when the orientation angle is 36 degrees. In other words, an antenna orientation of 36 degrees achieves the best positioning performance of the proposed localization method. Accordingly, δ was assigned a default value of 36 degrees for all of the remaining simulations.

C. Impact of Antenna Beam Width on Localization Performance

Fig. 8(a) shows the variation of the mean positional error of the proposed RSUDA scheme with the antenna beam width. (Note that the direction antennas of both RSUs are assumed to have the same beam width.) The mean positional error is found to increase from 1.79 m to 2.69 m as the beam width is increased from 10 to 18 degrees. As described in Section III, the proposed localization scheme uses the antennas' radio patterns (i.e., the slopes of two straight lines) to compute the vehicle position. However, since real-world directional antennas generate a radio pattern with a conical-like section rather than a perfectly straight line, a geometry-induced localization error inevitably occurs as indicated in Section III.C. Fig. 8(a) shows that the localization performance improves as the beam width reduces. Thus, θ was assigned a default value of 10 degrees in all of the remaining simulations.

To evaluate the performance of the moving vector starting point selection scheme presented in Section III.B, the beam width of the upper RSU's directional antenna (θ_b) was assigned the default value of 10 degrees while that of the lower RSU's antenna (θ_a) was progressively increased from 10 to 18 degrees. As shown in Fig. 8(b), the mean positional error remained approximately constant at around 1.8 m as the beam width of the lower RSU's antenna was increased. The results confirm that the start point selection scheme reduces the localization error by helping a vehicle to recognize the approximate starting coordinates at which it calculates its first moving vector as it travels through the radio pattern of the lower RSU's antenna. In other words, the performance of the proposed localization scheme is dependent only on the beam width of the upper RSU's directional antenna.

D. Impact of Vector Estimation Error on Localization Performance

In the proposed RSUDA localization method, each vehicle computes its moving vectors during the interval between receiving the beacon messages of neighboring RSU sets in order to determine its overall moving vector displacement and update its current position estimate accordingly. As described in Section III.B, the moving vectors are estimated in accordance with the information provided by the vehicle's odometer and compass. Thus, errors in the odometer and compass inevitably result in corresponding errors in the moving vector estimation and degrade the performance of the proposed localization scheme. The moving vector estimation concept used in the present study is similar to the DR approach adopted in [9], in which the errors in the estimated displacement accumulate as the travel distance

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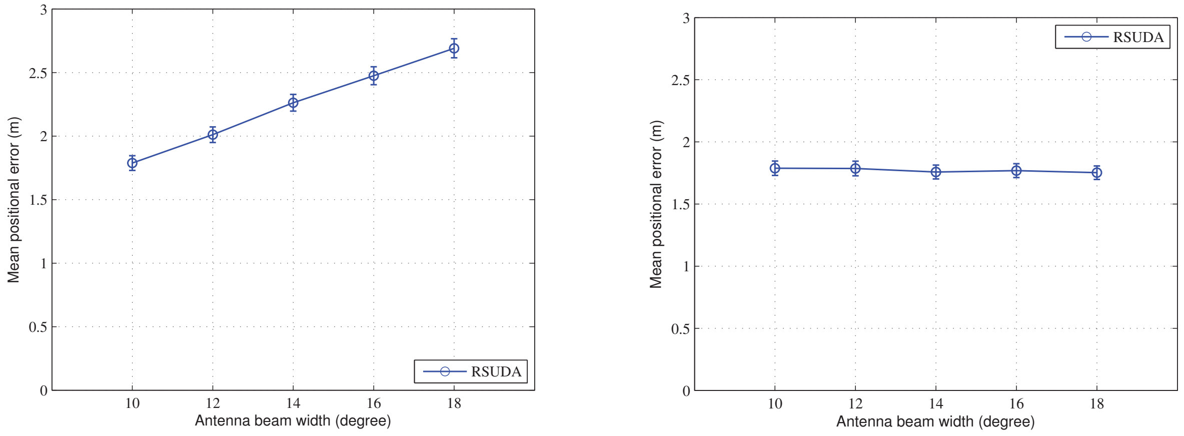
[4] Note that if we cannot set the RSU 10 m from the side of the road due to space limit, we can move RSU closer to the road while increase the beacon broadcast frequency.



(a)

(b)

Fig. 8. Mean positional error vs. antenna beam width: (a) Both θ_a and θ_b are increased from 10 to 18 degrees and (b) only θ_a is increased from 10 to 18 degrees and θ_b is assigned as 10 degrees.

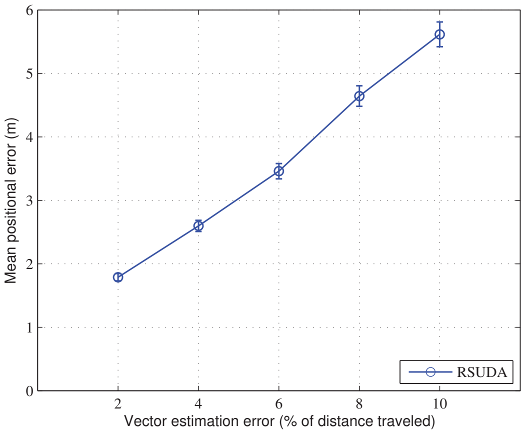


Fig. 9. Mean positional error vs. vector estimation error.

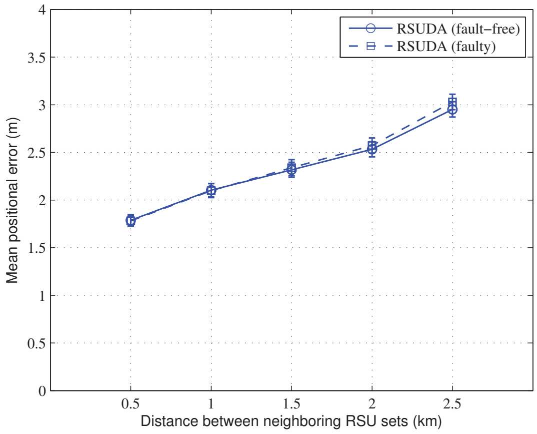


Fig. 10. Mean positional error vs. distance between neighboring RSU sets in fault-free and faulty environments.

increases. Thus, the error in the moving vector estimation in the present study can be defined as the percentage of the distance traveled [9], [42].

Fig. 9 shows the variation of the mean positional error of the proposed RSUDA localization method with different vector estimation errors. It is seen that the mean positional error increases from 1.79 m to 5.62 m as the vector estimation error is increased from 2% to 10%. It is noted that the simulation results presented in Fig. 9 are consistent with (24) and (25) in Section IV, which show that the localization accuracy of the proposed method increases as the vector measurement error reduces. According to [42], current DR systems achieve a maximum positioning performance of around 1% of the total distance traveled. Accordingly, the vector estimation error was specified as 2% in all of the remaining simulations.

E. Impact of Vehicle Speed on Localization Performance

Fig. 11 reveals that the mean positional error of the RSUDA scheme increase slightly as the vehicle speed is increased. The mean positional error is found to increase from 1.79 m to 1.90 m as the vehicle speed is increased from 60 to 100 km/h. This is because the measurement errors in the moving vector increase as the vehicle speed is increased. The moving vector measurement errors are sensitive to the increase of the travel distance, and hence, a larger distance was traveled by the vehicle with a higher speed since they measure at a fixed interval. Thus, the performance of the proposed RSUDA localization scheme is degraded.

F. Impact of RSU Deployment and Failure on Localization Performance

The simulations considered two different network environments, namely a fault-free environment in which all of the RSUs functioned correctly at all times and a faulty environment in which one RSU in the RSU set deployed at the end of the road was chosen at random and assumed to fail. Fig. 10 shows the variation of the mean positional error of the RSUDA scheme with different RSU deployments given faulty and fault-free environments, respectively. It is observed that for both environ-

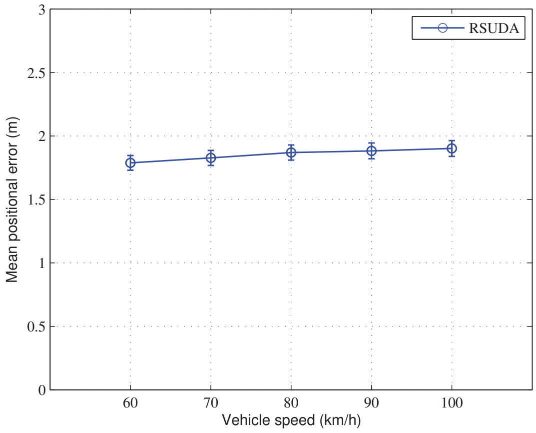


Fig. 11. Mean positional error vs. vehicle speed.

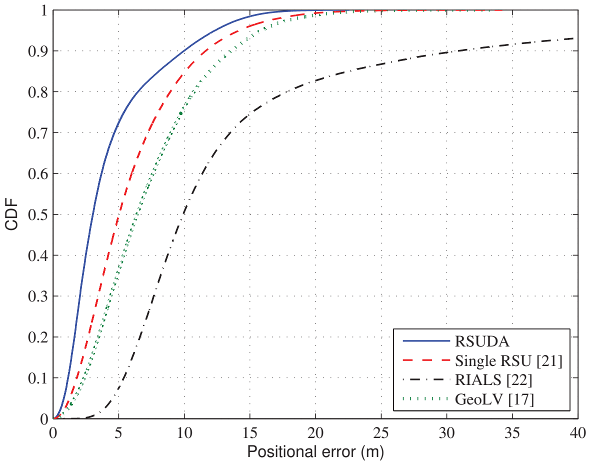


Fig. 12. Cumulative localization error distribution functions of RSUDA, Single RSU, RIALS, and GeoLV localization schemes.

ments, the mean positional error increases gradually as the distance between neighboring RSU sets is increased. This result is to be expected since as the distance between neighboring RSU sets increases, the vehicles are obliged to use their moving vector displacement estimates more frequently to update their position coordinates, and thus their localization performance is affected to a greater extent by measurement errors in the moving displacement vector. However, the positional RMSE in the faulty environment is greater than that in the fault-free environment when the distance between neighboring RSU sets is more than 1.5 km. This finding is reasonable since in the event of RSU failures, the vehicles utilize their previous position estimates and their estimated moving vector displacement to compute their positions. The previous position estimates are liable to error as a result of the antenna beam width and orientation. Furthermore, the accuracy of the previous position estimates is further degraded by errors in the moving vector measurement. Thus, the performance of the proposed localization scheme is further degraded.

The localization performance of the proposed scheme was compared with those of the GPS-free schemes, i.e., namely Single RSU [21] and RIALS [22], and one of the recent GPS-assisted schemes, i.e., namely GeoLV [17]. Note that the Single RSU, RIALS, and GeoLV schemes were deliberately chosen for comparison purposes since they are not only ones of the most recently-proposed vehicular localization methods, but also provide better localization accuracy than other existing localization algorithms (e.g., ref [19]).

Since both the Single RSU and RIALS localization schemes use only one RSU and the RSUDA scheme uses two RSUs for vehicle localization, the deployment cost (i.e., the number of required RSUs for localization) was set to be identical for fair performance comparison. With both the Single RSU and RIALS schemes, the RSUs were deployed on the left-hand-side of the road and fitted with omnidirectional antennas and were assumed to have a transmission range of 500 m [21], [22]. To guarantee that all of the vehicles have the ability to estimate their positions, at least four RSUs are required to be installed in a road segment with 3 km length and 12 m width for both the Single RSU and RIALS schemes and the distance between the neighboring RSUs was $2\sqrt{500^2 - 12^2} \approx 999.71$ m [22]. With the RSUDA scheme, two RSU sets (i.e., four RSUs in total as well) were deployed in the beginning and the end of the road segment respectively. Thus, the road length was assumed to be 3.2 km including the coverage of directional antenna of the RSUDA scheme. With the Single RSU and RIALS schemes, the distance between the RSUs and the passing vehicles was measured using a TOA ranging technique [43]. The ranging error was modeled as a normal distribution with zero mean and 3-m standard deviation in accordance with the results presented in [43]. The INS estimation error was assumed as the moving vector estimation error, as defined in Section V.D. For the Single RSU method, the vehicle's initial estimate was assumed to be obtained from a GPS receiver and the measurement error of the GPS receiver was modeled as a normal distribution with zero mean and 6-m standard deviation [12], [21]. For the RIALS method, the number of required intersecting circles used for localization was set as 72 [22]. With the GeoLV scheme, the vehicle's initial position was obtained from the GPS receiver and its error was also modeled as a normal distribution with zero mean and 6-m standard deviation. The vehicle dynamics (i.e., the travel direction and distance) error was assumed as the moving vector estimation error.

The cumulative localization error distribution functions shown in Fig. 12 provide an indication of the performance of the RSUDA, Single RSU, RIALS, and GeoLV localization schemes. The RSUDA localization scheme outperforms the Single RSU, RIALS, and GeoLV mechanisms. Specifically, the localization scheme estimates the positions of 72 percent of the vehicles within 5 m of their actual locations. By comparison, the Single RSU scheme locates only 50 percent of the vehicles with an accuracy of less than 5 m, the GeoLV scheme, only 36 percent of the vehicles, and the RIALS scheme, only 7 percent of the vehicles.

For further investigating the spatial performance comparison, Fig. 13 shows the variation of the positional accuracy of the four schemes with the location on the road. It is seen that the RSUDA scheme yields a better positioning accuracy than the Single RSU

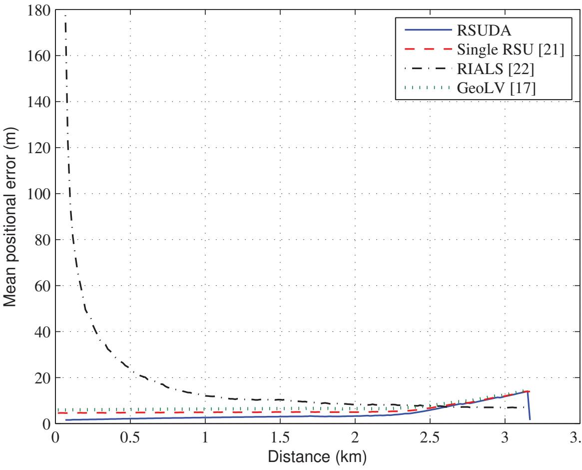


Fig. 13. Mean positional error vs. distance of RSUDA, Single RSU, RIALS, and GeoLV localization schemes.

and GeoLV schemes with all travel distance. The mean positional error of the RSUDA, Single RSU, and GeoLV schemes are gradually increased while the vehicles travel a longer distance. This is because the moving vector, INS, or vehicle dynamics measurement error is accumulated as the travel distance increases. The RSUDA scheme also performs much better than the RIALS scheme within 2.7 km travel distance. Specifically, the mean positional error of the RIALS scheme reaches more than 170 m within about 70 m initial travel distance. This is because the RIALS scheme requires obtaining a sufficient number of intersecting circles to reduce the localization accuracy. Although the mean error of the RSUDA scheme is higher than that of the RIALS scheme after 2.7 km travel distance, the RSUDA scheme can further correct the position error under 1.6 m after the vehicles travel through the next RSU set (see Fig. 13).

G. Performance Comparison with GPS-free and GPS-assisted Localization Schemes

VI. EXPERIMENTAL IMPLEMENTATION OF PROPOSED LOCALIZATION SCHEME

The practical feasibility of the proposed RSUDA localization scheme was evaluated by performing a series of experimental trials using the IWCU platform developed by ITRI. The aim of the experimental investigation was two-fold, namely (a) to confirm the real-world feasibility of the proposed scheme and (b) to verify the localization results obtained using the ns-2 simulator.

A. Methodology

Fig. 14. Map for experimental field.

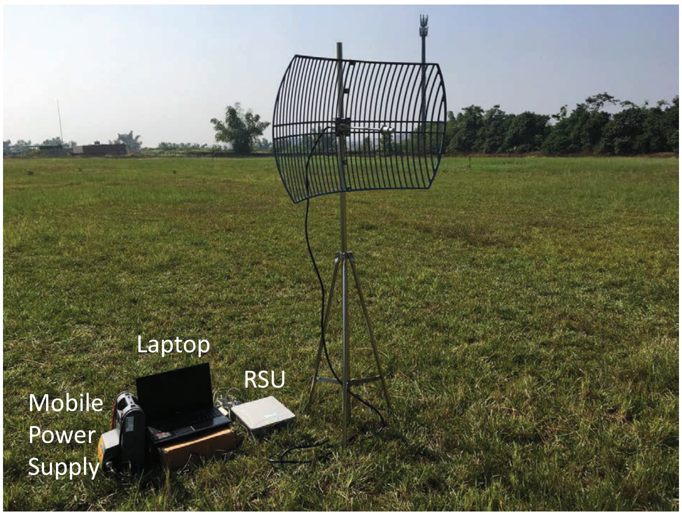


Fig. 15. IWCU RSU setup.

The experimental investigation was carried out in a campus road segment (see Fig. 14) and involved two RSUs and one OBU. The OBU and RSUs were loaded with Linux kernel 2.6.30 built-in processors and were equipped with 16 MB Flash and 64 MB SDRAM. Furthermore, all three devices were fitted with a GPS receiver and utilized the IEEE 802.11p standard, operating at 5.850–5.925 GHz, to support 10/100 Mbps Ethernet transmissions. The original RSUs were equipped with a 5 dBi omnidirectional antenna. Thus, to realize the localization scheme proposed in the present study, the original antennas were replaced with 24 dBi grid-directional antennas with an ideal horizontal beam width of approximately 10 degrees [36]. The grid-directional antennas of the two RSUs were attached to two poles separated by a distance of 1 m on one side of the field (see Fig. 15), while the OBU was mounted on the dash of a vehicle (see Fig. 16). Three laptop computers were connected to the RSUs and OBU via Ethernet to serve as two servers and a client, respectively. The communications between the RSUs and the OBU were handled using the WAVE Short Message (WSM) protocol prescribed in IEEE 1609.3 [44]. In broadcasting the RSU beacon messages, the servers delivered the message in a UDP format to the RSUs, and the message was then transformed into a WSM format and transmitted to the OBU over the control channel. On receipt of the beacon message, the message format was restored to the original UDP format and the message was then forwarded to the client.

In performing the experiments, the two RSU antennas were oriented at angles of $-36°$ and $36°$ relative to the perpendicular line of the road segment direction, respectively. Moreover, the OBU (i.e., the vehicle) moved (i.e., was driven) from A to B at a constant speed of approximately 40, 55, and 70 km/h along the road segment. Each RSU broadcast beacon messages at an in-

Fig. 16. IWCU OBU setup.

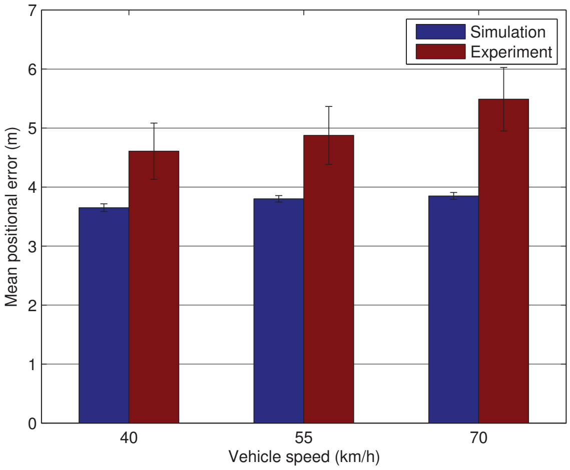


Fig. 17. Comparison of simulation results and experimental results for mean positional error of proposed localization scheme.

terval of 100 ms. Having received the beacon message from the first RSU, the vehicle continued moving until it received a message from the second RSU, at which point the OBU client immediately computed the vehicle coordinates using the proposed localization method. In performing the localization experiments, each experiment was repeated 50 times.

B. OBU Localization Performance

Fig. 17 compares the experimental localization results for the proposed scheme given the three vehicle speeds with the corresponding simulation results. Different from the default scenario in Section V, the simulation also considers an antenna orientation error of 5 degrees due to manual setting and a larger beam width of approximately 20 degrees based on our experimental measurements to reflect the realistic environment. It is seen that a good qualitative agreement exists between the two sets of results. As expected, the mean positional error of the proposed scheme increases with an increasing vehicle speed in both cases. This result is reasonable since the inaccuracy of the starting position determined by the proposed starting position selection scheme presented in Section III.B increases at a higher vehicle speed. The proposed selection scheme with a higher error locates the centerline of the antenna pattern, and hence the OBU localization performance is degraded. The greater positioning error of the proposed scheme in the experimental trials (compared to the simulation results) reflects the impact of the real-world implementation on the proposed system (e.g., variations in the antenna pattern, inaccurate vehicle speed measurements, etc.).

VII. CONCLUSION AND FUTURE WORK

This study has presented a RSU-based localization system for vehicles. In the proposed system, RSUs with fixed directional antennas are deployed at predetermined positions along the roadside and broadcast periodic beacon messages containing their location coordinates and the orientation angle of their antennas. Having received these messages from two consecutive RSUs, the vehicles compute their positions using straight-line intersection theory. The performance of the proposed method is enhanced by means of a RSU deployment method and a fault tolerance mechanism for overcoming the effects of RSU failures. The localization performance of the proposed scheme has been evaluated by means of ns-2 simulations. The results have shown that the RSUDA localization method outperforms the existing GPS-free and GPS-assisted methods. Finally, the feasibility of the proposed localization scheme has been demonstrated by an experimental trial conducted using real-world DSRC OBU and RSU devices. Future studies will investigate the impact of RSU failure on localization performance in the real experiments.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers and the editors for the valuable suggestions that improved this paper. Thanks to Dr. Yongmin Zhang for helpful discussion and proofreading. Thanks to Chong-Min Gao and Jian-Fu Huang for collecting the experimental results.

REFERENCES

[1] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, “Connected vehicles: Solutions and challenges,” *IEEE Internet of Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.
[2] K. Abboud, H.A. Omar, and W. Zhuang, “Interworking of DSRC and cellular network technologies for V2X communications: A survey,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9457–9470, Dec. 2016.
[3] Y. Cao *et al.,* “A decentralized deadline-driven electric vehicle charging recommendation,” accepted to *IEEE Syst. J.*, to be published.
[4] O. Kaiwartya *et al.,* “Internet of vehicles: Motivation, layered architecture, network model, challenges, and future aspects,” *IEEE Syst. J.*, vol. 4, pp. 5356–5373, Aug. 2016.
[5] B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins, *Global Positioning System: Theory and Practice*. Springer-Verlag, 1997.
[6] A. Boukerche, H. Oliveira, E. F. Nakamura, and A. Loureiro, “Vehicular ad hoc networks: A new challenge for localization-based systems,” *Comput. Commun.*, vol. 31, no. 12, pp. 2838–2849, July 2008.
[7] G. M. Djuknic and R. E. Richton, “Geolocation and assisted GPS,” *IEEE Comput.*, vol. 34, no. 2, pp. 123–125, Feb. 2001.
[8] W.-W. Kao, “Integration of GPS and Dead-reckoning Navigation Systems,” in *Proc. IEEE VNIS*, Oct. 1991, pp. 635–643.
[9] M. Amundson, “Dead Reckoning for Consumer Electronics,” Honeywell International, Tech. Rep., 2006.

[10] A. Benslimane, "Localization in vehicular ad hoc networks," in *Proc. Syst. Commun.*, Aug. 2005, pp. 19–25.

[11] R. Parker and S. Valaee, "Vehicle localization in vehicular networks," in *Proc. IEEE VTC*, Sept. 2006, pp. 1–5.

[12] R. Parker and S. Valaee, "Vehicular node localization using received-signal-strength indicator," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3371–3380, Nov. 2007.

[13] N. Drawil and O. Basir, "Intervehicle-communication-assisted localization," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 678–691, Sept. 2010.

[14] N. Alam, A. T. Balaei, and A. G. Dempster, "A DSRC doppler-based cooperative positioning enhancement for vehicular networks with GPS availability," *IEEE Trans. Veh. Technol.*, vol. 60, no. 9, pp. 4462–4470, Nov. 2011.

[15] J. Yao, A. T. Balaei, M. Hassan, N. Alam, and A. G. Dempster, "Improving cooperative positioning for vehicular networks ," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2810–2823, July 2011.

[16] T. Yan, W. Zhang, and G. Wang, "A grid-based on-road localization system in VANET with linear error propagation," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 861–875, Feb. 2014.

[17] O. Kaiwartya *et al.*, "Geometry-based localization for GPS outage in vehicular cyber physical systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 3800–3812, May 2018.

[18] E.-K. Lee, S. Y. Oh, and M. Gerla, "RFID assisted vehicle positioning in VANETs," *Pervasive Mobile Comput.*, vol. 8, no. 2, pp. 167–179, Apr. 2012.

[19] C. H. Ou, "A roadside unit-based localization scheme for vehicular ad hoc networks," *Int. J. Commun. Syst.*, vol. 27, no. 1, pp. 135–150, Jan. 2014.

[20] A. A. Wahab, A. Khattab, and Y. A. Fahmy, "Two-way TOA with Limited Dead Reckoning for GPS-free Vehicle Localization Using Single RSU," in *Proc. ITST*, Nov. 2013, pp. 244–249.

[21] A. Khattab, Y. A. Fahmy, and A. A. Wahab, "High accuracy GPS-free vehicle localization framework via an INS-assisted single RSU," *Int. J. Distr. Sensor Netw.*, vol. 11, no. 5, pp. 1–16, May 2015.

[22] H. Zarza, S. Yousefi, and A. Benslimane, "RIALS: RSU/INS-aided localization system for GPS-challenged road segments," *Wireless Commun. Mobile Comput.*, vol. 16, no. 10, pp. 1290–1305, July 2016.

[23] A. Fascista, G. Ciccarese, A. Coluccia, and G. Ricci, "A localization algorithm based on V2I communications and AOA estimation," *IEEE Signal Process. Lett.*, vol. 24, no. 1, pp. 126–130, Jan. 2017.

[24] A. Fascista, G. Ciccarese, A. Coluccia, and G. Ricci, "Angle of arrival-based cooperative positioning for smart vehicles," *IEEE Trans. Intell. Transp. Syst.*, to be published.

[25] J. J. Caffery and G. L. Stüer, "Overview of radiolocation in CDMA cellular systems," *IEEE Trans. Veh. Technol.*, vol. 36, no. 4, pp. 38–45, Apr. 1998.

[26] L. Cong and W. Zhuang, "Hybrid TDOA/AOA mobile user location for wideband CDMA cellular systems," *IEEE Trans. Wireless Commun.*, vol. 1, no. 3, pp. 439–447, July 2002.

[27] The Network Simulator—ns-2. [Online]. Available: http://www.isi.edu/nsnam/ns/

[28] K.-C. Lin and C.-H. Lin, "Development of telematics communication system with WAVE DSRC," in *Proc. IEEE SMC*, Oct. 2009, pp. 4158–4163.

[29] H.-H. Li and K.-C. Lin, "ITRI WAVE/DSRC communication unit," in *Proc. IEEE VTC*, May 2010, pp. 1–2.

[30] K.-Y. Ho, P.-C. Kang, C.-H. Hsu, and C.-H. Lin, "Implementation of WAVE/DSRC devices for vehicular communications," in *Proc 3CA*, May 2010, pp. 522–525.

[31] Industrial Technology Research Institute of Taiwan. [Online]. Available: http://www.itri.org.tw/eng/

[32] V. Rabinovich and N. Alexandrov, *Antenna Arrays and Automotive Applications*. Springer-Verlag New York, 2013.

[33] K. K. Chintalapudi, A. Dhariwal, R. Govindan, and G. Sukhatme, "Ad-hoc localization using ranging and sectoring," in *Proc. IEEE INFOCOM*, Mar. 2004, pp. 2662–2672.

[34] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, "Using directional antennas for medium access control in ad hoc networks," in *Proc. ACM MobiCom*, Sept. 2002, pp. 59–70.

[35] C. H. Ou, "A localization scheme for wireless sensor networks using mobile anchors with directional antennas," *IEEE Sensors J.*, vol. 11, no. 7, pp. 1607–1616, July 2011.

[36] RFCastle 5.7-5.9GHz Reflector Grid Directional Antenna. [Online]. Available: http://www.rfcastle.com/goods.php?act=view&catId=317

[37] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[38] F. S. Hillier and G. J. Libermann, *Introduction to Operations Research*. McGraw-Hill, 2014.

[39] Q. Chen *et al.*, "Overhaul of IEEE 802.11 modeling and simulation in NS-2," in *Proc. ACM MSWiM*, Oct. 2007, pp. 159–168.

[40] F. K. Karnadi, Z. H. Mo, and K.-C. Lan, "Rapid generation of realistic mobility models for VANET," in *Proc. IEEE WCNC*, Mar. 2007, pp. 2506–2511.

[41] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "SUMO—Simulation of Urban MObility: An overview," in *Proc. SIMUL*, Oct. 2011, pp. 63–68.

[42] V. Kukshya, H. Krishnan, and C. Kellum, "Design of a system solution for relative positioning of vehicles using vehicle-to-vehicle radio communications during GPS outages," in *Proc. IEEE VTC*, Sept. 2005, pp. 1313–1317.

[43] D. D. McCrady, L. Doyle, H. Forstrom, T. Dempsey, and M. Martorana, "Mobile ranging using low-accuracy clocks," *IEEE Trans. Microw. Theory Tech.*, vol. 48, no. 6, pp. 951–958, June 2000.

[44] 1609 WG - Dedicated Short Range Communication Working Group. [Online]. Available: http://standards.ieee.org/develop/wg/1609_WG.html

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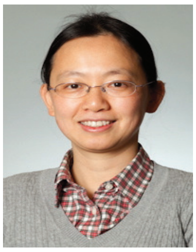

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