Joint Estimation of Vehicle's Position and Velocity With Distributed RSUs for OFDM Radar System

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***Abstract*—We develop a vehicle motion state estimation algorithm based on an orthogonal frequency division multiplexing radar system suitable for vehicle-to-infrastructure (V2I) communications scenarios. Due to the transverse movement with respect to the direction from the target to roadside unit (RSU), the measured velocity is distorted as the Doppler shift depends on the angle formed between the vehicle position and RSU. To compensate for the distorted velocity, the exact vehicle position is required. However, this cannot be obtained in a system with a single RSU. In this paper, we develop an efficient cooperative vehicle state estimation algorithm that reduces the number of RSUs required for localization compared to conventional schemes by eliminating unnecessary RSUs to overcome the degradation of target detection performance in low signal-to-noise ratio regimes. Furthermore, the singularity problem due to the absence of Doppler shift when the vehicle travels near the tangential direction can be addressed with spatially distributed RSUs. Numerical results verify that the proposed estimation algorithm outperforms the existing schemes in V2I scenarios.**

***Index Terms*—OFDM radar system, cooperative vehicle motion state estimation, distributed RSUs, V2I communications scenario**

I. Introduction

Intelligent transportation system (ITS) enhances the safety of transportation and maximizes the efficiency of road traffic management. Vehicle-to-everything (V2X) communications is a key enabler of ITS that shares information with communications devices installed in roadside units (RSUs). For V2X communications, many standardization groups have developed the physical layer architectures based on the orthogonal frequency division multiplexing (OFDM) system (e.g., LTE-V, 5G-NR, IEEE 802.11p) [1].

Autonomous driving requires recognizing the vehicle's surrounding environment for driving without human intervention. To achieve this goal, accurate vehicle motion state information, including the position and velocity of the vehicle, should be estimated to keep a safe distance between adjacent vehicles [2]. Among numerous methods developed to acquire the vehicle's mobility state information, the frequency modulated continuous wave (FMWC) radar is known to be the most popular one [3]. However, supposing all vehicles on the road are equipped with the FMCW radar, the target detection performance will be significantly degraded due to the mutual interference of radar signals between vehicles [4], [5].

OFDM communication-based radar is an attractive alternative for the efficient use of frequency resources since it provides both data communications and radar sensor functions simultaneously [6]. With the help of multiple access control, the interference can be effectively controlled. After installing the radar receiver module at the RSU's transmitter, the relative distance and velocity information are obtained by processing the OFDM signals reflected from vehicles [7].

Most of the existing radar algorithms have been developed to detect front targets, and the field of view typically does not exceed 20 degrees from the forward moving direction [8]. However, in the V2I scenario, RSUs should cover a broader field of view since vehicles travel in a transverse direction with respect to the direction from the vehicle to RSU. Considering that the OFDM radar system obtains the relative velocity based on the Doppler shift, the measured velocity of the target at RSU varies depending on the vehicle position, even if the vehicle travels at a constant velocity. Therefore, the Doppler coefficient should be appropriately modeled with V2I communications environments.

The cooperative RSU system allows vehicle localization on the road [9]. Existing localization algorithms (e.g., trilateration algorithm) have been developed using only the distance information based on the received signal strength obtained from at least three distributed RSUs [10]. Meanwhile, in the OFDM radar systems, RSUs acquire not only the distance information but also the relative velocity of the target. Therefore, it is necessary to develop a more efficient localization algorithm that does not waste additional information. So far, we believe that a localization algorithm that simultaneously utilizes distance and velocity information in the OFDM radar systems has not been developed. Furthermore, in the V2I scenario where RSUs are deployed along a straight line, there is a significant difference in signal-to-noise ratio (SNR) between RSUs, which affects the target detection performance. Thus, the number of RSUs required for vehicle localization needs to be reduced.

This paper aims to develop a vehicle state estimation algorithm suitable for the V2I environment. First, we develop a method to compensate for the distortion of the measured velocity caused by the transverse movement of the vehicle, and discuss the ambiguity problem that the true velocity cannot be determined in a single RSU system. Second, we propose an efficient 2-dimensional (2D) localization utilizing the relative velocity in the OFDM radar system. Finally, spatially distributed RSUs system can handle the singularity problem caused by the lack of Doppler shift near the tangential direction.

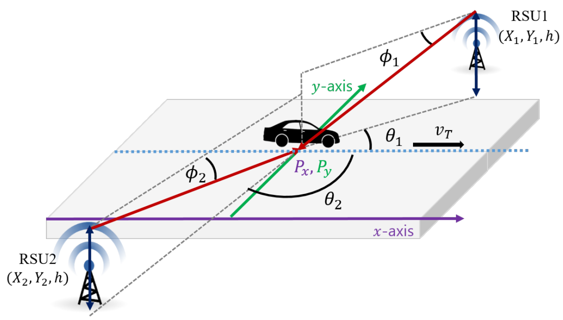


Fig. 1. OFDM radar system overview.

II. Principles of OFDM Radar

A. System Model

We consider an OFDM communication-based radar system operated at RSU. A baseband OFDM signal in the continuous-time domain at u-th RSU is expressed as

$$x_u(t) = \frac{1}{\sqrt{N}} \sum_{\ell=0}^{L-1} \sum_{n=0}^{N-1} s_u(n,\ell) e^{j2\pi f_n (t-\ell T_{sym})} \\ \mathrm{rect}(\frac{t-\ell T_{sym}+T_{cp}}{T_{sym}}),$$

where u denotes the index for RSU with a total of U RSUs, $n \in \{1, \cdots, N\}$ the subcarrier index, $\ell \in \{1, \cdots, L\}$ the symbol index, $s_u(\ell, n)$ the ℓ-th data symbol at the n-th subcarrier, $f_n = n\Delta f = n/T$ the frequency of n-th subcarrier in which Δf is the subcarrier spacing. In addition, T, T_{cp}, and $T_{sym} = T + T_{cp}$ represent the symbol duration, cyclic prefix duration, and extended OFDM symbol including the guard duration, respectively. Finally, $\mathrm{rect}(t)$ is the rectangular function with unity inside the interval $t \in [0, T)$, and zero outside it.

The position on the x-axis, y-axis, and velocity of a vehicle on the road are represented by p_x, p_y, and v_T, respectively. Assuming u-th RSU is deployed at (X_u, Y_u, h), the distance between the vehicle and u-th RSU is given as $d_u = \sqrt{(X_u - p_x)^2 + (Y_u - p_y)^2 + h^2}$. Furthermore, using the road geometry, the angular direction from RSU to the vehicle comprises vertical angle of arrival (AoA), $\cos\phi_u = \frac{\sqrt{(X_u-p_x)^2+(Y_u-p_y)^2}}{\sqrt{(X_u-p_x)^2+(Y_u-p_y)^2+h^2}}$, and the horizontal AoA, $\cos\theta_u = \frac{X_u - p_x}{\sqrt{(X_u-p_x)^2+(Y_u-p_y)^2}}$, such that

$$\begin{aligned}\psi_u &= \cos\phi_u \cos\theta_u \\ &= \frac{X_u - p_x}{\sqrt{(X_u-p_x)^2+(Y_u-p_y)^2+h^2}}.\end{aligned} \tag{1}$$

Fig. 1 illustrates that a vehicle travels along the x-axis served by two RSUs in the V2I communications scenario.

B. Distance and Velocity Estimation

The received OFDM signal reflected by the target at u-th RSU can be expressed as [1] [7], [11], [12]

$$y_u(t) = \frac{\alpha_u}{\sqrt{N}} \sum_{\ell=0}^{L-1} \sum_{n=0}^{N-1} s_u(n,\ell) e^{j2\pi f_n (t-\ell T_{sym}-\tau_u)} \\ e^{j2\pi f_u^D \ell T_{sym}} \mathrm{rect}(\frac{t-\ell T_{sym}+T_{cp}}{T_{sym}}), \tag{2}$$

where $\alpha_u \in \mathbb{C}$ is the magnitude of the signal reflection, which depends on the target radar cross section, $\tau_u = \frac{2d_u}{c_0}$ is the time-delay that takes to the target and back in which c_0 is the speed of light. Furthermore, f_u^D is the Doppler shift in which f_C is the carrier frequency and is a function of true velocity of the target and angular direction such that

$$f_u^D = \frac{2v_T}{c_0} f_C \psi_u. \tag{3}$$

Assuming $T_{cp} \geq \tau_u$ for all u, and sampling the received OFDM signal in (2) at $t = \ell T_{sym} + mT_s$ with $T_s = \frac{T}{N}$, the discrete-time OFDM symbol is expressed as

$$\begin{aligned} y_u(m,\ell) &= \frac{\alpha_u}{\sqrt{N}} \sum_{\ell=0}^{L-1} \sum_{n=0}^{N-1} s_u(n,\ell) e^{j2\pi(\frac{nm}{N} - f_n\tau_u)} e^{j2\pi f_u^D \ell T_{sym}} \\ &\overset{(a)}{=} \frac{\alpha_u}{\sqrt{N}} \sum_{\ell=0}^{L-1} \sum_{n=0}^{N-1} s_u(n,\ell) e^{j2\pi\frac{nm}{N}} e^{-j2\pi n\bar{\tau}_u} e^{j2\pi \bar{f}_u^D \ell\beta}, \end{aligned} \tag{4}$$

where (a) is represented by defining the normalized delay $\bar{\tau}_u \doteq \tau_u/T$, the normalized Doppler shifts $\bar{f}_u^D \doteq f_u^D/\Delta f$, and $T_{sym} \doteq \beta T$.

For simplicity, the discrete received symbol in (4) can be represented in matrix form such that

$$\mathbf{Y}_u^{m\ell} = \alpha_u \mathbf{W}_N^{-1} \mathbf{D}_N^*(\bar{\tau}_u) \mathbf{S} \mathbf{D}_L(\bar{f}_u^D \beta), \tag{5}$$

where $\mathbf{W}_N$ denotes the discrete Fourier transform (DFT) matrix with size N, and $\mathbf{D}_N(a) = \mathrm{diag}([1, e^{j2\pi a}, \cdots, e^{j2\pi a(N-1)}])$. However, the transmit symbol matrix, $\mathbf{S}$, in (5) hinders estimating the distance and velocity information. Therefore, the symbol matrix should be eliminated by transforming the signal into the frequency domain using the DFT matrix. The received OFDM matrix in the frequency domain with whitening the data symbol matrix is represented as

$$\begin{aligned} \mathbf{Y}_u^{f\ell} &= \mathbf{W}_N \mathbf{Y}_u^{m\ell} (./\mathbf{S}) \\ &\overset{(a)}{=} \alpha_u \mathbf{D}_N^*(\bar{\tau}_u) \mathbf{1}_{N*L} \mathbf{D}_L(\bar{f}_u^D \beta) \\ &= \alpha_u \mathbf{D}_N^*(\bar{\tau}_u) \underline{\mathbf{1}}_N \underline{\mathbf{1}}_L^T \mathbf{D}_L(\bar{f}_u^D \beta) \\ &= \alpha_u \underline{\mathbf{D}}_N^*(\bar{\tau}_u) \underline{\mathbf{D}}_L^T(\bar{f}_u^D \beta), \end{aligned}$$

where (a) is derived because the element-wise division $(./\mathbf{A})$ and the diagonal matrix are commutative, i.e., $\mathbf{D}_N(a)(./\mathbf{A}) =$

[1]For a simple analysis, the additive white Gaussian noise (AWGN) process does not represented in the received OFDM signal in (2). However, as studied in [11], the noise still follows a white noise process after removing the effects of the data symbols. Please see [11] for more details on the statistical properties of the AWGN when whitening the data symbols.

$(./\mathbf{A})\mathbf{D}_N(a)$. Note that $\mathbf{1}_{a*b}$ is the $a \times b$ all ones matrix, $\underline{\mathbf{1}}_N$ is the $N \times 1$ all ones column vector, and $\underline{\mathbf{D}}_N = \mathbf{D}_N \underline{\mathbf{1}}_N$.

Since the time-delay and Doppler shift of the target induce the phase shift for every OFDM subcarrier and symbol, respectively, the estimation of the time-delay and Doppler shift information is now converted to a spectral estimation problem. By taking the inverse DFT matrix over the subcarrier with size N and the DFT matrix over the symbols with size L, the 2D time-delay and Doppler shift profile can be represented as follows:

$$\begin{aligned}\mathbf{Y}_u^{dv} &= \mathbf{W}_N^{-1}\mathbf{Y}_u^{f\ell}\mathbf{W}_L \\ &= \alpha_u \underline{\mathbf{u}}_N^*(\bar{\tau}_u)\underline{\mathbf{u}}_L^T(\bar{f}_u^D\beta),\end{aligned}$$

where $\underline{\mathbf{u}}_N(a) \doteq \mathbf{W}_N\underline{\mathbf{D}}_N(a)$ is the $N \times 1$ column vector with a maximum value at the a-th element.

After converting the time-delay and Doppler shift into the distance and velocity of the target, take the absolute value of all elements in the 2D distance-velocity profile. Finally, the indices of the peak value represents the distance and velocity of the target.

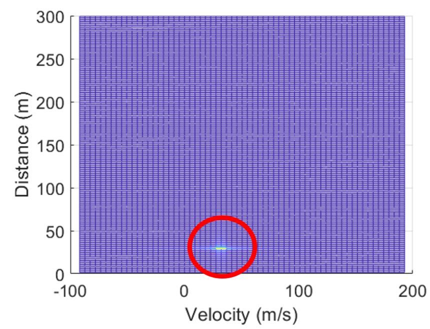
III. Cooperative Vehicle Mobility State Estimation

A. Problems in a System With Single RSU

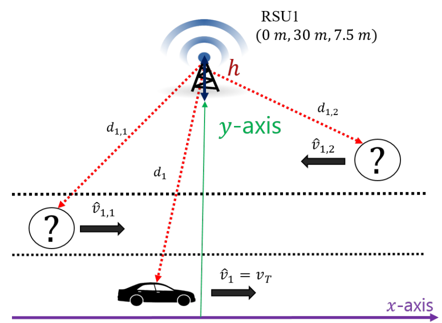
Most of the existing radar algorithms aim to detect front targets using the forward-collision radar mounted on the front of the vehicle [12]. Therefore, the horizontal AoA in (3) is negligible when estimating the target velocity. However, in the V2I communications scenario, the vehicle travels in a transverse direction with respect to the RSU. The angular direction between the vehicle and RSU changes significantly based on the vehicle position, which occurs in the cosine effect where the relative velocity, v, is lower than the true velocity, v_T. Therefore, the relative velocity should be appropriately compensated with the angular direction to overcome the cosine effect. The estimated velocity at u-th RSU is given as

$$\hat{v}_u = \frac{v_u}{\psi_u} = \frac{v_u d_u}{X_u - p_x}. \tag{6}$$

With a single RSU, RSU can only obtain the distance and velocity information, not the vehicle position p_x, which leads to an ambiguity problem where the measured velocity cannot be determined uniquely. Fig. 2(a) illustrates the example of 2D distance-velocity profile at RSU1 in which the vehicle located at $(p_x = -10 \text{ m}, p_y = 5 \text{ m})$ on the road, driving with $v_T = 22.2$ m/s. Assuming RSU1 is deployed at $(0 \text{ m}, 30 \text{ m}, 7.5 \text{ m})$, the distance between the vehicle and RSU1, $d_1 \simeq 27$ m. Due to the cosine effect, the measured velocity of the vehicle at RSU1 is calculated as $v_1 = \frac{v_T(X_1 - p_x)}{d_1} = 4.1$ m/s. Fig. 2(b) shows three different points with the same distance: the true vehicle point and two candidate points on the road. The coordinates of two points are set to $(p_{x,1} = -18 \text{ m}, p_{y,1} = 10 \text{ m})$, $(p_{x,2} = 20 \text{ m}, p_{y,2} = 18 \text{ m})$, respectively. The distances of two points from RSU1 are similar to the distance between RSU1 and the vehicle, such that $d_1 \simeq d_{1,1} \simeq d_{1,2}$. Now, we calculate the



(a) 2D distance-velocity profile.



(b) Three different points with the same distance.

Fig. 2. Example of the ambiguity problem.

compensated velocities of the three points using (6), and the estimated velocities are represented as

$$\begin{aligned}\hat{v}_1 &= \frac{v_1 d_1}{X_1 - p_x} \simeq 22.2 \text{ m/s}, \\ \hat{v}_{1,1} &= \frac{v_1 d_{1,1}}{X_1 - p_{x,1}} \simeq 11.1 \text{ m/s}, \\ \hat{v}_{1,2} &= \frac{v_1 d_{1,2}}{X_1 - p_{x,2}} \simeq -6.2 \text{ m/s},\end{aligned}$$

respectively. All three estimated velocities can be candidates for the true velocity considering the single RSU scenario. Therefore, if the exact vehicle position is not provided, we cannot specify the true velocity of the target.

Furthermore, even if the exact vehicle position is provided at RSU, the singularity problem due to the absence of the Doppler shift near the tangential direction also needs to be solved. Because the horizontal AoA approaches zero at the tangential point, i.e., the estimated velocity in (6) diverges.

B. Joint Estimation of Vehicle's Position and Velocity With Cooperative RSU System

To obtain the vehicle position on the road, spatially distributed RSUs should be jointly used. As studied in [9], the distance-based trilateration algorithm has been developed for 2D localization using a cooperative network. Each received signal strength (RSS) obtained from distributed RSU can be converted to the distance using the free-space path loss equation, which is inversely proportional to the distance [13]. The vehicle position on the 2D axis (p_x, p_y) can be calculated by utilizing the geometry of the circles, which is represented as

$$\begin{aligned}(X_1 - p_x)^2 + (Y_1 - p_y)^2 + h^2 &= d_1^2\\(X_2 - p_x)^2 + (Y_2 - p_y)^2 + h^2 &= d_2^2\\(X_3 - p_x)^2 + (Y_3 - p_y)^2 + h^2 &= d_3^2.\end{aligned}$$

Unlike the conventional RSS-based system, the OFDM radar system obtains vehicle distance and velocity information using the 2D FFT operation. In low SNR regimes, the peak in the 2D distance-velocity profile cannot be detected, which returns an arbitrary distance and velocity index. For applying the trilateration algorithm, at least three distance information is required, however, RSU deployed far from the vehicle may not obtain sufficient SNR for peak detection.

To handle this issue, we develop a 2D vehicle localization algorithm that reduces the number of RSU for vehicle localization. For eliminating the farthest RSU from the vehicle, we fully utilize the relative velocity obtained from two distributed RSUs to specify the vehicle position. The proposed 2D localization uses the two circle equations with (p_x, p_y) as a center and two relative velocity equations based on the road geometry in (1); Four equations can be formulated as follows:

$$(X_1 - p_x)^2 + (Y_1 - p_y)^2 + h^2 = d_1^2 \tag{7}$$
$$(X_2 - p_x)^2 + (Y_2 - p_y)^2 + h^2 = d_2^2 \tag{8}$$
$$v_T \cos\theta_1 \cos\phi_1 = v_1 \tag{9}$$
$$v_T \cos\theta_2 \cos\phi_2 = v_2. \tag{10}$$

Subtracting the equation (7) from equation (8) is given as

$$\begin{aligned}&2(X_1 - X_2)p_x + 2(Y_1 - Y_2)p_y\\&\quad = d_2^2 - d_1^2 + X_1^2 - X_2^2 + Y_1^2 - Y_2^2.\end{aligned} \tag{11}$$

The relative velocity equations in (9) and (10) obtained by the two RSUs can be rewritten as follows:

$$v_T = \frac{d_1 v_1}{X_1 - p_x} = \frac{d_2 v_2}{X_2 - p_x}, \tag{12}$$

since the angular direction at RSU1 is $\cos\theta_1 \cos\phi_1 = \frac{X_1 - p_x}{d_1}$, and the angular direction at RSU2 is $\cos\theta_2 \cos\phi_2 = \frac{X_2 - p_x}{d_2}$.

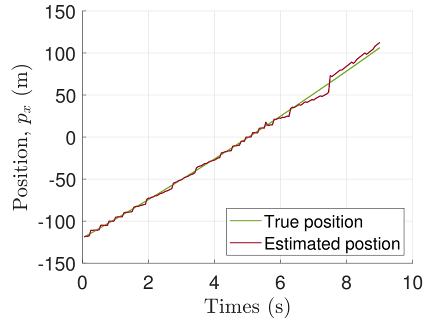
The system of linear equation with the equation (11) and (12) is formed as

$$\begin{pmatrix} 2(X_1 - X_2) & 2(Y_1 - Y_2) \\ d_1 v_1 - d_2 v_2 & 0 \end{pmatrix} \begin{pmatrix} p_x \\ p_y \end{pmatrix} = \begin{pmatrix} d_2^2 - d_1^2 + C \\ d_1 v_1 X_2 - d_2 v_2 X_1 \end{pmatrix},$$

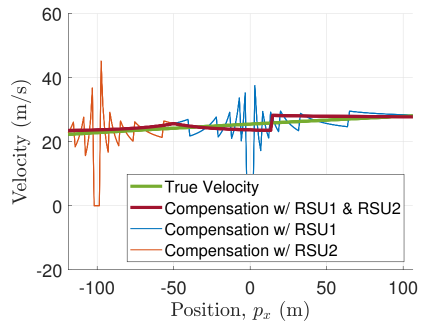
where $C \doteq X_1^2 - X_2^2 + Y_1^2 - Y_2^2$. Finally, the solution of the system equation, i.e., the estimated the vehicle position $(\hat{p}_x, \hat{p}_y)$, is calculated as

$$\begin{pmatrix} \hat{p}_x \\ \hat{p}_y \end{pmatrix} = \begin{pmatrix} \frac{d_1 v_1 X_2 - d_2 v_2 X_1}{d_1 v_1 - d_2 v_2} \\ \frac{d_2^2 - d_1^2 + C}{2(Y_1 - Y_2)} - \frac{(X_1 - X_2)}{(Y_1 - Y_2)} \frac{d_1 v_1 X_2 - d_2 v_2 X_1}{d_1 v_1 - d_2 v_2} \end{pmatrix}.$$

The true velocity of the vehicle, v_T, can now be estimated using the exact vehicle position. To avoid the singularity problem, we compensate for the measured velocity by selecting an RSU which obtains a larger relative velocity.



(a) Position estimation



(b) Velocity estimation

Fig. 3. Example of vehicle mobility state estimation.

IV. Simulation Results

Numerical results are provided to evaluate the proposed 2D localization performance. We consider a 5G new radio (NR) OFDM system using a center frequency of 3.5 GHz with the available bandwidth of $\{18, 36, 90\}$ MHz. Using the 15 kHz subcarrier spacing, the number of active subcarriers is $N = \{1200, 2400, 6000\}$, and the number of OFDM symbols is $L = 280$ considering the NR specification [14]. For simplicity, we set the reflection coefficient of the vehicle to $\alpha = 1$, and the path-loss exponent to two.

The vehicle movement is modeled using the discrete-time linear state model similar to [15]. The vehicle state model at discrete time index k with a sampling interval $T_s = LT_{sym}$ is represented as

$$\mathbf{t}^k = \mathbf{A}\mathbf{t}^{k-1} + \mathbf{b}\alpha + \mathbf{e}^{k-1},$$

where $\mathbf{t}^k = [p_x^k, p_y^k, v_T^k]^T \in \mathbb{R}^3$ the vehicle state vector, $\mathbf{A} = \begin{bmatrix} 1 & 0 & T_s \cos\vartheta \\ 0 & 1 & T_s \sin\vartheta \\ 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{3\times 3}$ the state-transition matrix, $\mathbf{b} = \left[\frac{T_s^2}{2}\cos\vartheta, \frac{T_s^2}{2}\sin\vartheta, T_s\right]^T \in \mathbb{R}^3$ the acceleration-transition vector. Furthermore, the acceleration variable is modeled by using Gaussian random variables $\alpha \sim \mathcal{N}(0, \sigma_\alpha^2)$ and the error transition vector, $\mathbf{e}^{k-1}$, follows the multivariate Gaussian distribution $\mathcal{N}(\mathbf{0}_3, \sigma_\omega^2 \mathrm{diag}[T_s^2\sigma_\omega^2 \cos^2\vartheta, T_s^2\sigma_\omega^2 \sin^2\vartheta, \sigma_\omega^2])$ with the steering angle of $\vartheta = \pi/2^7$.

We provide an example of the proposed vehicle mobility state estimation and that of performance with 90 MHz bandwidth. RSU1 and RSU2 are deployed at $(0\ \mathrm{m}, 50\ \mathrm{m})$ and $(-100\ \mathrm{m}, 0\ \mathrm{m})$. The height of the RSU is set to $h = 7.5$ m. The initial position of the vehicle on the road $p_x^0 = -120$ m, $p_y^0 = 25$ m, and traveling with $v_T^0 = 80$ km/h. As shown in Fig. 3(a), the position on the x-axis is estimated properly only using two RSUs as the vehicle travels along the x-axis. Fig. 3(b) represents an example of velocity compensation. The vehicle velocity is compensated with the estimated vehicle position using (6). In the case of only using RSU1, a singularity problem occurs when the vehicle travels near 0 m, and similarly, the same problem occurs near -100 m in RSU2 scenario. To solve this issue, we compensate the measured velocity by selecting the RSU which obtains the larger relative velocity. The estimation performance is evaluated based on a root mean squared error (RMSE) metric. The RMSE of the position on the x-axis, i.e., $\Gamma_x = \sqrt{\mathrm{E}(p_x^k - \hat{p}_x^k)^2}$, is given as 1.91 m, and the RMSE of the position on the y-axis, i.e., $\Gamma_y = \sqrt{\mathrm{E}(p_y^k - \hat{p}_y^k)^2}$, is given as 2.76 m. The velocity RMSE using only RSU1, i.e., $\Gamma_{\hat{v}_1} = \sqrt{\mathrm{E}(v_T^k - \hat{v}_1^k)^2}$, is $\Gamma_{\hat{v}_1} = 4.384$ m/s, the velocity RMSE using only RSU2 is $\Gamma_{\hat{v}_2} = 4.378$ m/s, and the velocity RMSE using both RSUs is $\Gamma_{\hat{v}_{1,2}} = 1.166$ m/s.

Another simulation is provided for evaluating the estimation performance of the proposed localization algorithm and that of the existing algorithm [13]. RSU1, RSU2, and RSU3 are deployed at $(0\ \mathrm{m}, 50\ \mathrm{m})$, $(-100\ \mathrm{m}, 0\ \mathrm{m})$, and $(100\ \mathrm{m}, 0\ \mathrm{m})$ respectively. The initial position of the vehicle on the road x-axis is set to $p_x^0 = -150$ m traveling with $v_T^0 = 80$ km/h. The conventional algorithm uses only the distance information from the three distributed RSUs. In contrast, the proposed algorithm simultaneously utilizes both the distance and relative velocity information by selecting the two nearest RSUs. We generate 15,000 Monte-Carlo simulations and find the detection failure cases where the error between the true and estimated positions is out of a pre-defined threshold, which is set to 5 m. As shown in Fig. 4, the detection failure probability of the proposed algorithm outperforms the existing algorithm under the same bandwidth, and the additional gain is obtained by using the larger bandwidth. Considering that RSUs are typically deployed at intervals of 200 m [16], the SNR difference between two RSUs deployed at both ends is up to 46 dB, assuming the free space path-loss. As a result, the trilateration scheme is unsuitable for the V2I communications scenario since the farthest RSU from the vehicle does not obtain sufficient SNR. Meanwhile, the proposed algorithm shows a low detection failure probability because it excludes the inappropriate RSU.

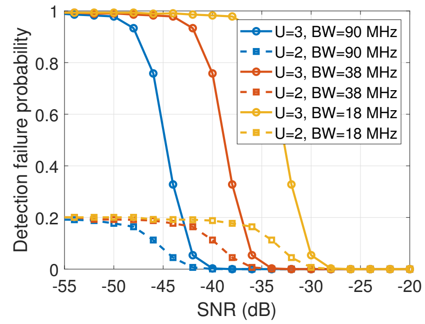


Fig. 4. Position detection failure probability.

V. Conclusion

In this paper, we proposed the joint vehicle's position and velocity estimation algorithm using the cooperative RSU system. In the V2I communications scenario, the measured velocity at RSU is distorted due to the transverse movement of the vehicle with respect to RSU. First, we discussed the importance of obtaining the exact vehicle position for compensating the distorted velocity, and the singularity problem of the compensated velocity in a system with single RSU. Second, we proposed the vehicle localization algorithm that requires only two RSUs by fully utilizing relative velocity to overcome the degradation of peak detection performance in low SNR regimes. Finally, the cooperative RSU system increased the state estimation performance by providing a spatial diversity with the different relative velocities at each distributed RSU. Simulation results verified that the proposed vehicle motion state estimation algorithm is more suitable for the V2I scenario than the conventional scheme.

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