Hybrid mmWave/DSRC vehicular communication for next generation connected vehicles

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Millimeter wave (mmWave) vehicular communication is investigated in this paper, to achieve Gbps data rate for future connected vehicles. A novel hybrid mmWave and dedicated short-range communication (DSRC) vehicular communication approach is introduced to minimize the overhead related to beam searching and alignment, utilizing vehicle position information obtained from DSRC. Vehicular channel model is developed considering realistic 3D environment and traffic model, which is validated by measurement results. Cooperative vehicular positioning based on IEEE 802.11p DSRC is proposed, and enhanced position information is used to reduce beam searching overhead.

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1. Introduction

Intelligent transportation systems (ITS) depend on vehicular communication, in which vehicles and installed road-side units (RSUs) exchange position data, safety warnings and traffic information. Vehicular communication is currently developed based on IEEE 802.11p DSRC at 5.9 GHz with data rate up to 27 Mbps [1]. Future connected vehicles however will require Gbps data rates [2], which can only be achieved practically at mmWave bands. Directional high gain antenna arrays are required, but the communication system has to suffer from the overhead associated with extended beam searching space. Moreover, optimum beam pairs must be selected with low latency because of high mobility of the communicating vehicles. Beam alignment method considered in IEEE 802.11ad depends on two steps [3]: beam searching in the transmitter using quasi Omni-directional pattern and beam refinement protocol for optimizing beam pairs. This technique however is ineffective for high mobility vehicular communication environment, and efficient beam searching techniques are needed.

2. Literature review

Vehicular channel models are developed in [4-6] based on IEEE 802.11p DSRC at 5.9 GHz using simulation and experimental measurements. These studies define the vehicular channel, based on vehicle density, considering the outline of objects (buildings and foliage) adjacent to the road. The impact of obstructing vehicles on the road is not considered. A more realistic and efficient channel model is developed in [7] based on extensive measurements performed in urban and highway environments at Porto in Portugal.

Global positioning system (GPS) provides coverage to most of the earth surface and exhibits low-cost devices, making it beneficial to be incorporated into vehicles. However, GPS based positioning suffers from the lack of ubiquitous availability and susceptible to higher errors (5m to 15m) which is not acceptable for vehicular applications [8]. Recently, vehicular positioning based on installed RSUs has emerged as a more authentic alternative solution. However, conventional GPS-free positioning techniques [9, 10] require the vehicles to interact with at least four RSUs to obtain precise positioning. These techniques increase the system cost due to the requirement of more RSUs and delay the positioning decisions. Furthermore, vehicular positioning technique that only depends on RSUs suffer from the lack of line-of-sight (LOS) communications between vehicles and RSUs in urban scenarios.

mmWave communications depends on the beam steering to select candidate beams from a large number of directional narrow beams. The alignment of transmitter and receiver beam pairs introduces a trade-off between beam searching overhead and throughput [11]. Although beam-sweeping techniques are used to overcome this trade-off, it cannot achieve perfect beam alignment, which leads to degradation of the channel gain [12-14]. Beam steering technique for emerging 60 GHz mmWave communications is provided in [15, 16]. However, all of these prior techniques require time-consuming operations that depend on accurate channel estimations. Steering techniques are also extremely susceptible to Doppler spread of high mobility vehicular environments.

In this paper, cooperative vehicular positioning technique is introduced to improve the positioning accuracy and enhance beam steering capability. Analysis is based on a ray-tracing model that is validated with published measurement results. Based on the enhanced position information, hybrid mmWave/DSRC vehicular communication system is proposed and investigated to reduce the beam searching overhead for establishing mmWave communication link. Instead of exhaustive search to find optimum beam pairs between communicating vehicles, the proposed technique selects an extremely smaller number of beam pairs based on the position information obtained from DSRC to facilitate faster beam alignment.

The remaining parts of the paper are organized as follows. Section 3 describes the proposed hybrid mmWave/DSRC system for mmWave vehicular communication. The developed channel model and its validation with measured results are provided in Section 4. Cooperative vehicular positioning technique is described in Section 5. Statistical analysis of the proposed hybrid system to reduce beam searching overhead are described in Section 6. Final conclusion is given in Section 7.

3. Hybrid Vehicular Communication using mmWave/DSRC

We introduce an effective approach to minimize the beam searching overhead based on the vehicle position information obtained from DSRC. Fig. 1 shows the considered scenario.

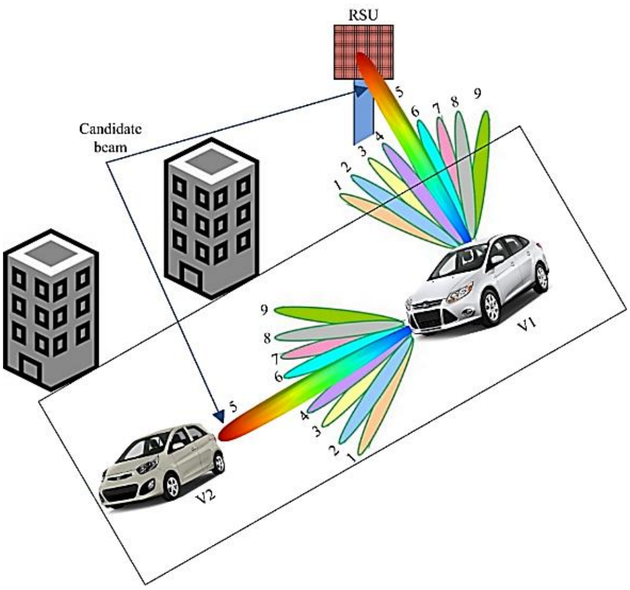


Fig. 1. Millimeter wave vehicular communication scenario with position-aided beam searching and alignment

Let us assume vehicle V1 wants to establish a mmWave communication link with neighbor vehicle V2 or RSU. Vehicle V1 needs to test many beams because of extremely narrow beamwidth of mmWave communications. If vehicle V1 knows approximate position information of mmWave transceiver in V2 or RSU by using DSRC messages, it will be quite easier to identify the candidate beams without significant performance loss. For example, if higher positioning accuracy can be achieved by DSRC, the system can only search for beams (4, 5 and 6) as candidate beams and selects beam 5 to establish mmWave communication link. In case of V2I communications, it is more advantageous of using DSRC based position information. RSU located beside the roads exhibits wider angular coverage and periodically broadcast its position information for the vehicle entering into its coverage to identify the candidate beams to establish mmWave V2I communication link.

4. Traffic and wave propagation model

Realistic and efficient modeling of the channel is the basis for successful evaluation of vehicular communication system. Realistic modeling of the channel requires the consideration of complex environment related to communicating vehicles, such as static objects (buildings, road terrain and foliage) and moving objects e.g. vehicles. The time-variant nature of the vehicular channel is not only affected by the motion of the communicating vehicles, but also by surrounding vehicles and objects adjacent to the road. The motion of the vehicles and the frequency band make vehicular communication systems distinguished from the conventional cellular systems. Thus, to develop a realistic channel, proper consideration of the scenario is necessary.

4.1. Vehicular channel model

Fig. 2 shows the ray-tracing model for vehicular urban channel which is developed using Wireless Insite [17]. The model randomly considers objects such as road terrain, road divider, buildings of different size and shape, and tree foliage adjacent to the road. It also includes vehicles with communication unit and vehicles without communication unit as obstacles. These objects are designed individually and characterized with relevant material properties as shown in Table 1. Finally, these objects are integrated into a complete urban vehicular channel model. This combination yields a virtual connected vehicle environment through arbitrary scenarios and allows for the investigation of positioning and communication performances.

The calculations are made by shooting rays from the transmitters and propagating them through the defined geometry for channel model. These rays interact with geometrical features and make their way to receiver locations. The components of radio propagation are combined into the channel impulse response (CIR) between the transmitter (r_{Tx}) and the receiver positions (r_{Rx}). The CIR contains the contributions from all multipath components (MPCs) individually, given as

$$h(r_{Tx}, r_{Rx}, \tau, \phi, \psi) = \sum_{l=1}^{L} h_l(r_{Tx}, r_{Rx}, \tau, \phi, \psi) \quad (1)$$

$$h_l(r_{Tx}, r_{Rx}, \tau, \phi, \psi) = a_l \delta(\tau - \tau_l)\delta(\phi - \phi_l)\delta(\psi - \psi_l) \quad (2)$$

where, the variables, a_l, τ_l, φ_l and ψ_l are the complex amplitude, time-delay, direction-of-departure (DoD) and direction-of-arrival (DoA) respectively, related to the lth MPC.

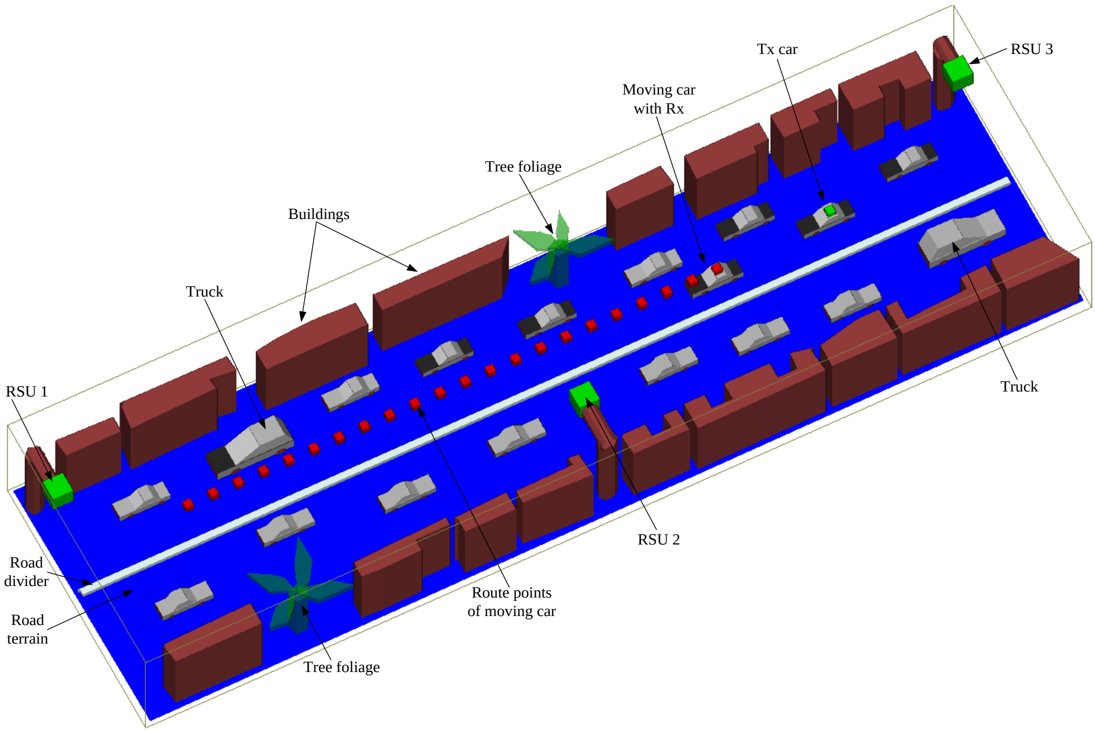


Fig. 2. Developed vehicular channel model for urban road using Wireless Insite ray-tracing simulator

Furthermore, L is the total number of MPCs. For vehicular *time-variant* channels, all multipath parameter components in eq. (2) become functions of time t. Thus, for vehicular channel, we can modify eq. (1) as *time-variant* CIR as

$$h(r_{Tx,}r_{Rx,}t,\tau,\phi,\psi) = \sum_{l=1}^{L} h_l(r_{Tx,}r_{Rx,}t,\tau,\phi,\psi) \quad (3)$$

Table 1. Considered object characterization

Object	Material
Body of vehicle	Metal
Vehicle mirrors	Glass
Wheels	Rubber
Front and rear bumpers	Plastic
Road terrain	Asphalt
Buildings	Brick
Tree foliage	Wood and leaf

4.2. Validation with experimental measurements

The important channel characteristics such as path-loss and received power were measured in real-world scenarios. The experiments were performed in urban environment at Porto, Portugal. The impact of moving objects (vehicles) and static objects (buildings and foliage) has been considered based on the received power and path-loss for varying distance. The experiment includes two vehicles equipped with DSRC devices. Each vehicle was equipped with a NEC LinkBird-MX, a custom-built development platform for vehicular communications [18]. These DSRC devices operate at the 5.85-5.925 GHz band and implement the IEEE 802.11p wireless standard. Built in GPS receiver of each Linkbird-MX provides the locations of the vehicles, and the received signal power was recorded throughout the experiments.

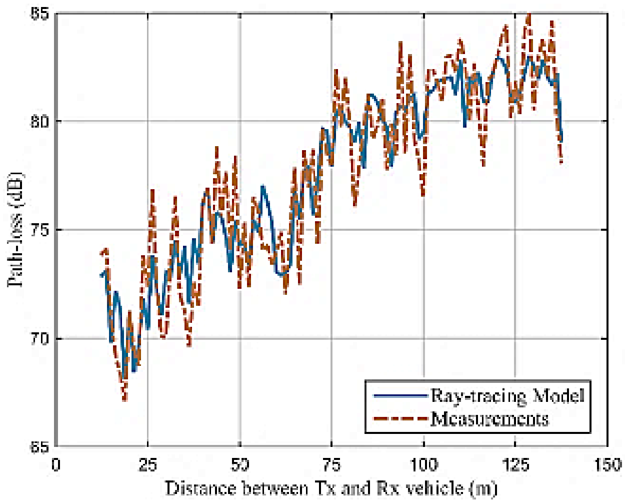
To generate reliable channel models, path-loss and received power for varying distance between communicating vehicles are investigated. Fig. 3 shows the path-loss and received power obtained from the developed ray-tracing model and measurements. It is observed that the path-loss and received power based on our developed ray-tracing model are in good agreement with the measurement results provided in [7]. The details of model validation are provided in our previous work [19].

5. Cooperative vehicular positioning

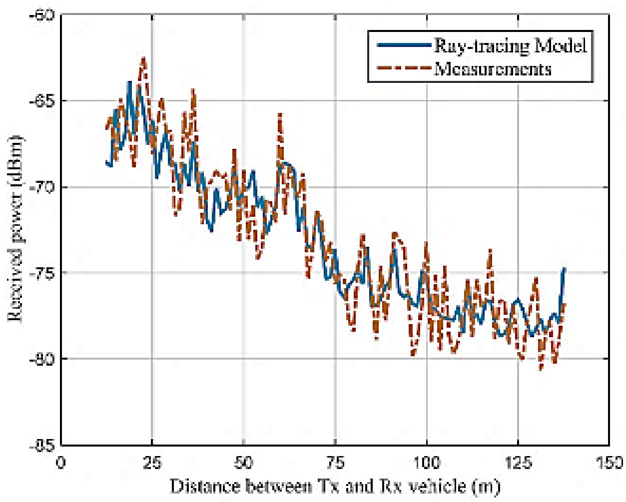
We consider a GPS-free cooperative vehicle positioning technique based on time-of-arrival (TOA) and direction-of-arrival (DOA) estimations of signal from three RSUs and cooperative neighbor vehicles on the road.

In our approach, each vehicle not only performs its positioning independently using V2I communication, but also cooperates with nearby vehicles (exchange position information) in order to achieve higher positioning accuracy. Each vehicle fuses positioning information from its neighbor vehicles and RSUs to estimate its own position. Fig. 4 shows an example scenario of the proposed cooperative positioning approach.

Let us consider that the candidate vehicle V1 wants to estimate its position and V4 is a neighbor cooperative vehicle. Three RSUs periodically broadcast their position information and the time-stamp at which the signal is initiated. The candidate vehicle estimates its position using the time-stamp and TOA or DOA information of the LOS reference signal from three RSUs. However, vehicle V2 is not equipped with communication unit and it obstructs the LOS communication between V1 and RSU3. This causes higher positioning error for the candidate vehicle V1. We can overcome this problem by communicating and obtaining reference signal with position information from cooperative neighbor vehicle V4. Finally, the candidate vehicle estimates the own position by fusing the TOA or DOA data from road-side units and cooperative vehicle.



(a)



(b)

Fig. 3. Comparison between developed Ray-tracing model and measurement results. (a) Path-loss (b) Received power

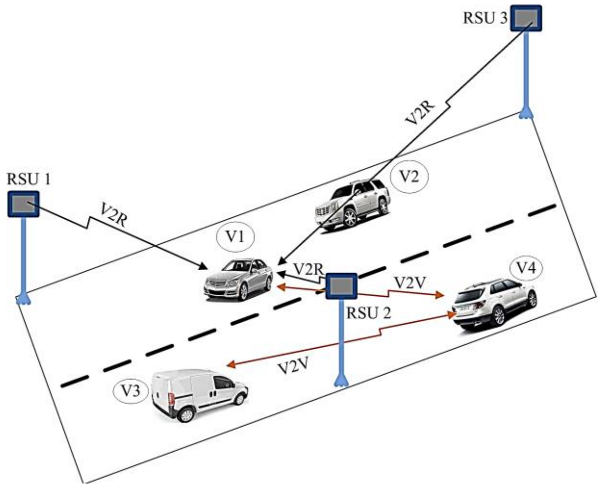


Fig. 4. Cooperative vehicular positioning scenario

We can evaluate the positioning error by estimating *m* number of reference signal from RSU and *n* number of reference signal from cooperative vehicles using TOA or DOA data which is given as,

$$\hat{x} = \arg\min_{x} \sum_{k=1}^{m+n} \frac{[r_k - d_k(x)]^2}{{\sigma_{r_k}}^2} \tag{4}$$

where, d_k is the actual distance and r_k is the estimated distance between candidate vehicle and RSU or cooperative vehicle. The term σ^2 denotes the variance of the estimated distance. Eq. (4) is equivalent to the minimization problem using maximum likelihood (ML) estimator. If we consider that the error distribution is known, the ML approach maximizes the PDFs of TOA or DOA estimations to obtain the vehicle position.

The positioning error is determined using TOA or DOA estimated data from the ray-tracing simulation. The distances between vehicle and RSUs or cooperative vehicle is obtained from TOA or DOA data, which are then processed using tri-lateration or multi-lateration algorithm [20] to estimate the positions of candidate vehicle. Finally, positioning error is computed as absolute difference between the estimated positions and actual positions of the vehicle.

Fig. 5 shows the position error considering RSU for reference signal as well as considering both RSU and cooperative vehicle for reference signal using TOA and DOA estimations respectively. The results of V2I positioning approach considering four RSUs provided in [21] has also been included for fair comparison with our proposed method. It is observed that the proposed cooperative positioning method exhibits consistently less positioning errors as compared to other method provided in [21]. Table 2 summarizes the average positioning error estimated by different methods.

Table 2. Positioning error using different methods

Method	Avg. position error (m)	
	TOA	DOA
V2I using 4 RSUs	3.41	3.92
Cooperative method using 3 RSUs	0.94	1.12

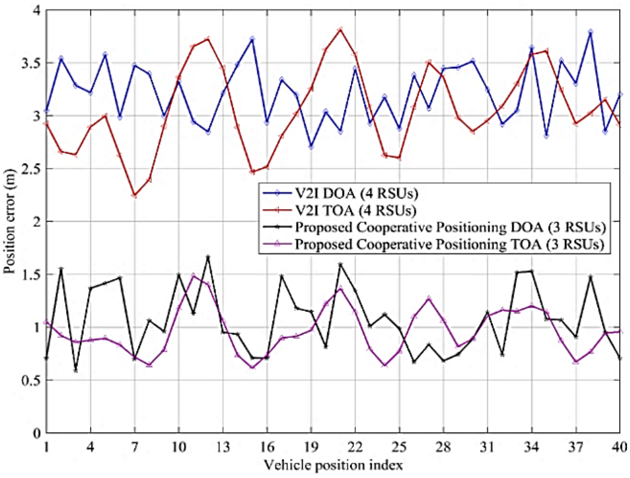


Fig. 5. Positioning error based on different techniques

6. Beam searching overhead reduction using proposed method

To evaluate the proposed position aided beam searching technique as mentioned in Section 3, we consider V2V communications where transmitting and receiving vehicles are equipped with *M* × *M* elements of uniform rectangular array (URA). In general, the total beam searching space corresponds to azimuth and elevation plane can be considered as -180° ≤ ϕ ≤ 180° and -90° ≤ θ ≤ 90° respectively. The beamwidth of current mmWave commercial antenna ranges from 1° to 15° [22]. The relation between channel coherence time and beamwidth can be given as [23, 24]

$$T_c(\theta) = \sqrt{\frac{\frac{1}{\beta^4}-1}{(2\pi f_d)^2\theta^4+\frac{1}{2\theta^2\beta^4}\left(\frac{\lambda f_d \sin\mu_r}{D}\right)^2}} \quad (5)$$

where, T_c denotes the channel coherence time, β, θ and λ are the channel temporal correlation coefficient, beamwidth and wavelength respectively. The terms D, μ_r and f_d denote the distance between communicating vehicles, main-lobe pointing angle and Doppler frequency respectively. Fig. 6 shows the channel coherence time vs. beamwidth considering vehicle speed, v = 30 m/s and operating frequency, f_c = 60 GHz and μ_r = 1°. Typically, the channel temporal correlation coefficient (β) ranges from 0.3 to 0.9 [23], we consider, β = 0.5. It is observed that, if beamwidth is extremely narrow then beam pointing error occurs which limits the channel coherence time. On the other hand, wider beamwidth is susceptible to Doppler spread. Thus, we consider the beamwidth of 3° and 5° in our analysis.

For mmWave vehicular communications in real environments, a vehicle should be equipped with multiple antenna arrays on front bumper and rear bumper as well as on roof to prevent the effects of blockages. Let us consider that V1 and V2 are transmitting and receiving vehicles equipped with mmWave antenna arrays on front and rear bumpers respectively as shown in Fig. 1. Considering the region without the effect of blockage, let us minimize the beam searching space for azimuth plane as -90° ≤ ϕ ≤ 90° and elevation plane as 0° ≤ θ ≤ 90°. For exhaustive search, all possible beams fall into this searching space needs to be tested. The relation between beam searching space and total number of candidate beams for exhaustive search is given as

$$N_E = \frac{(\phi_{max}-\phi_{min})(\theta_{max}-\theta_{min})}{{\theta_B}^2} \quad (6)$$

where, the values of ϕ and θ are the minimum and maximum values of azimuth and elevation plane index respectively. The term θ_B denotes the beamwidth. For position-aided beam alignment, the relation between required number of training beams and positioning error can be formulated as

$$N = \frac{2}{\theta_B}\tan^{-1}\left(\frac{P_E}{2L}\right) \quad (7)$$

where, P_E, L and θ_B denote the positioning error, distance between communicating vehicles and beamwidth respectively. The total number of candidate beam considering both azimuth and elevation plane is given as

$$N_T = N_{az} \times N_{el} \quad (8)$$

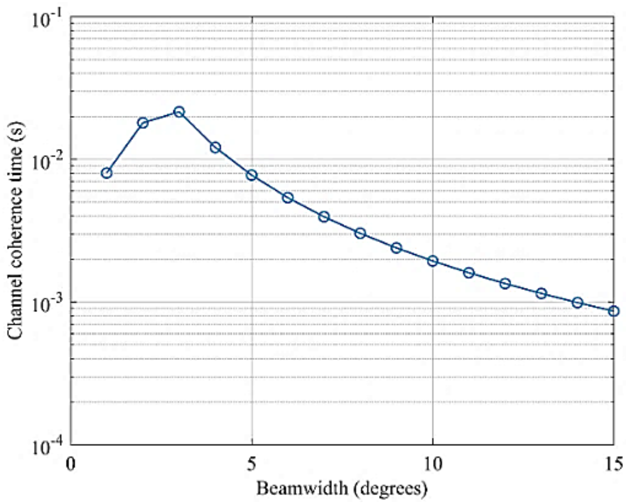


Fig. 6. Channel coherence time vs beamwidth

Fig. 7 shows the number of required candidate beam based on positioning errors for beamwidth of 3° and 5° considering L = 10 m. It is observed that higher positioning error increases the required number of candidate beams. Even with poor accuracy of position information, beam searching overhead is reduced significantly. However, lower positioning error i.e. reduced beam searching overhead is advantageous for high mobility environments of vehicular communication.

Now, let us consider the statistical analysis of the proposed idea based on the probability distributions. The cumulative distribution function (CDF) can be given as

$$F_X(x) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{\frac{-(y-\mu)^2}{2\sigma^2}} dy = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \quad (9)$$

where, erf(.) denotes the error function. The variables x is provided as the number of candidate beams related to the positioning errors. The term μ and σ denotes the mean and standard deviation of x. Fig. 8 shows the stairs plot of CDF for number of training beam required based on position information obtained from DSRC using proposed cooperative positioning method and V2I positioning. It is observed that significant reduction of beam searching overhead is obtained using the proposed cooperative positioning method as compared to V2I positioning. Table 3 summarizes the average number of training beams required for different methods.

Table 3. Beam searching overhead of different methods

Beamwidth	**Exhaustive search**	**V2I positioning (4 RSUs)**	**Cooperative positioning**
3^0	1800	356	32
5^0	648	132	12

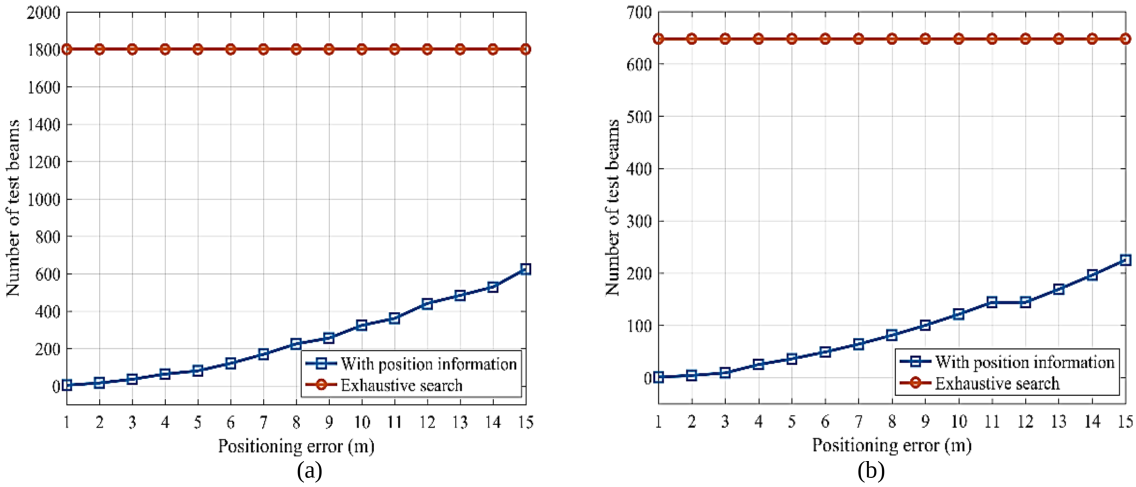
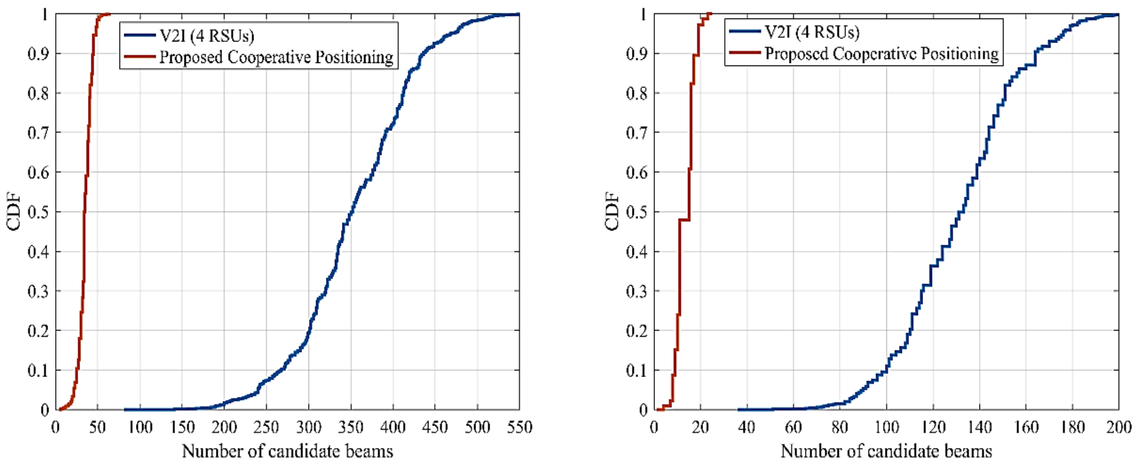


Fig. 7. Positioning error vs number of candidate beams. (a) beamwidth = 3° and (b) beamwidth = 5°



(a) (b)

Fig. 8. CDF of required number of candidate beams based on V2I positioning and proposed cooperative positioning (a) beamwidth = 3^0 and (b) beamwidth = 5^0

7. Conclusion

Beam searching overhead and the presence of blockage effects make mmWave systems challenging for vehicular applications. The concept of position-aided beam searching and alignment has been proposed to overcome these challenges. Cooperative approach is proposed to enhance vehicular positioning accuracy. In order to investigate this approach, realistic vehicular urban channel model is developed using Wireless Insite ray-tracing simulator. The model is validated with measurement results. Positioning accuracy is shown to improve significantly using the proposed cooperative approach, and positioning data is used to reduce the overhead of beam alignment of mmWave vehicular communication. In addition, the proposed hybrid mmWave/DSRC system provides an extended frequency diversity scheme that can enhance the quality of vehicular communication to support the next generation ITS.

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References

[1] J. B. Kenney, Proceedings of the IEEE **99**, 1162 (2011).
[2] N. Lu, N. Cheng, N. Zhang, X. Shen, J. W. Mark, IEEE Internet of Things Journal **1**, 289 (2014).
[3] Q. D. Ho, D. Tweed, T. Le-Ngoc, Long Term Evolution in Unlicensed Bands, ed: Springer, pp. 31-41, 2017.
[4] N. Avazov, M. Pätzold, IEEE Trans. on Vehicular Technology **65**, 1070 (2016).
[5] P. Liu, B. Ai, D. W. Matolak, R. Sun, Y. Li, IEEE Trans. on Vehicular Technology **65**, 5862 (2016).
[6] W. Viriyasitavat, M. Boban, H. M. Tsai, A. Vasilakos, IEEE Vehicular Tech. Magazine **10**, 55 (2015).
[7] M. Boban, J. Barros, O. Tonguz, IEEE Transactions on Vehicular Technology **63**, 4146 (2014).
[8] K. Liu, H. B. Lim, E. Frazzoli, H. Ji, V. Lee, IEEE Trans. on Vehicular Technology **63**, 2544 (2014).
[9] A. Ghosh, V. V. Paranthaman, G. Mapp, O. Gemikonakli, J. Loo, IEEE Communications Magazine **53**, 80 (2015).
[10] R. Parker, S. Valaee, IEEE Trans. on Vehicular Technology **56**, 3371 (2007).
[11] H. Shokri, L. Gkatzikis, C. Fischione, IEEE Int. Conf. on Communications (ICC) 1292 (2015).
[12] P. Wang, Y. Li, L. Song, B. Vucetic, IEEE Communications Magazine **53**, 168 (2015).
[13] S. Kutty, D. Sen, IEEE Communications Surveys & Tutorials **18**, 949 (2016).
[14] W. Kim, J. Bae, S. J. Lee, International Conference on Information and Communication Technology Convergence (ICTC) 1252 (2015).
[15] V. Raghavan, J. Cezanne, S. Subramanian, A. Sampath, O. Koymen, IEEE Journal of Selected Topics in Signal Processing **10**, 543 (2016).
[16] B. W. Ku, D. G. Han, Y. S. Cho, ETRI Journal **38**, 81 (2016).
[17] Remcom. Wireless Insite. Available: http://www.remcom.com/wireless-insite.
[18] A. Festag, R. Baldessari, W. Zhang, L. Le, A. Sarma, M. Fukukawa, NEC Technical Journal **3**, 21 (2008).
[19] A. Hossain, I. Elshafiey, A. Al-Sanie, Journal of Internet Technology (JIT) **19**(1), 289 (2018).
[20] A. Norrdine, Proceedings of the 15th International Conference on Indoor Positioning and Indoor Navigation, Sydney, Australia 13 (2012).
[21] M. Rohani, D. Gingras, V. Vigneron, D. Gruyer, IEEE Intelligent Transportation Systems Magazine **7**, 85 (2015).
[22] Millitech. Available: http://www.millitech.com/index.htm.
[23] G. D. Durgin, T. S. Rappaport, IEEE Transactions on Antennas and Propagation **48**, 682 (2000).
[24] J. Palacios, D. De Donno, J. Widmer, IEEE Int. Conf. on Computer Communications 1 (2017).

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