Two-Way TOA with Limited Dead Reckoning for GPS-Free Vehicle Localization Using Single RSU

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***Abstract*—Road safety applications in Vehicular Ad Hoc Networks (VANETs) necessitate highly accurate vehicle localization techniques. Unfortunately, Global Positioning System (GPS)-based localization techniques do not only suffer from the lack of ubiquitous GPS coverage but also are susceptible to high localization errors (10 m to 30 m). Consequently, such techniques are not suitable for road safety applications. Recently, GPS-free localization based on vehicle communication with installed roadside units (RSUs) has emerged as a more accurate alternative. However, existing GPS-free techniques require the vehicle to communicate with two RSUs in order to achieve high localization accuracy. Such techniques either increase the system cost due to the high number of needed RSUs or delay the localization decisions. In this paper, we propose a GPS-free localization framework that uses two-way time of arrival with partial use of dead reckoning to locate the vehicles based on communication with a *single* RSU. Our results show that the accuracy of the proposed framework is 13.1% to 20.1% better than the techniques that use 1 RSUs while completely depending on dead reckoning, and only 3% to 8.9% worse than those techniques that use 2 RSUs on both sides on the road.**

***Index Terms*—localization; roadside unit; dead reckoning;**

I. Introduction

Vehicular Ad Hoc Networks (VANETs) is a kind of Mobile Ad Hoc Networks (MANETs) with some distinguishing differences in power constraints, mobility patterns and speeds. On one hand, the power constraint is not a major challenge in VANETs as is the case in MANETs. On the other hand, VANETs are characterized with vehicles moving in an organized pattern with high traveling speeds unlike MANETs. VANETs are considered as an essential development for future road safety applications. A dedicated bandwidth in the 5.9 GHz band (Dedicated Short-Range Communications: DSRC 5.9 GHz) for intelligent transportation systems has been approved in US, Japan and Europe [1]. DSRC is exclusively used for the two main VANET communication schemes: Vehicle-to-Vehicle (V2V) and Vehicle-to-Road (V2R) communications.

This paper presents a low-cost – yet highly accurate – GPS-free integrated localization framework for vehicular safety applications. Unlike related work [2], [3] which typically use 2 roadside units (RSUs) for localization, our goal is to have each vehicle determining its location with respect to a single RSU in order to decrease the required number of RSUs, and consequently, reduce the cost of the localization system installation. The constraint of using a single RSU in vehicle localization poses a significant challenge in locating the vehicles with high accuracy.

The proposed localization framework consists of two stages: determining the driving direction, followed by computing the vehicle location in the Y-dimension. Existing driving direction determination techniques use the received beacons either from two RSUs deployed on both sides of the road [2], or from two consecutive RSUs deployed on the same roadside [3]. In contrast, our approach is to label the RSUs at the road entrance points and use them as references and *instantaneously* determining the driving direction once the first beacon of a new RSU is received. To compute the Y-location of the vehicles, we propose a range estimation technique based on two-way time-of-arrival (TOA) ranging [4]. In our Y-localization technique, each vehicle estimates its distance to the RSU every time the periodic beacon messages are received from the RSUs which contain the ID of the RSU and the Y-location of the RSU. After a vehicle receives a beacon, the vehicle initiates a two-way packet handshake to estimate the distance between the RSU and the vehicle using the proposed two-way TOA ranging technique, and consequently, calculates the Y-location of the vehicle. Such a calculation of the Y-location of vehicles based on range estimation is only valid when the distance between the RSU and the vehicle is large compared to the width of the road. When the vehicle approaches the RSU, the accuracy of the proposed technique deteriorates (as the underlying assumptions are no longer valid). Hence, when the vehicle is in the vicinity of an RSU, we use dead reckoning. Dead reckoning [5] is widely used for localization in the absence of GPS coverage in GPS-based localization techniques. Our results show that the accuracy of the proposed single-RSU localization framework significantly approaches the accuracy of the localization using 2 RSUs on two sides of the road [2], and significantly outperforms localization using 1 RSU with the use of dead reckoning all the way [3].

The rest of the paper is organized as follows. In Section II, we review the related literature. We present the system model in Section III. In Section IV, we present our two-way TOA with limited dead reckoning localization framework. Then we evaluate the performance of the proposed framework in Section V and conclude the paper in Section VI.

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II. Related Work

Many localization techniques have been proposed for VANETs which can be classified into GPS-based and GPS-free techniques.

A. GPS-based Localization

Such localization approach uses the Global Positioning System (GPS) to determine the position of each vehicle. The basic GPS localization technique [6] uses GPS receivers to continuously receive the data being sent by the GPS satellites. The received data is used to estimate the vehicle's distance to at least four known satellites using a technique called Time of Arrival (ToA), and then computes the actual position via trilateration.

GPS-based techniques suffer many challenges. One main challenge is the low accuracy of GPS systems (10 m - 30 m) that is not good for use in vehicle collision warning systems [7]. Therefore, several modifications of the basic GPS technique have been proposed to increase the accuracy of GPS-based localization. An example of such methods is the Radio-Frequency-GPS (RF-GPS) [8] that employs a Differential GPS (DGPS) concept to improve the GPS accuracy. DGPS [9] is a method to improve the positioning of GPS using one or more reference stations at known locations, each equipped with at least one GPS receiver. The reference station(s) calculates the error and broadcasts it.

Another problem in GPS-based techniques is the existence of tall buildings which prevent the GPS receivers on vehicles to receive strong satellite signals. Assisted-GPS (A-GPS) has been proposed to enhance the performance of standard GPS in devices connected to the cellular network by using an A-GPS server [10]. Although, there exists some enhanced versions of GPS such as the A-GPS and RF-GPS, they require extra infrastructures, and hence, added cost.

B. GPS-free Localization

The need for GPS-free localization techniques comes from the facts that the accuracy of GPS positioning algorithms (with localization error between 10 m and 30 m) are not accurate enough for collision warning system applications. Thus motivated, new techniques using Roadside Units (RSUs) [2] and [3] have been proposed to eliminate the need to use GPS techniques. RSUs are installed on both side ways of the road and all the vehicles are equipped with Onboard Unit (OBU) devices that are able to communicate with the RSUs. Hence, each vehicle has the ability to estimate its coordinates relative to the RSUs. The author of [2] assumed that there are two roadside units (RSUs) installed on both sides of the road and each vehicle estimates its location related to those two RSUs using a technique called *faulty-free*. The author in [2] also illustrates another scenario, called *faulty*, in which one of the RSUs fails such that only one RSU remains functional.

Alternatively, [3] assumed that vehicles use only one RSU out of those deployed only on one side of the road to determine their initial position, and use dead reckoning to update the positions all the way. Dead reckoning [2] is a technique that is originally used for localization in the absence of GPS coverage in GPS-based techniques which is an effective alternative to inter-vehicle communications techniques [11] and [12]. The proposed approach in [3] does not use any distance-measuring techniques such as time of arrival (TOA) [13], time difference of arrival (TDOA) [14], and received signal strength (RSS) [12]. In contrast to the aforementioned related work, we target using a single RSUs with two TOA ranging and partial dead reckoning only near the RSU.

III. System Model

In our system model, vehicle localization is not based on GPS receivers. Instead, we assume that all vehicles are equipped with Onboard Unit (OBU) devices that are used to determine the vehicle's distance to the RSUs using V2R communication. We use the dedicated short-range communications (DSRC 5.9 GHz) for intelligent transportation systems over which the IEEE 802.11p operates. We exploit RSUs deployed only on one side of the road to locate the vehicles. The RSUs broadcast periodic beacons containing the ID of the road and the location of the RSU. Each vehicle is equipped with a digital odometer and a compass to be used for dead reckoning, which are common and available devices in modern vehicles.

We assume that vehicles move on dual carriageway highway separated by a central reservation. The road is straight all the way and there are multiple entry and multiple exit points along the road. Each entry point is equipped with a RSU. We assume that the entry/exit points are interleaved (i.e., at a given Y-location we can have only one entry to the road with an exit on the other side) as the typical case depicted in Fig. 1. The road has shoulders that a vehicle can use to reverse the deriving direction. However, the road does not have any intersections. We assume that the distance between the RSU and the vehicle R is large and the width of the road W is too small compared to its length L, and hence, the curvature is assumed to be nearly linear.

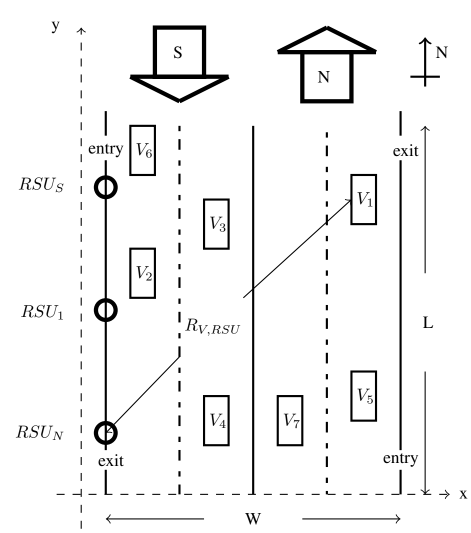

Figure 1. Illustration of the system model.

IV. THE PROPOSED SINGLE RSU LOCALIZATION FRAMEWORK

In order to achieve our targets stated above, we divide our proposed technique into two stages called driving direction determination and the localization of the vehicle.

A. Determining the Vehicle Driving Direction

This section discusses our proposed technique to find the driving direction which can be either North (N) or South (S). The proposed algorithm is invoked every time the vehicle enters a new road. In [2] a technique for determining the driving direction using two roadside units installed on both sides of the road has been proposed. A vehicle determines its driving direction by comparing the angle between its current movement vector with the North and South roadside units. Meanwhile, the authors in [3] assume that there are two RSUs installed on both sides of the road and each vehicle should receive and evaluate the position information of the two RSUs to get the driving direction. Given our system model, the major challenge here is how to get the driving direction with the help of only one RSU installed on one road direction and minimize the start up time.

We propose the following technique to determine the driving direction. We first assume that there are two types of roadside units: one type which is at the entry points of the road. The second type of RSUs are in the middle of the road between the entry points. We assume that an entry RSU broadcasts the driving direction either N or S while a middle RSU has a NULL direction field in its beacon. When a vehicle first enters the road, it will determines its driving direction based on the direction of the first beacon received from an entry RSU. As the vehicle moves along the road, it receives a beacon from a middle RSU which contains the ID and the location of the RSU. The driving direction is updated to be either the same or the opposite direction based on the ID of the new RSU (included in the incoming beacon) and the ID of the previous RSU (stored on the OBU which initially is set to Null). Therefore, even if the vehicle make a U-turn using the shoulder, comparing the new received RSU ID with the ID stored on the OBU will allow the vehicle to know that the driving direction have been switched. Algorithm 1 outlines the proposed algorithm assuming that the RSU ID increase in the North direction.

B. Vehicle Localization

The goal of this stage is to calculate the Y-location of the vehicle. In our proposed RSU-based localization scheme, each vehicle estimates its distance to the RSU on the basis of periodic beacon messages which contain the ID of the RSU and its Y-coordinate denoted by L_{RSU}. When a vehicle receives a beacon, it computes the distance between the vehicle and the RSU, $R_{V,RSU}$, using the appropriate ranging technique as discussed next.

As shown in Fig. 1, and given that the RSU is located at location L_{RSU}, a vehicle V is located at either:

$$y_V = L_{RSU} \pm R_{V,RSU} \quad (1)$$

Algorithm 1 Algorithm for Driving Direction Determination

```
Initialization: Driving Direction = NULL
if Receive(Beacon) and Beacon.Direction ≠ NULL then
    Driving Direction = Beacon.Direction
    Current RSU = Beacon.ID(RSU)
else
    if Beacon.ID(RSU) > Current RSU then
        Driving Direction = North
    else
        Driving Direction = South
    end if
    Current RSU = Beacon.ID(RSU)
end if
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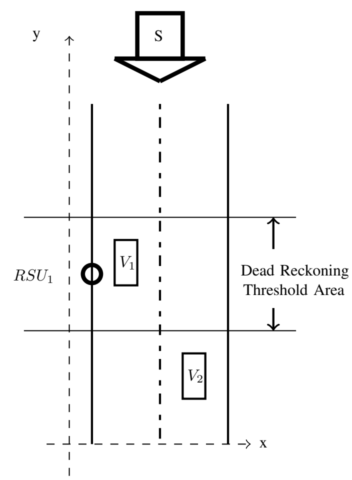

Figure 2. Dead reckoning is partially used when a vehicle moves nearby an RSU (within a certain threshold).

where $R_{V,RSU}$ is the distance between the RSU and vehicle V. The sign of $R_{V,RSU}$ is dependent on the driving direction obtained in the previous stage and whether $R_{V,RSU}$ tends to increase or decrease.

It is worth mentioning that equation (1) is only valid under the assumption that the distance between the RSU and the vehicle is large enough and the width of the road is too small compared to its length, and hence, the curvature is assumed to be a line as per our system model. When the vehicle moves closer to the RSU, this assumption is no longer valid. Therefore, we divide the localization of the vehicles into two techniques: one that computes the range $R_{V,RSU}$ using two-way time of arrival (TOA) when $R_{V,RSU}$ is greater than a certain threshold. The other localization technique uses dead reckoning, when $R_{V,RSU}$ is less than this threshold. The threshold – depicted in Fig. 2 – is computed using the a target localization error as will be shown in Section V.

1) Localization via V2R Communication for Distant Vehicles: When the vehicle is far from the RSU, we estimate the distance between the vehicle and the RSU, $R_{V,RSU}$, using V2R communication. Many techniques are used for range measurements such as received signal strength (RSS) [12], angle of arrival (AoA) [15], time difference of arrival

(TDOA) [14], and time of arrival (TOA) [13]. In our proposed technique, we use the two-way reciprocal time of arrival [4] technique which is preferred in the presence of multipath interference and does not need synchronization between the transmitter and the receiver. Recall that DSRC systems should be resilient to multipath fading [16]. The proposed two-way reciprocal time of arrival technique works as follows. When the vehicle receives a beacon from the RSU, the vehicle will send a ready to send for two-way TOA (RTS-T) packet at time t_1. The RSU will reply with a clear to send two-way TOA (CTS-T) packet which contains the delay (τ) experienced at the RSU (which might come from collisions and processing time). The CTS-T is received at the vehicle at time t_2 as shown in Fig. 3. The difference between the time the CTS-T is received and the time the RTS-T is sent is equal to the propagation time of the RTS-T plus the processing delay(s) within the RSU plus the propagation time of the CTS-T, i.e.,

$$t_2 - t_1 = \frac{R'_{V,RSU}}{C} + \tau + \frac{R_{V,RSU}}{C} \tag{2}$$

where $\frac{R'_{V,RSU}}{C}$ and $\frac{R_{V,RSU}}{C}$ are the propagations times of the RTS-T and CTS-T packets, respectively, and C is the free-space propagation speed. Equation (2) can be rewritten as

$$(t_2 - t_1 - \tau)\, C = R_{V,RSU} + R'_{V,RSU} \tag{3}$$

where $R_{V,RSU}$ is the distance between the RSU and the vehicle at instant t_2 and $R'_{V,RSU}$ is the distance between the RSU and the vehicle at instant t_1, as shown in Fig 4.

Recall that the x distance between the vehicle and the road side is negligible with respect to $R_{V,RSU}$ and $R'_{V,RSU}$ as per the assumed system model. Hence, the vehicle displacement can be approximated with an increment/decrement in the Y direction, depending on whether the vehicle is moving away/towards the RSU, i.e.,

$$R'_{V,RSU} \cong R_{V,RSU} \pm \Delta y \tag{4}$$

Substituting with $R'_{V,RSU}$ given in (4) into (3), we get

$$(t_2 - t_1 - \tau)\, C = 2R_{V,RSU} \pm \Delta y \tag{5}$$

Consequently, the Y-location of the vehicle y_V given in (1) is computed using $R_{V,RSU}$ given by

$$R_{V,RSU} = \begin{cases} \frac{(t_2 - t_1 - \tau)C + \Delta y}{2}, & \Delta R > 0 \\ \frac{(t_2 - t_1 - \tau)C - \Delta y}{2}, & \Delta R < 0 \end{cases} \tag{6}$$

where $\Delta R = R_{V,RSU}(i+1) - R_{V,RSU}(i)$, and $R_{V,RSU}(i)$ is the estimated range after receiving the i^{th} beacon from the RSU. The sign of ΔR determines whether the vehicle is approaching or moving away from the RSU. The only unknown in the above equations is Δy. A vehicle locally computes Δy as $\Delta y = (t_2 - t_1)v$ where v is the average vehicle speed. Hence, our proposed ranging technique computes the Y-location of the vehicle using a single RSU. As the vehicle moves towards the RSU, the previous two-way ranging technique will not be valid since the assumption leading to (4) does not hold any more. Therefore, we propose to use dead reckoning to update the Y values as explained next.

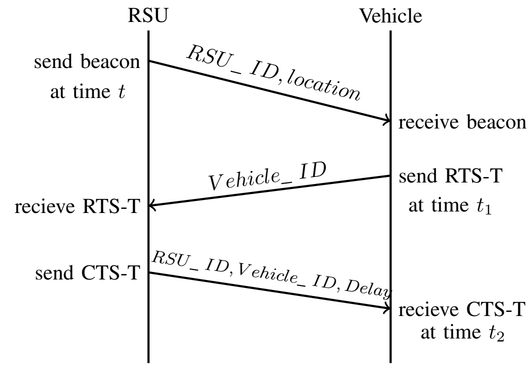

Figure 3. The timeline of the proposed two-way TOA packet handshake.

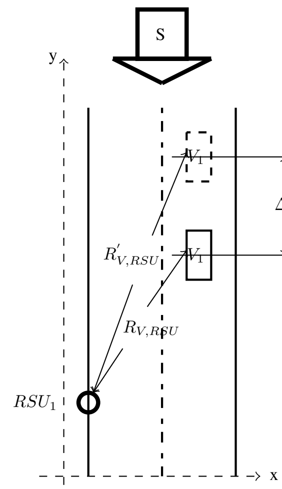

Figure 4. Range estimation using two-way TOA.

2) Localization via Dead Reckoning for Nearby Vehicles: Dead reckoning [5] is a ranging technique developed to GPS-based localization that is used during the absence of GPS coverage. By using dead reckoning, the current position of a vehicle is computed based on its last known location and using information such as the movement direction, speed, acceleration, and distance. In practical VANETs, dead reckoning can be used only for short periods of GPS unavailability, or be combined with map knowledge. However, dead reckoning cannot be use over long periods of time. The following equation describes the dead reckoning localization

$$y_{new} = y_{old} + vT \tag{7}$$

where v is the vehicle speed, T is the sampling time, y_{new} is the current Y-location of the vehicle and y_{old} is the previous Y-location of the vehicle. Dead reckoning is best used in highways where the vehicles move in straight lines [3].

When the vehicle approaches the RSU, the localization accuracy using V2R communication degrades. Hence, we switch from using V2R communication to dead reckoning localization in this short area around the RSU to achieve the highest possible accuracy. We define a threshold distance at which we switch between V2R communication and dead

Table I
SUMMARY OF SIMULATION PARAMETERS

Communication range of each RSU	500 m
Number of lanes per direction	3
Packet size	300 Byte
Bit rate	3 Mbps
Beacon broadcast rate	1 per sec
SIFS	32 μsec
AIFS	50 μsec
Slot time	9 μsec
(CW_{min}, CW_{max})	(15, 1023)

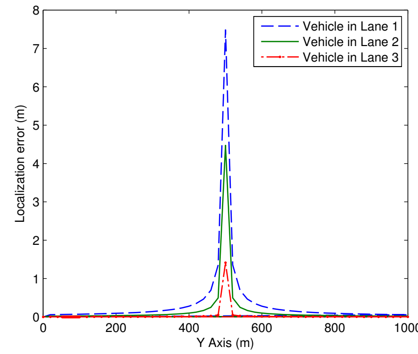

Figure 5. Determination of the dead reckoning threshold.

reckoning. As shown in Fig. 2, when a vehicle is located inside the threshold area around the RSU, it will use dead reckoning, where the curvature effect is too large to be ignored. After a vehicle exits the threshold area around the RSU, it will use the above proposed two-way TOA for localization.

V. SIMULATION RESULTS

Here we evaluate the performance of the proposed framework using Matlab simulations. We assume that vehicles move on dual carriageway highway, each direction has three lanes, separated by a central reservation. The road is straight line. The length of the road is 3 Km, and 3 RSUs are used, each has a 500 m communication range: South RSU (placed at y = 500 m), North RSU (placed at y = 1500 m), middle RSU (placed at y = 2500 m) as shown in Fig. 1. The PHY and MAC layer parameters are configured according to the IEEE 802.11p protocol [17]. Table I summarizes the values of the used 802.11p parameters and the other simulation parameters. A RSU broadcasts periodic beacons containing the ID of the road and the location of the RSU every one second. The mobility model of the vehicles is based on the modified random waypoint model in which a vehicle updates its lane every 5 seconds to one of the equiprobable lanes of the road [18]. According to the measurements presented in [4], two-way TOA ranging techniques are susceptible to errors due to channel fluctuations, hardware, and other inaccuracies. Hence, we follow [4] and include the two-way TOA measurement noise modeled as an additive normal distribution with zero mean and 3 m standard deviation.

A. Estimation of the Dead Reckoning Threshold

In order to estimate the threshold used to determine the used localization technique, we simulate our framework with the curvature error as the only type of error. We consider a single vehicle moving at 20 m/s. As shown in Fig. 5, the further the lane a vehicle is using from the RSU the higher the localization error. Consequently, the wider the road the bigger the distance around the RSU during which dead reckoning will be used. From Fig. 5, we deduce that the threshold should be set to 100 m for a vehicle moving at 20 m/s in a road with three lanes in each direction and 40 m for a vehicle moving in a road with two lanes per direction.

B. Single Vehicle Localization Error

First, we simulate the proposed framework on only one vehicle moving on the road with three lanes in each direction. We compare its accuracy against the *faulty-free* technique [2] (which uses two RSUs, one on a different side of the road), and *RSU-assisted* localization [3] (which uses one RSU and uses full dead reckoning all the way).

Fig. 6 shows that our proposed technique gets higher localization accuracy than RSU-assisted localization due to the limited use of dead reckoning in our proposed technique compared to the RSU-assisted localization technique. Recall that the proposed framework only uses dead reckoning in a limited distance around the RSU while RSU-assisted localization uses. According to [5], the position estimation error in dead reckoning scheme is around 0.3% of travel distance. Hence, the localization error *unboundedly* increases with travel distance in RSU-assisted localization technique. Fig. 6 also shows that even though we are using only one RSU for localization, we get slightly worse accuracy than the faulty-free localization technique which uses two RSUs. More specifically, the worst-case RMSE localization error of our proposed framework is only 15.2 % higher than the worst-case RMSE of the faulty-free localization technique. While the RMSE localization error of the RSU-assisted grows to be 81% higher than the faulty-free localization worst-case RMSE error. Note that while the average RMSE of the proposed framework is 3.3 m, it ranges between 10 m and 30 m in GPS-based techniques [7]. Hence, the accuracy of our proposed framework is 67% to 89% better such GPS techniques.

C. Impact of vehicle speed

Fig. 7 shows the impact of the vehicle speed on the RMSE for our proposed technique, faulty-free, and RSU-assisted localization techniques. While faulty-free localization achieves the least RMSE localization error of 3 meters, the RMES error of the proposed framework increases from 3.09 m to 3.27 m (i.e., 3% to 8.9% higher than the faulty-free RMSE) as the vehicle speed increases from 16 to 30 m/s. Meanwhile, the RSU-assisted localization RMSE increases from 3.495 m to 3.935 m (i.e., 16.33% to 31% higher than the faulty-free RMSE). In other words, the localization accuracy of our proposed scheme is slightly influenced by the change

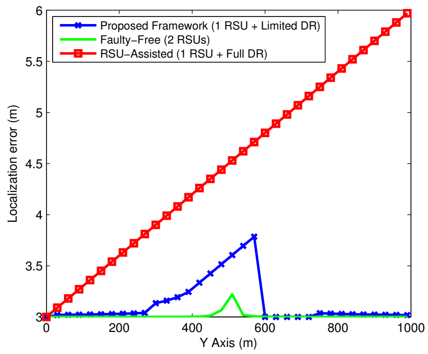

Figure 6. Accuracy of different localization techniques.

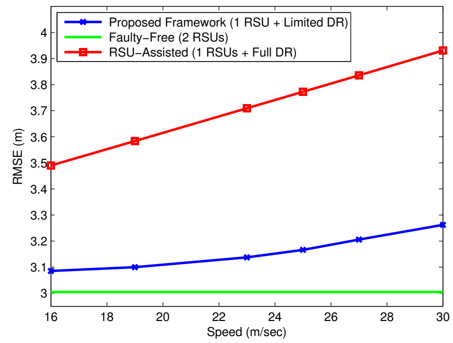

Figure 7. The impact of vehicle speed on the localization accuracy.

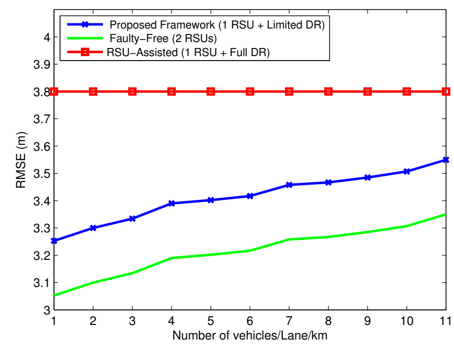

Figure 8. The impact of traffic density.

of the vehicle speed compared to RSU-assisted scheme, yet close enough to the accuracy of the faulty-free localization (that uses 2 RSUs) while our scheme only uses a single RSU.

D. Impact of Traffic Density

Fig. 8 shows the impact of vehicle traffic density on the RMSE error for the different localization techniques. The RMSE of the proposed framework increases from 3.2 m to 3.55 m as the number of vehicles increased from 1 to 11 vehicles/lane/km. Likewise, the faulty-free technique RMSE increases with the same rate as our technique. The RMSE error increase with the number of vehicles is due to the delay taken to get the location of each vehicle after receiving beacons from the RSU. This delay comes from the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism used in IEEE 802.11p [17]. On the other hand, the RMSE error of the RSU-assisted framework remains constant at 3.8 m (which is 8.5% higher than the worst case RMSE of 3.55 m in our scheme) regardless the number of vehicles since the RSU-assisted approach does not use any ranging technique.

VI. Conclusion and Future Work

In this paper, we have proposed a GPS-free vehicle localization framework using two-way TOA with limited dead reckoning. In our proposed approach, RSUs are deployed in one side of the road and only one RSU is needed for accurate vehicle localization. Compared to existing localization schemes which use multiple RSUs for vehicle localization, we decrease the required number of RSUs, and hence the cost, and in the same time get a high accuracy compared to existing single RSU techniques. The future work will focus on improving the localization accuracy using V2V. By using V2V communications, we can dispense the need to use dead reckoning, and hence, remove the error due to using dead reckoning. Furthermore, we shall use V2V communications to compute the separation between vehicles in the X-dimension in addition to the Y-localization presented in this paper.

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