A DSRC Doppler-Based Cooperative Positioning Enhancement for Vehicular Networks with GPS Availability

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Abstract—Position information, as a fundamental element for many of the modern vehicle-based logistic applications, is comprehensively provided by Global Navigation Satellite Systems (GNSS) such as Global Positioning System (GPS). A variety of applications including navigation and Intelligent Transpiration Systems (ITS) require position data with certain accuracy. However, the shortcomings of GNSS, such as limited accuracy and availability, have been a motivation for recently emerging Cooperative Positioning (CP) methods based on vehicle-vehicle and/or vehicle-infrastructure communication. The majority of earlier CP methods assume availability of distances between the participating nodes as a main parameter, using common techniques of radio ranging such as Received Signal Strength (RSS), Time of Arrival (TOA), and Time Difference of Arrival (TDOA). However, the feasibility of these radio ranging methods in the harsh environment of vehicular networks is questionable. Avoiding the radio ranging challenges, in this article, a new CP method is presented for improving the GPS estimates using inter-node range-rates based on the Doppler shift of the carrier of Dedicated Short Range Communication (DSRC) signals, the nominated medium for vehicular communication. Depending on the speed of the participating vehicles and traffic intensity, improvement of up to 48% over the GPS accuracy is achieved. Because the Doppler Effect is used, relative mobility of the nodes, which is generally a challenge for radio-ranging techniques, is a requirement for the proposed method, making it a more suitable solution for vehicular applications. Addressing the viability the proposed technique, Doppler-based range-rating is verified in practice using DSRC transceivers. A section of highway is surveyed and modeled for simulation purposes. Also, GPS estimates are provided through feeding GPS signals, generated by a GPS signal generator, to a real GPS receiver.

I. INTRODUCTION

POSITION data is an important and fundamental basis of many systems in civilian, military, and industry applications. Vehicular applications are among the most demanding systems for accurate position information. Nowadays GNSS such as GPS are used for localization. While vehicular navigation systems can generally rely on GPS-based positioning, other emerging systems in vehicular networks may not be able to use GPS data, due to its limited accuracy and availability. Safety-related applications, such as collision avoidance and lane-level guidance are some examples. Tackling the accuracy problem, some innovative approaches have been presented in recent years for positioning accuracy enhancement within vehicular networks, based on communicating data among the nodes of a network. This concept, called “Cooperative Positioning”.

A. Cooperative Positioning

Cooperative Positioning (CP) is not necessarily limited to vehicular applications and has been considered for many other sensor networks with or without mobility. An overview of CP techniques in wireless sensor networks is presented in [1-2], covering general concepts such as dynamic large scale networks, time varying topologies, centralized and distributed algorithms, and range-based techniques. CP has been considered for positioning enhancement of different aspects, accuracy, availability, and reliability. A variety of modern CP techniques based on vehicular communication and Radio Frequency Identification (RFID) are proposed in [3-11]. The majority of the CP methods, presented in these articles, are based on estimated distance between the nodes of the network. The distance between the nodes is assumed to be estimated by some radio ranging method but the constraints and limits of radio ranging techniques, imposed by the communication medium and mobile environment, and the impacts of these measurements on the CP algorithm are not well acknowledged. RSS, TOA, and TDOA are the most common techniques considered for radio ranging [12] in cooperative positioning algorithms. Achieving the ranging accuracy required or assumed for CP algorithms is almost impossible using existing
techniques. Avoiding the fundamental limitations of radio ranging for vehicular environments [13], this article presents a range-rate-based CP algorithm using Doppler shift between a target node and its neighbours. The main motive behind this novelty is that the Doppler shift is considerably less distorted by channel fading and multipath which are dominant sources of errors in a vehicular environment. Frequency Difference of Arrival (FDOA) of the signals from synchronized transmitters with known position has been considered for localization purposes [14-15]. The proposed method does not require synchronization between participating nodes and uses Doppler shift to improve GPS-based position estimates. In this work, the Doppler-based range-rating is practically tested, using DSRC packets, and the results are used in simulations.

B. Doppler-Based Range-Rating

Range-rate between a transmitter and receiver can be estimated based on Doppler shift or integrated carrier phase difference between a transmitter and receiver [16-17]. The important point is that the Carrier Frequency Offset (CFO), the difference between the received and locally generated frequencies, is not simply a result of the Doppler Effect for transceivers operating with commercial crystal clocks. The clocks’ drifts in the receiver and transmitter cause a deviation from the nominal carrier frequency as well. For this, the CFO of the received signal is a combination of Doppler shift and clock drift. For the velocities of a vehicular environment, the frequency deviation due to the Doppler Effect is much less than clock drift. Estimating the clock drift portion of the CFO is necessary for extracting the Doppler from CFO. A method is proposed for this in [18]. For the algorithm presented in this article, as we assume the availability of GPS for the vehicles, the clock errors can be assumed to be resolved using GPS carrier phase [19] and Doppler shift will be provided by CFO.

C. Vehicular Communication

Considering the harsh vehicular environment and related communication concerns such as the high level of the mobility of the nodes, multipath, and environmental dynamics caused by vehicles and pedestrians, a modified version of the Wireless Local Area Network (WLAN) protocol, IEEE802.11p has been proposed for Wireless Access in the Vehicular Environment (WAVE). A dedicated bandwidth of 75MHz in the 5.850 to 5.925 GHz band has been assigned for vehicle-vehicle and vehicle-infrastructure communication by the U.S. Federal Communications Commission (FCC) [20]. Similarly, the European Telecommunications Standards Institute (ETSI) and Japanese Association of Radio Industries and Businesses (ARIB) have dedicated a similar bandwidth for such communication [21-22]. This bandwidth is called DSRC. DSRC range is about 1000 m for Line of Sight (LOS) conditions and its channels are shared for the network nodes using Orthogonal Frequency Division Multiplexing (OFDM) [23-24]. Estimation of CFO is necessary for OFDM systems. In [25-26] some methods of CFO estimation for OFDM protocols are presented. Assuming the availability of GPS for vehicles, there is also a potential to remove the DSRC clock errors using GPS timing [19]. The proposed method can be implemented on vehicular communication platforms which are going to be standard in the near future [27]. Thus, the viability of this technique is not a concern from a cost point of view.

D. Aim, Assumptions, Constraints, and Approach

For the presented method, it is assumed that the traveling vehicles have an initial estimate of their position based on GPS. They can communicate their identity and GPS-based position and velocity with their neighbours, other vehicles within DSRC range. In the proposed technique, there is no need for an infrastructure node but having such nodes can increase the performance and costs together. This will be considered for the future steps. The aim of the presented method is to improve the positioning accuracy of a target vehicle using the received data from the neighbours and range-rates between the target vehicle and neighbours. The range-rate is estimated based on the extracted Doppler shift from the CFO of the received packets. As Doppler shift is a result of relative mobility, the neighbours of interest are those traveling in the opposite direction because the relative range-rate between the neighbours traveling in the same direction as the target vehicle is not high enough to generate a detectable Doppler. This will be clear when the achieved accuracy for the Doppler shift estimates is discussed. Practical deployment of the proposed technique requires an expensive test setup including a number of GPS and DSRC equipped vehicles which is not possible for the time being. Here, a specific approach is adopted for deployment and evaluation of the proposed algorithm avoiding solely simulated data. The results show up to 48% improvement over GPS-based positioning, depending on the speed of the participating vehicles and traffic intensity.

Section II defines the problem and explains the solution. In section III, the viability of the solution is discussed and the adopted approach for providing more realistic and reliable data for verifying the proposed method is explained. Section IV investigates the achievable performance and its boundaries before conducting the simulations. In Section V, simulation results are explained and section VI concludes the contribution of this work and outlines the future related research.

II. PROBLEM DEFINITION AND SOLUTION DESIGN

A. Problem Definition

Assume there is a highway, or a main two-way street, with enough GPS coverage and traffic intensity, especially for opposite lanes, of n, vehicles/km. It is assumed that all vehicles are equipped with a GPS receiver and DSRC transceiver to communicate their data. A target vehicle is defined as a vehicle which knows its own GPS-based position and velocity and receives those of the neighbours’ through DSRC and estimates the range-rates to the neighbours using Doppler shift of the received packets. The problem is finding a CP algorithm for deployment in the target vehicle in order to improve the
GPS-based position estimates fusing the available data. The neighbours are defined as those vehicles traveling in the opposite direction to the target vehicle due to the required relative mobility for the Doppler Effect and within the range of DSRC. Figure 1 shows a schematic of the situation.

B. CP System and Solution Mathematics

Figure 2 shows the block diagram of the CP system in the target vehicle. Target vehicle receives the GPS-based positions of the neighbours through DSRC. The CFO of the received signal from each neighbour contains Doppler shift which is proportional to range-rate between the target vehicle and that neighbour. Target vehicle fuses its GPS-based position and velocity and those of the neighbours with Doppler shifts of the received signals in order to improve its position estimates. For data fusion, an Extended Kalman Filter (EKF) [28] is designed as the core of the CP algorithm. The state space model of the movement of the target vehicle is assumed to be

\[
\dot{\theta}(t) = F\theta(t) + G\xi(t)
\]

where \(\theta=[x \ y \ v_x \ a_x \ a_y ]^T\) is the state vector containing position \((x,y)\), velocity \((v_x,v_y)\), and acceleration \((a_x,a_y)\) of the target vehicle. \(x\) and \(y\) are along East (E) and North (N) axes respectively. \(F\) is the transpose operator. \(F\) is state transition matrix, \(G\) models the system noise transition, \(\xi\) is the system noise, \(t\) is time and \(\tau\) is sampling period. For simplicity, two dimensional positioning is considered but the method can be easily expanded for three dimensional positioning. There is

\[
F = \begin{bmatrix}
I & \tau & 0.5\tau^2I \\
O & I & \tau I \\
O & O & I
\end{bmatrix}, \quad G = \begin{bmatrix}
0.5\tau^2I \\
\tau I \\
I
\end{bmatrix}, \quad \xi = \begin{bmatrix}
\xi_x \\
\xi_y \\
\xi_a
\end{bmatrix}
\]

where \(I\) is a 2x2 identity matrix, \(O\) is a 2x2 zero matrix, and \(\xi_x\) and \(\xi_y\) are the acceleration noise along E and N axes respectively. For the system model presented by Eq. (1), the following observation model can be defined:

\[
\Psi(t) = h(\theta(t)) + \gamma(t)
\]

where \(h=[x \ y \ v_x \ ... \ \omega_i]^T\) is a nonlinear observation vector in terms of \(\theta\) and \(\gamma\) is the observation noise.

![Fig. 1. Target and neighbour nodes in a four-lane two-way street](image)

\(\omega_i\) is the Doppler shift of the signal from the neighbour \(i\). Assuming \(f\) as the carrier frequency of the DSRC, there is

\[
\omega_i = \frac{f}{c} \frac{dr_i}{dt}, \quad r_i = \sqrt{(x-x_i)^2 + (y-y_i)^2}
\]

where \(c\) is the speed of light, \(r_i\) is the distance between the target vehicle and neighbour \(i\), and \((v_x,v_y)\) is the position vector of the neighbour \(i\). Eq. (4) can be reformulated to

\[
\omega_i = -\frac{f}{c} \left[ \frac{(x-x_i)(v_x-v_o)+ (y-y_i)(v_y-v_o)}{\sqrt{(x-x_i)^2 + (y-y_i)^2}} \right]
\]

where \((v_x,v_y)\) is the velocity vector of the neighbour \(i\). Due to the nonlinearity of \(h\), an EKF is considered with the Taylor expansion of the Eq. (5) around an arbitrary state vector \(\hat{\theta}\):

\[
\omega_i = h_\theta \dot{\theta} + \omega_i
\]

where \(h_\theta = \partial h(\theta)/\partial \theta \hat{\theta} - \hat{\theta} \) and \(\omega_i\) is the estimated Doppler shift of the DSRC packets received from the neighbour \(i\) and

\[
\Psi(t) = H\theta(t) + \gamma(t)
\]

If GPS-based position and velocity of the target vehicle and those of the neighbours are used for constructing \(\hat{\theta}\) and \(\hat{\omega}\), it leads to

\[
Z = \begin{bmatrix}
\tilde{p}_1 \ 
\vdots 
\tilde{p}_4
\end{bmatrix}
\]

where \(\tilde{p}_i = \hat{p}_i + h_\theta \hat{\theta} - \hat{\omega}\) and \(\hat{\omega}\) is the estimated Doppler shift of the DSRC packets received from the neighbour \(i\) and

\[
H = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
h_{11} & h_{12} & h_{13} & h_{14} & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
h_{41} & h_{42} & h_{43} & h_{44} & 0 & 0
\end{bmatrix}
\]

where

\[
\begin{align*}
\dot{h}_{11} = & \frac{\partial \omega}{\partial x} = \frac{(y-y_i)(v_y-v_o)-(x-x_i)(v_x-v_o)}{r_i} \\
\dot{h}_{12} = & \frac{\partial \omega}{\partial y} = \frac{(x-x_i)(v_x-v_o)-(y-y_i)(v_y-v_o)}{r_i} \\
\dot{h}_{13} = & \frac{\partial \omega}{\partial v_x} = \frac{x-x_i}{r_i}, \quad \dot{h}_{14} = \frac{\partial \omega}{\partial v_y} = \frac{y-y_i}{r_i}
\end{align*}
\]

Reconsidering the system and linear observation (measurement) models from Eq. (1) and Eq. (8), there is

\[
\begin{bmatrix}
\theta(t) + \xi(t) \\
Z(t) = H\theta(t) + \gamma(t)
\end{bmatrix}
\]

and the covariance of the system noise is \(Q = \sigma_c^2 GG^T\) where \(\sigma_c\)

![Fig. 2. Block diagram of the proposed CP system](image)
is the Standard Deviation (STD) of $\zeta_x$ and $\zeta_y$. The covariance of observation noise is

$$R = \text{diag}[\sigma_u^2, \sigma_v^2, \sigma_{\omega}^2, \ldots, \sigma_n^2]$$

where $\text{diag}[\cdot]$ represent a diagonal matrix with the diagonal elements in the brackets. $\sigma_u$ and $\sigma_v$ are the STD of GPS-based position and velocity estimates respectively and $\sigma_{\omega}$ is the STD of the error of the estimated Doppler shift. It is assumed that $H$ can be estimated using GPS-based data. Now, $F$, $G$, $H$, $Q$, and $R$ are known and a Kalman filter [28] can be deployed.

III. VIABILITY OF THE SOLUTION AND DATA PREPARATION

A complete experimental setup for evaluating the performance and verifying the feasibility of the proposed CP system is very expensive and difficult to setup. Therefore, the following steps and simplifications are made to prove the viability of our findings.

1. A section of a highway is accurately surveyed for defining the routes for the simulated vehicles and generating GPS signals.
2. Traffic intensity of the road is simulated over a wider range than that of a typical highway based on the real logged data.
3. The diversity of the speeds of the simulated vehicles are set based on the real data logged in a highway in order to provide a consistent speed profile for model vehicles.
4. GPS-based positions and velocities for the target vehicle and neighbours are provided by a real GPS receiver using generated GPS signals with a GPS signal generator.
5. Doppler-based range-rating, as a key parameter in the proposed CP method, is examined and verified with a pair of DSRC transceivers. The statistical results are used for preparing the required data.

A. Traffic Intensity and Speed Diversity

A parameter that must be considered for the CP algorithms is the number of participating vehicles. This parameter is directly affected by the traffic intensity of the road. In a realistic situation, a set of logged speed data of the passing vehicles on the I-94 highway in Minnesota, USA is considered. These data were gathered by speed cameras observing 4 lanes, 2 lanes in each direction, at Site#25 on the I-94 and provided by Minnesota Department of Transportation. Figure 3 shows the traffic intensity over 24 hours. The typical traffic intensity shown in this figure implies that CP performance, which generally depends on the number of the participating vehicles, may change at different times. To investigate a broader range of traffic intensities, the performance of the proposed method will be evaluated for the traffic intensities up to 50 vehicles /km. The other parameter is the diversity of the speed of the passing vehicles from the average speed of the traffic. Using the aforementioned logged data, Figure 4 shows the STD of the speed of the passing vehicles from the average speed of the traffic over 24 hours. As can be seen, the variation of the speed is almost constant over 24 hours and is about 10 km/h.

A similar situation is set for the simulated vehicles in this article.

B. Simulating the Route for the Vehicles

For defining the traffic path and preparing a model for GPS signal generation, a surveyed section of the Southern Cross Drive in Sydney, Australia, is considered. Figure 5 shows the surveyed section. For surveying, a Leica 1200 GPS RTK Rover is used with antenna mounted on the top of a car for logging the position and velocity, with accuracy of cm, while travelling along the route. The points logged by the rover and the lane width are used for estimating the center of adjacent lanes. The resulting map is used for defining the path for simulated vehicles and also for generating appropriate GPS signals.
C. GPS-Based positions and velocities

For better evaluation of the viability of the presented method, the required GPS-based position and velocities of the simulated vehicles are provided by a GPS receiver, a NordNav-R30, which logs the GPS-related data including position and velocity estimates. The GPS signals for the receiver are generated by a GSS6560 Multi-Channel GPS/SBAS Simulator from SPIRENT. Defining the time and location for this system, it generates GPS signals, which are observable in that location and time. For the purpose of this work, a series of vehicular motion models with different speeds, between 54 km/h and 90 km/h, following the prepared map, over a certain period of time are defined for GSS6560 and the generated signals are fed to the antenna input of the GPS receiver. Some barriers, approximately consistent with the observed obstacles around the surveyed highway, are defined for the GSS6560 for simulating the random and temporary GPS signal blockages. Based on the logged data by the GPS receiver, Figure 6 shows an example of the number of visible satellites for the target vehicle travelling at 72 km/h. As can be seen, after 45th second some fluctuations occur in the number of visible satellites due to the modeled signal blockage. The impact of this fluctuation on GPS performance will be shown in section V. Also, multipath, an important source of GPS-based positioning error [29], is modeled by the GSS6560. The results of this step are the datasets containing GPS-based positions and velocities for the vehicles travelling in different lanes and at different speeds. These vehicles can be defined as target or neighbour vehicles.

D. Doppler-Based Range-Rating with DSRC

Using the range-rate between the participating nodes is a distinguishing feature of the presented CP algorithm compared to distance-based CP methods which were noted in section I. The main motive behind this is the poor achievable ranging accuracy using the common radio-raging methods such as TOA, TDOA, and RSS which is actually not helpful for CP purposes [13]. In the presented method, the CFO values of the DSRC packets are used for range-rate estimation as described in the section I.B. The idea of Doppler-based range-rating is verified with an experiment carried out in 986-1072 Anzac Parade, Sydney, Australia. The test setup includes two MK2 DSRC transceivers from CohdaWireless and a Leica 1200 GPS RTK Rover. MK2 modules, working at 5.9 GHz, can log the CFO of the received packets.

One of the MK2 modules, operating as a receiver, is installed in a vehicle with the antennas mounted on the roof and the other one, operating as a transmitter, is by the roadside with the antennas mounted at a fixed and accurately surveyed point. A Leica 1200 GPS RTK Rover is installed in the car for estimating the accurate position of the travelling vehicle in order to calculate the real range-rate between the transmitter and vehicle. The transmitter broadcasts DSRC packets on channel 180 at a rate of 100 packets per second. The vehicle is driven at about 60 km/h and passes by the transmitter. Figure 7 shows the Doppler shift of the received packets over a symmetric period of time before and after passing the transmitter. As can be seen, the Doppler shift trend shows the passage of the vehicle at t=0. The Probability Density Function (PDF) of the noise of the CFO measurement is depicted in Figure 8. As can be seen, The PDF is approximately zero mean asymmetric Gaussian with right and left STD of about 120 Hz and 100 Hz respectively. Since the difference between the left and right STD is not great, for the remainder of this work, for ease of modeling, the noise of the measured CFO is considered to be a zero mean Gaussian with STD of 110 Hz. Considering this and Eq. (4) with DSRC frequency, 5.9 GHz, the PDF of the Doppler-based range-rating error is a zero mean Gaussian with STD of 5.6 m/s (≈ 20 Km/h). Now, the possibility of CFO-based range-rating using DSRC packets is verified and the behavior of the CFO observation noise and achievable precision are known. These insights will be used for setting the parameters for simulating the proposed CP method.

IV. ACHIEVABLE PERFORMANCE

Before evaluating the proposed CP method, a boundary for achievable performance is discussed in this section. It is expected that the performance of the proposed method will be better than that of a standalone GPS receiver and limited to this boundary.

![Fig. 7. The Doppler shift of the received packets in the moving vehicle](image)

![Fig. 8. The PDF of the CFO measurement error](image)
For this, the Cramer Rao Lower Bound (CRLB) [30] of the proposed CP method is discussed. Assuming the measurement vector $Z$ of Eq. (8), the CRLB is the inverse of the Fischer Information Matrix (FIM) [30] of the measurements, $I_z$:

$$I_z(u) = E \left[ \left( \frac{\partial \ln(f(Z|u))}{\partial u} \right)^T \left( \frac{\partial \ln(f(Z|u))}{\partial u} \right) \right]_{u = U}$$ (15)

where $E[I]$ is the Expected value operator, $f$ is the conditional PDF of $Z$ provided $u$, the vector of interest for estimation, is known as $U$. Assuming the statistical independence and Gaussian PDF for the elements of $Z$ and $u = [x \ y]^T$, $f$ can be defined as

$$f(Z|u) = \frac{\text{Exp}[-\frac{1}{2} (Z - \eta)^T R^{-1} (Z - \eta)]}{(2\pi)^{m/2} \sqrt{\text{det}(R)}}$$ (16)

where $\eta$ is the mean of $Z$ and $n$ is the number of the neighbours. Replacing Eq. (16) in Eq. (15), the elements of $I_z$ are found:

$$I_z(k,k) = \frac{1}{\sigma_k^2} + \frac{1}{\sigma_n^2} \sum_{i=1}^{\tilde{e}} \frac{\partial \omega_i}{\partial u(k)} \frac{\partial \omega_i}{\partial u(k)}$$ (17) and

$$I_z(l,l) = \frac{1}{\sigma_n^2} \sum_{i=1}^{\tilde{e}} \frac{\partial \omega_i}{\partial u(l)} \frac{\partial \omega_i}{\partial u(l)}$$ (18)

and the required derivatives in Eq. (17) and Eq. (18) are available from Eq. (11) to Eq. (13). The CRLB is $C_u = (I_z)^{-1}$. This boundary covariance is used in the next section as an indicator for optimality of the proposed method.

V. SIMULATION RESULTS

In this section, the proposed CP method is evaluated through simulations based on the insights and prepared datasets as explained in section III. Two types of simulations are conducted, one for evaluating the performance of the proposed CP method for a single case and the other for analyzing it from a statistical point of view and varying some parameters.

A. Single trial and results

As a sample case, with regard to section III.A, it is assumed that the traffic intensity of the road is 20 vehicles $/km$ and the average speed of the traffic is about 72 km/h. The road is defined as described in the section III.B and the target vehicle moves from South to North (Figure 5). The prepared GPS-based positions and velocities, using the GSS6560 and NordNav R30™, are considered for GPS-based positions and velocities. For defining a traffic case with a certain speed, a number of moving vehicles, depending on the required traffic intensity, are created following the opposite route of the target vehicle with a random initial position. These are the neighbours if travelling within the DSRC range of the target vehicle. For CFO observations, the Doppler shifts of the packets from each neighbour are simulated using the real range-rates between the target vehicle and neighbours and adding CFO observation noise, using the identified model in section III.D. The DSRC range is set to 300 m and vehicles travelling in the opposite direction passing within this range of the target vehicle are considered to be neighbours at each epoch. The following errors are defined for position estimates along the East and North axes:

$$\begin{align*}
\epsilon E_{\text{GPS}} &= \hat{x}_{\text{GPS}} - x , \quad \epsilon N_{\text{GPS}} = \hat{y}_{\text{GPS}} - y \\
\epsilon E_{\text{CP}} &= \hat{x}_{\text{CP}} - x , \quad \epsilon N_{\text{CP}} = \hat{y}_{\text{CP}} - y
\end{align*}$$ (19)

In Eq. (19), $\epsilon E$ and $\epsilon N$ refer to positioning errors along the East and North axes respectively. The GPS subscript denotes GPS-based data and the CP subscript represents the proposed CP method outcome. Running a single trial of CP simulation, Figures 9 and 10 show the positioning errors for East and North respectively. As can be seen, the CP outperforms GPS. Also, the effect of a GPS signal blockage model, from the 45th second, on the GPS performance and error mitigating reaction of the CP is obvious. Figure 11 compares the overall positioning error, the distance between real and estimated position, for GPS and CP.

The other point is the performance of the proposed CP method which is close to the CRLB. Table 1 summarizes the results. In this table, the achieved enhancement by the CP method and optimality of that, $\mu$ and $\zeta$, are calculated as follows.

$$\begin{align*}
\mu &= \frac{1}{\text{CP RMSE}} \times 100 , \quad \zeta = \frac{\text{Avg. CRLB}}{\text{CP RMSE}} \times 100
\end{align*}$$ (20)

and drms (Distance Root Mean Square) is the distance between the estimated and real position [29]. As can be seen, while the overall accuracy of the GPS-based positioning is about 14.4 m, the proposed CP technique leads to 8.9 m accuracy. Examining the results, the functionality and performance of the proposed method for a sample case is verified.

![Fig. 9. CP and GPS performance along the East axis](Image)

![Fig. 10. CP and GPS performance along the North axis](Image)
for different speeds and traffic intensities, different cases are
the results, the performance of the proposed CP method is
the proposed CP method for different conditions. According to
speed is calculated. The traffic intensity is varied between 5 to
vehicles
enhancement of about 48% over the GPS-based position
is
B.
A more comprehensive evaluation including the effect of
traffic intensities and speeds of the vehicles is discussed next.

### Statistical Results

For analyzing the performance of the proposed CP method
for different speeds and traffic intensities, different cases are
created with a similar method to that in Section V.A. Each case
is simulated 5000 times and the average of the achieved
performance for each combination of traffic intensity and
speed is calculated. The traffic intensity is varied between 5 to
50 vehicles /km and the different average speed of the traffic
are 54, 72, and 90 km/h. Figure 12 shows the performance of
the proposed CP method for different conditions. According to
the results, the performance of the proposed CP method is
almost constant for different traffic intensities above 15
vehicles /km. Regarding the performance criteria, Eq. (20),
enhancement of about 48% over the GPS-based position is
achieved for lower speeds. Although more intensive traffic
leads to a higher number of neighbours, the uncertainty of the
position and velocity of the neighbours limits the achievable
performance. For this the performance improvement is
saturated for higher traffic intensities. This also can be seen in
Eq. (17) and Eq. (18), where n is not increasing the
information of the measurements directly.

The other noteworthy result from Figure 12 is the higher
performance for lower speeds. At lower speeds, the link
lifetime is longer. Here, link lifetime is the duration of
communication between the target vehicle and a neighbour.

Table 2 shows the average link lifetime at each speed for the
conducted statistical simulation. Regardless of traffic intensity,
shorter link lifetime for each neighbour is equivalent to less
information contributed to the CP algorithm for positioning
enhancement. Figure 13 shows the behavior of the achieved
performance for different link life times and traffic intensity of
20 vehicles /km.

Another noteworthy point is that although the performance
of the method increases for lower speeds, the CP system
cannot be deployed for vehicles travelling in the same
direction. Considering Figure 4, diversity of the speeds of the
vehicles travelling in the same direction is about 10 km/h. This
is not detectable with 110 Hz STD of CFO noise, equivalent to
20 km/h at DSRC frequency, 5.9 GHz. Also, this can be
considered as the minimum relative speed for the proposed CP
method.

### VI. Conclusion

A novel method for vehicular Cooperative Positioning (CP)
is proposed. The functionality and performance of the method
is verified. Recent CP algorithms rely on radio ranging
methods whose viability, in a vehicular environment, is
questionable. Avoiding this issue, the proposed CP method is
designed based on range-rate between a target vehicle and
neighbours. Due to the limitations in providing a real test setup
for the whole system, a specific approach is adopted for
providing the required data and verifying the viability of the
major elements. Doppler based range-rating, using DSRC
packets, is tested and verified practically and the obtained
statistical model is used for setting the simulation parameters.

A section of a real highway is surveyed and used as a map
for defining motion models for the model vehicles with
different speeds. These motion models were defined for a GPS
signal generator and required GPS-based positions and
velocity for the CP algorithm are obtained with a real GPS
receiver.

### Table 2

<table>
<thead>
<tr>
<th>Avg. Speed (km/h)</th>
<th>Avg. Link Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>19.1</td>
</tr>
<tr>
<td>72</td>
<td>14.9</td>
</tr>
<tr>
<td>90</td>
<td>12.3</td>
</tr>
</tbody>
</table>

### Fig. 13.

Link life time and achieved performance (20 vehicle/km)
The important GPS-related errors and issues such as multipath and signal blockage are considered for GPS signal generation. The performance of the proposed algorithm is investigated through two types of simulations, single trial and statistical. The obtained positioning enhancement varies between 28% and 47% above GPS-based poisoning, depending on the speed of the vehicles. This corresponds to 7.2 m to 5.3 m precision with CP, when GPS precision is 10 m. Improving the functionality of the proposed method for higher speeds and decreasing the CFO-based range-rating errors are future work for the presented method.

VII. REFERENCES

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