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# Vehicle detection through wireless vehicular communication

Dimitrios Vlastaras\*, Taimoor Abbas, Daniel Leston and Fredrik Tufvesson

## Abstract

Vehicles in the future are anticipated to have the ability to communicate and exchange useful information in order to avoid collisions. However, for this cooperation to be possible, all vehicles will have to be equipped with compatible wireless modules, based on, e.g. IEEE 802.11p (used in ITS-G5 or WAVE), which implements intelligent transport systems operating in the 5 GHz frequency band. During the implementation phase of the system, there will be many older vehicles without such equipment that can cause hazard as information about them will not be available to vehicles equipped with IEEE 802.11p modules. In this paper, we present a system to be used as a roadside unit (RSU), developed explicitly for infrastructure-to-vehicle (I2V) communication that can solve the aforementioned traffic safety problems. The system consists of a universal medium-range radar (UMRR) and an IEEE 802.11p modem integrated together to detect vehicles, with or without communication capabilities, and forward their position and speed vectors to vehicles, with IEEE 802.11p modules installed, for collision avoidance. Tests have been performed by using our system in parallel with vehicles in which IEEE 802.11p modules are installed and comparing the content in the Cooperative Awareness Messages obtained from both systems. Accuracy tests have been performed in order to verify the system, and Kalman filtering is applied on the radar data to improve the accuracy of the system further.

**Keywords:** Roadside unit; Universal medium-range radar; Infrastructure-to-vehicle; ITS-G5; WAVE; IEEE 802.11p; Kalman filter

## Introduction

Intelligent transportation systems (ITS) can be defined as a group of technological solutions in telematics designed to improve the safety and efficiency of terrestrial transportation. Both the European standard for ITS, ITS-G5 and its American counterpart, WAVE, are based on the IEEE 802.11p amendment to the IEEE 802.11 standard. Those standards define procedures to broadcast the position and speed vectors of each individual vehicle so other nearby vehicles can collect this information and use it for safety purposes.

This technology comes with a problem during the implementation phase, as just a few of the vehicles in circulation will actually be equipped with on-board devices. This paper focuses on addressing this problem by implementing a roadside unit (RSU) that scans for vehicles and emulates cooperative awareness messages (CAM) from them as if they had their own IEEE 802.11p onboard

broadcasting modules [1]. This has been done using an IEEE 802.11p wireless modem together with a universal medium-range radar (UMRR).

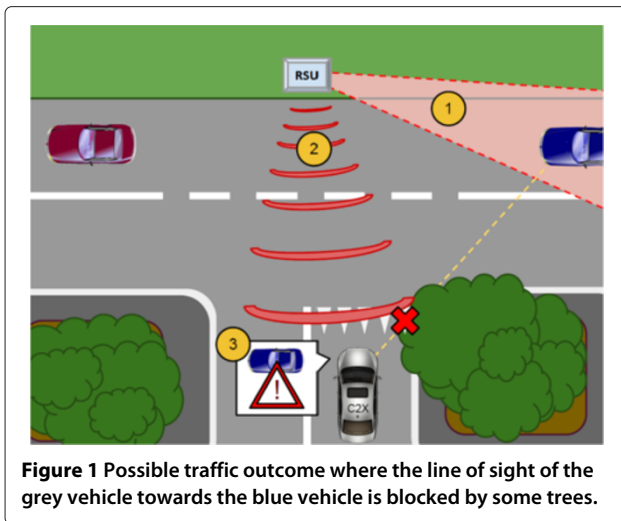
In the example portrayed in Figure 1, the intelligent car in grey color, reaches an intersection where there is a known risk of collision with other vehicles due to the low visibility of the cars that approach from the right.

If all the vehicles in the example had a vehicle-to-vehicle/infrastructure (V2X) communication system, they would broadcast their position and speed vectors, and therefore, the vehicle that aims to enter the main road would be aware of the risk of an accident. Nevertheless, a more realistic scenario would be that where the majority of the vehicles are not equipped with such a system.

However, the device described in this paper can be placed in the intersection, monitoring all the vehicles that approach from the east and broadcasting their position and speed vectors as if they had their own on-board devices.

In the example above, the blue car is not equipped with a V2X communication system and it is driving at a high

\*Correspondence: dimitrios.vlastaras@eit.lth.se  
Department of Electrical and Information Technology, Lund University, Box 118, SE-22100 Lund, Sweden



**Figure 1** Possible traffic outcome where the line of sight of the grey vehicle towards the blue vehicle is blocked by some trees.

speed. The driver in the grey car, equipped with V2X, is not capable of seeing it since there are some trees blocking the line of sight (NLOS). Since the RSU is placed at the intersection, it will detect the blue car (1) and will transmit instant values of its position and speed vectors to the grey car (2). The V2X vehicle will then be notified about the approaching car and will alert the driver of the risk of collision if he or she decides to enter the main road (3).

The effect of intersections in vehicle-to-vehicle (V2V) communications has been widely studied in the past [2], and it has been concluded that most of the power contributions arise in the presence of the line of sight (LOS). Therefore, solutions that extend LOS, such as this roadside unit, will play a major role in the future of urban vehicular communications.

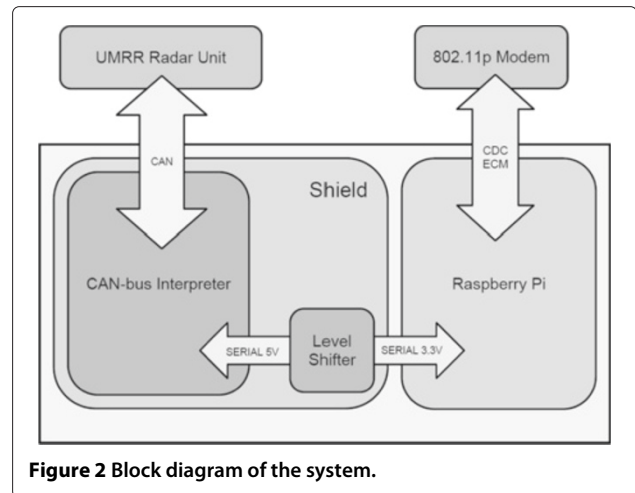
Traffic accidents, especially those taking place nearby or at intersections, have been studied during recent years, and methods have been developed to be able to predict and avoid them [3-6]. However, a solution such as this RSU for detection of older vehicles in conjunction with automatic braking systems or warning systems in newer vehicles is to the authors' best knowledge new and has not been presented before. It can significantly improve the safety of terrestrial transportation by avoiding accidents rather than predicting them.

### System description

The RSU consists of three main parts: a UMRR unit, an IEEE 802.11p wireless modem and an embedded system that provides interfaces and intelligence to them both as seen in Figure 2.

#### Universal medium range radar

The radar has the capability of detecting vehicles up to 160 m of distance and with 25 cm of accuracy [7]. The technology utilizes microwaves in the 24-GHz band for



**Figure 2** Block diagram of the system.

detection of objects. It also incorporates smart functionality such as detection of vehicles that are solely moving in one direction, distinguishing between different kinds of vehicles and/or pedestrians and also providing their speed and position vectors. This information is later being embedded into wireless frames and broadcasted to other vehicles.

This UMRR was designed for in-vehicle and traffic monitoring installations and it communicates with its surroundings over the CAN-bus protocol [8]. Therefore, the rest of the system has to implement the same protocol in order to send commands and receive responses to/from the UMRR.

#### IEEE 802.11p wireless modem

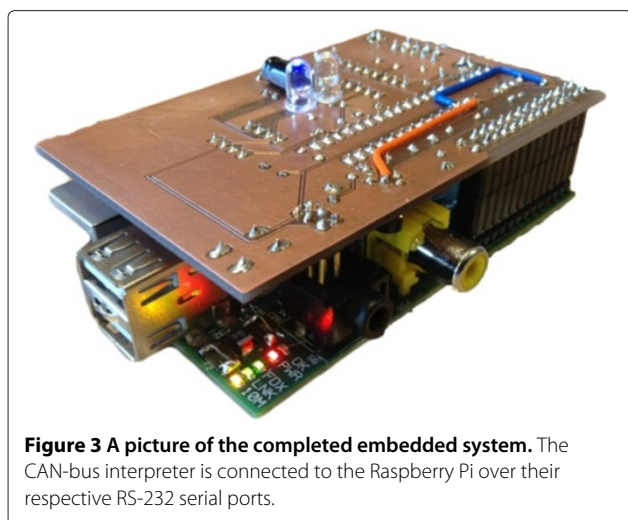
The modem incorporated in this RSU is a very basic one. It does not implement the full ITS-G5 standard; however, it is transmitting and receiving information on the 5.9-GHz band using the IEEE 802.11p amendment.

The modem connects to the embedded system using the CDC-ECM<sup>a</sup> standard. Frames are sent to the modem over the user datagram protocol (UDP). The only task that the modem has to perform is to open up those UDP datagrams and broadcast their payload wirelessly. The payload is expected to be frames according to the ITS-G5 standard.

#### Embedded system

The responsibility of the embedded system is to connect the UMRR unit with the IEEE 802.11p modem and run all the required software in order to meet the system requirements. The speed and position vectors of each vehicle are reported using GeoNetworking (GN) [9], basic transport protocol (BTP) [10] and CAM [11] frames.

The embedded system is composed of two main parts: a CAN-bus shield and a Raspberry Pi<sup>b</sup> as seen in Figure 3. The CAN-bus shield is responsible for the



**Figure 3** A picture of the completed embedded system. The CAN-bus interpreter is connected to the Raspberry Pi over their respective RS-232 serial ports.

communications with the UMRR unit over CAN-bus and the Raspberry Pi is responsible for running the main algorithms and for the communications with the IEEE 802.11p modem over CDC-ECM.

The two parts communicate with each other over their respective RS-232 serial ports. The CAN-bus shield uses 5 V as reference for logic voltage while the Raspberry Pi uses 3.3 V. A voltage level shifter has been put in place to solve this problem.

### Functional tests

Two different kinds of tests were performed in Gothenburg, Sweden. The first test, communication test, was to determine whether the IEEE 802.11p Modem could successfully communicate with Volvo Drive C2X<sup>c</sup> equipment or not. The second test, verification test, was to determine whether the RSU ITS-G5 implementation followed the ITS-G5 specifications [9-11] by comparing frames from another ITS-G5 source, e.g. a Drive C2X Volvo car, to frames generated by the

### Communication test

The RSU was powered up and started broadcasting simulated traffic frames. A Drive C2X receiver was configured and all received wireless frames were saved to a binary file that was later inspected in Wireshark<sup>d</sup> using ITS-G5 dissectors<sup>e</sup>. The acquired frames could successfully be interpreted by the Wireshark dissectors, which meant that the RSU was generating valid GN, BTP and CAM frames with correct format and that the IEEE 802.11p modem was compatible with Drive C2X equipment.

### Verification test

During this test, a setup with three main components was used: the RSU, a Drive C2X receiver and a Drive C2X Volvo car with an ITS-G5 implementation.

```

A Latitude: 57°44'2647.69"N (577354698)
  Longitude: 11°51'3102.12"E (118616989)
  Speed: 10.44 m/s | 37.58 km/h (1044)
  Heading: 5.4° (54)

B Latitude: 57°44'2647.97"N (577355470)
  Longitude: 11°51'3102.42"E (118617823)
  Speed: 10.00 m/s | 36.00 km/h (1000)
  Heading: 240.0° (2400)
  
```

**Figure 4** Frame received from the RSU (A) and frame received from a Drive C2X Volvo car (B).

The RSU was installed and configured next to a road and the Drive C2X receiver was also installed and configured in the same spot. The Volvo car was driven on the road next to the RSU a few times. The external Drive C2X receiver was capturing frames during this time.

Once the test was completed, the captured frames were analyzed and compared side by side in Wireshark. An example of logged frames can be seen in Figure 4. The logged frames were almost identical with the only deviation being the car's heading, as the heading reported by the RSU was in relation to the direction of the radar while the heading reported by the Drive C2X car was in relation to the North.

The radar bearing was roughly measured with a smartphone, and after compensating for the radar alignment, the heading of the car was calculated to 230°, which is close to the reported heading of 240°, and within an acceptable error margin for a smartphone.

### Accuracy tests

Functional tests were performed on the RSU as mentioned above, but other aspects also needed to be tested. One of those was the accuracy of the reported time in conjunction with the accuracy of the coordinates in the GN/CAM frames down to centimetre level. Accuracy measurements were performed with the help of a state-of-the-art global positioning system (GPS) positioning device [12].

### Objectives

GN and CAM frames contain a timestamp as well as the WGS84<sup>f</sup> geographic coordinates of a vehicle [9,11]. It is very important that the reported timestamp is actually the correct timestamp when the vehicle was at the reported coordinate, because the accuracy of the position estimate depends on the accuracy of the time estimate. Delays might be introduced as a result of processing time that various algorithms utilize. Therefore, it is important to measure and report these delays and their impact on the accuracy of the position estimate.



## Methodology

The measurement setup consisted of the RSU on a 5-m tripod, see Figure 5, a high precision GPS receiver that reports coordinates with errors in the centimetre-level range [12] mounted on a Volvo V70 car, see Figure 6. A 350-m straight patch of road was selected as measurement route, see Figure 7.

The car drove 22 times down the street towards the RSU while logging its coordinates and timestamps with the high-precision GPS receiver. At the same time, the RSU was detecting the car and also logging its coordinates and timestamps.

GPS time was used on both systems. A GPS receiver was temporarily fitted on the RSU for time synchronization. According to [13], GPS time is typically accurate within 40 ns, which is more than enough since the maximum logging resolution of the RSU is 1 ms.

## Results

### Time errors

The first measurement was used as a calibration run. The goal with this measurement was to find possible errors in the time domain.

The RSU was using UTC time, since its network time protocol (NTP) daemon was compensating for leap seconds [14]. However, the GPS receiver was using pure GPS time, and therefore, the extra leap seconds were compensated for the RSU. According to [15], the offset between GPS time and coordinated universal time (UTC) is 16 s, as the current number of leap seconds is 16 s [16].

Also, a millisecond level fine-tuning was made numerically on the time offset. The offset that minimized the distance error was selected.

### Spatial errors

The RSU can detect both distance to a vehicle (X coordinate) and sidewise displacement of a vehicle (Y coordinate). Thus, both directions and their errors were studied separately.

In order to find possible errors in the spatial domain, all measurements were compensated for the time offset. The distance from the RSU to the car was compensated for the value that minimized the mean X-error, and the sidewise movement of the car was compensated for the position of the GPS device on the car.

In Figure 8, a measurement sample can be seen. The difference in distance between the RSU and GPS data is the spatial error which can be seen in Figure 9. However, what is more interesting to analyze is the error of all the measurements as a function of the distance from the RSU to the car as seen in Figure 10. From that, we can read the root mean square error (RMSE) as a measure of accuracy. For X,  $RMSE_x = 248$  cm, and for Y,  $RMSE_y = 38$  cm.

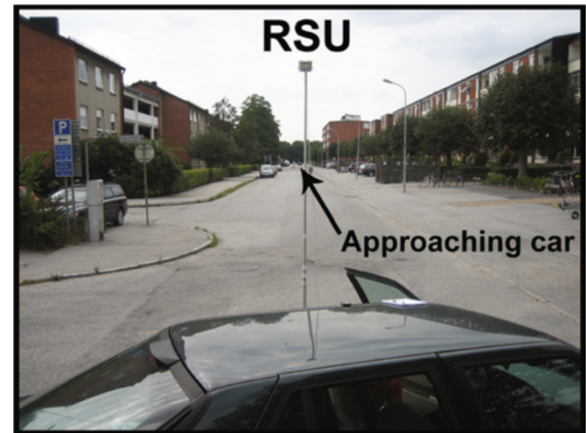


Figure 5 The RSU pointing towards the street.



Figure 6 High-accuracy GPS with an external antenna mounted on the top of the car.

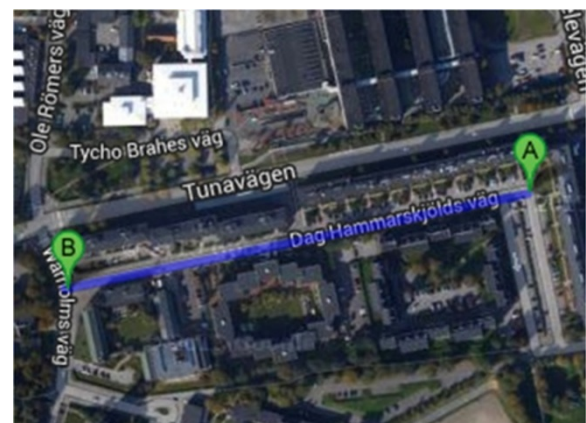
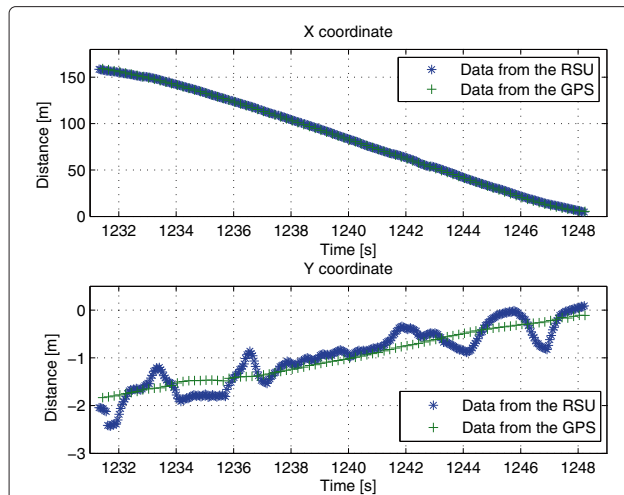


Figure 7 The long straight part of Dag Hammarskjölds street in Lund, Sweden. The RSU was placed at point A pointing towards point B. Images: ©2013 CNES/Spot Image, DigitalGlobe, Lantmäteriet/Metria. Map data: ©2013 Google.



**Figure 8** Positions reported during one of the 22 sample runs. The upper graph displays data for the distance from the RSU to the vehicle (X) and the lower graph displays data for the sidewise movement of the vehicle (Y).

When the car is within 28 m from the RSU, a deterministic behavior can be observed, as the car is going out of the main beam of the radar, as seen in section A of the upper graph of Figure 10. A least squares model that describes this behavior can be found, reversed and added to the data in order to eliminate the error.

#### Vehicle reference point

It is also of interest to investigate whether the reference point of the RSU on the car is changing as the car is approaching the RSU. A slope different from zero on the least squares approximation in Figure 10 would indicate that. As it can be seen, the slope is near 0 both for the X and Y directions. Therefore, it is indicated that the reference point of the RSU on the car is fairly static.

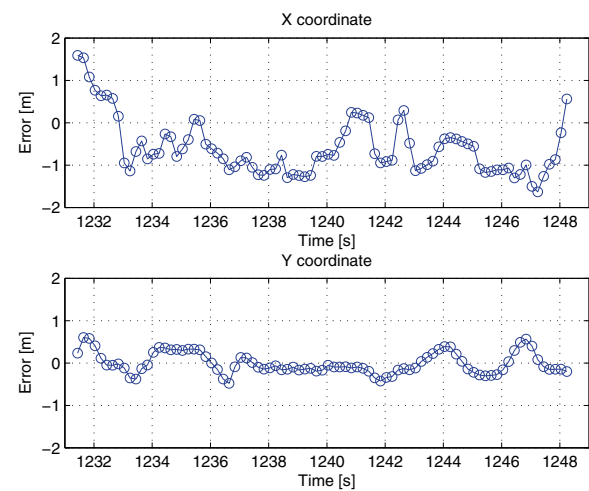
#### Weather implications

Tests in various weather conditions, such as rain, snow and fog have not been performed. However, the system's detection performance is not expected to change significantly in bad weather conditions. According to the radar manufacturer [7], the radar *works in adverse conditions, almost unaffected by weather, and independent of sunlight, in a wide temperature interval (-40 to +85°C).*

#### Smoothing and path prediction

As seen above, the RSU data is not error-free. Also, there are parts of measurements where the RSU cannot see the vehicle and it does not report any data during that time. This can occur due to a shadowing effect or other disturbances.

In order to tackle those problems, a Kalman filter has been introduced for the RSU data. A Kalman filter can



**Figure 9** Error between RSU and GPS data from same measurement as in Figure 8, as a function of time.

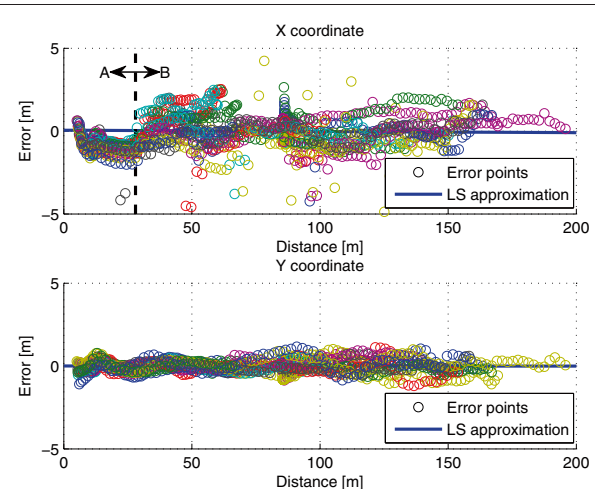
produce a statistically optimal path estimate for some given noisy path observations given that the process model, process noise and measurement noise are known or can be estimated [17].

#### Dynamic model

To describe the vehicle dynamics, we use a constant velocity model (CV) ([18], p. 338), as depicted below:

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \quad (1)$$

$$z_k = Hx_k + v_k, \quad (2)$$



**Figure 10** Scatter plot displaying error as a function of distance from RSU to car for all measurements. For the X coordinate, a deterministic behavior can be seen near the radar in section A, which can be compensated for by an appropriate model. The least squares (LS) approximation of the upper part of the figure is based on data from section B. The root mean square error for X is  $RMSE_x = 248$  cm and for Y is  $RMSE_y = 38$  cm.

where  $x_k = [p_k \ v_k]^T$  is the state of the system,  $u_k$  is an optional control input,  $w_k$  is the process noise,  $z_k$  is the measurement,  $v_k$  is the measurement noise and

$$A = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}, B = 0 \quad (3)$$

$$H = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = I, \quad (4)$$

where  $\Delta t$  is the time between each measurement observation. Moreover, the process noise  $w_k$  and measurement noise  $v_k$  are assumed to be normally distributed with mean  $\mu = 0$  and covariance  $\sigma_w^2 = Q$  and  $\sigma_v^2 = R$  [19].  $H$  is the identity matrix since there are measurements for both components of the state (position  $p_k$  and velocity  $v_k$ ), and it is assumed that these measurements are independent.

### Implementation

The Kalman filter implementation utilizes a recursive algorithm which consists of a time update, where the next state of the system is 'predicted', and a measurement update, where the earlier prediction is 'corrected'.

During the time update, the following operations are performed:

$$\hat{x}_k^- = A\hat{x}_{k-1} \quad (5)$$

$$P_k^- = AP_{k-1}A^T + Q. \quad (6)$$

Also, when there is a measurement observation at a certain time slot, a measurement update is being performed with the following operations:

$$K_k = P_k^- (P_k^- + R)^{-1} \quad (7)$$

$$\hat{x}_k = \hat{x}_k^- + K_k (z_k - \hat{x}_k^-) \quad (8)$$

$$P_k = (I - K_k) P_k^-. \quad (9)$$

If a measurement observation is missing, then the same operations are being performed, but with Kalman gain set to zero,

$$K_k = 0 \quad (10)$$

$$\hat{x}_k = \hat{x}_k^- \quad (11)$$

$$P_k = P_k^-. \quad (12)$$

Here,  $\hat{x}_k^-$  and  $P_k^-$  are priori (before measurement update) and  $\hat{x}_k$  and  $P_k$  are posteriori (after measurement update) state estimate and error covariance, respectively.  $K_k$  is the Kalman gain.  $B$  and  $H$  are not seen in the equations above since  $B = 0$  and  $H = I$ .

### Parameter estimation

The process noise covariance  $Q$ , measurement noise covariance  $R$ , initial error covariance  $P_0$  and initial state vector  $\hat{x}_0 = [\hat{p}_0 \ \hat{v}_0]^T$  are Kalman filter parameters that have to be estimated.

The process noise is often unknown and that complicates the estimation of the filter parameters. However, since the GPS data is much more accurate than the RSU data, it is assumed that the GPS data is error-free in order to get an acceptable filter parameter estimation. Also, as Welch and Bishop [19] state, '*Often times, superior filter performance (statistically speaking) can be obtained by tuning the filter parameters  $Q$  and  $R$ .*'

### $Q$ and $R$

The process noise covariance  $Q$  was calculated from the distribution of the GPS data noise and tuned in a way that minimizes the root mean square measurement error (RMSE):

$$Q_x = 10^{-3} \begin{bmatrix} 5.4212442813 & 0 \\ 0 & 8.1657541509 \end{bmatrix} \quad (13)$$

$$Q_y = 10^{-5} \begin{bmatrix} 7.0235962884 & 0 \\ 0 & 0.0130178705 \end{bmatrix}. \quad (14)$$

The measurement noise covariance  $R$  was similarly calculated by looking at the distribution of the error between the GPS and RSU data:

$$R_x = \begin{bmatrix} 2.4824824996 & 0 \\ 0 & 6.3782090266 \end{bmatrix} \quad (15)$$

$$R_y = 10^{-1} \begin{bmatrix} 1.4246746491 & 0 \\ 0 & 0.1792773482 \end{bmatrix}. \quad (16)$$

Both distributions were assumed to be Gaussian.

### Initial error covariance $P_0$

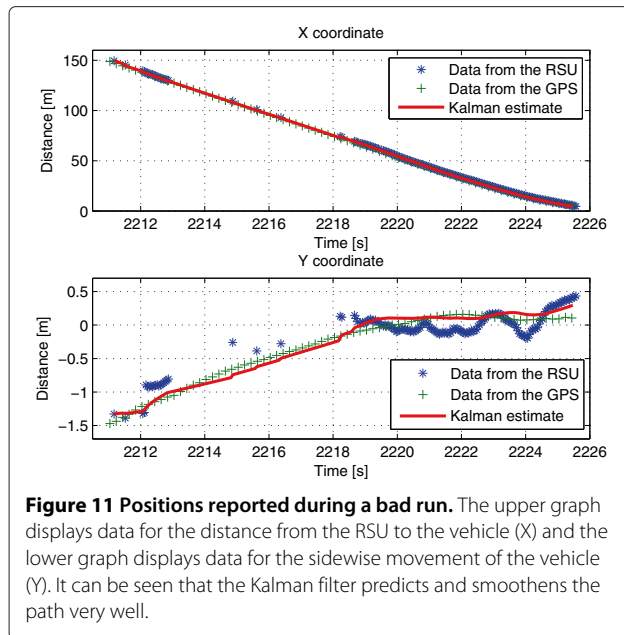
The initial error covariance  $P_0$  was set equal to the process noise covariance  $Q$  and tuned by a factor that minimizes the root mean square measurement error (RMSE):

$$P_0^x = \begin{bmatrix} 50 & 0 \\ 0 & 6000 \end{bmatrix} Q_x \quad (17)$$

$$P_0^y = \begin{bmatrix} 200 & 0 \\ 0 & 4000 \end{bmatrix} Q_y. \quad (18)$$

### Initial state vector $\hat{x}_0$

The initial state vector contains two components; the initial position  $\hat{p}_0$  and the initial velocity  $\hat{v}_0$ . The initial position was set equal to the first measurement observation  $\hat{p}_0 = z_0$  and the initial velocity was set equal to the mean velocity for each coordinate;  $\hat{v}_0^x = -10.37$  m/s and  $\hat{v}_0^y = 0.06$  m/s.



## Results

The aim with Kalman filtering was to smoothen and predict the path for gaps in the RSU data. As it can be seen in Figures 11, 12 and 13, the goal has been reached.

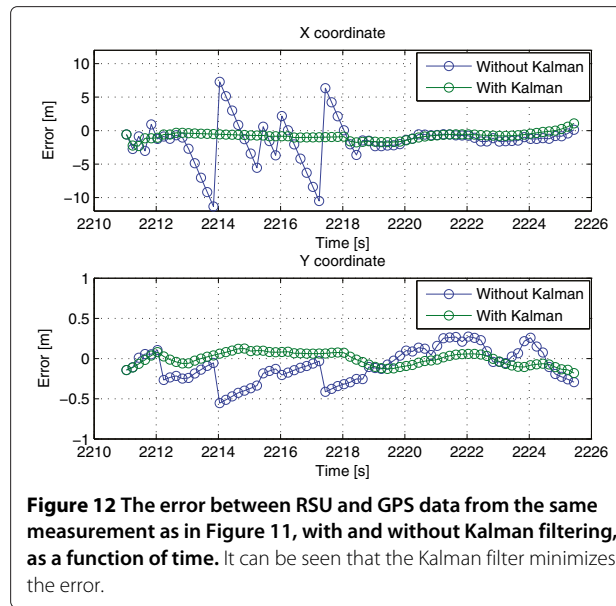
The RMS measurement error for the X coordinate has decreased from  $RMSE_x = 248$  cm to  $RMSE_x = 146$  cm. The RMS measurement error for the Y coordinate has remained the same at  $RMSE_y = 38$  cm. However, for most of the measurements, as the one depicted in Figures 11 and 12, the error has decreased. It has increased for a handful of measurements which brings the RMSE up.

## Conclusions

Throughout the article a roadside unit (RSU) that implements the ITS-G5 standard has been described. It is able to emulate vehicle-to-vehicle/infrastructure (V2X) communications of non-intelligent vehicles within the sight of a radar, thus providing a better integration of ITS-G5 vehicles in the future.

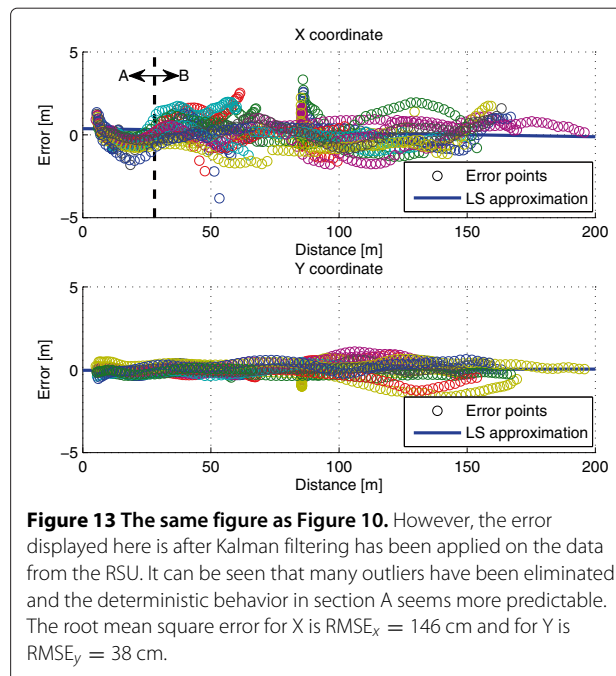
An embedded system succeeds on connecting a microwave radar and an IEEE 802.11p modem, providing an intelligent device in the middle that is powerful enough to perform all needed calculations.

Functional tests have been performed in order to confirm the RSU's ability to communicate with other devices that implement the same standard and to verify the system's reported values such as coordinates and speed. Both tests have been successful. Accuracy tests have been performed and the system's accuracy shows promising results. The accuracy in X and Y directions has been measured to 248 and 38 cm, respectively when using raw RSU data.



Kalman filtering has also been applied to the RSU data. As a result, the reported positions from the RSU are smoother, continuous and more accurate. After filtering has been applied, the RMS error in the X and Y directions has decreased to 146 and 38 cm, respectively.

With this technology, intelligent transportation will be realized earlier during the implementation phase, where just a small portion of vehicles on public roads will feature a cooperative communications system. It is also a long-term solution, since older vehicles will keep driving on





public roads for a long time. By implementing the system in blind spots, intelligent vehicles will benefit from extra active safety as they will be warned about surrounding vehicles.

## Endnotes

<sup>a</sup>CDC-ECM is an implementation for Ethernet over USB.

<sup>b</sup>The Raspberry Pi is a credit-card-sized single-board computer.

<sup>c</sup>Drive C2X is a European integrated project on ITS deployment.

<sup>d</sup>Wireshark is a free and open-source packet analyzer.

<sup>e</sup>The ITS-G5 dissectors were fetched from AMB Consulting (Antibes, France).

<sup>f</sup>WGS84: World Geodetic System 1984, last revised in 2004 according to the National Geospatial-Intelligence Agency.

## Competing interests

The authors declare that they have no competing interests.

## Authors' contributions

DV is the main author of this paper and has done most of the research. He built the software and hardware for the RSU and performed tests and measurements. DL was responsible for the hardware design. He also participated in the early testing. TA and FT supervised the work. All authors read and approved the final manuscript.

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