Distance Estimation for Database-Assisted Autonomous Platooning

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Abstract. This paper presents the improved distance estimation for the purpose of Database-assisted Autonomous Platooning and V2V channel modelling. The proposed approach combines commonly used GPS-based measurements with UWB-based measurements to benefit from both solutions. While GPS allow for unlimited measurement range, the UWB improves accuracy for short range. The paper is based on real-word measurements.

Keywords: Distance estimation · GPS-based measurements · UWB-based measurements · Database assisted platooning · Position and location measurements · Cognitive radio · Vehicular dynamic spectrum access

1 Introduction

Recent years have abounded in many achievements in the field of vehicle traffic automation. Automatic Fare Collection systems, intelligent traffic-light steering or in general Intelligent Transportation Systems (ITS), deployed widely in numerous cities around the globe, are just selected examples of *cities' smartification*. In these cases, the decisions to be made regarding the potential change of the system setup are supported by the infrastructure elements (e.g. road side units mounted on lamps posts or traffic lights), and as such constitute a good example of cooperation between the users and system. However, a significant progress has been made in the last years towards real implementation of autonomous driving concept. Adaptive Cruise Control (ACC) system has been investigated for many years, but recently it has been successively implemented in contemporary cars offered by numerous brands. ACC provides not only the option of speed control (i.e. keeping the value of set velocity or not-exceeding the fixed upper limit). By using dedicated radars or lidars, it controls the distance to the slower car driving ahead. Cooperative version of ACC, known widely as CACC, tends to improve the overall car and system safety level, by means of wireless message exchange between cars within some coverage area. Such an approach is particularly important in case of car platooning, where the *car trains* form a

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connected convoy, whose behaviour is controlled in wireless way. A number of empirical studies have been performed to evaluate the performance of platooning supported by IEEE 802.11p-based wireless communications, e.g. [1,2].

However, one of the main problems of CACC is the reliability of information exchange between platoon vehicles. From the perspective of data exchange between the platoon members, it is realized by means of short-range wireless communications schemes, such as Dedicated Short-Range Communications (DSRC) or cellular networks (Cellular-V2X, C-V2X). It has been shown, however, that the performance of IEEE 802.11p-based CACC may be significantly reduced as a consequence of even moderate increase in road traffic. This is due to the resultant wireless channel congestion [3–6]. One of the prospective solutions to this problem is to use of a dual-band transceiver that can operate simultaneously in two different frequency bands.

In our approach we concentrate on the so-called Vehicular Dynamic Spectrum Access (VDSA) scheme [7,8], where the traffic may be offloaded from the congested channels to the unoccupied or less occupied frequency bands. The decision of changing channel may be made either solely by the platoon leader or may be supported by the information stored in the context database and delivered to the platoon leader in order to make its decision more reliable. Following the concept of cognitive radio, where secondary network uses frequency bands of the licensed network in an opportunistic way, we select the so-called TV White Spaces (TVWS). In this case, the primary stakeholders are Digital Terrestrial Television (DTT) operators, who broadcast their services to remote users. Moreover, we assume that there exist a database subsystem deployed along the streets to support VDSA procedures.

As the selection of TV band has significant advantage (i.e. stable occupation of the particular TV-channels), there is a strong need to propose a reliable channel propagation model applicable to this band and adjusted to the high-speed scenario. In particular, the typical one or two-slope pathloss models have to be tuned to the platooning scheme, where e.g. the transmitter's and the receiver's speed is high, so the surrounding environment is changing fast. Moreover, the impact of cars present on the propagation path has to be included. However, while performing real-time measurements it appeared that the pahtloss modelling is highly sensitive to localization errors of the transmitter and receiver. The simplest approach, where the position of cars (and in consequence inter-car distance) is derived based on Global Positioning Systems (GPS) signal, cannot be applied when the distances between the cars are small (comparable to typical average GPS location errors). On the other side, application of radar- or lidar-based distance systems is accurate but cannot be applied for larger distances. Thus, there is strong need for a reliable model that allows in consequence for accurate pathloss analysis both in short and long distances. Such a model may be also applied by the database subsystem while evaluation of any distance-related parameters needed in VDSA procedure. In our paper we propose such a model, as well as the algorithm for its application for distance measurements.

The rest of the paper is organized as follows. We first discuss the problem of high impact of measurements inaccuracies on the functioning of VDSA scheme and on designing appropriate pathloss model applicable in such database-oriented system. Next, we present performed experiments and propose the combined approach to distance estimation that may be suitable for both database-assisted platooning and V2V channel modelling, we discuss also its application opportunities. Finally, the paper is concluded.

2 Negative Impact of Distance Measurement Errors

The uncertainty of location of the transmitter and receiver may lead to significant failures in VDSA functioning at least twofold; first, it may influence all location or distance related entries in the database subsystems, e.g. database will provide results based on wrong values, associated with other positions. Second, the models applied in the database (e.g., the applied pathloss model) strongly rely on the accuracy of distance measurements during the conducted measurements campaigns.

2.1 Impact on Distance-Related Entries in Databases

As indicated, in our research We concentrate on utilization of unoccupied television channels known as TVWS [9,10]. In particular, we focus on shifting control channel (CCH) traffic from nominal 5.9 GHz band into the TV band with the support of database assisted system. TVWS are of particular interest, as it may be emphasised that both - the location of the DTT transmitters, and the assignment of TV channels to the certain transmission points, are relatively stable in long time-scale. Thus, such information may be stored in dedicated database subsystem, implemented with the aim of supporting VDSA algorithm [11]. As the access to such data may improve the performance of VDSA scheme, the reliability of this approach highly depends on the accuracy of the database entries. The database used for VDSA may be populated with data gathered in the dedicated measurement campaigns, where the DTT signal power can be detected and stored with presumed spatial resolution. Unfortunately, filling the map with appropriate values of presumed level of confidence requires high accuracy of localization information. Location uncertainty has direct negative impact on the quality of entries stored in the database, as such kind of errors will influence the decisions made by the database system in VDSA scheme. However, in VDSA not only location-dependent data is needed, but also information which rely on distances from a certain location. In other words, it is necessary to achieve reliable distance-related information at given location. For example, it may be necessary to estimate the pathloss between the transmitter and receiver (in our case, platoon leader and other platoon members), which will be later used in the VDSA algorithm and selection of the best TV channel. The pathloss observed between two particular points depends on the calculation of distance, and any errors will have negative impact on the derived pathloss value. However, the problem of location uncertainty appears also in this case, and may even accumulate, when the distance is computed based on the location data stored in the database.

2.2 Impact on Pathloss Modelling

Moreover, as already indicated in the introduction, while performing the pathloss measurements, it is highly important to guarantee high accuracy of the location or distance measurements. Wrong distance measurement will influence the distribution of the measured pathloss values leading to wrong pathloss model. Such wrongly adjusted pathloss model will in turn have negative impact on the database functioning as described above. As distances between the cars in the platoon may vary from some meters to kilometers, there is a need to derive the solution for guaranteeing high accuracy of distance measurements (and modelling) in the entire range of distances.

2.3 Combined Distance Measurement Scheme

The immediate and natural solution is to use navigation-base systems, like GPS to derive the distance between two locations. However, during conducted measurements we have observed that of-the-shelf GPS modules are burdened with some measurement error, whose standard deviation may be unacceptable for databases assisted VDSA especially when the distances are low, i.e. GPS-based distance error is constant with distance that results in very high relative error for short distances and low for significantly distanced vehicles. Thus, we have searched for other technical solutions to proceed with measurement of distance-related values. In particular, the ultra wideband (UWB) system has been utilized to detect the true distance. The experiments have shown that such an approach offers high accuracy (in terms of some centimeters), but it cannot be used for distances longer than tens of meters. In consequence, there is a need for dedicated mathematical model that can combine these two approaches. In this paper, we proposed the combined (GPS and UWB-based) approach to distance estimation that may be suitable for both database-assisted platooning and V2V channel modelling. The need for such a hybrid distance estimation model is caused by constant characteristics of error obtained with GPS-based measurement. Observe that typically in VDSA system the pathloss (in dB) is modeled as linearly dependent from logarithm of distance. An influence of such an error on the results is presented in Fig. 1 for 4 different errors (i.e. $+1$ m, $+4$ m, -1 m and -4 m) affecting the reference $y = x$ line (exact distance without an error). It can be clearly seen that the error is the more significant the lower $log_{10}(x)$ value is. As such, UWB distance measurement system, characterized by significantly low variance but range limited to few tens of meters, can fix the main drawback of GPS-based distance measurements. Moreover, the error is presented in this way (not a commonly used squared error) because now it is easier to observe that even small distance error can significantly affect the slope of the pathloss model used.

The purpose of this paper is to present the improved approach to distance measurements based on GPS and UWB systems data fusion that enhance quality of distance measurement, especially for low distances.

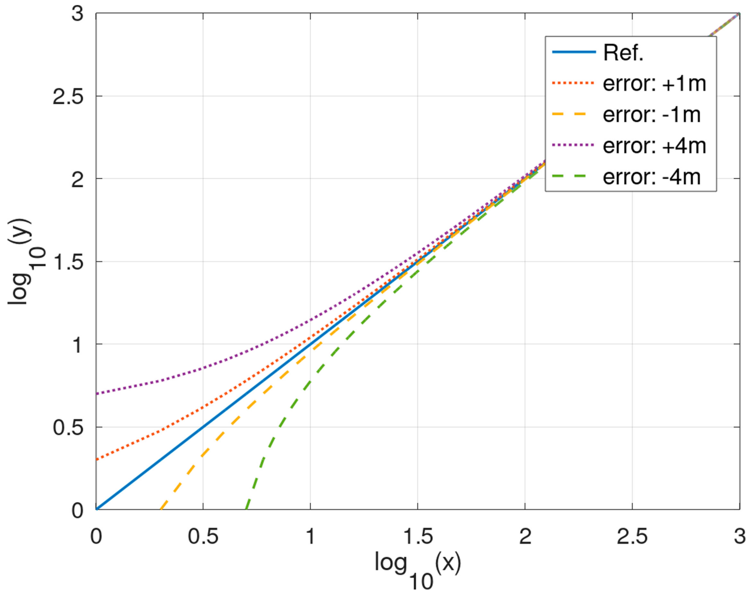

Fig. 1. An exemplary $log_{10}(.)/log_{10}(.)$ plot for constant error introduced.

3 Pathloss Measurements - Conducted Experiment

The channel measurement setup is composed of two cars. The first car (transmitter), was equipped with a USRP N210 module with a WBX extension card and a GPSDO module with an external antenna and a PCTEL LPBMLPVMB/LTE antenna with a gain of 3 dBi. The measured transmitted power is equal to 4.3 dBm, which corresponds to an EIRP value of 7.3 dBm.

The R&S FSL 6 spectrum analyzer connected to a laptop via an Ethernet connection was installed in the second vehicle, acting as a receiver. A wideband AOR 753G antenna with 0 dBi gain was used. In addition, the SYNGIO BU-353 GPS receiver was used. It allowed to determine the location of the vehicle at a given moment in time, as well as its speed and azimuth of movement. Reception processing is based on obtaining time and frequency synchronization according to the note 1MA199, and then calculating the value of the Signal to Noise Ratio (SNR). The receiver sensitivity was established by processing the white noise samples with a scheduler at the input of the spectrum analyzer. In the case of 1000 runs, the estimated SNR values ranged from -17.7 dB to -12.9 dB. It is assumed that the signal is considered correctly received when the SNR value is higher than −13 dB (false alarm probability close to 0.1%). Knowing the transmit power, the total received power and the SNR of the received frame/sequence, the propagation suppression was determined.

In order to allow for improved distance calculation, Ultra Wideband devices, TREK1000 from Decawave [12] were installed. One in each car. The TREK1000 is a wireless transceiver operating according to IEEE802.15.4-2011 standard that allows for range measurement with high accuracy. While one device (in *transmitter* car) was only powered, the second module (in *receiving* car) was connected directly to the laptop for saving logs. As it was observed that the system range is significantly reduced while the UWB antennas are placed inside the cars, about 1.8 m long cables were used to connect antennas placed at the rooftop and UWB transceivers operating inside each car. While the UWB system reports distance about 3.5 times per second, the GPS receivers report positions once every second.

In order to assess correctness of distance measurement between two cars in a dynamic scenario, an experiment was planned. As both distances measured using GPS coordinates (with Vincenty algorithm [13]) and UWB devices can be erroneous, a reference was needed. It was done in a static scenario (called initial experiment) while measuring *real* distance using measuring tape. Three distances between cars were enforced, i.e., 4.5 m, 20.25 m and 44 m. In each case logs from a few minutes were saved for postprocessing. For each distance the offset and standard deviation were estimated (see Table 1). In the last row the table is enriched with mean values.

Table 1. Statistics for GPS and UWB measurements for the initial experiment

	GPS		UWB	
	Offset	Std. dev.	Offset	Std. dev.
Ref. = 4.50 m	2.9855	4.0150	5.0692	0.0284
Ref. = 20.25 m	2.6734	3.8944	4.7326	0.0291
Ref. = 44.00 m	3.1894	5.4421	5.2571	0.0358
Mean value	2.9494	4.3984	5.0196	0.0309

It is observed that for both technologies the calculated offset is fixed, i.e., does not depend from the distance. The offset introduced by the GPS measurements is caused by the fact that in the transmitter car the transmitting antenna (used for V2V channel modeling) was placed at the end of the rooftop while GPS antenna was placed below the car windshield what caused the mismatch in the measurements (due to the use of SUV car the difference is significant). In the case of UWB, offset was introduced by the cables used to connect antennas. Taking into account length of both cables (3.6 m) and average signal propagation velocity (ca. 0.7c) expected offset should be equal to 5.14 m what is almost exactly the value obtained in the experiment. As such the measured offset can be used for data correction. On the other hand, the error measured by standard deviation cannot be easily removed. Based on the above results it can be stated that the distances obtained with the use of UWB are far more precise ($\sigma_{GPS} >> \sigma_{UWB}$) than the results obtained using GPS.

The instantaneous distance measurement error (after removal of the calculated offset) for initial experiment is presented as a function of sample index (time related) in Fig. 2 for the case of 44 m real distance.

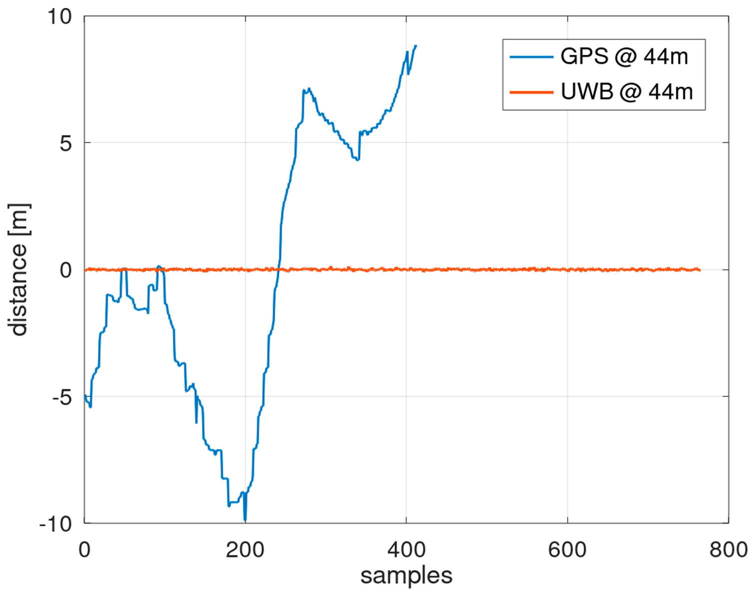

Fig. 2. Fluctuations of the GPS and UWB distance error around the mean value for 44 m static scenario

Obtained curves reflects the values of σ_{GPS} and σ_{UWB} (GPS curve suffer from significant oscillations while UWB have almost no fluctuations). Moreover, it is visible that the GPS-based distance error is significantly correlated in time.

In Fig. 3 a histogram presenting the operation range of both approaches obtained during the main experiment is presented. It needs to be mentioned that the shape of the GPS histogram is affected not by its performance but by the experiment itself. The shape of the UWB histogram clearly shows that useful range is significantly shorter (90% of measurements is below 83.25 m), what highlights the biggest drawback of the used UWB.

Last aspect that also affect the measurements is the number of gaps and its sizes (in the main experiment). Histogram presenting their distribution is shown in Fig. 4.

This figure clearly shows that in the case of GPS-based measurements the gaps in the results are very rare and most of the gaps have a small size. The opposite situation is observed for the UWB-based measurements. In this case very small gaps are very often and wider gaps are also possible.

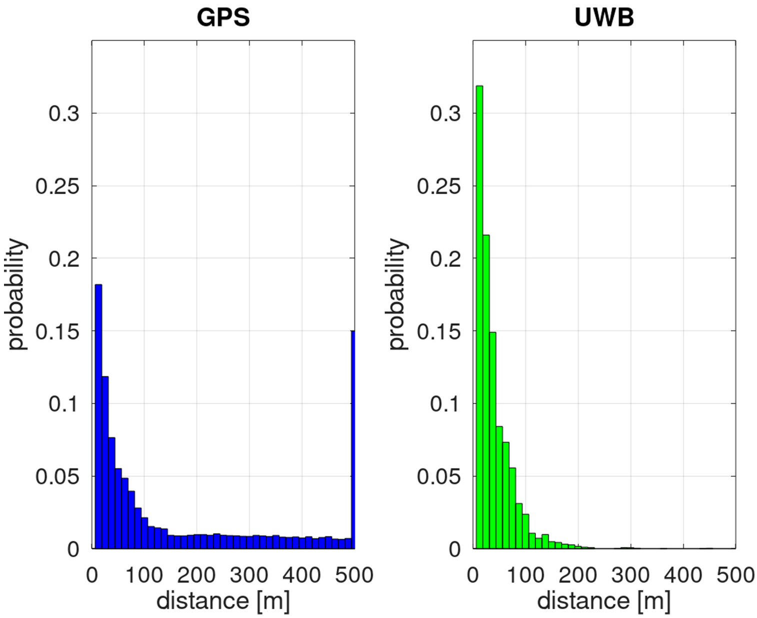

Fig. 3. Histogram of measured distances for GPS (left) and UWB (right) during the main experiment

4 Proposed UWB and GPS-Based Distance Measurements Fusion

As already mentioned, one of the most common approach to measure the distance are the GPS receivers. This approach is relatively simple and offers wide range of measurements, however, is affected with non-sufficient quality. On the other hand UWB based approach implemented in TREK 1000 offers improved measurements quality but significantly lower operating range.

Based on the information presented in previous Section the following algorithm for effective UWB-based and GPS-based combining have been developed.

The first step of the algorithm is to calculate the standard deviation of the UWB-based and GPS-based measurements so these values could be used in the main loop of the algorithm. In the next step a resampling procedure (as a method for signal reconstruction) is performed to handle with short discontinuities. Due to significant error introduced to the output model by this method in the case of insufficient data, this method was limited to 20 samples in the case of UWB measurements (gap length is shorter than ca. 6 s) and 6 samples (corresponds to 6 s) in the case of GPS results. Most suitable approach to find these values is to verify the MSE against the gap size (choose the value just before the increase in MSE become unacceptable). Within the third step of the algorithm the GPS data are up-sampled. The goal of this step is to obtain GPS measurements exactly at the same time instants as for the UWB. Step number four of the algorithm

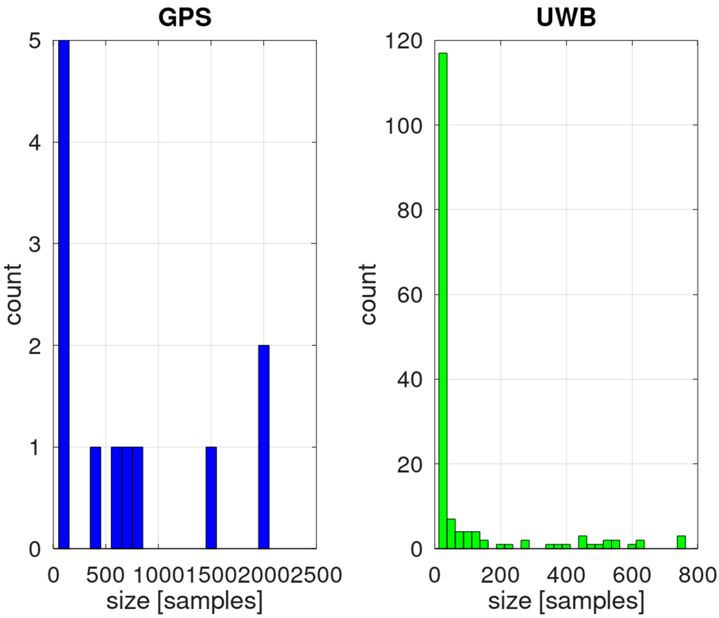

Fig. 4. Histogram of discontinuities for GPS (left) and UWB (right) obtained during the main experiment

combines the data of GPS and UWB. Procedure assumes that if for the given time instant both the measurements are available (GPS and UWB) the output value is calculated with the use of maximum ratio combining with the weights calculated based on the σ_{GPS} and σ_{UWB}. In the case if only GPS or only UWB measurement is available, this measurement is taken directly to the output. If, at this level, neither GPS nor UWB measurement is available algorithm returns no distance for this time instant. Above steps, in general, are able to generate good quality data, however, transition from GPS + UWB to GPS only or from GPS only to GPS + UWB may generate sudden step in output data. To mitigate this disturbance additional filtering with the Hanning window has been performed. The Hanning filter has been feed up with a difference between the GPS and UWB measurements (calculated on last GPS + UWB samples just before the transition to GPS only state or on first samples just after transition from GPS only to GPS + UWB state). Filtered signal, considered as a correcting signal, is subsequently added to the output given after step four. Exemplary curves presenting input GPS and UWB measurements as well as the output data (with and without filtering) for the part of main experiment are shown in Fig. 5.

Based on the above algorithm a statistics showing the percentage contributions of different combinations obtained at the output in the case of main experiment is shown in Table 2.

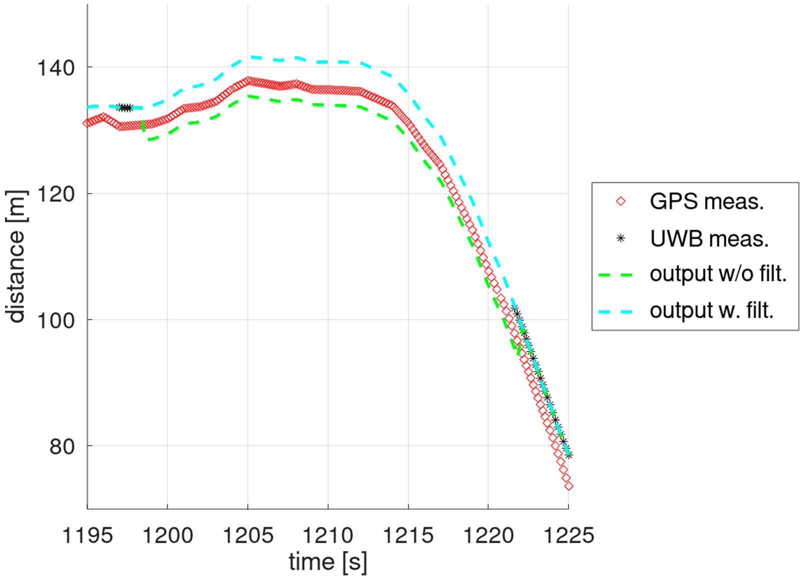

Fig. 5. GPS and UWB input data and calculated distances

Table 2. Different combinations in output distances and its percentage contribution

Type	[%]
GPS + UWB	43.96
GPS only	35.44
UWB only	8.58
No data	12.02

5 Conclusions

In this paper we have proposed a new approach to distance estimation in vehicular applications, such as the database-assisted platooning. It has been shown that the presented solution, relying on the data fusion and analysis from two sources: GPS receiver and UWB-based wireless system, allows to overcome some of the limitations of the individual approaches (i.e. using only GPS or UWB), such as the low accuracy or limited range. The proposed algorithm works in two possible modes: simultaneous use of GPS + UWB or relying on the GPS, with the low-accuracy GPS measurements modified using the estimated correction factor obtained by comparing the results at short distances with ones for the highly-accurate UWB-based system. Furthermore, to ensure smooth transition between the two operation modes, a Hanning window-based filtering has been applied based on a selected number of recent measurements. The described experimental evaluation of the proposed algorithm revealed that it allows to obtain a reliable set of distance measurements both for short and medium distances, thus being an interesting solution for vehicular applications.

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