Technical Evaluation of Cooperative Systems Experience from the DITCM Test Site

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Abstract

Cooperative systems are being developed for commercial application in the near future. Standardisation of the architecture and communication is progressing and large scale field tests are conducted to test and validate cooperative systems. Standards, requirements or specifications for safety applications are largely absent. Yet, technical evaluation of field test data shows that requirements on time synchronization, positioning accuracy and communication performance, need to be defined to meet basic requirements of applications, such as the required distances and time gaps for warning drivers. This paper presents the methodology and infrastructure of the DITCM test site for technical evaluation, and shows field test results that motivate further standardisation of applications and basic technology.

Keywords: Cooperative Systems, Standardisation, Communication, Positioning, Field Operational Tests

Introduction

Concepts and prototypes of cooperative systems have been developed, demonstrated and field tested over the last decades. A maturity level of cooperative systems has been reached that enables larger scale field operational tests with hundreds to a few thousands of vehicles. First series of commercial products are expected to enter the market soon, which means that the products should provide the cooperative functionality and maintain driver and traffic safety.

The emerging behaviour of cooperative systems is inherently more complex than that of the individual systems alone due to the many-to-many interactions for cooperative stations. Differences in implementations of HMI, applications, sensing, communication devices, will lead to differences in the system behaviour. Technical evaluation of the correct, safe and reliable operation, and ultimately the verification and validation of the system in cooperation, is a necessity for efficient and safe traffic.

Standardization is an important step in this process. In Europe, standards for communication interfaces and architecture [1], and message formats like a Cooperative Awareness Message (CAM [2]), Decentralized Environmental Notification Messages (DENM) or a Signal Phase And Timing (SPAT) are under development by ETSI, CEN and ISO. The expected behaviour of applications and requirements for driver advice are specified in a less concrete manner. The Basic Set of Applications (BSA) [3] describes the functionality of applications where drivers get warnings to improve traffic flow and for safety critical situations. Examples are the Green Light Optimal Speed Advice (GLOSA), slow vehicle warning, emergency electronic brake lights and collision risk warning. These applications inform a driver upon detection of an event and give an advice on speed, distance or time to the event. The advice to a driver changes when the risk level increases from informative to warning or severe warning. The risk level is typically defined in terms of the relative time or distance to the event, such as a time-to-collision, (time) headway, or time to the next phase change of a traffic light.

Imagine a vehicle on motorway driving at 30 m/s approaching a slow vehicle or other obstacle. In the worst case, a minimum time to the event could be set at 2 sec in which the driver must respond. If we factor in the response time of a driver of say 1 sec, then the severe warning should be displayed 3 sec before the event, i.e. at a distance of about 100m before the event location. The standards mentioned above do not set requirements on the basic technology of cooperative systems, such as the time synchronization, positioning and communication performance. What performance is feasible, what error margins are likely, and how could this impact driver advice?

Over the last few years, several cooperative systems have been evaluated in field tests on the DITCM test site [4]. Typical performance issues with the basic technology seem to reappear. This paper present the approach for technical evaluation and examples of the issues, and concludes with an assessment of the worst case impact on the accuracy of advices to drivers.

DITCM approach to Technical Evaluation of Cooperative Systems

A cooperative vehicle or road side unit is equipped with an ITS Station that implements the ITS communication reference architecture [1]. An ITS Station consists of an Application Unit (AU) and a Communication Unit (CU). The AU has a platform to run applications and facilities for managing the communication and message handling, situation awareness and potentially data fusion. The AU on a Vehicle ITS Station (VIS) also interfaces with the HMI or on-board display to exchange information between applications and the driver. The CU transmits and receives the messages via Geonetworking over ITS G5.

Standardization in Europe has mainly focused on the communication aspects to ensure that ITS-Stations can exchange standardised messages. For other aspects, norms or specifications are less clear, for example:

- Application layer: There are no specifications on user needs, requirements, or specifications of cooperative applications, like criteria for safety margins (distance/time) or severity levels (information, warning, severe warning). This means that applications, system and components can potentially provide inconsistent functionality and behaviour.
- Facilities and Access layer: There are no specifications or requirements on performance of basic technology like for time synchronization, positioning accuracy, antenna patterns, or communication range.

In absence of specifications or norms, the performance of the system in terms of time synchronisation, positioning and communication performance can still be evaluated and quantified. These directly affect system performance, application performance and the accuracy of advices to the driver.

In field tests, all input and output of the components on ITS Stations are logged for post evaluation of the functionality and performance. However, the logging of the ITS Stations themselves cannot provide objective reference data to diagnose any synchronisation, positioning or communication errors. To evaluate and quantify performance objectively an independent reference measurement system is necessary, i.e. a system that operates stand-alone from the ITS-Stations and has known error margins.

DITCM infrastructure on the A270/N270 Test Site

The Dutch Integrated Test site for Cooperative Mobility [4] is a collaboration of over 20 public and private partners, focussing on open innovation and acceleration of the introduction of cooperative systems. DITCM operates a variety of facilities for testing cooperative systems including simulation environments, hardware in the loop laboratories to a field test site.

The field test site provides a mixed traffic environment for testing cooperative systems in normal traffic on the public roads. The test site infrastructure was initially developed along the A270 motorway and gradually extended to also include urban sections with controlled intersections on the N270 from the cities of Helmond to Eindhoven in the Netherlands.

The A270/N270 test site is specifically developed for testing, verification, validation and evaluation of cooperative systems. The test site is fully covered by a network of traffic detection and communication systems, a series of Roadside ITS Stations (RIS) and Central ITS Stations (CIS) and a Test Management Center (TMC). Part of the test site is used here that is under direct control of the TMC to log ITS station data. The architecture is sketched in Figure 1 and described in more detail in [5][6].

The test site has 51 fixed cameras to monitor and track all individual vehicles in real time on the motorway and at the intersections. This provides the independent measurement system to evaluate positioning accuracy of vehicles.

A series of 16 G5 Communication Units (CU) are installed near the intersections and along the motorway. The test site has a series of Road side and Central ITS Stations that implement the reference architecture [1] with an Application Unit (AU) and a Communication Unit or ITS Gateway (CU). However, the communication and application units are implemented such that they can handle multiple flavours of message sets and applications simultaneously, and the CUs and AUs from a RIS or CIS can be linked in a many-to-many configuration (Figure 1). This allows to run the message sets and applications simultaneously from different projects on a single RIS or CIS, and to allocate subsets of the RISs to different projects. It also allows to isolate a subset of RISs and CISs as an evaluation system operating independently of the RISs and CISs under testing.

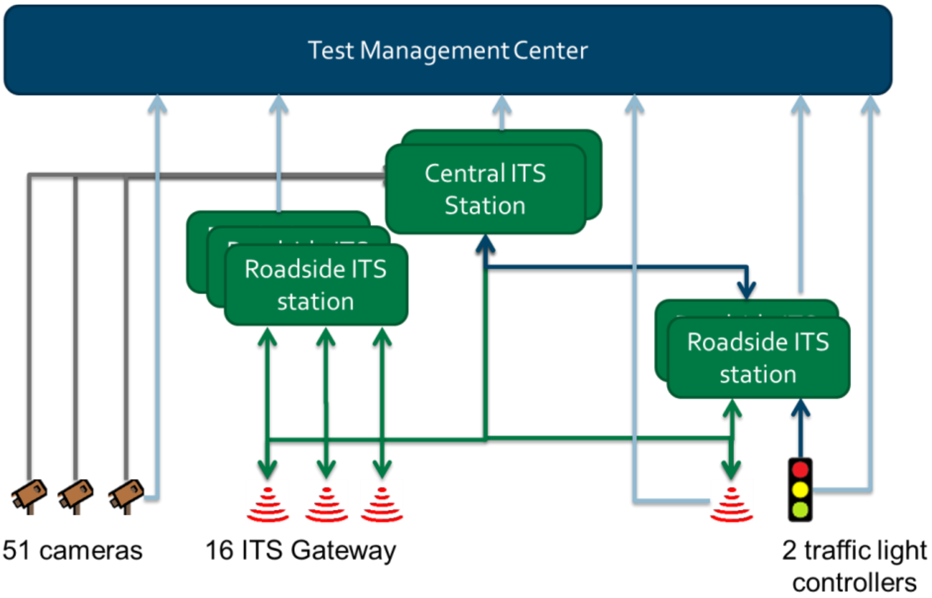

Figure 1 - High level architecture of the DITCM test site infrastructure

The Test Management Center (TMC) logs all data on-line from the cameras, communication and applications on the RISs and CIS. The TMC also provides the tools for on-line analysis and evaluation of the log data. The received V2I messages are decoded, validated and interpreted for monitoring events and application performance. Vehicle tracks from CAM messages can be compared or fused with VBM tracks in real time. The TMC can also provide UMTS communication to exchange data online with the VIS and to collect log data for online analyses and evaluation. Offline, the log data from vehicles is collected, analysed and validated against the log data from VBM, RISs and CISs.

The DITCM test site has been used for several national and international projects, e.g. SPITS [7][8], GCDC [9], Connect & Drive [10], CONTRAST [11], DRIVE-C2X [12], in which many different road side, vehicle and central ITS Stations from DITCM and third parties have been tested. Performance issues seem to re-occur and the following sections show typical results.

Time synchronization

Time synchronization between ITS-Stations is an essential condition for interaction and cooperation. All data exchanged between ITS-Stations is time stamped with a generation time and has an implicit or explicit time validity. The time stamp enables a receiver to align the received data to its own time scale and maintain a consistent cooperative and situational awareness of its environment. Consequently, if ITS-Stations are not time synchronized, or not aware of time differences, the data cannot be aligned in time, resulting in errors in relative positioning, safety distance, time gaps to an event and the advice to drivers. A second issue typical for technical evaluation is that the time stamping of log data from different ITS-Stations cannot be aligned and compared for analysis.

All DITCM road side equipment, including the communication units, RISs, CISs and logging systems are NTP time synchronised. The absolute time offset of the CUs compared to UTC time is within 5 msec, and is known with an accuracy better than 1 msec. All measurements have been corrected for the known time offset of the CUs. All G5 messages received by the CU of a RIS (RCU) are time stamped on the physical interface of the RCU.

Time offsets and synchronisation of a VIS can then be estimated on-line on a RIS by comparing the generation time in the received CAM ($T_{CAM\_generation\ time}$) with the reception time of the raw packet on the RCU ($T_{reception}$). The time difference between these two measurements is the sum of the offset of the clock in the VIS used to time stamp the CAM generation time, the delay in the AU and CU of the VIS before transmission, the transmission time between the VIS and RIS, and the time between reception and time stamping of the reception time at the RCU. The transmission time and time between reception and time stamping on the RCU are both in the order of 0-2 msec, and negligible compared to the total measured delay. Therefore, this time difference measurement is a measure for the sum of the time offset and delay in the AU and CU of the vehicle.

Time offsets between ITS-Stations

The time offset and delay in the AU and CU of the VIS cannot be separated in external measurements on the RCU, and should be determined from the on-board log data of the VIS. The delay depends on the system implementation and the processing load on the VIS. The delay has a minimal contribution to the time difference and a quickly varying contribution due to the processing load. For real-time estimation of time synchronisation, we can assume that the minimal time delay is small in comparison to the time offsets we are interested in. This time offset can then be estimated as the moving minimum value over small time intervals as:

$$\text{Time\_offset} = T_{\text{reception}} - T_{\text{CAM\_generation time}}$$

Figure 2 shows a snapshot of the time offsets of 13 VISs measured simultaneously in a field test. The magnitude of the time offsets obviously depends on the implementation in a particular VIS. It can be observed that 6 vehicles have a time offset within +/-100ms and 11 vehicles (85%) are within +/-500 ms compared to UTC. It also shows that some vehicles have a time offset larger than 1 sec. Note that in [2] the time between data acquisition, time stamping, and sending of the CAM is specified to be within 50 msec. Older data should not be sent. This is obviously not realised in Figure 2.

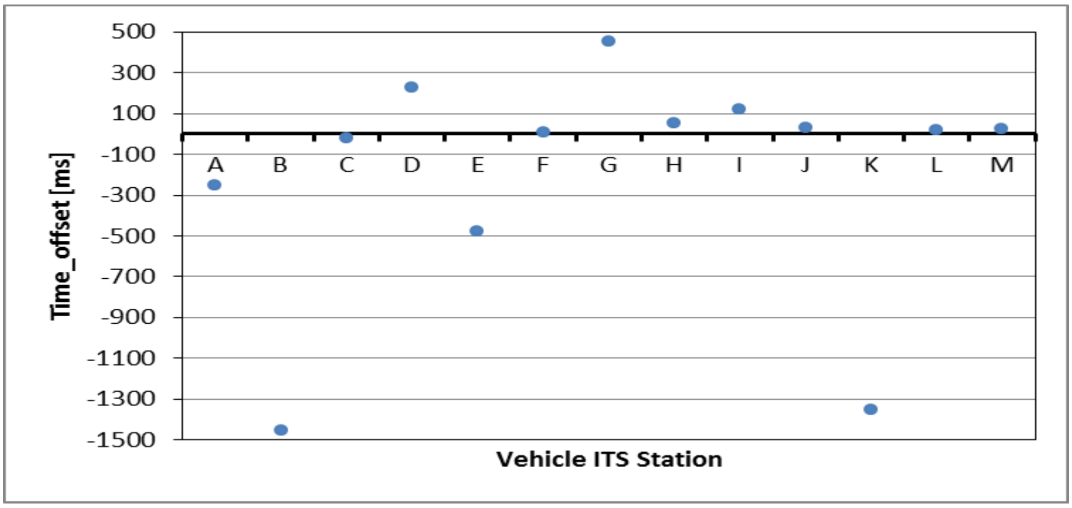

Figure 2 - Real-time monitoring of time offsets of Vehicle ITS-Stations (A – M)

Synchronization mechanisms

Several mechanisms can be used to synchronise the system time of vehicle ITS Stations. The immediate effects of time synchronisation can be observed as regular patterns in the continuous measurements of the time offset. In the previous section, the time offsets were minimized over a moving time window to estimate a system time offset. Figure 3 shows the continuous time offset after normalization to correct for the system time offset of each VIS from Figure 2. The following patterns can be observed that are most likely caused by synchronisation at the VIS:

- A horizontal line indicates that a stable and constant time offset is maintained (within the accuracy of this approach),
- A slanted line indicates a constantly drifting time offset that is not corrected,
- A saw-tooth pattern indicates a frequent time adjustment to correct the drift. A frequency of 1 Hz updates is typical for standard GPS time-synchronization,
- A wave-like pattern indicates a continuous (high frequency) time-synchronization mechanism like NTP via 3G.

It can be observed that it is feasible to keep time offsets within a window of 20 msec. However, it can also be observed that variations larger than 30 ms are not unlikely, and if no synchronization mechanism is applied that time can drift by almost 100ms/15min =~1E-4.

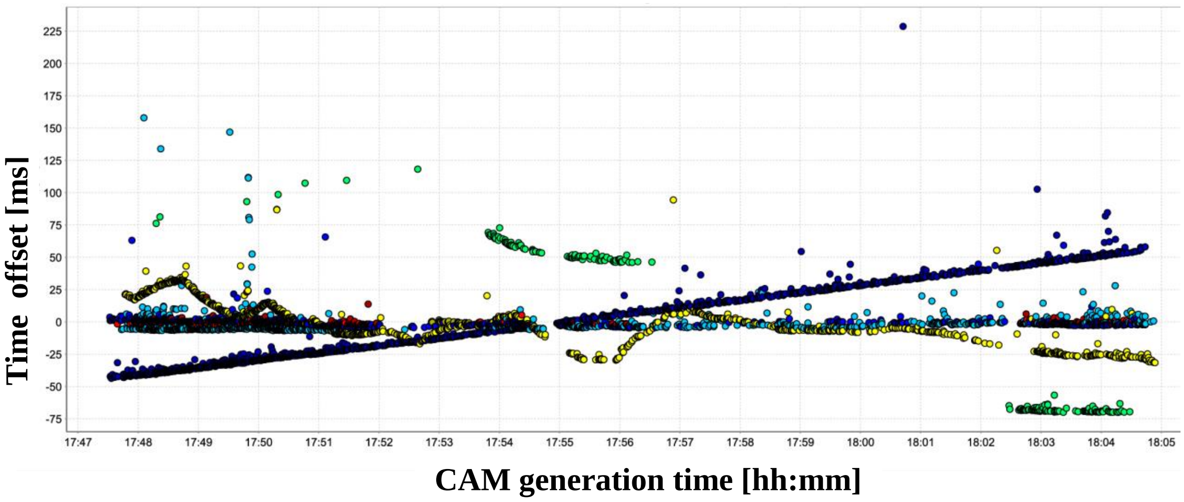

Figure 3 - Effects of time synchronisation mechanisms in Vehicle ITS Stations (colour).

Positioning accuracy

The positioning accuracy directly affects the accuracy of the distance to an event. The positioning accuracy cannot be evaluated from the logging of a VIS itself and requires external reference measurements. The DTCM infrastructure allows to evaluate positioning accuracy of Vehicle ITS Stations using RTK-GPS or Video Based Monitoring (VBM). The RTK-GPS positioning system is very accurate but can only be used in one or a few vehicles for off-line evaluation. VBM is a system that uses the fixed cameras for real-time tracking of vehicles in camera range [13]. VBM provides trajectories of positions and speeds at 10 Hz, and for all cooperative and normal vehicles, from which headways and time-to-collisions can be calculated for safety assessment.

The positioning accuracy of VBM is in the order of 0.5 - 1 m in longitudinal direction and 0.1 to 0.25 m in lateral direction. The accuracy depends on multiple factors, primarily on the distance to the camera, but also lighting conditions and even type of vehicle. This system has shown to be robust under various operating conditions such as day and night time, and under sunny, cloudy or rainy weather types and with snow [14].

The vehicle positioning accuracy can be evaluated from the difference between VBM positions and the vehicle positions broadcasted in CAMs or from the on-board logging. The position error is defined as:

$$\text{Position\_error} = \text{Position}_{\text{VBM}} - \text{Position}_{\text{CAM}}$$

The CAM positions are taken for the CAM generation time after correction for the time offset from the previous section. The VBM time stamp is the time stamp of a video frame and is NTP time synchronized. The position error is positive if the CAM position lags the VBM position. Figure 4 shows the error measures for two vehicles driving at the same speed at the same time on the same motorway section. Note that VBM measures the position of the rear bumper of a vehicle, while the CAM position is the front bumper. This implies a constant negative bias of the vehicle length in Figure 4.

Figure 4 show significant variations in the vehicle position errors and two temporal effects. Vehicles are driving on the motorway at about 30 m/s. The higher frequency jitter is caused by timing differences between VBM and CAM updates. The left vehicle has CAM position update frequency of 10 Hz and the right vehicle of 1 Hz, causing a deviation of about 18 m in longitudinal direction relative to the VBM positions.

The coarse (low frequency) effect results from GPS positioning. The longitudinal error of the left vehicle is 6 m on average, or 10 m with correction of a vehicle length of 4 m, with a standard deviation of 3 m. The standard deviation suggests a variation resulting from GPS updating, errors and data filtering. A systematic error of 10 m suggests a delay between data acquisition and time stamping. At a vehicle speed of 30m/s, this delay is about 333 msec, which is much larger than the required 50 msec [2].

The longitudinal error of the right vehicle is much higher and varies between -40 and +30m with an average of -9 m, or -5 m with vehicle length correction, and a standard deviation of 18 m. It should be noted that the vehicle positioning system performed as expected during the test in Figure 4 and that the occasional loss of GPS performance results in even larger errors or complete loss of a positioning capability.

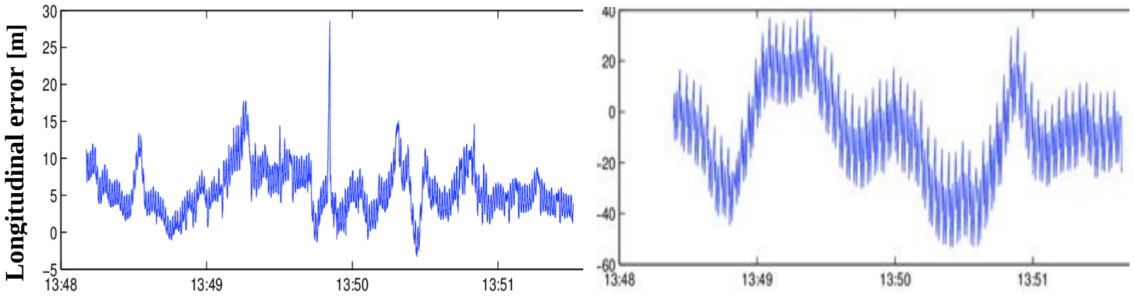

Figure 4 - Longitudinal position errors for two vehicles over time [hh:mm].

Communication performance

The communication performance of Vehicle ITS Stations can be evaluated from the message reception on Road side Communication Units (RCU). The communication performance is, amongst others, determined by the packet delivery ratio (PDR), which is the ratio of the number of received and transmitted packets. The PDR is determined by the received signal strength (RSSI), the quality of the receiver and the noise levels.

A RCU has the complete networking stack, including a Geonetworking implementation from TNO and Peek Traffic [15]. The RCUs all have 2 independent communication channels. One channel is used as part of the system under testing. The second channel can be used in listen only mode. At the mac layer, all communication is captured to determine signal strength and packet loss as a function of position for all test vehicles. The location of the RCUs is such that the packet delivery ratio is 100% over the full length of the motorway [15]. Communication performance can now be evaluated in two approaches.

Direct PDR and RSSI measurements

To enable the measurement of the PDR and RSSI, the wireless interface of a CU is cloned in the software driver on the mac level. On the cloned interface, the radiotap header containing the RSSI information is enabled, and all outgoing and incoming packets are captured and stored for offline analysis. The RSSI and PDR are determined from the captured CAM packets at a single RCU as a function of communication distance to 10 passing VISs in Figure 5 (left). The distance is negative in upstream direction of the RCU, which is the communication distance to the front of the vehicle.

The VIS of the green line shows a significantly higher received signal strength (5-10 dBm) than all other vehicles. This might be due to a higher transmit power or antenna with higher gain. It results in a significantly larger communication range, especially for positive distances.

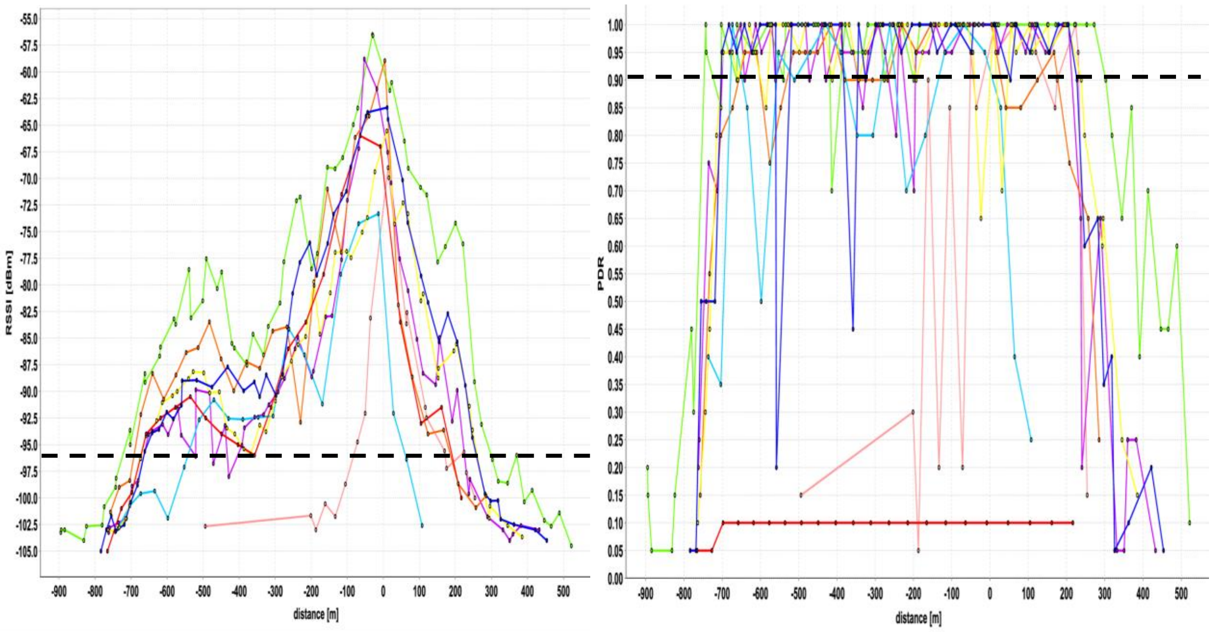

Figure 5 - Received signal strength (RSSI - left) and Packet Delivery Ratio (PDR - right) measured on a RCU as a function of the distance from 10 sending VISs (colour). Negative distances indicate that the vehicle is driving towards the RCU.

To quantitatively determine a maximum effective communication distance, a minimum threshold is set for the PDR>0.90. When disregarding an occasional spike, most vehicles have an effective communication range of 700m to the front of the vehicle and 250m to the rear. A few VIS have a significantly smaller range. The pink line shows a VIS with a much smaller range of 50 m to the front of the vehicle, and the light blue line shows a VIS with a much smaller range of 50m to the rear. The directionality is caused by the antenna profile and placement on the vehicle.

The PDR is determined as a 1 second moving average of received messages, assuming that CAMs are transmitted at 10Hz. When a vehicle adapts the CAM frequency, the PDR estimates will be incorrect. The red line shows a vehicle sending CAMs at 1 Hz, thereby reducing the delivered packets by a factor of 10.

Rapid PDR extraction from RSSI measurements

The determination of the PDR is influenced by the statistical accuracy of the measurement, and by the assumption of a CAM transmission rate of 10Hz. To overcome these issues, the PDR can also be extracted from the RSSI and a known relation between PDR and RSSI. This relation is depending only on the details of the receiver, and not on the sender, and has been calibrated in situ for all RCUs on the test site. Figure 6 (left) shows this calibration of PDR for RSSI for the RCU in Figure 5.

From this measurement, it can be concluded that the received signal strength of -96 dBm is sufficient for a PDR of 0.90 or better. All VIS in Figure 5 (left), except the red and pink, cross the -96 dBm somewhere between -750m and -350m in front of the vehicle and between 120-280 m to the rear. The spread at the vehicle front side is rather large compared to the rear. The reduced RSSI at these distances results in significant fluctuations of the moving averages of the PDR. The statistical noise on the PDR measurements makes it difficult to draw conclusions on the performance of an individual vehicle. Estimating the PDR from the measured RSSI is less sensitive to statistical noise (cf. Figure 5 to Figure 6). Furthermore, this method works for any message type, even if not transmitted at a fixed and/or high rate, like the red vehicle.

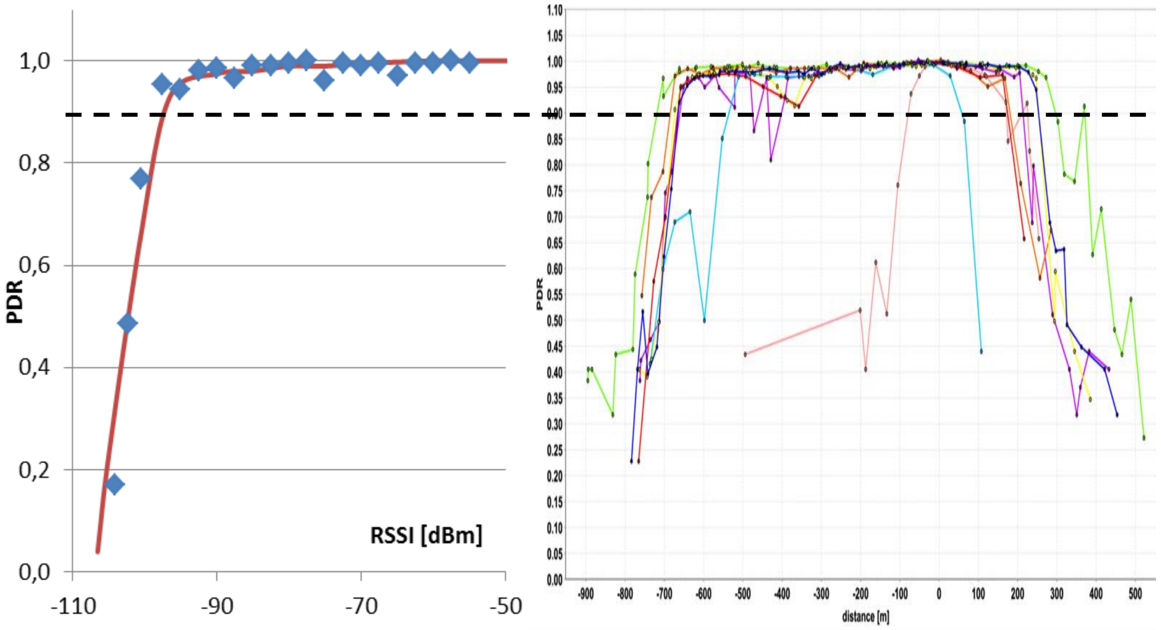

Figure 6 - PDR versus measured RSSI (left) with the calibration function in red. PDR estimated from the measured RSSI (right).

Effects on applications and driver advice

The above sections presented typical performance results for time synchronisation, positioning, and communication of cooperative vehicles of different origin. These results were obtained in recent field tests on the DITCM test site. Large variations in performance are observed. Ultimately, these variations impact the possible accuracy of the distance or time to an event advised to drivers.

An estimate can be made of the effects on driver advices in a Vehicle ITS Station (VIS). We consider two situations as worst case scenarios:

1. The example of section 1; a host VIS with a speed of 30m/s requires a warning 3 sec or 100m before an event occurring with another VIS that sends CAM and DENM messages with similar or larger errors but of opposite signs, such that the total error is the sum of the vehicle errors.
2. A GLOSA application [3]; a host VIS approaches a traffic light with a speed of 15 m/s. The Road side ITS Station (RIS) updates the time-to-next-phase-change in a SPAT message when the VIS is 6 sec (about 100 m) before the stop line and should make a stop or go decision. We assume that the time and position errors of the RIS are negligible compared to the errors of the VIS.

Figure 6 shows that most Vehicle ITS Stations (VIS) have a minimal communication range of 700 m to the front of the vehicle and 250 m to the rear. The antenna patterns are obviously biased to receive warnings from ITS stations ahead rather than warning followers. However, communication ranges as small as 50m to the front or rear have also been measured, which clearly cannot satisfy the communication demands of cooperative applications.

Time synchronization mechanisms can keep a time offset within 20ms variation on Vehicle ITS Stations (VIS) and the Road side ITS Stations (RIS) can be kept within 5 msec. Without synchronization however the time offset drifts away as fast as 400ms/hr (Figure 3), meaning that the time offset will increase by 1 sec every 2.5 hours.

Two classes of implementations of Vehicle ITS Stations (VIS) can be considered:

1. In a simplified approach, a VIS uses the reference positions in the CAM and DENM as is for computing a driver advice. Generation times of the messages are ignored.
2. A VIS fuses information based on the generation time and reference position in the CAM and DENM. Most likely, the host VIS synchronises its system clock and also filters out the short term variations in reference positions in the messages.

In situation 1, a driver advice is determined from the distance of the host vehicle to the reference position in the DENM. Figure 4 shows that a systematic offset in vehicle position of +/-10m is common, while values of +/- 20 m with temporary outliers of +/- 40 m are not uncommon.

In implementation 1, the worst case error of the distance-to-event is twice the momentary error; i.e. the worst case error is 40 m on average and 80 m when the temporary outliers are not filtered. A time-to-event is derived from the distance and speed, and has an error similar to the distance-to-event error. These errors are of the same order as the warning distance and time!

In implementation 2, it can be assumed that the host VIS has an average position error in the order of 10m. It can also be assumed that the host VIS filters out the short term variations in reference positions in the messages, and the worst case systematic distance-to-event error is in the order of 20 to 30m. The error in time-to-event, when driving at 30 m/s is 0.7 to 1 sec, and similar to the driver reaction time. Potentially, the host VIS can estimate the time offset relative to the other VIS from the generation times in successive CAMs. If not, then the time offset will introduce an additional distance error, equal to the total time offset between the two vehicles times the vehicle speed of 30 m/s. The worst case error in the time-to-event increases with the time offset error. As shown in Figure 7, the errors can be smaller than for implementation 1, but the errors rapidly increase with time offset, so correction for time offsets is necessary as part of the fusion process.

In situation 2, a remaining time to next phase change or a speed advice is given to the driver. The error in speed advice is similar to the distance in situation 1. The error in a time advice is equal to the error in the time offset. Implementation 1 does not correct the time offset of the host vehicle, so an outlier VIS with a time offset of 1.5 sec (Figure 2) will generate an error in the time-to-event of 1.5 sec. The same holds for implementation 2 if time offset is not corrected.

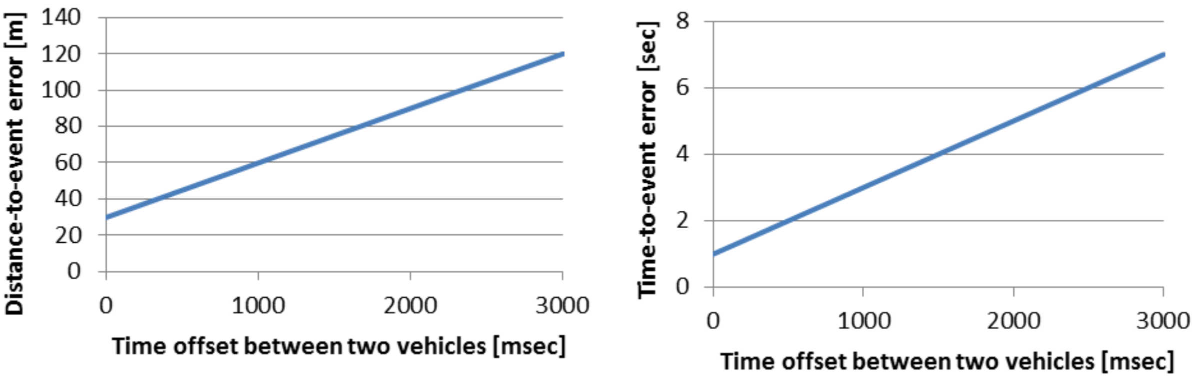

Figure 7 – Advice errors for situation 1 and implementation 1, with a systematic error in the distance-to-event of 30m and without correction of time offsets.

Discussion and future work

The above sections presented typical performance results for time synchronisation, positioning, and communication of cooperative vehicles of different origin. These results were obtained in recent field tests on the DITCM test site. Large variations in performance are observed between Vehicle ITS Stations from different projects and developers. The variations in performance will have a significant impact on the possible of applications and the accuracy of distance and time to an event advised to drivers. Worst case situations are sketched in which the errors in the distance and time to an event have the same magnitude as the advice. Such an advise would be useless to the drive and not impact traffic safety when a warning or severe warning should be provided.

Field test results also show that existing technology is available to improve time synchronisation, positioning and communication performance. It should also be assumed that ITS Stations should be robust against communication failures, timing and positioning issues. However, in a cooperative system, the driver advice does not only depend on the performance of the driver's host vehicle and the specifications of a single manufacturer. If there are no requirements on time synchronization, positioning accuracy or communication performance in the standards, cooperative systems may be released on public roads that will cause safety issues.

Standards or common specifications should therefore be defined to set performance requirements on time synchronisation, positioning and communication, and especially for criteria for applications to deal with performance issues and for allowable tolerances for driver advice.

Testing safety applications on a public road is prohibitively dangerous, especially in the severe warning situations around 2 sec before an incident. Therefore these application should be tested on either a private test track or in a test facility. DITCM operates a test facility called the "Vehicle Hardware in the Loop" laboratory (VeHIL) [16]. VeHIL allows to carry out safety and time critical tests in which the vehicle under test is placed on a roller bench (Figure 8), while robots execute relative movements around the test vehicle to represent the neighbouring vehicles. The real vehicle, with its on-board sensors, communication, and cooperative applications, can be tested to the limits. The main advantages of this test facility is that it allows a complete system test in a safe and reproducible manner and it enables fine-grained tuning of the sensors and applications.

Figure 8 - Time-critical tests executed in VeHIL

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