Real-World Evaluation of C2X-Road Side Warning Devices

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***Abstract*—Road side warning devices play an important role in car-to-car communication. Interestingly however, a detailed experimental evaluation of such devices is missing. Furthermore, although these devices should be able to perform self-positioning to work properly, little attention has been paid to this: mostly, it is assumed that GPS hardware could be used. In this paper, we show that road side warning devices can use information from vehicular beacon broadcasts to approximate their position *without* dedicated positioning hardware. We analyze existing techniques for this and discover that a straight forward approach leads to a high lateral positioning error that can prevent the determination of the traffic flow actually affected by the hazard. We present an algorithm to overcome this and evaluate our concept in an extensive experimental study.**

I. Introduction

Car-to-car communication (C2CC) can increase road traffic safety and efficiency by informing the driver about hazards [1] or traffic jams [2]. Though the research focus has mostly been laid onto vehicle-centered systems, the idea to equip other road traffic-related devices with computing capabilities has also been around for a while. However, a more thorough analysis—especially an experimental one—has been missing up to now. In this paper, we alleviate this issue.

In particular, we focus on road side warning devices in the form of warning triangles [3], enhanced with C2CC capabilities. As this inexpensive and purely visual version of a road side warning device is mandatory for each vehicle in some countries, it is a good candidate for being enhanced. By replacing their old warning triangles, even owners of vehicles without C2CC units could benefit from this technology. Furthermore, if a vehicle's C2CC unit becomes damaged, e. g. due to an accident, such devices could act as fallback solutions. The basic idea behind the enhanced version is simple: in case of a hazard, the warning triangle is placed ahead of the danger area and transmits warning messages to approaching vehicles. Obviously, these messages should contain information about *which* part of the road is affected so that non-affected vehicles within radio range do not need to alert their drivers unnecessarily. Hence, the warning device should also know its current position.

Existing approaches [4], [5] assume that such a device implements self-positioning capabilities via Global Navigation Satellite Systems (GNSS) such as GPS. In contrast to that, we show that periodic beacon messages transmitted by each vehicle can be used to perform self-positioning via multilateration, thus not requiring the support of such systems. In addition to the scientific interest, there are economic and technical reasons to motivate this approach: first, integrating a GPS-chip raises system cost, complexity, and energy consumption. Without such chips, devices use less energy and are cheaper (in mass-market devices, a few cents make a difference). Second, vehicles' sensors, like odometers, allow improvement to the vehicles' positioning, especially in areas where GNSSs do not work, e.g. in tunnels or on thoroughfares through forests. As our system derives its position from the vehicles' beacons, it inherits this property.

Our contribution is the first algorithmic design and experimental case study of a stand-alone road side warning device for C2CC. We use existing multilateration approaches to implement the system with GNSS-free self-positioning capabilities and provide a detailed description of the basic functioning. We show that due to the special structure of vehicular movements, these existing multilateration techniques alone do not provide sufficiently accurate position information. Instead, a domain-specific lateral positioning error is likely to occur. We present a solution for this.

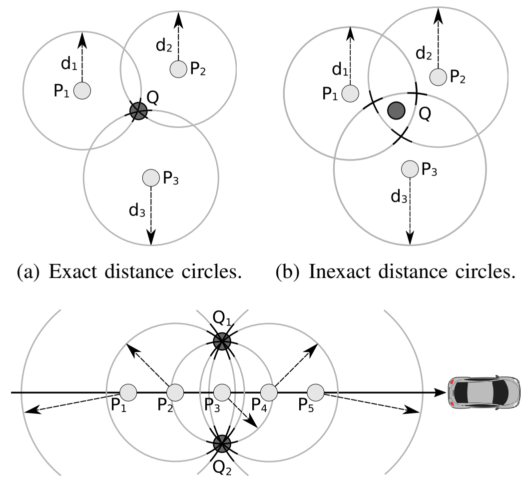
Section II gives an overview on related work, followed by Section III with the introduction of the algorithmic concept behind the warning triangle and its self-positioning system. In Section IV, we then present an experimental evaluation of this concept. Section V concludes the paper.

II. Related Work

Current traffic regulations make a number of offline warning systems mandatory, such as a warning triangle [3], among others. These triangles are normally carried in the trunk of a vehicle and are erected on the roadside, a certain distance upstream of the danger area. Such a warning triangle is a purely passive device equipped with clearly visible reflectors. Since it is already a well-known road side warning device that can easily be upgraded with communication capabilities, we will use it as an exemplary application throughout the paper.

The general idea to transmit traffic-related warning messages wirelessly was first presented in 1977 [6] by allowing the vehicles to transmit the warnings themselves. This car-to-car centered approach has been adopted in subsequent work, e. g. [1]. Though the concept to transmit warning messages from a stand-alone device to approaching vehicles seems obvious at first sight, neither a technical description nor an experimental evaluation is available. The only projects that have dealt with these issues up to now were a demonstration during the 2008 Car to Car Communication Consortium Forum [4] and a setup tested in the context of the Willwarn-project [5]. These differ in three key points from the results in this paper: they rely on a GPS-based positioning of the warning device, they do not present a technical description, and they do not provide an evaluation of the approach.

Road side units have also been used to exchange data with traffic lights [7] or to provide connectivity in the deployment phase of C2CC technology [8]. However, these approaches clearly differ from our goal to develop a stand-alone warning device. The area of positioning, also important for our work, gained a lot of attention in recent years. It ranges from commercial WiFi positioning to systems for wireless sensor networks [9]. The localization of vehicles via triggered messages from other vehicles is covered in [10]. In contrast to our work, the system must work for moving vehicles and thus faces some constraints, e. g. at least three vehicles need to simultaneously transmit a reply message to a request. Furthermore, the presented results are based on simulations while we provide a detailed real-world study.



(a) Exact distance circles. (b) Inexact distance circles.

(c) Ambiguous result of a multilateration.

Figure 1. Localization by multilateration.

III. Concept

In this section, we discuss our proposed system's concept and focus on the information which must be derived from the vehicles' beacons. We see that common positioning by multilateration can lead to a very high domain-specific lateral error. We then present an algorithm to determine the direction of the traffic flows that are affected by the announced hazard to compensate for this.

A. Overview

Our enhanced warning triangle should be usable like a regular, existing one: it is removed from a vehicle's trunk, then unfolded and carried along the road to an *upstream position* whereby vehicles pass before driving past the hazard area. There it stays until the incident site is cleared.

Users benefit from our proposed warning triangle in every stage of usage: Once a driver has unfolded and placed the warning triangle in position to warn approaching drivers, the triangle begins to broadcast generic warning messages periodically. As there is no further information available in this phase, these messages contain a mere warning about a local hazard. Due to the limited radio range of IEEE 802.11p interfaces used in C2CC, every receiver of the message is close to this hazard and can consider such a general warning as relevant. However, not all receivers will actually *pass* the danger area. Therefore, the messages should ideally contain enough information to enable a receiver to individually decide on a warning's relevance. Consequently, the warning triangle calculates and transmits this more specific information—in our approach, this is, among others, its position—as soon as it is placed at its final stand. When the triangle is removed from the upstream position, it returns to sending general warning messages to protect the person carrying the device.

A vehicle decides on the relevance of a received message by determining whether it is going to pass the announced position or not. The first source of information for this decision is the location propagated by the warning triangle. Although this narrows down the affected area, possible positioning inaccuracies of the warning device and the vehicles still make this decision difficult. Therefore, the warning messages should also contain information about the affected driving directions. This is calculated by our system whenever possible and included as a *heading angle range* in the warning messages. A warning is relevant for all vehicles approaching the announced location with a heading within the specified range to overcome heading measurement inaccuracies.

B. Localization

Depending on the application area, different methods for the localization with wireless signals are available [9]. Most of these, however, require dedicated positioning hardware on the sender or receiver side. Instead, we propose to derive the warning triangle's position from the content of *beacon messages* sent by passing vehicles [11]. Such messages include information like the sender's current position or the beacon's transmission power [4] and are typically sent at regular intervals (current discussions indicate a frequency of 1-10 Hz). These beacons are used by safety applications to allow vehicles to be constantly aware of each other.

The information about the senders' positions can be exploited to infer the receiver's position as it is depicted schematically in Figure 1: each light gray point P_i marks a position from where a beacon has been sent. The circles around these points refer to the (exact or approximate) distances between the senders and the receiver at the unknown position Q at the moment of the respective beacon's transmission. If the exact distances were known as depicted in Figure 1(a), the receiver could calculate its own location from the positions P_i and distances d_i using a multilateration algorithm. However, the receiver does not know the distances to the senders but has to approximate them. For the presented application, we use the

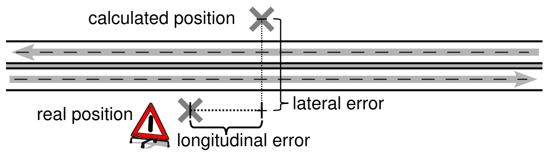


Figure 2. Longitudinal and lateral error in the position calculation.

so-called *Received Signal Strength Indicator (RSSI)*, as it is even provided by off-the-shelf hardware. It describes the signal strength above the noise floor and can be easily converted into the strength of a received radio signal in dBm. Since signal strength decreases over the covered distance, RSSI measurements allow to approximate the distance between sender and receiver. This decrease can be expressed by the path loss $L_0 = P_{tx} - L_{tx} - P_{rx} - L_{rx}$ of the signal that is calculated from the transmission power and loss (P_{tx}, L_{tx}) and the reception power and loss (P_{rx} and L_{rx}).

To calculate the distance d between a station that transmits signals with a carrier frequency f_c and a receiving station, L_0 can be employed in a so-called path loss model. Such a model approximates the path loss under certain conditions. In our approach, we use the free-space model [12] that considers only the direct line of sight propagation. Using this model, d can be approximated as

$$d = 10^{\frac{L_0 - 32.44 - 20 \cdot \log(f_c)}{20}} .$$

Although more elaborate propagation models exist [13], parameter tuning for these can be difficult and unreliable. Furthermore, our experiments have shown that the free-space model works very well for the range of short distances relevant for the considered application. Generally, with any radio propagation model, the impact of effects like reflections or scattering cannot be fully eliminated. Therefore, a signal strength measurement only allows to *approximate* the covered distance. For this reason, the distance circles around the senders do not intersect in one particular point, as depicted in Figure 1(b). This makes a pure multilateration impossible.

To overcome inaccuracies that result from these imprecise input parameters, we consider a larger number of measurements. Based on these, we calculate the location where the sum of distances to all distance circles is minimal, thus being the most likely position of the device. This is an optimization problem, solvable with e. g. the *method of least squares*.

This algorithm applies for most situations. But since a lot of streets feature a relatively linear design at least within the radio range covered by a road side device, the warning triangle might receive beacons from positions $P_1, \ldots, P_n$ that roughly lie on a straight line, see Figure 1(c). In this case, two possible solutions Q_1 and Q_2 for the multilateration (in fact, two local minima for our optimization problem) exist. In such a setting, not the true position of the warning device, but the initial starting value of the iterative optimization determines which of the two possible solutions is found.

To analyze the influence of domain-specific properties of the input data in our evaluation, we differentiate between two kinds of positioning errors. As depicted in Figure 2, a *lateral* error refers to an inaccuracy perpendicular to the driving direction while a *longitudinal* error corresponds to a deviation in this direction. The mentioned ambiguity results primarily in a lateral error of the location approximation, while the longitudinal precision is rather high.

Initially, this seems to be a major problem. However, this is why the warning triangle also calculates and transmits the above-mentioned heading angle: a correct longitudinal location coupled with the driving direction for which the hazard warning is relevant allows for an accurate determination of the warning relevance within the vehicles.

C. Heading Constraint

The warning device's calculation of the heading for which the warning is relevant (*heading constraint*) is based on some basic observations: the warning device will be set up on the hazard's side of the road, so that affected vehicles will pass it at a significantly smaller distance than non-affected vehicles. Hence, beacons from vehicles on the affected side of the road will be received by the warning device at a higher signal strength level and the subsequence of beacons with the highest average signal strength will most likely originate from vehicles that are in the very act of passing the device.

To exploit these properties, the device stores the heading angles with the corresponding signal strength measurements from the received beacons in separate, per-vehicle sequences of chronologically ordered tuples. As assumed earlier, the b consecutive tuples, for which the average signal strength value is maximal, are supposed to belong to their originator's passing of the warning triangle. Therefore, we keep these tuples for further processing. For the remaining measurements, it is solely logged that beacons from the particular heading angles have been received at all.

Next, for each possible heading angle, the average signal strength from the set of gathered tuples is determined; this allows to weaken the effects of outlier measurements. Subsequently, the moving average of these values is calculated, where the averages are weighted by the number of measurements from which they have been calculated. In doing so, the major driving directions are emphasized and isolated.

The number of vehicles from which measurements need to be taken to determine the heading constraint depends on multiple factors. Such are the street topology, the number of different major driving directions or the number of actual affected vehicles, which pass the device. In each of our experiments, already less than ten measurements in total allowed a correct calculation of the respective heading constraint.

Once the major driving directions have been isolated, the heading constraint is determined and propagated only on two conditions: 1) there has to be a heading interval of signal strength averages with a peak at angle γ significantly larger than any other interval's peak in the measurement set. This condition follows the observation that a significant difference of signal strength measurements for two heading angles results from a large spatial or constructional, thus radio-blocking lane separation. Therefore, a hazard is only relevant for the side of the road with the strongest signal. Without such a difference, the lanes seem to be close, causing both directions to be affected by the hazard. According to this condition, the heading constraint is only propagated in case of clearly separated lanes. 2) There are also measurements for the heading angle $\gamma_o = \gamma + 180 \mod 360$, i. e. the opposite driving direction. This guarantees that our decision is based on data for both directions γ and γ_o and is not ignoring the opposite direction just due to the absence of measurements. If one condition fails, no heading constraint will be issued.

We are completely aware that the heading of the closest traffic flow could also be retrieved by an electronic compass within each device. However, the *closest* traffic flow is not always the only affected one. In contrast to electronic compasses, our algorithm takes this observation into account.

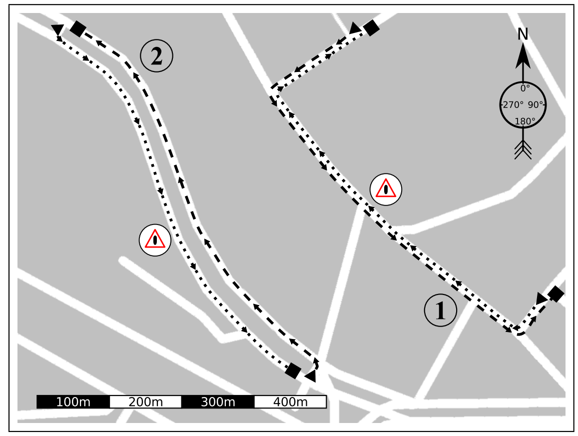
IV. Experimental Evaluation

A. Setup

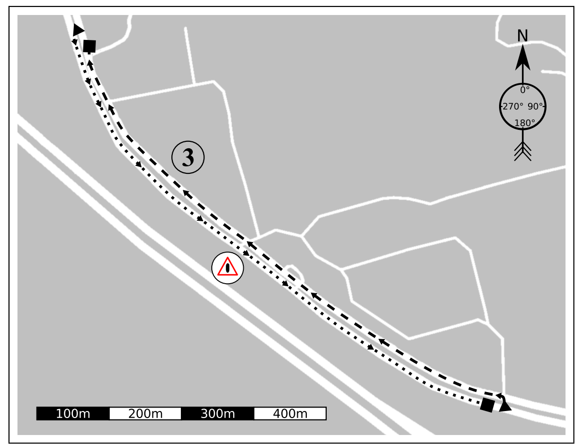
To evaluate the proposed system under realistic conditions, we performed an extensive outdoor measurement study with various parameters, such as different environments, vehicles or weather conditions. In our experiments, two identical Lenovo X61 Thinkpads with PCMCIA IEEE 802.11a/b/g adapters and external antennas were employed. Due to a +5 dBi antenna gain, both stations worked with a total transmission power of 24 dBm. We also measured the antenna's static loss parameters to improve the accuracy of our estimations[1]. With a patch for the `madwifi-0.9.4`-driver, we were also able to extract the RSSI value for each received packet. In all experiments, we used both computers simultaneously. One acted as *On Board Unit (OBU)* in the vehicle and transmitted beacons at a rate of 5 Hz. These contained the vehicle's position and the transmission power for this beacon, as proposed in [4]. To determine its position during the experiments, the OBU was equipped with a GPS receiver. Both the GPS and WiFi antennas were mounted on the vehicle's roof top. The second computer served as communication-enabled warning triangle and was situated on the shoulder of the road. Its location was determined prior to the experiment using a GPS device, but solely to evaluate the position approximation accuracy after the experiment.

As shown in Figure 3, we chose inner-city test tracks in different surroundings to evaluate our system regarding the topology, movement and radio propagation: encircled warning triangle icons denote the second computer's locations during the respective experiments. Track 1 covered three regular road segments without any constructional lane separations, allowing the presumably best possible radio propagation from all lanes. The middle road segment, where the warning triangle was located, had two lanes in each direction. On Track 2, there were also two lanes in each direction, but also a green area with trees and tram rails in between. Moreover, a line of

[1]As outlined in Section III-B, the transmission power and loss must be known to derive the sender-receiver distance from the RSSI-value.



(a) Tracks 1 and 2.



(b) Track 3.

Figure 3. Geographical experiment setup.

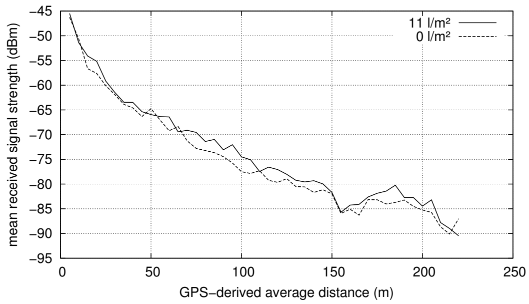
parking cars in the middle was blocking the direct line of sight from the warning device to the far side of the road, most likely affecting the radio propagation. Track 3 had one lane for each direction with a green area and sparsely distributed small tress in between, so that merely a low radio propagation limitation was expected.

We drove each track several times in both directions to emulate the presence of multiple vehicles, thus creating multiple movement and radio traces. Each experiment consisted of at least five such loops.

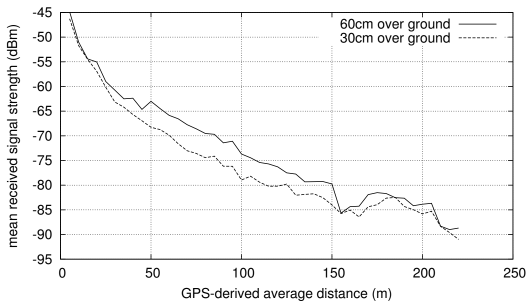
B. Influence of External Factors

The algorithms proposed in Section III are based on signal strength measurements derived from the RSSI value provided by our WiFi adapters. Since this is an important system parameter, we first analyze its dependency on external parameters. As the experiments have been conducted for various conditions such as different amounts of precipitation (AOP), multiple vehicle models, or antenna altitude above ground, the impact of these factors can be assessed.

Figure 4 summarizes our observations and plots the received signal strength over the GPS-derived distance between sender and receiver. In general, a parameter has a high impact on



(a) Track 1: amount of precipitation (AOP).



(b) Track 1: antenna altitude.

Figure 4. Impact of parameter modification on the received signal strength.

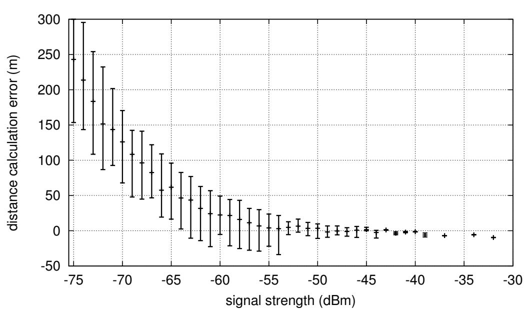


Figure 5. Distance computation-error using the Free-Space-Model.

the received signal strength if the respective curves differ significantly. However, this difference for AOPs of $0\,\frac{l}{m^2}$ (sunny weather) and $11\,\frac{l}{m^2}$ (heavy rain) is surprisingly low, as depicted in Figure 4(a). A similar conclusion can be drawn from the experiments with different vehicles (VW Golf and Smart Fortwo). In contrast, Figure 4(b) shows a sensitivity of the received signal strength to the altitude of the warning device's antenna. There is a difference of up to 7 dBm for distances of 50 m to 150 m. However, since the mounting point of the antenna can be optimized by the triangle's manufacturer, this should not be a major drawback.

We have seen that the received signal strength does not show a systematic distortion in presence of a variation of external environmental factors. We therefore conclude that the results for localization and heading calculation, presented in the next sections, apply to a broad range of scenarios.

C. *Accuracy of RSSI-based Distance Calculation*

An important system parameter is the accuracy of the distance between sender and receiver, approximated as described in Section III-B. This accuracy is crucial for the localization and determination of the heading constraint. Figure 5 shows the minimum, maximum and average distance computation error for the respective signal strength measured on Track 2. The results are representative for the other tracks. At very low signal strengths, the error rises to more than 300 m. As a consequence, beacons with a received signal strength below a certain threshold should not be used for the localization.

D. *Accuracy of Localization*

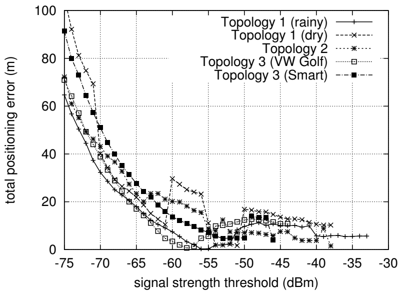
For all conducted experiments, we have evaluated the accuracy of the multilateration algorithm. Following the observations from the last section, we have analyzed the positioning error for an increasing signal strength threshold. Figure 6(a) depicts the result of this analysis as the total position error for each experiment over the used threshold. The error decreases with an increasing threshold. However, at some point, too many beacons have been excluded so that the localization error increases again at a threshold of approximately -50 dBm. Going a step further, we can focus on the lateral and longitudinal error. Comparing these errors depicted in Figure 6(b) and 6(c), it is obvious that the lateral error indeed is significantly larger than the longitudinal error. Thus, including heading constraints into warning messages is indeed a necessary step to only address affected vehicles. Furthermore, based on these experiments, we conclude that a signal strength threshold between -55 dBm and -50 dBm is reasonable, since within this range, longitudinal errors of less than 5 m could be achieved in all experiments.

E. *Accuracy of Heading Calculation*

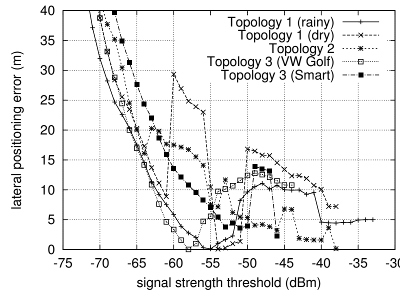
For the determination of the heading constraint, we have split each driven loop into two measurements. This is depicted in Figure 3 by different line patterns. While the dotted parts of the tracks mark the lanes directly affected by the imaginary hazard, the dashed parts refer to the opposite and thus less-affected or non-affected traffic flow.

We have isolated the major driving directions as described in Section III-C. The restrictiveness of the heading constraint can be varied with the parameter b, i. e. the number of regarded, consecutive signal strength measurements: the lower its value, the more narrow and conservative the constraint will be. For our evaluations, we chose a relatively small value of $b = 5$, still achieving exact results. Figure 7 shows the weighted average of the selected signal strength measurements for the corresponding driving directions. The filled curves refer to the heading intervals identified by our algorithm. In contrast, the vertical black line marks the manually determined *true heading* for which a warning message would be relevant. Ideally, the algorithm should find a heading close to the manually determined one.

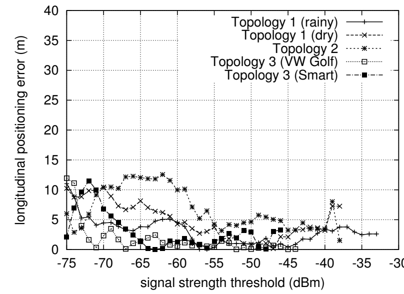
In our evaluations, the correct heading angle could be identified for all tracks. Next, we analyzed the peak level differences



(a) Total error.

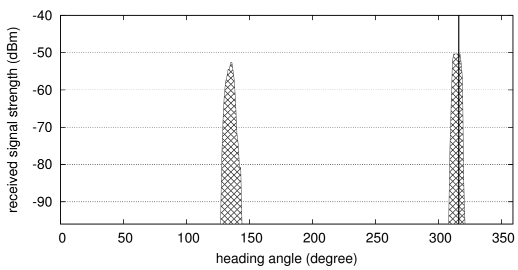


(b) Lateral error.

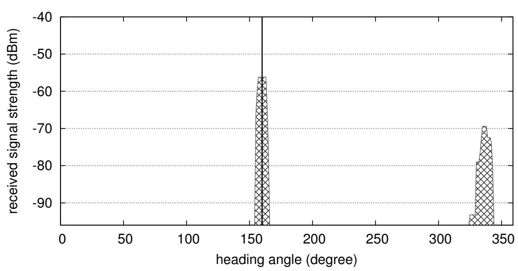


(c) Longitudinal error.

Figure 6. Accuracy of multilateration with minimum RSSI settings.



(a) Topology 1, $11\frac{l}{m^2}$ (rainy).



(b) Track 2.

Figure 7. Measured signal strengths over heading.

in our measurements. Therefore, an empirically determined ten percent difference between the top and every other signal peak level was set up as a simple criterion to identify a heading as constraint. This criterion was clearly fulfilled for Track 2 with a peak level difference of $15.7\,\text{dBm}$, as shown in Figure 7(b). This indicates a significant spatial difference between the traffic flows with the respective headings, which corresponds to our assumptions. For Track 1, depicted in Figure 7(a), the peak levels were very close, so that no heading constraint was set up by our algorithm, which is in accordance with our expectations. For Track 3, the peak level differences for the experiments with different vehicles were close to the ten percent threshold, so that a constraint was set up based on the measurements with the VW Golf, but not for those with the Smart ForTwo.

V. Conclusions

This paper shows that existing road side warning devices can easily be enhanced to participate in car-to-car communication. In contrast to existing, satellite-based systems, we propose to derive the warning device's position from information propagated in the vehicles' periodic beacon messages via multilateration. As standard multilateration exhibits a high lateral positioning error due to the linear distribution of usual vehicular position measurements, we present a new algorithmic approach to also identify the affected traffic flow's driving direction. We have conducted an extensive experiment study that underlines the robustness and practical suitability of our approach. The proposed warning system not only bears a high potential for the area of inter-vehicular safety communication, but also can be composed of a minimal, therefore inexpensive and simple set of hardware: a small embedded CPU, a few KB of RAM, and a communication interface will suffice.

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