Rethinking Cooperative Awareness for Future V2X Safety-critical Applications

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Abstract—**In this paper, we redefine cooperative awareness to include both GPS and communication-induced position errors. We reduce the GPS error through fusion-based Cooperative Localization (CLoc), and exchange such information instead of GPS coordinates. We mitigate the communication-induced errors by a novel awareness control strategy aiming at breaking the 10Hz barrier using a very lightweight awareness message. We evaluate the scalability limit of our strategy and show via simulation results that we can reach a packet Inter-Reception Time (IRT) of 15ms up to 50m at a channel load below 60%, leading to a position awareness error below 0.8m. This is a 4x improvement compared to current standards, and is an enabler to the reactivity and precision required by future ITS-G5 autonomous vehicles.**

I. Introduction

Safety-related C-ITS applications are based on Cooperative Awareness (CA) obtained by periodic broadcast of GPS information from connected vehicles. CA being critical to them - it allows to detect vehicles' positions and accordingly anticipate danger - it has been extensively investigated in literature in order to quantify its dependability and scalability. Although no formal CA definition exists, a common method for quantifying awareness consists of its reliability (i.e ratio of detected neighbors compared to neighbors present in an ideal communication range [1]–[3]), and its precision (i.e freshness of neighbor GPS positions). Several awareness control studies (in conjunction with congestion control) have been proposed and analyzed [4]–[7], which illustrated the challenge of adjusting transmit power, rate or modulation to optimize CA reliability and precision.

Quantifying the precision of CA as the time between two successive receptions of a CA message[1], previous studies aimed either at reducing the time between two CA message reception or to predict mobility between them. However, all previous studies widely assumed a perfect precision of the GPS information itself, and ignored the impact of GPS uncertainty on CA. It has yet been shown through recent European projects (HIGHTS[2], TIMON[3]) that the GPS precision is too low, and future V2X applications require Cooperative Localization (CLoc) strategies to meet their precision requirements. Although being ignored in CA so far, GPS errors are expected to have a larger impact on CA precision than any of the currently proposed awareness control strategies.

[1]This metric is known as Inter-reception time (IRT) or Inter-Packet Gap (IPG) in various studies.

[2]http://hights.eu/

[3]https://www.timon-project.eu/

In this paper, we redefine cooperative awareness by including the impact of GPS information and describe the first sketch of a new CA strategy to meet the high precision CA required by future V2X safety applications. More specifically, our contributions are: (i) we introduce CLoc to reach highly precise node position (4x that of GPS) (ii) we define a new *Precise Awareness Message (PAM)* adapted to CLoc, which is only 1/4th the size of current Cooperative Awareness Message (CAM); (iii) we propose and evaluate the performance of a High Precision Awareness Control strategy reaching CA rates up to 100Hz at a sub-meter precision.

The rest of the paper is organized as follows: Section II discusses position errors in cooperative awareness. Section III introduces our awareness control mechanism and provides preliminary evaluation results. Finally, Section IV discusses new challenges exposed by the preliminary results.

II. High Precision Cooperative Awareness

A. Background on Cooperative Localization (CLoc)

In Vehicular Ad hoc NETworks (VANETs), an "ego" vehicle can consider its neighbors as potential "virtual anchors" [8]–[10] (i.e. mobile anchors with only approximate knowledge about their own positions). The principle of vehicular CLoc works in three phases. First, each vehicle piggybacks its *absolute* position information in a "Beacon" sent over "V2X" communication links[4]. Through the reception of these "Beacons", a given "ego" vehicle becomes aware of the *absolute* position estimates of its neighbors. The second phase consists of using the "Beacon" signal statistics to sample *relative* position-dependent information from these "virtual anchors" (e.g., Vehicle-to-Vehicle (V2V) distances, relative angles, etc.). Ad hoc trilateration can then be locally applied to fuse the latter information with on-board GNSS position estimates and further enhance the *absolute* localization (see Fig. 1). In the final phase, the "ego" vehicle cooperates to improve the localization of other vehicles by further broadcasting its fusion results in subsequent "Beacons". CLoc has already been applied in [8]–[10] to fuse on-board GPS positions with opportunistic V2V Received Signal Strength Indicators (RSSIs) out of "Beacons" such as CAMs, relying on the V2X ITS-G5

[4]To remain technology neutral, a "Beacon" is a message periodically broadcast by each node, while "V2X" (Vehicle-to-X) refers to any technology capable of Device-to-Device (D2D) communication in a vehicular context.

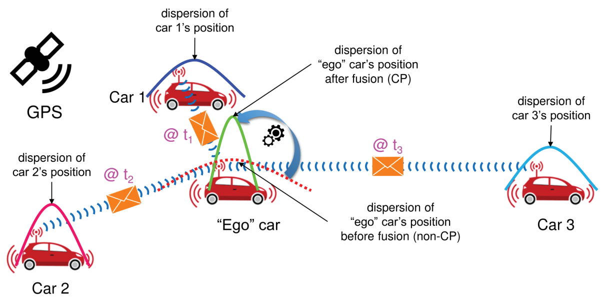


Fig. 1. "Ego" car receiving asynchronous CAMs from one-hop "virtual anchors" to perform distributed CLoc. The dispersion of CLoc location estimates (through both GNSS and ITS-G5) is expected to be lower than that of non-CLoc estimates (i.e., standalone GPS).

technology.[5] A major advantage of using V2V RSSI lies in the full compliance with future ITS-G5 connected vehicles[6].

B. Cooperative Awareness Errors & Mitigations

CA errors are composed of two components: (i) errors due to GPS inaccuracy, (ii) errors due to the distance moved between two successive reception (IRT) of a CAM, as depicted in Fig. 2. The former may reach $2-10m$ [8] depending on the environment and satellite availabilities, which is clearly non negligible to CA. The latter may reach $2m$, considering $10Hz$ periodic CAM and vehicles moving at $20m/s$. Doubling the CAM periodicity, may halve the IRT error (1m instead of $2m$) as shown in the 2nd row, but the gain is marginal considering $2-10m$ GPS errors.

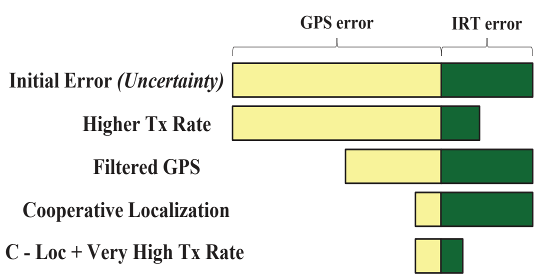
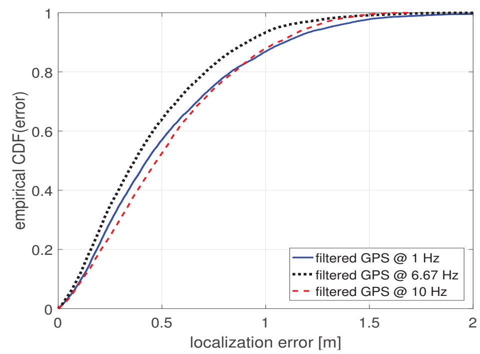


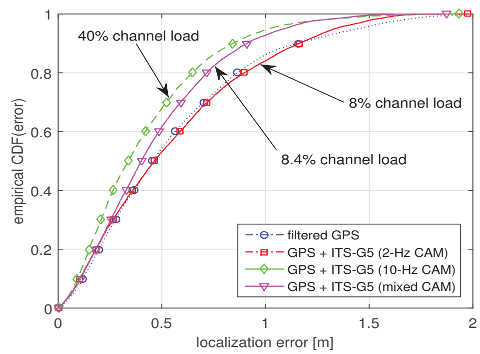
Fig. 2. Conceptual Representation of Awareness Error due to GPS and IRT.

On the other hand, reducing GPS errors via filtering or CLoc without addressing the IRT error, cannot by itself improve CA (see Fig. 2, 3rd and 4th rows). Considering GPS filtering, although increasing the CAM transmit rate could help, spatial and temporal correlations in GPS signal create a fundamental limit in the filtering rate [8]. As shown in Fig. 3a, GPS filtering at 10Hz achieves similar precision as 1Hz, both being worse than the optimum value of 6.67 Hz. GPS common errors cause correlations on its measurements, hence, the filter cannot average out the noise leading to performance degradation, especially when transmitting GPS positions at very high rate [8]. Accordingly, any CAM periodicity higher than 6.67Hz actually degrades the quality of filtered GPS.

As shown in Fig. 3b, compared to GPS filtering, CLoc significantly improves localization error, but sharing the output



(a) Filtered GPS



(b) Cooperative Localization

Fig. 3. Fusion strategies to improve GPS errors.

of the fusion filter with neighbors creates up to 40% Channel Load. Hoang et al. [9], [10] proposed transmitting less CLoc messages and complementing with a high frequency lightweight message called *tinyCAM* for RSSI-based ranging. As shown in Fig. 3b, this strategy has a minor impact on CLoc precision, yet at a significantly smaller overhead (8% vs. 40% channel load). However, as *tinyCAM* does not contain any position information, so by itself cannot be used for CA.

In this work, we integrate both approaches: replacing GPS with CLoc and increasing the CLoc Tx rate up to 100Hz[7]. This effectively mitigates the CA errors in both categories (Fig. 2, last row), and accordingly truly improves the CA precision.

C. Precise Awareness Message (PAM)

As described in Sec. II-A and in Fig. 3, exchanging GPS data is not useful to CA precision. Instead, the output of CLoc fusion filters needs to be exchanged in the form of an estimate of the distribution of a Particle Cloud[8]. However, such message format does not exist in current ETSI/IEEE/ISO specification. We therefore define a new message type called *Precise Awareness Message (PAM)* to exchange CLoc data. This message is designed to have the lowest possible channel footprint to enable transmission rate as high as 100Hz. As described in Hoang et al. [9], CLoc data requires 2x32-bit scalars for position, and 3x32-bit scalars for the filter covariance matrix. Including ID and $Time$, a PAM message will be composed of a 5x32-bit scalars and 2x64-bit scalars,

[5]CAM and ITS-G5 are European counterparts to the Basic Safety Message (BSM) and Dedicated Short Range Communication (DSRC) in the US.

[6]ITS-G5 is expected to be available in every vehicle sold from 2019.

[7]The 100Hz value is selected for IRT and CLoc errors to be of similar magnitude.

[8]If Kalman Filters are used, then Kalman coefficients are exchanged.

summing up to 28 bytes[9]. PAM has therefore a lower footprint on the wireless channel than CAMs (between 300-800 bytes).

As a PAM message is transmitted at 100 Hz, vehicle dynamics (speed, direction etc.) can be derived from subsequent messages and don't need to be transmitted. Moreover at that transmit rate, it is impossible to perform crypto-verifications on each PAM for each neighbor. Accordingly, to save bandwidth, security trailers are not transmitted[10]. Fusion engines are powerful tools to reject outliers and forged data in particular at high rates, and as such we expect the CLoc fusion engine to be capable of rejecting false location data from malicious neighbors. We leave this to future work.

D. Cooperative Awareness Control

Aiming at 100Hz, the Tx power of PAM must also be adjusted to avoid saturating the wireless channel. A sub-meter awareness precision is not required at any range, but PAM must still cover sufficient neighbors involved in future V2X safety-critical applications. The theoretical Channel Load, considering all the neighbors are visible to each other, can be calculated as:

$$ChannelLoad = \frac{TxRate * MessageSize * NbofNodes}{DataRate}$$

Considering a Tx rate of 100Hz, message size of 70 bytes and data rate of $6Mb/s$, 50 nodes produce a theoretical CL of 46.7%. In this implementation, we therefore fix the Tx rate to 100Hz and adjust the Tx power to have 50 neighbors in range, yet not exceeding a target channel load limit (e.g. 60%) according to the ETSI TS 103 175 specification [11]. We believe a precise awareness for 50 immediate neighbors to be sufficient for vulnerable road users detection or future automated vehicles.

III. Preliminary Simulation Results

A. Simulation Settings

We performed a numerical evaluation based on Matlab Monte Carlo simulations for the CLoc aspects and iTETRIS simulation platform [12] for V2V communications aspects.

For CLoc, we systematically consider a fleet of 15 vehicles moving according to a Gauss-Markov model, focusing our analysis on a segment of the entire vehicle flow. CAMs could be received up to practical transmission ranges of 1000 m. However we consider a nominal selective CLoc scheme that incorporates only the most informative messages from its nearest neighbors, like in [13]. Accordingly, simulating 15 vehicles is enough to avoid border effects or artifacts, while preserving the generality of the obtained CLoc results. In addition, the CLoc filter/fusion engine is based on Particle Filter (PF).

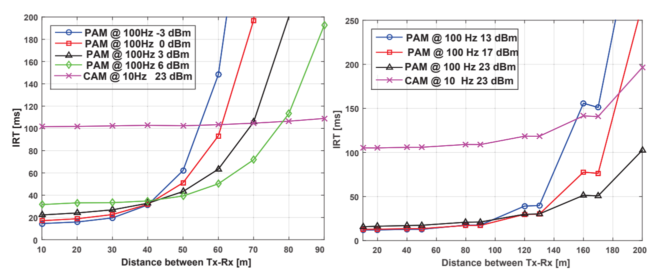
To evaluate V2V communication performance, a 2km strip 6-lane sub-urban highway is simulated with ITS-G5 equipped vehicles driving steadily at 20m/s following a Gauss-Markov mobility model[11]. We consider a highly dense scenario with 100 vehicles/lane/km and a sparse scenario with 25 vehicles/lane/km. To neglect border effect, we ignore vehicles within 500m, on both end of the highway. Simulations are based on the ETSI ITS stack available on iTETRIS, including WINNER B1 correlated fading. Main simulation parameters are summarized in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Transmit Power	-3 to +23 dBm
Transmit Rate	PAM: 100Hz CAM: triggering condition
Packet Size	PAM: 70 bytes CAM: 300 bytes
Preamble Detection Threshold	ITS-G5: -92 [dBm]
Mobility	Gauss Markov, Memory level 0.95, Sampling period 0.1 [s] Speed: 20 [m/s]
Density	Sparse: 25 veh/lane/km Dense: 100 veh/lane/km
Fading	WINNER B1 (Urban Microcell) (Correlated Gaussian & Ricean)
Performance Indicators	Inter Reception Time (IRT) (95% Confidence Intervals – 50 runs)
GPS errors (rms) in x and y	5 [m] [8]
Number of particles	1000

B. Communication Results

We compute the Inter-reception time (IRT) between successive receptions of PAM/CAM in dense and sparse traffic scenarios. For each scenario, the Tx power is selected to optimize the IRT at a distance covering 50 neighbors.



(a) Dense Scenario (b) Sparse Scenario

Fig. 4. Packet Inter Reception Time.

*1) **Dense Scenario**:* Figure 4a shows the packet IRT versus the distance between the transmitter and the receiver for a node density of 100 vehicles/lane/km. In this dense scenario, each node has at least 50 neighbors within a radius of 40 m. Transmitting PAM at 100Hz at a transmit power ranging between -3 to +3dBm guarantees a 15ms IRT to neighbors within 10m, and a 30ms IRT to all 50 neighbors within 40m. The channel load (CL) is 61.6% for -3dBm, 64.2% for 0dBm and 66.0% for 3dBm 100Hz PAM respectively. Beyond that distance or at higher Tx power, the IRT exponentially increases due to the increasing communication density. The PAM IRT is smaller than 10-Hz CAMs up to 50m.

*2) **Sparse Scenario**:* Figure 4b shows the packet IRT for a sparse node density of 25 vehicles/lane/km. 50 immediate neighbors being located within a distance of 160m, a higher Tx power is required. While 13dBm (CL 45.4%) or 17dBm

[9]PAM may reach up to 70 bytes as function of lower layers headers.

[10]We yet envision to transmit one PAM with full security trailer at 1Hz for neighbor verification.

[11]Although more realistic models can be used, we matched the mobility models used by CLoc in Matlab.

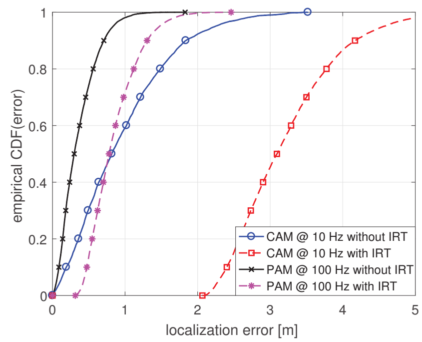


Fig. 5. CA Precision, including High Rate Awareness

(CL 54.3%) provide a 20ms IRT below 100m, only 23dBm provides an optimum 50ms IRT (CL of 63.2%) to the nearest 50 neighbors. This sparse scenario provides proportionally larger IRTs compared to dense scenarios (e.g. for 50 neighbor range, the IRT are 30ms and 50ms for dense and sparse scenario respectively). A clear 70-100ms IRT gain compared to 10Hz CAMs is also observable.

C. CLoc Results

We investigate the overall Awareness precision of CAM and PAM by means of Cumulative Distribution Functions (CDFs) of localization errors. Fig. 5 provides localization errors first for CLoc only and second also including the localization errors from IRT.

10-Hz CAM gives high localization errors (median error of 0.82m without IRT and 3.1m with IRT) in comparison with that of the filtered GPS only in Fig. 3a (median error of less than 0.5m). This is due to error propagation from uncorrected and thus low-accuracy GPS positions of neighboring vehicles, and also from alleviated IRT errors.[12]

100-Hz PAM, on the other hand, shows a significantly higher precision (median error of 0.3m without IRT and 0.78m with IRT). This high performance is achieved by accurate positional information in PAM (fusion data instead of GPS) and low IRT errors due to 100Hz transmission. From these results, PAM-based Awareness provides a 4x factor increase compared to CAM-based Awareness.

IV. Discussion and Conclusion

In this work, we redefine Cooperative Awareness by integrating and mitigating the impact of GPS errors. Instead of exchanging GPS data, we showed it is more efficient to exchange Cooperative Localization (CLoc) data. We accordingly introduced a new Precise Awareness message (PAM) and drew the first sketch of an Awareness control strategy aiming at high precision awareness supporting up to 100Hz Tx rate. Jointly, CLoc and the awareness control strategy provides unprecedented awareness precision compared to pure CAM-based awareness.

Although at early stage, we showed that using CAMs is not the right strategy for high precision awareness, as GPS position is not the right information to convey and CAMs waste wireless channel resource. Replacing CAM with PAM, we showed that the 10Hz limit can be largely extended up to 100Hz without exceeding a channel load limit of 60%, and providing a 2-5x faster reactivity to contextual changes.

We will extend this work to clarify and further enhance our proposed High Precision Awareness Control strategy in the following directions:

- We observed that 100Hz Tx rate also induced heavy packet losses. An optimal Tx rate should be found to minimize the IRT.
- The target neighbor density should be configurable dynamically depending on the channel load and application requirements.
- CLoc and PAM should be fully integrated to evaluate their mutual impact.
- High Tx rate will exacerbate correlated packet losses. Tx power randomizations might be beneficial.
- Backward compatibility - as long-range awareness is also required, CAM might still be required but at a lower rate.

[12] The vehicles might be accurately positioned by multisensor fusion but only the GPS positions are broadcast by CAMs.

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References

[1] H. j. Gunther, O. Trauer, and L. Wolf, "The potential of collective perception in vehicular ad-hoc networks," in *2015 14th International Conference on ITS Telecommunications (ITST)*.

[2] D. Eckhoff, N. Sofra, and R. German, "A performance study of cooperative awareness in ETSI ITS G5 and IEEE WAVE," in *2013 10th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, 2013.

[3] P. M. d'Orey and M. Boban, "Empirical evaluation of cooperative awareness in vehicular communications," in *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*.

[4] M. Sepulcre, J. Gozalvez, O. Altintas, and H. Kremo, "Integration of congestion and awareness control in vehicular networks," *Ad Hoc Networks*, vol. 37, 2016.

[5] M. Sepulcre, J. Gozalvez, O. Altintas, and H. Kremo, "Adaptive beaconing for congestion and awareness control in vehicular networks," in *2014 IEEE Vehicular Networking Conference (VNC)*.

[6] G. Bansal, H. Lu, J. B. Kenney, and C. Poellabauer, "EMBARC: Error model based adaptive rate control for vehicle-to-vehicle communications," in *Proceeding of the tenth ACM international workshop on Vehicular inter-networking, systems, and applications*. ACM, 2013.

[7] C.-L. Huang, Y. P. Fallah, R. Sengupta, and H. Krishnan, "Intervehicle transmission rate control for cooperative active safety system," *IEEE Trans. on Intelligent Transportation Systems*, 2011.

[8] G. M. Hoang, B. Denis, J. Härri, and D. T. M. Slock, "Breaking the gridlock of spatial correlations in GPS-aided IEEE 802.11p-based cooperative positioning," *IEEE Trans. on Vehicular Technology*, 2016.

[9] G. M. Hoang, B. Denis, J. Härri, and D. T. M. Slock, "On communication aspects of particle-based cooperative positioning in GPS-aided VANETs," in *2016 IEEE Intelligent Vehicles Symposium (IV)*.

[10] G. M. Hoang, B. Denis, J. Härri, and D. T. M. Slock, "Mitigating unbalanced GDoP effects in range-based vehicular cooperative localization," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*.

[11] ETSI, "ETSI TS 103 175 intelligent transport systems (its); cross layer dcc management entity for operation in the its g5a and its g5b medium."

[12] M. Rondinone et al., "iTETRIS: A modular simulation platform for the large scale evaluation of cooperative ITS applications," *Simulation Modelling Practice and Theory*, 2013.

[13] G. M. Hoang, B. Denis, J. Härri, and D. T. Slock, "Select thy neighbors: Low complexity link selection for high precision cooperative vehicular localization," in *2015 IEEE Vehicular Networking Conference (VNC)*.