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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 through smooth spatial degradations and adjusted message contents. 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.

Index Terms

Congestion and awareness control in vehicular networks; V2V, V2I and V2X communications and networking protocols; Cooperative Localization

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1 Introduction

Safety-related C-ITS applications are based on Cooperative Awareness (CA) obtained by periodic broadcast from connected vehicles of their GPS information. 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], and which illustrated the challenge of adjusting transmit power, rate or modulation to optimize CA reliability and precision.

Although 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, GPS precision is expected to have a larger impact on CA precision that any of the currently proposed awareness control strategies.

In this paper, we redefine cooperative awareness by including the impact of GPS information and describe the first sketch of new CA strategies to meet the high precision CA required by future V2X safety applications. More specifically, our contributions are as follows: (i) We introduce CLoc to reach highly precise node position (4x that of GPS) (ii) We define a new awareness message adapted to CLoc, which only requires 1/4 of current Cooperative Awareness Message (CAM) size; (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 2 discusses the implication of position errors in cooperative awareness. Section 3 introduces the awareness control mechanisms and provides preliminary evaluation results. Finally, Section 4 finally discusses new challenges exposed by the preliminary results.

[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/

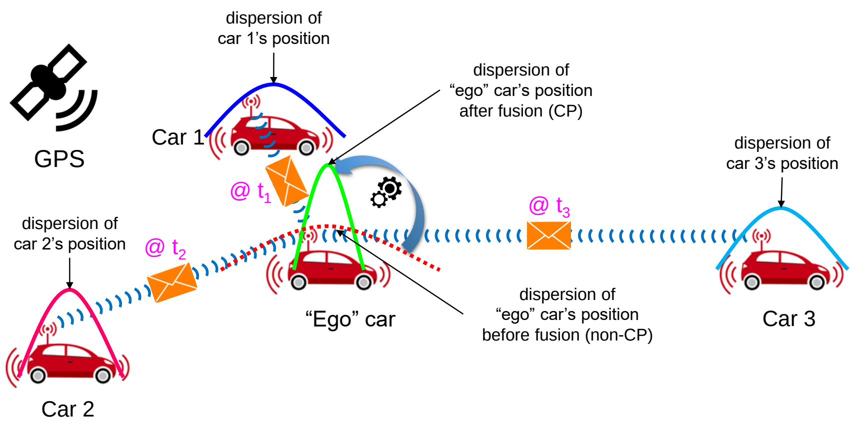


Figure 1: "Ego" car receiving asynchronous CAMs from one-hop "virtual anchors" to perform distributed CLoc. The dispersion of CLoc location estimates (through both GNSS and ITS-G5) is expected to be lower than that of non-CLoc estimates (i.e. standalone GPS)

2 High Precision Cooperative Awareness

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

[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.

[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.

2.2 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 of a CAM (IRT). The former may reach $2 - 10m$ [8] as function of the environment, and mostly depend on the satellite availabilities. The latter may reach $2m$, considering $10Hz$ periodic CAM and vehicles moving at $20m/s$. GPS errors are clearly non negligible to CA.

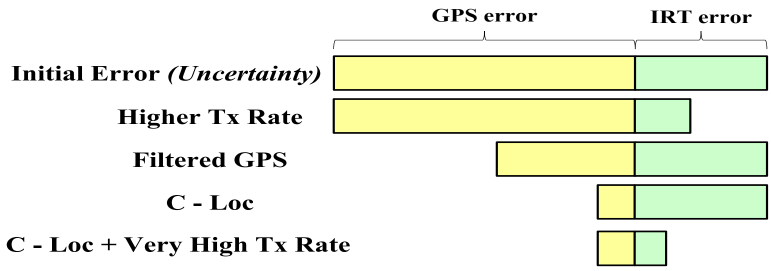
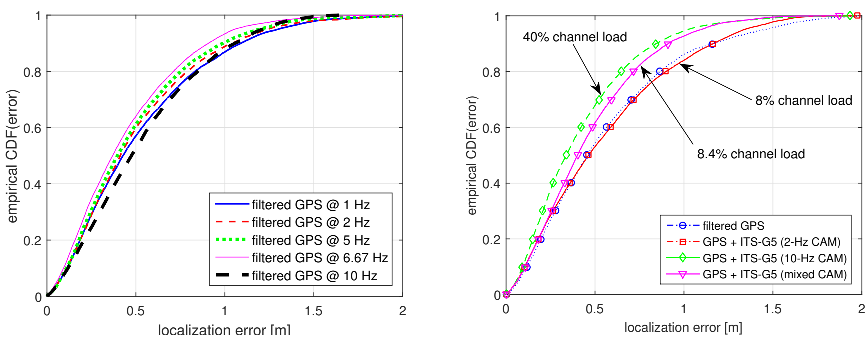


Figure 2: Conceptual Representation of Awareness Error due to GPS and IRT.

As depicted in Fig. 2, 2nd row, while most of the studies aiming at improving CA plays with the IRT (higher Tx Rate), GPS errors are not addressed and take a more prominent role. For example, if the CAM periodicity is doubled (20Hz), the IRT may be divided by two (1m instead of $2m$), but the gain is not significant considering the $2 - 10m$ GPS errors.

On the other hand, studies proposed to reduce GPS errors either through filtering or CLoc but not addressing the IRT side, it cannot by itself improve CA (see Fig. 2, 3rd and 4th rows). Although increasing the CAM transmit rate may also help GPS filtering, spatial and temporal correlations in GPS signal create a fundamental limit in the filtering rate. As shown in Fig. 3a, filtering at 10Hz brings the same precision to 1Hz, and less than 6.67 Hz. Accordingly, any CAM periodicity higher than 6.67Hz will actually increase the GPS error.



(a) Filtered GPS (b) Cooperative Localization

Figure 3: Fusion strategies to improve GPS errors.

As shown in Fig. 3b, CLoc significantly improves GPS errors but at the cost of non negligible overhead. Sharing the output of the fusion filter with neighbors creates up to 40% Channel Load. Hoang et al. [9, 10] proposed a strategy to transmit very small packets called *tinyCAM* for trilateration at a high rate, while CLoc packets would be transmitted less. 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, *tinyCAM* not containing any position information, cannot be used for CA and the IRT component is actually worsened.

In this work, we integrate both approaches: replace GPS with CLoc and increase the CLoc transmit rate. This effectively mitigates the CA errors in both categories (see Fig. 2, last row), and accordingly truly improves the precision of CA.

2.3 Position and Time Message (POTI)

As described in Sec. 2.1 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[7]. However, such message format does not exist in current ETSI/IEEE/ISO specification. We therefore define a new message type called *Position and Time (POTI)* to exchange CLoc data. This message is meant to remain small to reduce its footprint on the wireless channel. 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 POTI message will be composed of a 5x32-bit scalars and 2x64-bit scalars, summing up to 28 bytes[8]. POTI has therefore a lower footprint on the wireless channel than CAMs (between 300-800 bytes).

Our objective being to provide a transmit POTI packets at a rate up to 100Hz, we need to keep the POTI footprint as low as possible. Accordingly, we do not transmit vehicle dynamics (speed, direction), as dynamics maybe differentiated from subsequent POTI messages. We also do not transmit security trailers as no currently existing hardware could do crypto-verifications at our target rate. Moreover, CLoc fusion filters are strong tools to detect outliers, and we expect them to be more efficient than crypto-protections to ignore data spoofing[9].

2.4 Cooperative Awareness Control

Aiming at 100Hz, the Tx power of POTI must also be adjusted to avoid saturating the wireless channel. A sub-meter awareness precision is not required at long range, but POTI must still cover sufficient neighbors involved in future V2X safety-critical applications. We sketch here a preliminary concept of a coopera-

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

[8] POTI may reach up to 70 bytes as function of lower layers headers.

[9] We will conduct a dedicated study to confirm that claim.

tive awareness control for High Precision Awareness to operate according to the following functional blocks:

- *Target Channel Load* - POTI aims at a 60% Channel Load
- *Transmit Rate Control* - POTI adjust Tx rate to 100Hz transmit rate
- *Transmit Power Control* - POTI adjusts the Tx power to maximize the neighbor coverage for the target Channel Load.

Accordingly, the challenge is to extract the optimal number of neighbors for 100Hz at 60% channel load. Table 1 shows theoretical impact of increasing the number of neighbors on the channel load considering a 100Hz Tx rate policy. As it may be observed, the optimal neighbor density is 50, although in real deployments, such number will be adjusted according to the channel load. This number is yet considered to be largely sufficient in case of detection of vulnerable road users or future automated vehicles.

Table 1: Impact of Neighbor Density on Channel Load for 100Hz POTI

Neighbor Density	Channel Load
40	37.3%
50	46.7%
60	56%

3 Preliminary Simulation Results

3.1 Simulation Settings

We performed a numerical evaluation based on Matlab Monte Carlo simulations for the CLoc aspects and iTETRIS simulation platform [11] 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 vehicles flow. CAMs could indeed 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 [12]. 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[10]. We consider a highly dense scenario with 100 vehicles/lane/km and a sparse scenario with 25 vehicles/lane/km.

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

To neglect border effect, we ignore vehicles within 500m both side of the highway. Simulations are based on the ETSI ITS stack available on iTETRIS, including WINNER B1 correlated fading. Although POTI messages are 28 bytes long, we consider 70 bytes in order to integrate the ITS stack headers. Main simulation parameters are summarized in Table 2.

Table 2: Simulation Parameters

Parameter	Value
Transmit Power	-3 to +23 dBm
Transmit Rate	POTI: 100Hz CAM: triggering condition
Packet Size	POTI: 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

3.2 Communication Results

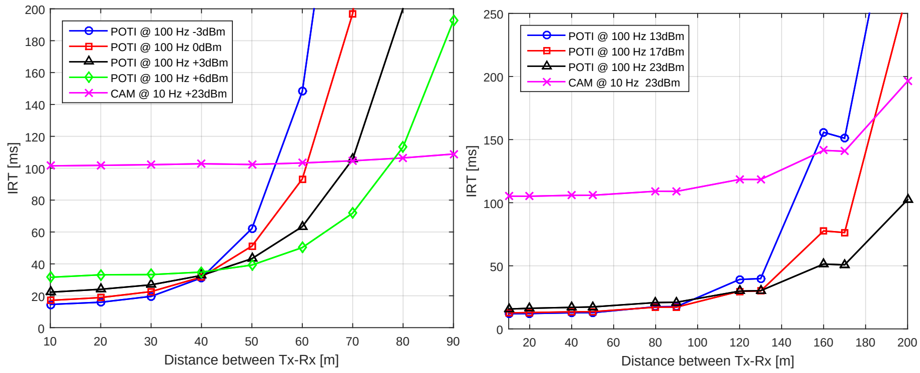
We compute the Inter-reception time (IRT) between successive receptions of POTI/CAM in dense and sparse traffic scenarios. For each scenario, the Tx power is selected to optimize the IRT at a distance covering 50 neighbors.

3.2.1 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 POTI 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 is 61.6% for -3dBm, 64.2% for 0dBm and 66.0% for 3dBm 100Hz POTI. Beyond that distance or at higher Tx power, the IRT exponentially increases due to the increasing communication density. The POTI IRT is smaller than 10-Hz CAMs up to 50m.

3.2.2 Sparse Scenario

Figure 4b shows the packet IRT for a sparse node density of 25 vehicles/lane/km. 50 neighbors being located within a distance of 160 m, a higher Tx power is re-



(a) Dense Scenario

(b) Sparse Scenario

Figure 4: Packet Inter Reception Time.

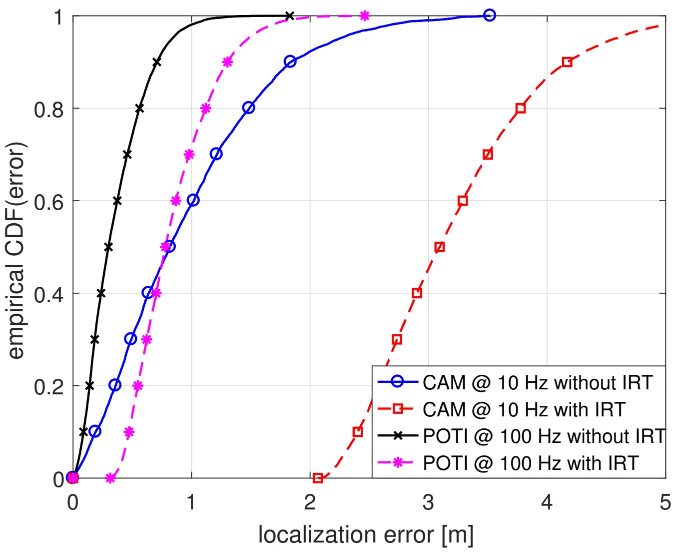


Figure 5: CA Precision, including High Rate Awareness

quired. While 13dBm (CL 45.4%) or 17dBm (CL 54.3%) provide a 20 ms IRT below 100m, only 23dBm provides an optimum 50ms IRT (CL of 63.2%) to the 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.

3.3 CLoc Results

We investigate the overall Awareness precision when CAM or POTI are used 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 Awareness gives high localization errors (median error of 0.82 m without IRT and 3.1 m with IRT) in comparison with that of the filtered GPS only in Fig. 3a (median error of less than 0.5 m). This is due to error propagation from uncorrected and thus low-accuracy GPS positions of the neighboring vehicles, and also from alleviated IRT errors.[11]

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

4 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 to be more efficient to exchange Cooperative Localization (CLoc) data. We accordingly introduced a new Position and Time (POTI) message 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 CAM are not the right strategy to reach high precision Awareness, as it does not conveys the right information and waste wireless channel resources. Replacing CAMs with POTI, we showed that the 10Hz limit can be largely extended up to 100Hz for the same channel usage, at no impact on Awareness precision 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 minimizing the IRT.
- The target neighbor density should be configurable and depends also on the channel load and application requirements.
- CLoc and POTI should be fully integrated to evaluate their mutual impact.
- High Tx rate will exacerbate correlated packet losses. Tx power randomizations might be beneficial.

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

- Backward compatibility - as long-range awareness is also required, CAM might still be required but at a lower rate.

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