Avancées et défis de la localisation véhiculaire coopérative

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Présentation en session plénière / Plenary session communication

Résumé / Abstract

A terme, les applications associées aux systèmes de transports intelligents coopératifs (C-ITS) requerront une information de localisation fiable et précise. En particulier, pour les applications C-ITS de deuxième génération, telles que la conduite autonome (HAD) ou la prévention des risques d'accident pour les usagers vulnérables de la route (VRUs), le système de positionnement par satellites (GNSS) semble aujourd'hui insuffisant, notamment en matière de continuité de service. Ces applications nécessitent en effet un niveau de précision sub-métrique constant, quelles que soient les conditions d'utilisation.

En théorie, la Localisation Coopérative (CLoc) devrait permettre aux véhicules de palier la faiblesse relative de leurs propres systèmes de localisation, en s'appuyant sur 1) des échanges de données de proche en proche (ex., leurs dernières positions estimées, voire leurs données GNSS brutes), 2) l'acquisition de distances relatives les séparant (typiquement, sur la base de liens radio), 3) d'autres modalités de mesure issues de capteurs embarqués (inertiel, odométrie…) et enfin, 4) la fusion de l'ensemble de ces informations. Toutefois, dans le contexte très particulier des réseaux véhiculaires ad hoc (VANET), les approches coopératives conventionnelles ne s'avèrent pas pleinement satisfaisantes et nécessitent des ajustements importants, en raison de la spécificité des motifs de mobilité rencontrés, d'un canal de communication véhicules à véhicules (V2V) fortement contraint (en termes de capacité et de contrôle décentralisé des émissions) et de la nature des mesures à intégrer dans le processus de fusion (potentiellement non Gaussiennes et corrélées dans le temps et/ou l'espace).

Dans le cadre de cette conférence invitée, nous introduirons à titre d'exemple un schéma de fusion générique reposant sur un simple filtre particulaire, ainsi que sur l'exploitation de messages coopératifs normalisés de type 'CAM' (cooperative awareness messages) prévus par le standard V2V ITS-G5. Nous décrirons en particulier une méthode permettant de synchroniser les données reçues de la part des véhicules voisins, tout en réduisant la complexité de calcul et l'impact sur les communications inter-véhiculaires (ex. via une sélection des liens/voisins les plus informatifs, l'approximation paramétrique des messages, ainsi qu'un contrôle du format et du taux des paquets émis). Nous étendrons ensuite ce schéma de manière à intégrer des mesures de distances V2V plus précises, basées sur la technologie radio impulsionnelle 'IR-UWB'. A cette occasion, nous aborderons les problèmes spécifiques de propagation d'erreur et de confiance excessive dans les résultats de la fusion, caractéristiques des filtres coopératifs. Finalement, afin de traiter certains cas particulièrement pathologiques (ex. absence de GNSS dans les tunnels, forte erreur selon l'axe orthogonal à la route), nous considèrerons l'apport d'autres capteurs embarqués (centrale inertielle, compte-tour et détecteurs de voie), ainsi que d'unités de bord de route (RSUs) dotées de moyens de communication V2I.

L'approche proposée a été testée sur la base de simulations canoniques, de données de mobilité réalistes, ainsi que de données expérimentales. Ces travaux de recherche ont fait l'objet d'une thèse récente, menée au CEA-Leti (Grenoble) en collaboration avec EURECOM (Sophia Antipolis).

COOPERATIVE VEHICULAR LOCALIZATION: RECENT PROGRESSES AND CHALLENGES

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OUTLINE

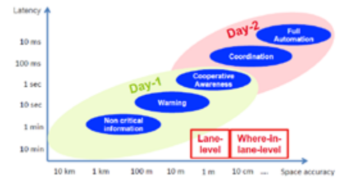
- Context and Motivations
- V2V Cooperative Localization
- Hybrid V2V Cooperative Localization
- Hybrid V2X Multisensor Cooperative Localization
- Conclusions and Perspectives

COOPERATIVE – INTELLIGENT TRANSPORT SYSTEMS (C-ITS)

- **Wireless communication** between vehicles **(V2V)** and roadside infrastructure **(V2I)** → **V2X**
  - Road traffic safety
  - Road traffic efficiency

Source: Daimler

- **C-ITS applications road map (C2C-CC): Day-1 & Day-2**



High accuracy absolute localization is needed, regardless of **operating conditions**

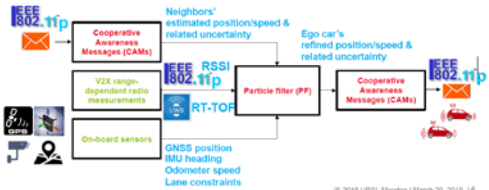
COOPERATIVE LOCALIZATION BASICS

- Expected benefits
  - Neighbors (hopefully well positioned) → "Virtual anchors"
  - Diversity, redundancy, geometric ambiguity solving → Better accuracy/resilience

- Methods mostly validated under moderate mobility so far (e.g., WSN)
  → Open/unprecedented challenges in the vehicular context

CONSIDERED TECHNOLOGIES

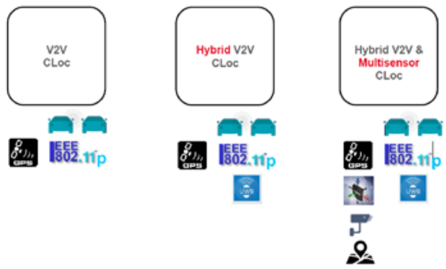
Maturity	Technology	Frequency	Metric
Today	ITS-G5 / 802.11p	5.9 GHz	RSSI
Today	IR-UWB / 802.15.4a	~ 4 GHz	TOA / RT-TOF
Prospective	4G LTE V2X	2 GHz	Under specification
Prospective	5G mmWave V2X	30 – 100 GHz	AOA / AOD / TOA
Prospective	WiFi extension	2.4 GHz	Not standardized



CHALLENGES & OPEN RESEARCH QUESTIONS

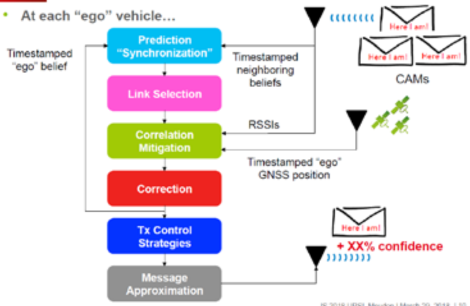
Can **sub-meter localization accuracy** be already met through **low-complexity CLoc strategies** between connected vehicles with **standard technologies**?

GRADUAL ASSESSMENT APPROACH



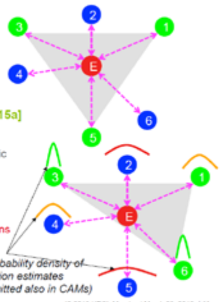
NOMINAL COOPERATIVE FRAMEWORK

- At each "ego" vehicle…



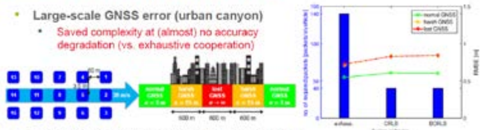
LINKS SELECTION
NON-BAYESIAN VS. BAYESIAN CRITERIA

- **Link selection** based on **theoretical positioning performance bounds (CRLB)** conditioned on a priori sub-constellations
  - Non-Bayesian CRLB criterion [Hoang15a]
    - Radio link quality
    - Geometry of neighboring vehicles (GDOP)
    - All involved positions assumed deterministic (& perfect)
  - Bayesian CRLB criterion [Hoang15b]
    - Radio link quality
    - Geometry of neighboring vehicles (GDOP)
    - Uncertainty of neighbors' estimated positions

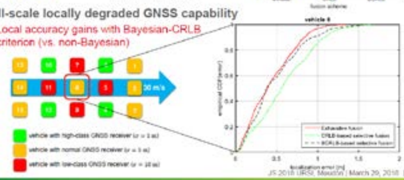


LINKS SELECTION
PERFORMANCE EVALUATION

- Large-scale GNSS error (urban canyon)
  - Saved complexity at (almost) no accuracy degradation (vs. exhaustive cooperation)

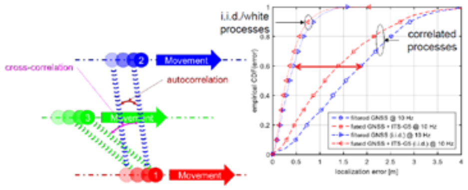


- Small-scale locally degraded GNSS capability
  - Local accuracy gains with Bayesian-CRLB criterion (vs. non-Bayesian)



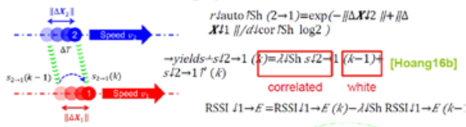
IMPACT OF SPACE-TIME MEASUREMENT NOISE CORRELATIONS

- Why is correlation a threat ?
  - Inherent/specific to constrained vehicular mobility under typical refresh rates
  - Cannot properly filter out error processes (assumed white)
  - Misses hidden/fruitful location info
  - Causes filter over-confidence (in inaccurate estimates)



MITIGATION OF SPACE-TIME CORRELATIONS

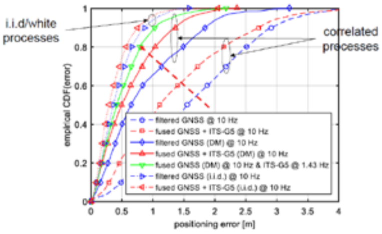
- Signal level mitigation
  - Empirical cross-measurement correlations
    → Compensate for info loss
  - Differential measurements
    → Eliminate the correlated part (back to i.i.d./white assumptions)



- Protocol level mitigation
  - Adaptively decreased cooperative fusion rate
    → Collect uncorrelated measurements

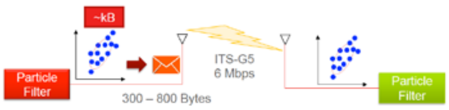
MITIGATION OF SPACE-TIME CORRELATIONS
PERFORMANCE EVALUATION

- ECDF of localization errors for different correlation mitigation schemes in a highway scenario (steady-state mobility)



IMPACT ON V2X COMMUNICATIONS

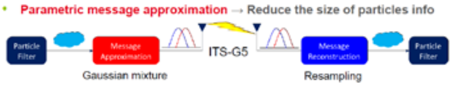
- Location estimation by distributed particle filter (PF)
  - Posterior by a set of random state samples
  - Any process nonlinearity and noise distribution
  - High number of particles, generating heavy communication load due to belief messages passing



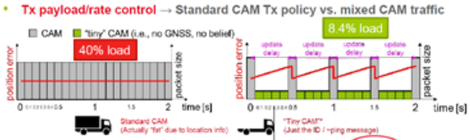
- **Challenges**
  - Limited CAM size
  - Limited channel capacity
  - ETSI Decentralized Congestion Control (DCC)
    - Reduced CAM rate (e.g., 2 Hz) → Expected accuracy degradation

MESSAGE APPROXIMATION & TX CONTROL

- **Parametric message approximation** → Reduce the size of particles info



- **Tx payload/rate control** → Standard CAM Tx policy vs. mixed CAM traffic

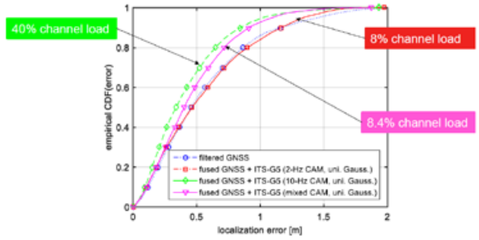


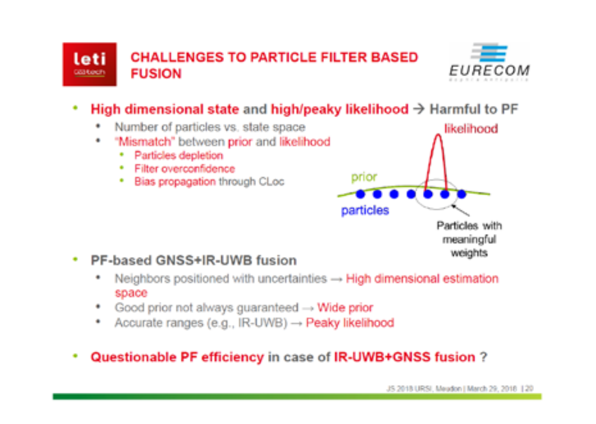
- **Tx power control** for "tiny CAMs" (for RSSI only)

[Hoang16a]

MESSAGE APPROXIMATION & TX CONTROL
PERFORMANCE EVALUATION

- ECDF of localization errors for different message approximation and transmission control strategies (1000 particles)




CHALLENGES TO PARTICLE FILTER BASED FUSION
EURECOM
High dimensional state and high/peaky likelihood → Harmful to PF
Number of particles vs. state space
"Mismatch" between prior and likelihood
Particles depletion
Filter overconfidence
Bias propagation through CLoc
likelihood
prior
particles
Particles with meaningful weights
PF-based GNSS+IR-UWB fusion
Neighbors positioned with uncertainties → High dimensional estimation space
Good prior not always guaranteed → Wide prior
Accurate ranges (e.g., IR-UWB) → Peaky likelihood
Questionable PF efficiency in case of IR-UWB+GNSS fusion ?
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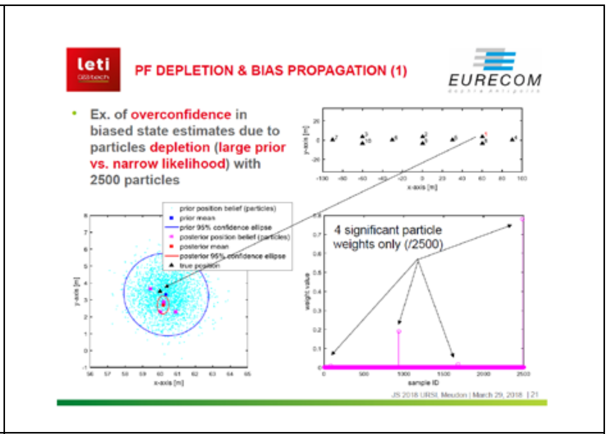
PF DEPLETION & BIAS PROPAGATION (1)
EURECOM
Ex. of overconfidence in biased state estimates due to particles depletion (large prior vs. narrow likelihood) with 2500 particles
prior position belief (particles)
prior mean
prior 95% confidence ellipse
posterior position belief (particles)
posterior mean
posterior 95% confidence ellipse
true position
4 significant particle weights only (/2500)
x-axis [m]
y-axis [m]
weight value
sample ID
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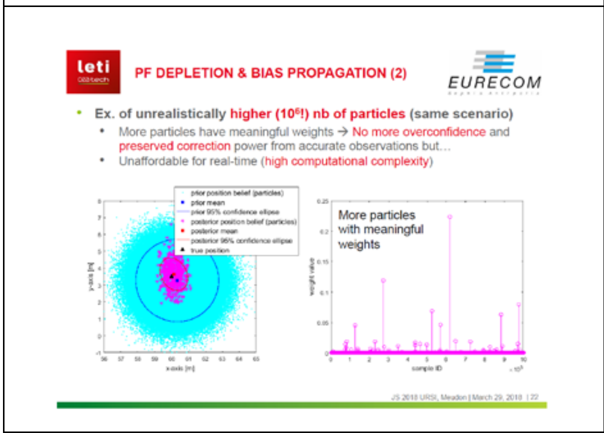
PF DEPLETION & BIAS PROPAGATION (2)
EURECOM
Ex. of unrealistically higher (10⁶!) nb of particles (same scenario)
More particles have meaningful weights → No more overconfidence and preserved correction power from accurate observations but…
Unaffordable for real-time (high computational complexity)
prior position belief (particles)
prior mean
prior 95% confidence ellipse
posterior position belief (particles)
posterior mean
posterior 95% confidence ellipse
true position
More particles with meaningful weights
x-axis [m]
y-axis [m]
weight value
sample ID
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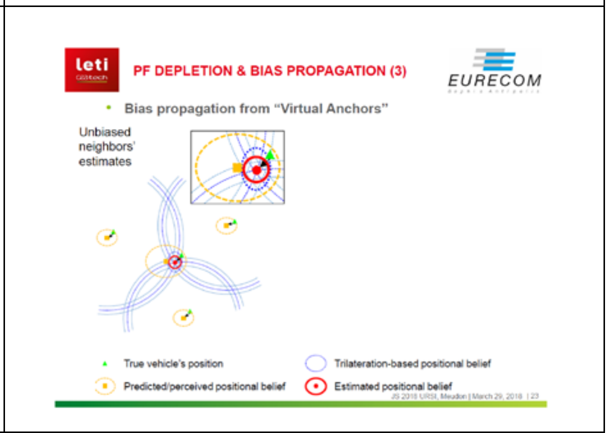
PF DEPLETION & BIAS PROPAGATION (3)
EURECOM
Bias propagation from "Virtual Anchors"
Unbiased neighbors' estimates
True vehicle's position
Trilateration-based positional belief
Predicted/perceived positional belief
Estimated positional belief
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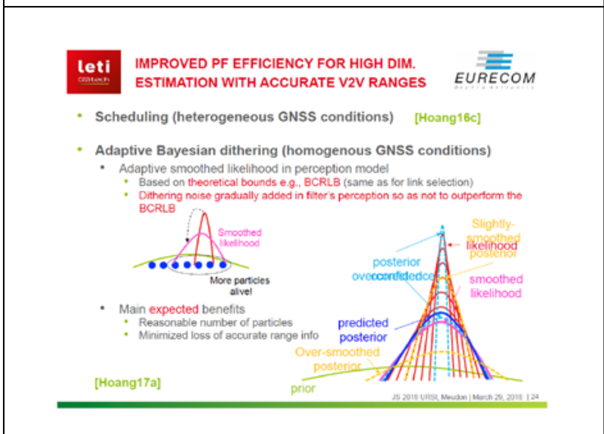
IMPROVED PF EFFICIENCY FOR HIGH DIM. ESTIMATION WITH ACCURATE V2V RANGES
EURECOM
Scheduling (heterogeneous GNSS conditions) [Hoang16c]
Adaptive Bayesian dithering (homogenous GNSS conditions)
Adaptive smoothed likelihood in perception model
Based on theoretical bounds e.g., BCRLB (same as for link selection)
Dithering noise gradually added in filter's perception so as not to outperform the BCRLB
Smoothed likelihood
More particles alive!
Main expected benefits
Reasonable number of particles
Minimized loss of accurate range info
[Hoang17a]
Slightly-smoothed likelihood
posterior
overconfident
posterior
smoothed likelihood
predicted posterior
Over-smoothed posterior
prior
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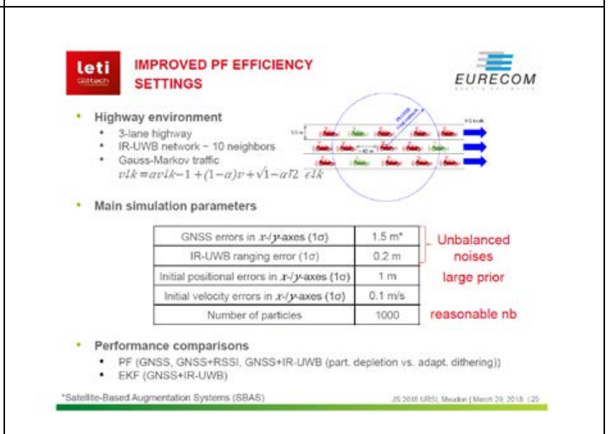
IMPROVED PF EFFICIENCY SETTINGS
EURECOM
Highway environment
3-lane highway
IR-UWB network ~ 10 neighbors
Gauss-Markov traffic
Main simulation parameters
GNSS errors in x-/y-axes (1σ) | 1.5 m*
IR-UWB ranging error (1σ) | 0.2 m
Initial positional errors in x-/y-axes (1σ) | 1 m
Initial velocity errors in x-/y-axes (1σ) | 0.1 m/s
Number of particles | 1000
Unbalanced noises
large prior
reasonable nb
Performance comparisons
PF (GNSS, GNSS+RSSI, GNSS+IR-UWB (part. depletion vs. adapt. dithering))
EKF (GNSS+IR-UWB)
*Satellite-Based Augmentation Systems (SBAS)
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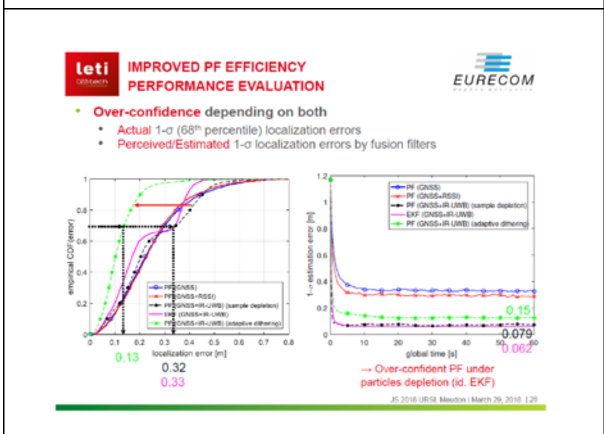
IMPROVED PF EFFICIENCY PERFORMANCE EVALUATION
EURECOM
Over-confidence depending on both
Actual 1-σ (68th percentile) localization errors
Perceived/Estimated 1-σ localization errors by fusion filters
empirical CDF(error)
localization error [m]
PF (GNSS)
PF (GNSS+RSSI)
PF (GNSS+IR-UWB) (sample depletion)
EKF (GNSS+IR-UWB)
PF (GNSS+IR-UWB) (adaptive dithering)
0.13
0.32
0.33
1-σ estimation error [m]
global time [s]
0.15
0.079
0.062
→ Over-confident PF under particles depletion (id. EKF)
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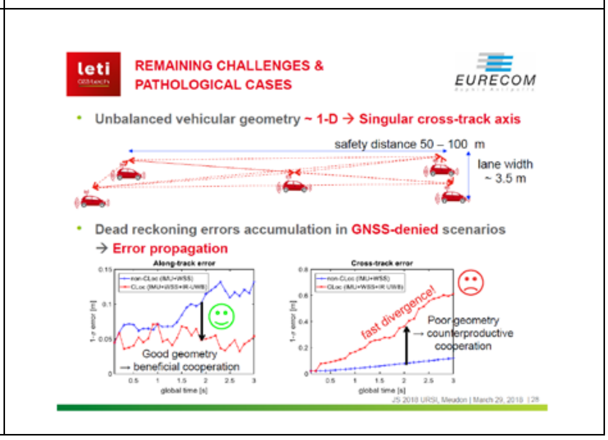
REMAINING CHALLENGES & PATHOLOGICAL CASES
EURECOM
Unbalanced vehicular geometry ~ 1-D → Singular cross-track axis
safety distance 50 – 100 m
lane width ~ 3.5 m
Dead reckoning errors accumulation in GNSS-denied scenarios
→ Error propagation
Along-track error
Cross-track error
Good geometry → beneficial cooperation
fast divergence!
Poor geometry → counterproductive cooperation
global time [s]
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MULTISENSOR FUSION FOR IMPROVED CROSS-TRACK LOCALIZATION

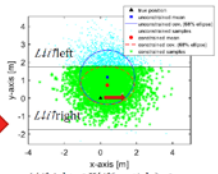
- **IMU gyroscope ω_k integration**

$$x_{k+1} \approx x_k + \Delta T s_k \cos(\theta_k + 0.5\Delta T \omega_k)$$
$$y_{k+1} \approx y_k + \Delta T s_k \sin(\theta_k + 0.5\Delta T \omega_k)$$
$$\theta_k = \theta_k + \Delta T \omega_k$$

Prediction step in PF

- **Camera-based lane detection**

&



$L_i^{right} < X_i(\text{particle}) < L_i^{left}$

$X_i(\text{particle}) \geq L_i^{left}$,
$X_i(\text{particle}) \leq L_i^{right}$

[Hoang17b]

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IMPROVED CROSS-TRACK ERRORS SETTINGS

- **Highway environment**
  - 2-lane highway, 7 vehicles
  - Gauss-Markov mobility traffic

$$v_k = \alpha v_{k-1} + (1-\alpha)\bar{v} + \sqrt{1-\alpha^2}\, e_k$$

- **Performance comparisons**
  - 2 main configurations: non-CLoc vs. CLoc (V2V IR-UWB)

GNSS	Non-CLoc
GNSS + IMU + WSS	Non-CLoc
GNSS + lane constraints	Non-CLoc
GNSS + V2V IR-UWB	CLoc
GNSS + V2V IR-UWB + IMU + WSS	CLoc
GNSS + V2V IR-UWB + lane constraints	CLoc
GNSS + V2V IR-UWB + IMU + WSS + lane constraints	CLoc

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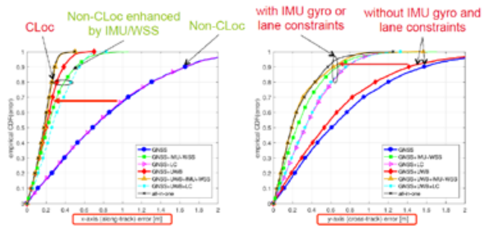
IMPROVED CROSS-TRACK ERRORS PERFORMANCE EVALUATION

- **ECDF of 1-D localization errors along x (left) and y (right) axes**



Individual information source affects each component of position error differently

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CONCLUSIONS

- Sub-meter accuracy through CLoc with existing technologies?
  - (Conditionally) yes !
    - Typically, precision improved from 2 m down to 30 cm in 80% in most favorable simulated scenarios
  - Various challenges inherent to the cooperative vehicular context
    - Information asynchronism
    - Space/time measurement correlations
    - Computational complexity and information selection
    - Communication constraints (imposed by underlying standards)
    - Relative geometry
  - Other open questions ahead (future work)
    - Context-aware cooperative fusion (large-scale/long-term)
    - Security and privacy of involved V2X cooperative links
    - Fusion partitioning and data kind (e.g., wrt. juridical responsibility → See autonomous cars accidents)
    - New location-enabled applications and services (mapping/cartography, automotive IoT, crowd sensing…)

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