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RETNET Real-Time Networks

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Deterministic Ethernet: Addressing the Challenges of Asynchronous Sensing in Sensor Fusion Systems

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Outline

- Advanced Driver Assistance Systems (ADAS)
- Problem definition
- Understanding the OOSM problem
- Methods for measurement timestamping
- The use of deterministic Ethernet networks for precise timestamping
- Results
- Conclusions and future work

Outline

- **Advanced Driver Assistance Systems (ADAS)**

ADAS Introduction

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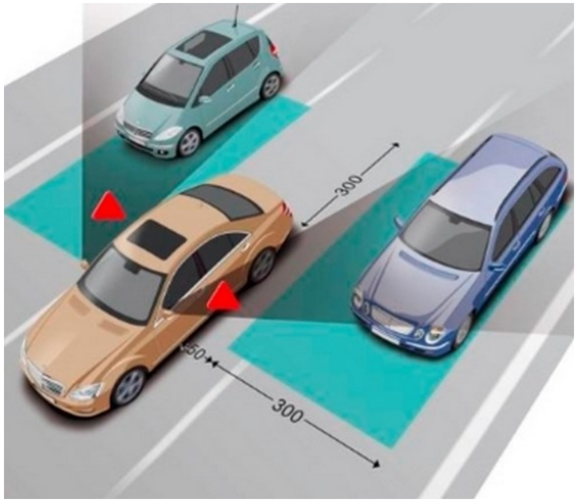
Informing

Warning



Controlling

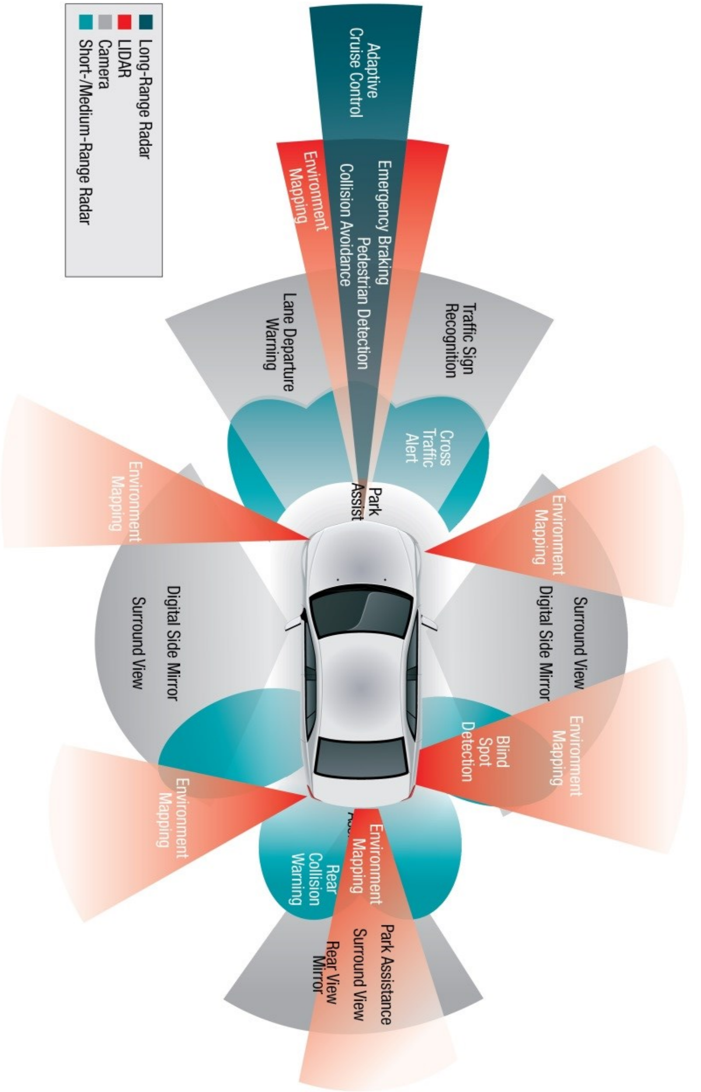
Sensor fusion

Sensing:
- Long and Short Range Radars
- Ultrasonic sensors
- LiDARs
- Mono and Stereo Cameras

Ego-vehicle sensors
- Gyro, accelerometer
- Wheel speed sensors
- Steering angle sensor
- GPS

Virtual sensors:
- Digital maps
- Wireless communication

Sensor fusion



Outline

- Advanced Driver Assistance Systems (ADAS)
- **Problem definition**

Performance of sensor fusion systems

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Efficiency of the fusion algorithm

- Average number of missed targets,
- Average number of extra targets and etc..

Quality of the input data

Improvement and quality assessment of the input data:

- Specifically the degree in confidence in terms of attributes such as reliability and credibility

Rate at which the data is provided to the fusion system:

- Rate of the sensors (measurement cycle)
- Quality of the communication link (latency, jitter)

Neglect → OOSM → Perf. Decrease

Outline

- Advanced Driver Assistance Systems (ADAS)
- Problem definition
- **Understanding OOSM problem**

Open questions

HOW DOES THE
OOSM OCCUR?

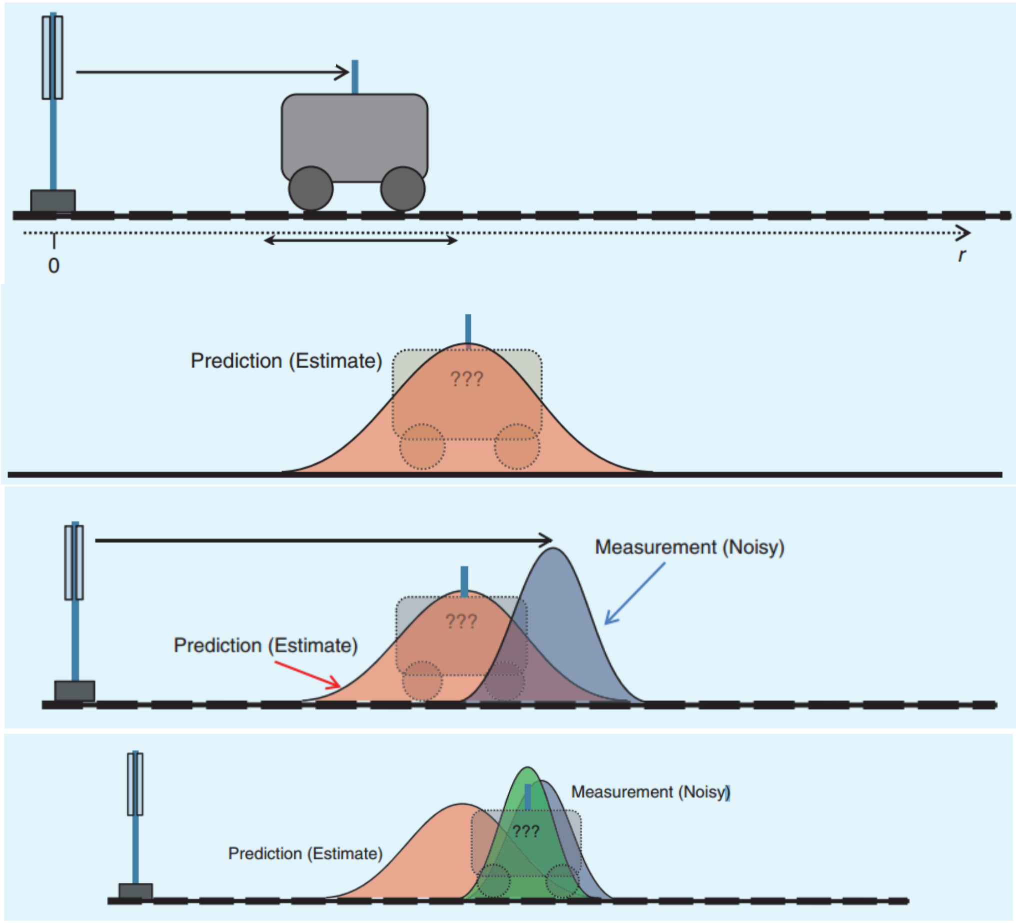
HOW DOES THE
OOSM
EFFECTS THE
SENSOR FUSION SYSTEM?

→

Kalman filter

The Kalman Filter

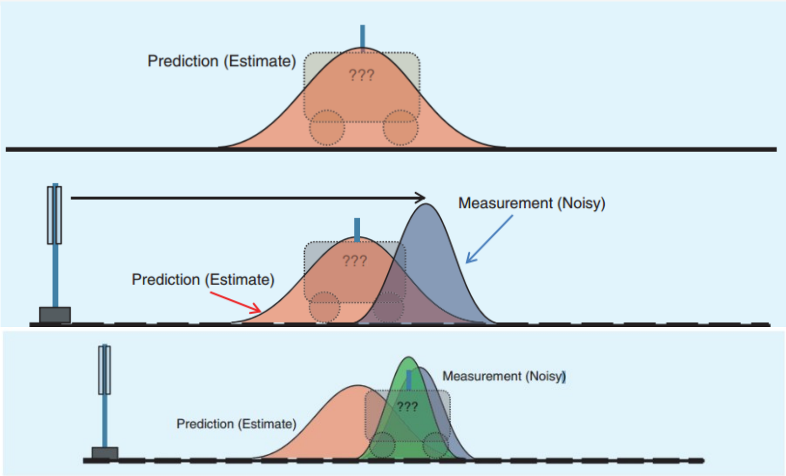
An optimal recursive data processing algorithm, that computes the best estimate of the current target state, based on the preceding target state estimate, the current measurement and the control input (ut).



THE BEST ESTIMATE
WE CAN MAKE OF
THE LOCATION OF AN OBJECT
IS PROVIDED BY COMBINING OUR
KNOWLEDGE FROM THE PREDICTION
AND THE MEASUREMENT

The Kalman Filter

1. $\hat{x}_t = A_t \bar{x}_{t-1} + B_t u_t + \epsilon_t$
2. $\hat{z}_t = H_t \hat{x}_t + \beta_t$
3. $\bar{x}_t = \hat{x}_t + K(z_t - \hat{z}_t)$



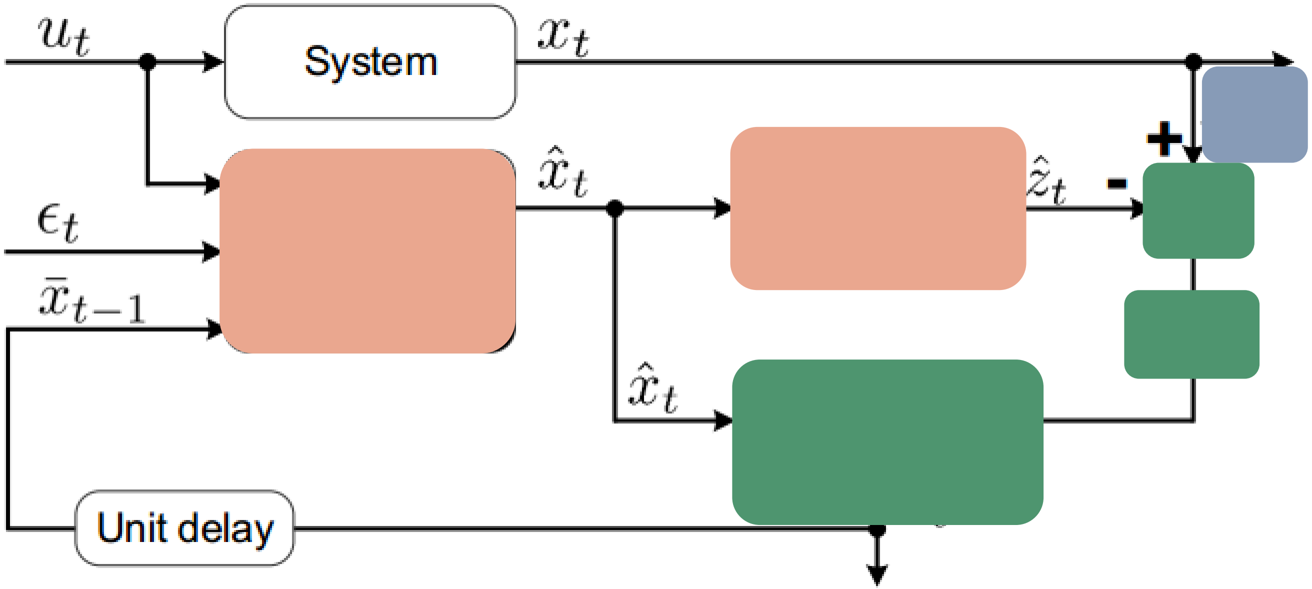
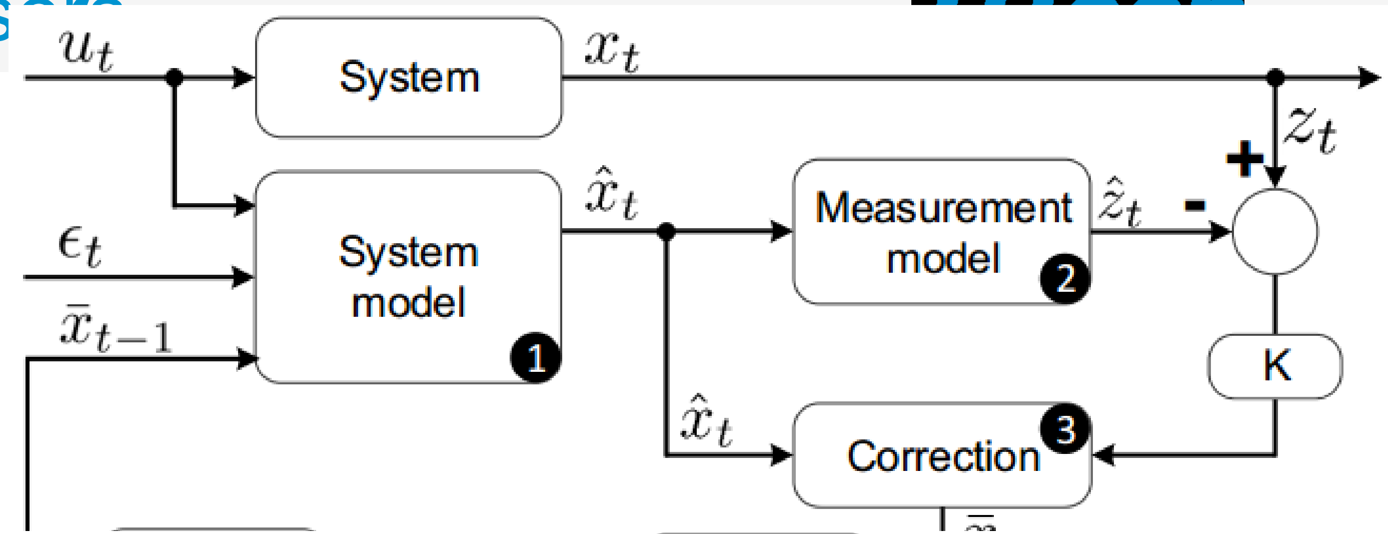


Fig. 1. Kalman filter block diagram.

Application of Kalman filter for multiple sensors



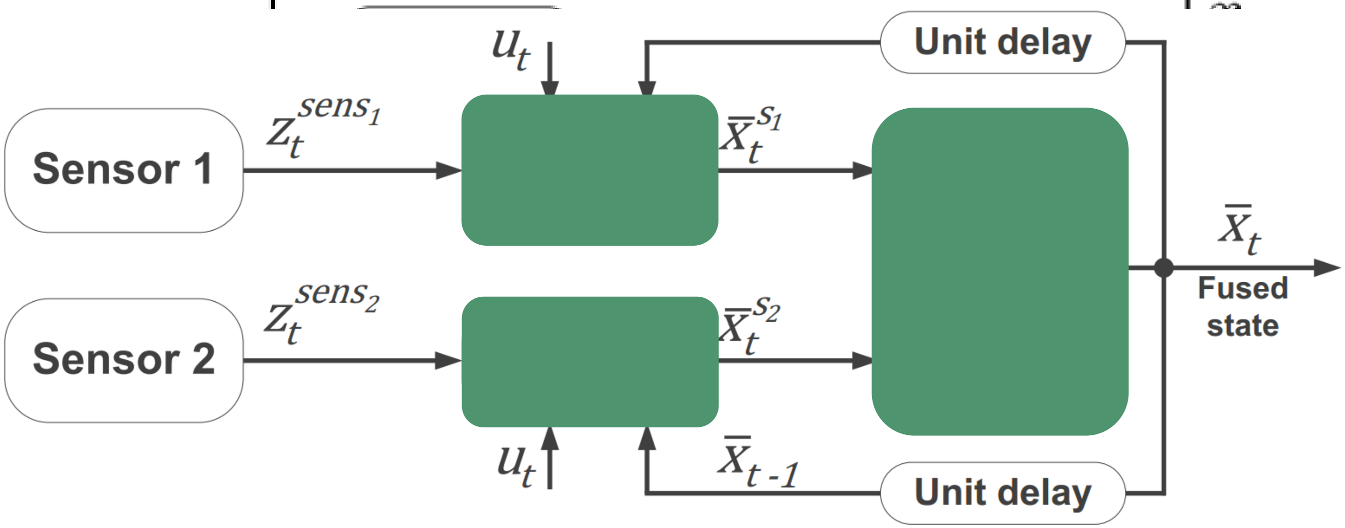


Fig. 2. State vector fusion.

The occurrence of OOSM

- Differing measurement latency times
- Asynchronous sensing

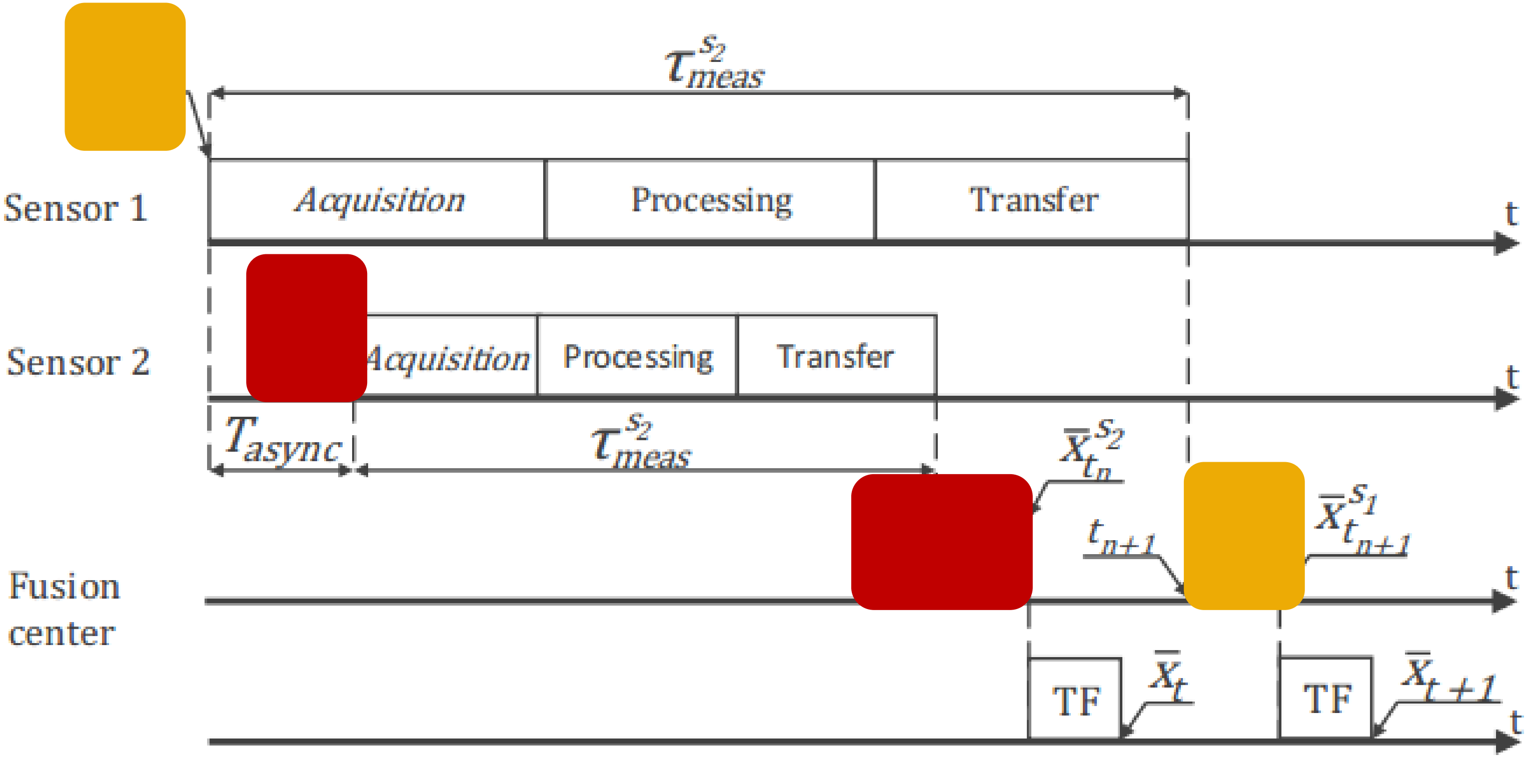


Fig. 3. Example for out-of-sequence measurement.

The effect of OOSM

TABLE II
TRACKING TWO CYCLE OF KALMAN FILTER PROCESS.

1: $\hat{x}^{s2}_{t_n} = A_{t_n}\bar{x}_{t_{n-1}} + \epsilon_{t_n}$	5: $\hat{x}^{s1}_{t_{n+1}} = A_{t_{n+1}}\bar{x}_{t_n} + \epsilon_{t_{n+1}}$
2: $\hat{z}^{s2}_{t_n} = H_{t_n}\hat{x}^{s2}_{t_n} + \beta_{t_n}$	6: $\hat{z}^{s1}_{t_{n+1}} = H_{t_{n+1}}\hat{x}^{s1}_{t_{n+1}} + \beta_{t_{n+1}}$
$\bar{x}^{s2}_{t_n} = \hat{x}^{s2}_{t_n} + K(z^{s2}_t - \hat{z}^{s2}_{t_n})$	$\bar{x}^{s1}_{t_{n+1}} = \hat{x}^{s1}_{t_{n+1}} +$
$\bar{x}_{t_n} = \bar{x}^{s2}_{t_n}$	$\bar{x}_{t_{n+1}} = \bar{x}^{s1}_{t_{n+1}}$

NTMO

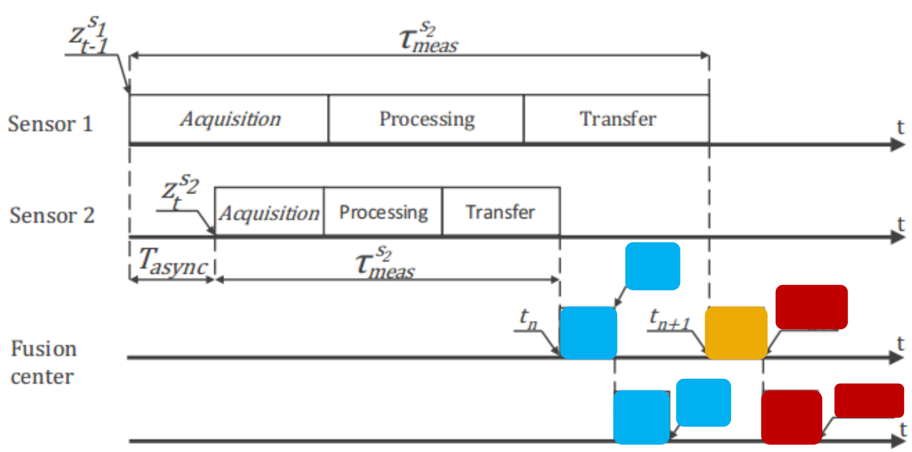


Fig. 3. Example for out-of-sequence measurement.

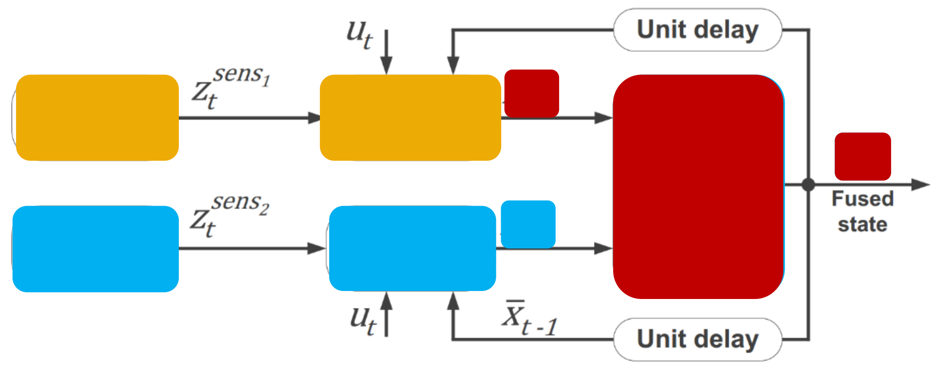


Fig. 2. State vector fusion.

The amount of the error introduced by NTMU

Size of NTMU	The Kalman gain	Velocity
$\Theta = (t_{arrival} - t_{acquisition})$	Constant K=1	Constant speed

Error introduced by the NTMU

$$\varepsilon_{\Theta} = V \times (t_{arrival} - t_{acquisition})$$

Handling the OOSM

Sophisticated algorithms

Single-lag and multi-lag OOSM

Simple algorithms

Buffering algorithm

Assumption

Precise timestamp

Not valid

Lack of SWRC

Chronological order

Not guaranteed

OOSM

NTMU

Inevitable

The amount of the error introduced by imprecise measurement

Size of NTMU	Error introduced by (ε_{tp})
Error of the timestamp (ε_{tp})	$\varepsilon_{\Theta} = V \times \varepsilon_{tp}$

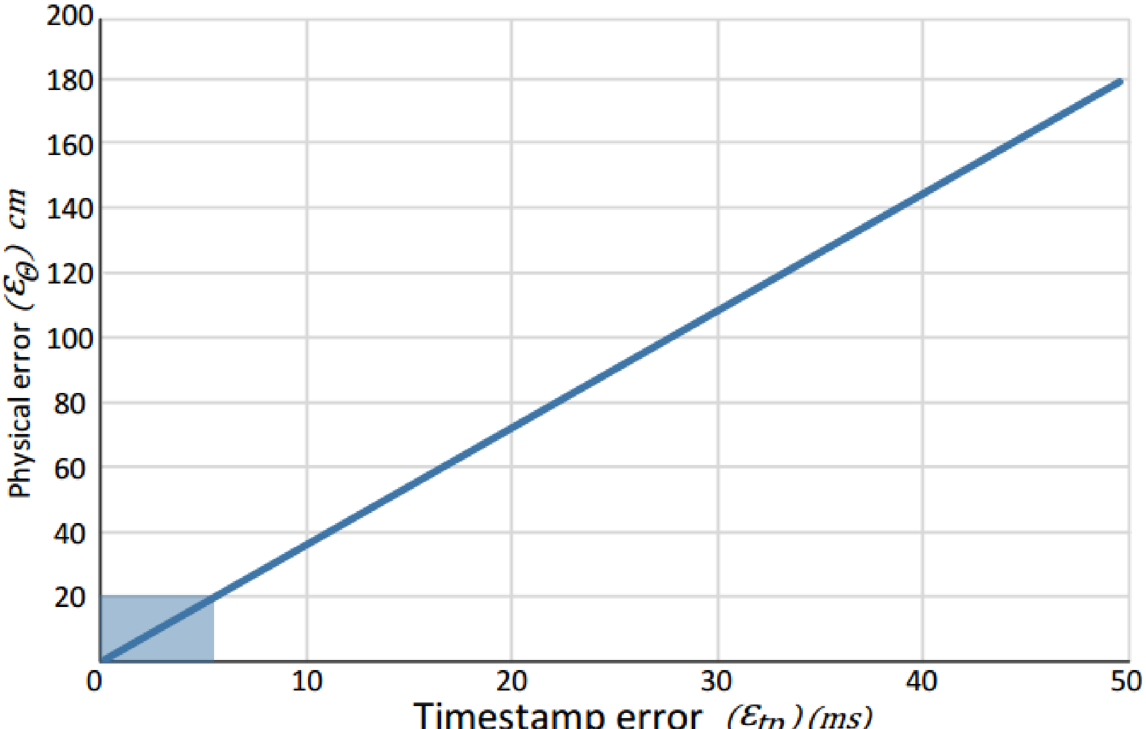


Fig. 4. Physical error (ε_{Θ}) that will be introduced to the optimal state estimate $(\bar{x}_{t_{n+1}})$ by the error of the timestamp (ε_{tp}).

Vehicle speed
130 Km/h

Objective
Error <= 20cm

Outline

- Advanced Driver Assistance Systems (ADAS)
- Problem definition
- Understanding the OOSM problem
- **Methods for measurement timestamping**

Timestamping data at arrival (Centralized method)

Measurement latency. time	τ_{mt}
Measurement cycle time	T_c
Measurement transf. time	τ_{mt}

Error of the timestamp	ε_{tp}
Precision of the cycle time	π'
Communication jitter	$\Delta t_j'$

$$\tau_m = T_c + \tau_{mt} \quad (9)$$

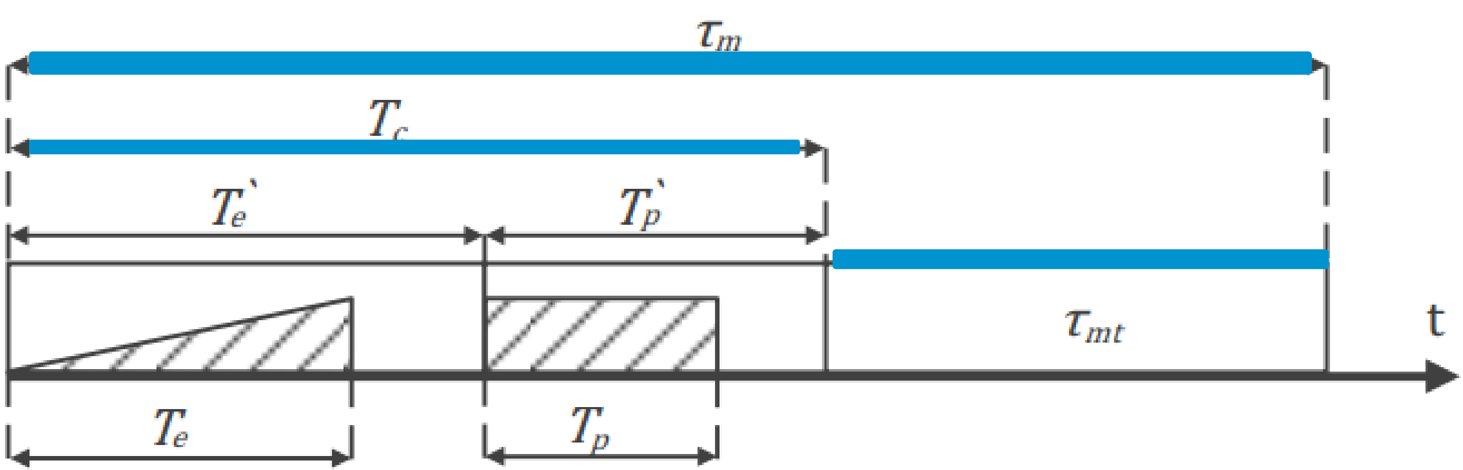


Fig. 5. Measurement latency time.

Triggering method

Trigger latency. time	τ_t
Trigger transfer latency	τ_{tt}
Activation latency	T_r

Error of the timestamp	ε_{tp}
Communication jitter	$\Delta t_j''$
Constant trigger lat. time	56µs

$$\tau_t = \tau_{tt} + T_r \quad (14)$$

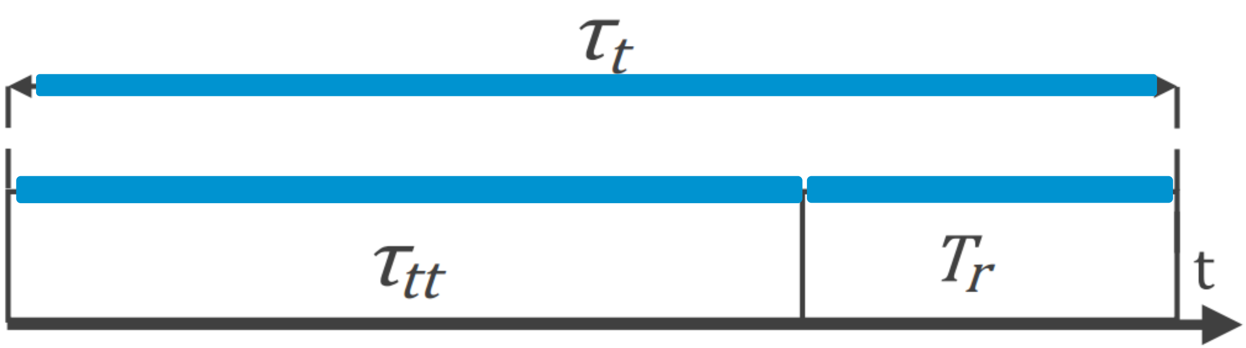


Fig. 6. Trigger latency time.

Timestamping at the time of acquisition (distributed method)

Sensors
Measurement with timestamp

Benefit
No cycle times
No transfer times

Difficulty
Global time

Global sync. mechanism
Needed

Precision of the timestamp
Precision of the sensor internal clock with respect to UTC time. (π'')

Error of the timestamp

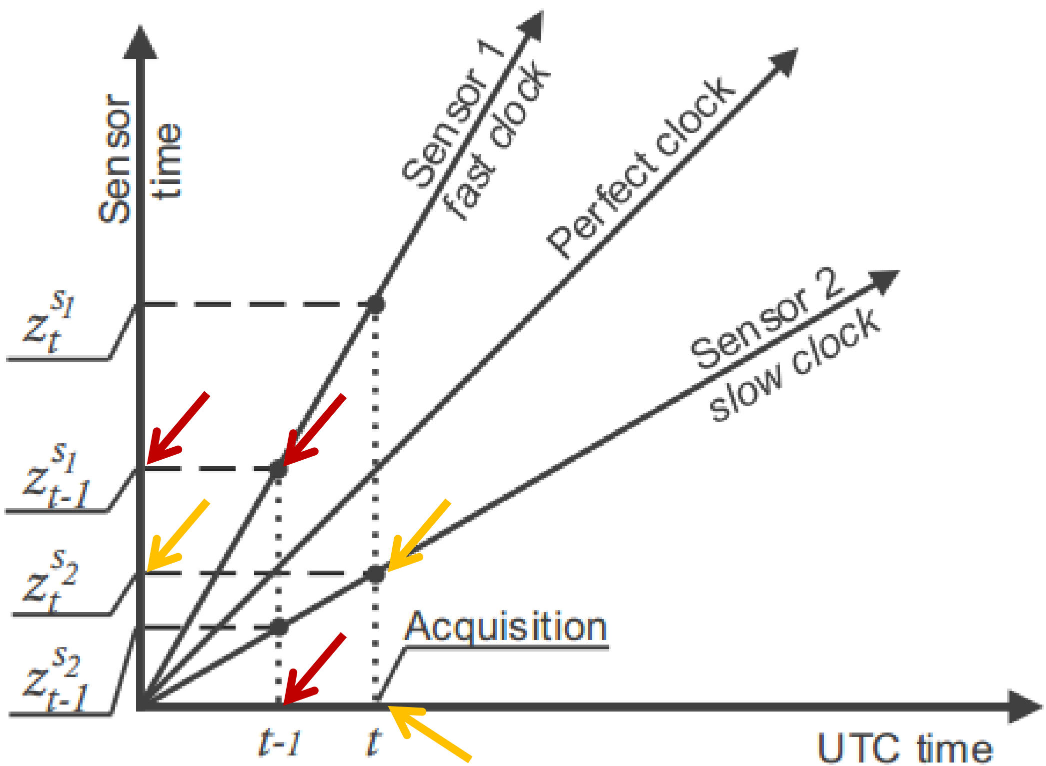


Fig. 7. Clock drifting.

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- **The use of deterministic Ethernet networks for precise timestamping**

What do we target

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Centralized approach	Triggering app.	Distributed app.
$\varepsilon_{tp} = \pi' + \Delta t_j'$ (13)	$\varepsilon_{tp} = \Delta t_j''$ (16)	$\varepsilon_{tp} = \pi''$ (19)

Communication standards

- Ensure a system-wide synchronized time
- Low jitter data transmission

Standard Ethernet

+ AVB / TSN

AVB	IEEE 802.1AS	Sync accuracy 1 µs
AVB	IEEE 802.1Qav	Jitter ~10 – 100 µs
TSN	IEEE 802.1Qbv	Jitter 1 µs

+ SAE AS6802

SAE AS6802	Sync accuracy 1 µs
	Jitter 1 µs

Suitability of the standards for achieving precise timestamps

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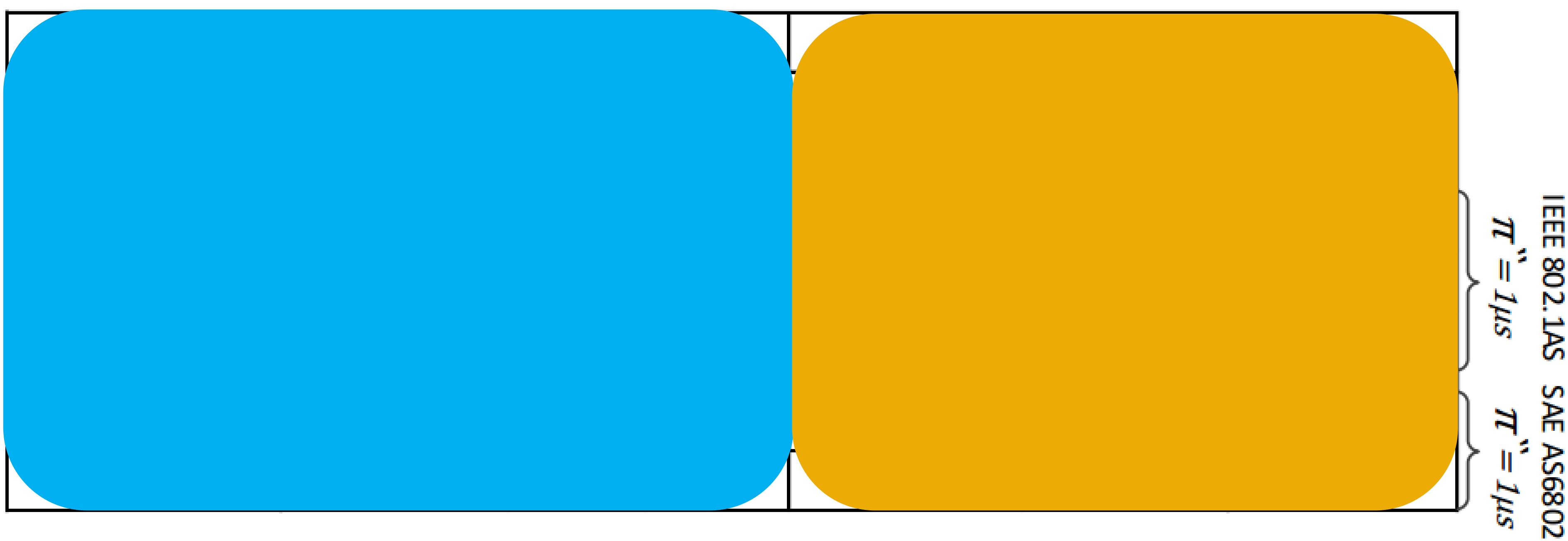
Standards and their spec.	Timestamp precision
• Traffic class • The data that is transmitted • Maximum communication jitter *(Numbers taken from simulation based performance comparisons)*	Assumed to be achieved with: • Centralized, triggering or distributed approach. • If one or more comm. Standards are used.



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- **Results**

Error introduced by the timestamp precision

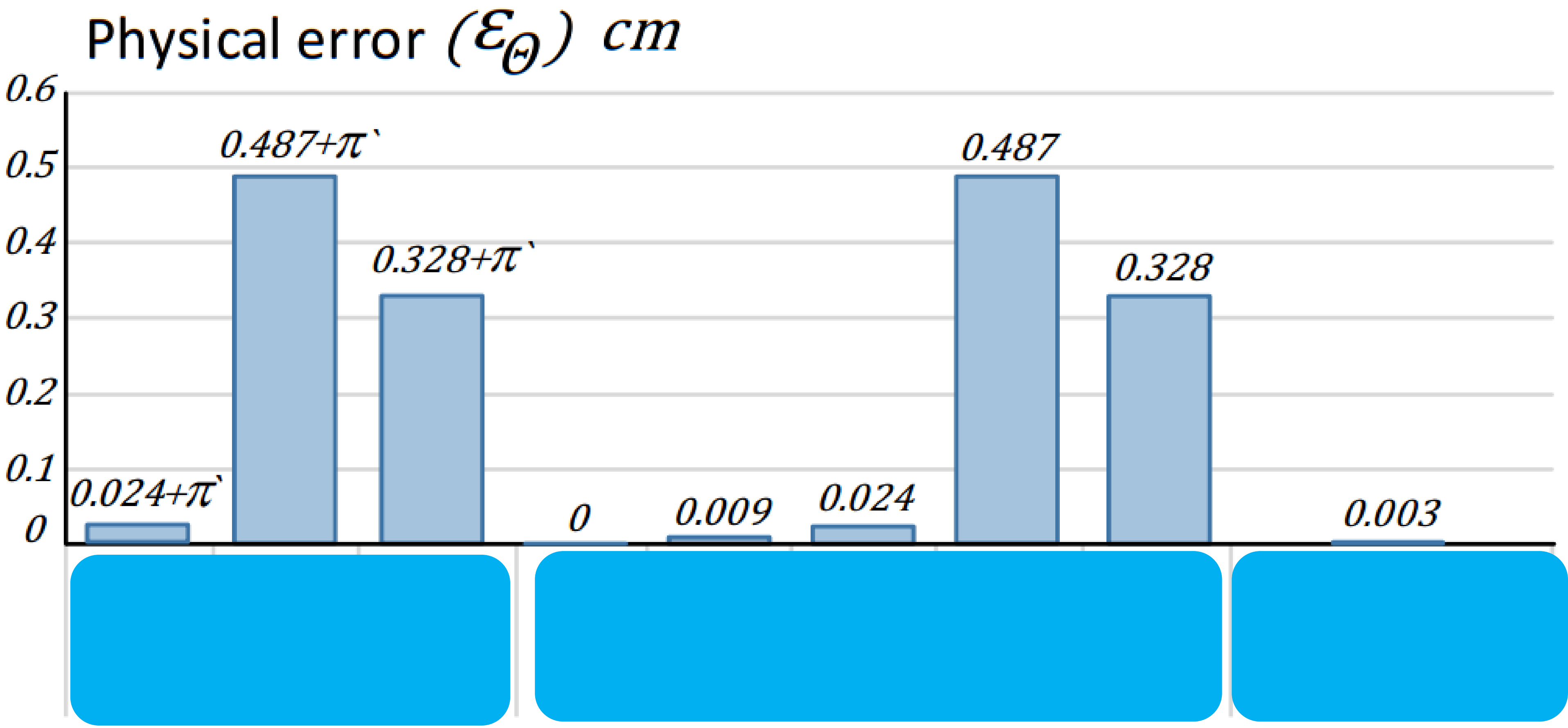

Fig. 9. The error (ε_{Θ}) introduced to the optimal state estimate using different timestamping methods in combination with different traffic classes and synchronization standards.

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Conclusions

Objectives of our research

Study the benefits of different communications standards for the application area of sensor fusion systems..

Prerequisites

1. Understanding the Kalman filter
2. The cause of OOSM and how they affects the Kalman filter
3. How the absence of precise measurement timestamp leads to NTMU, same as the caused by the OOSM,
4. And finally investigate the methods for sensor measurement timestamping and formulate their precision

Based on this knowledge

- We were able to show that communication standards can contribute for solving the problem of NTMU.
- By minimizing the error introduced to the optimal state estimate down to the range from **0 to less than 0,5cm** depending on the timestamping methods and the communication standards used.

Future work

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Optimistic results

consequence of idealized conditions and communication Specifications.

Verification

Simulation based studies to verify the correctness of the theoretical assumptions made in this paper.

Thank You for Your Attention!

Ensuring Reliable Networks

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Timestamping data at arrival (Centralized method)

Measurement latency. time	τ_{mt}
Measurement cycle time	T_c
Measurement transf. time	τ_{mt}

$$\tau_m = T_c + \tau_{mt} \quad (9)$$

$$\pi' = T_c' - T_c \quad (11)$$

$$\Delta t_j' = \tau_{mt}^{max} - \tau_{mt}^{min} \quad (12)$$

$$\varepsilon_{tp} = \pi' + \Delta t_j' \quad (13)$$

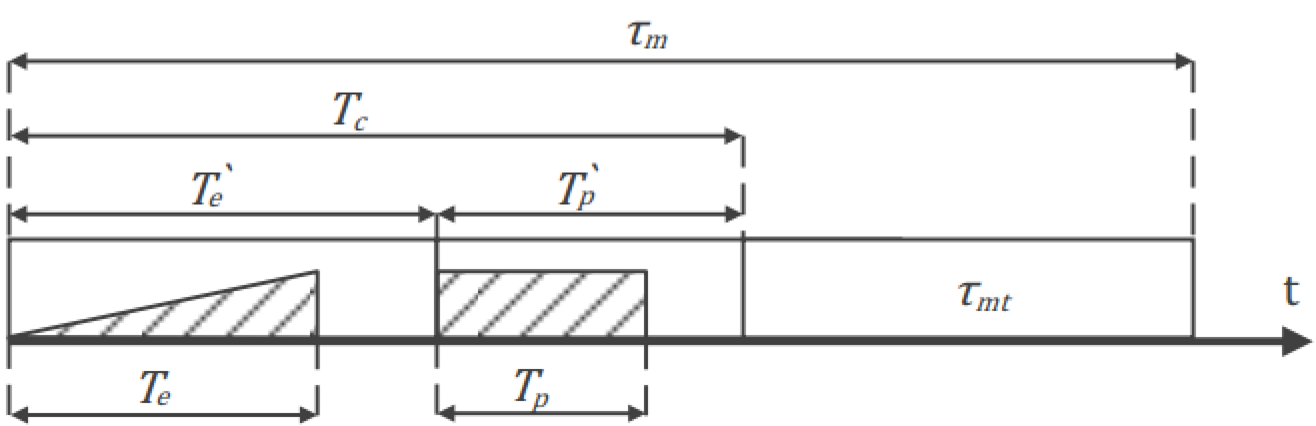

Fig. 5. Measurement latency time.

Drawback of current solutions

- Assume a timestamp with precise timestamp
- Not valid: due to the lack of system wide-reference clock.

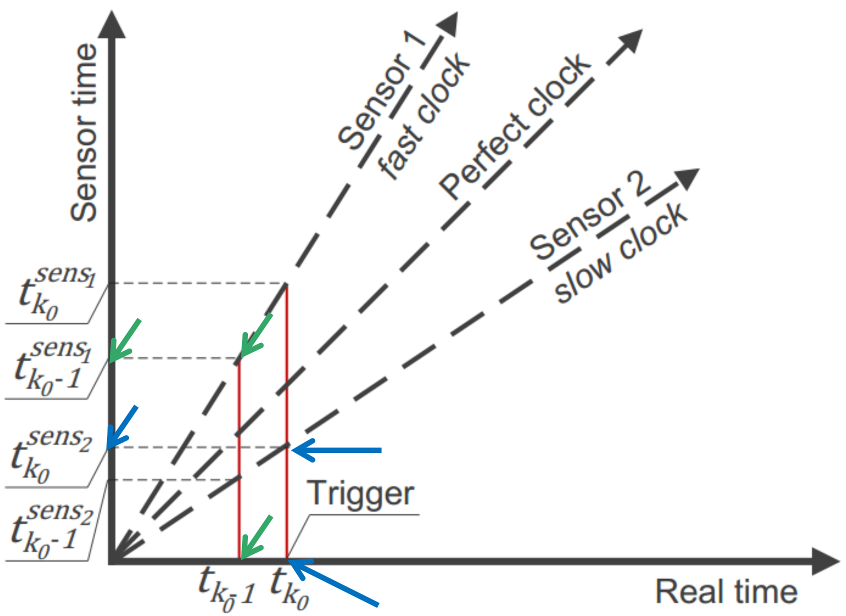

Fig. 4. Clock drifting.

Deterministic sensor data acquisition

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- **Deterministic Behavior**

A system exhibits a deterministic behavior when the performance measures of its services are predicable under a number of conditions and characterized by specific nonrandom equations

- **Context of in-vehicle networks**

The most important performance measure is message latency

- **Context of multi-sensor data**

Result of non-deterministic message latency are multi-sensor data fusion systems are the out-of-sequence measurements.

- **Solution**
  - Exploring the features of different real-time network technologies:
    - TTEtthernet,
    - AVB,
    - TSM
  - Explore their ability of achieving deterministic behavior in the process of acquisition of sensory data from different ADAS sensors
  - Abilities:
    - Tightly synchronize the data acquisition from multiple cameras, LiDARs, LRR and SRR
    - Provide a “time-stamp” for each measurement

The Kalman Filter

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1. $\hat{x}_t = A_t \bar{x}_{t-1} + B_t u_t + \epsilon_t$
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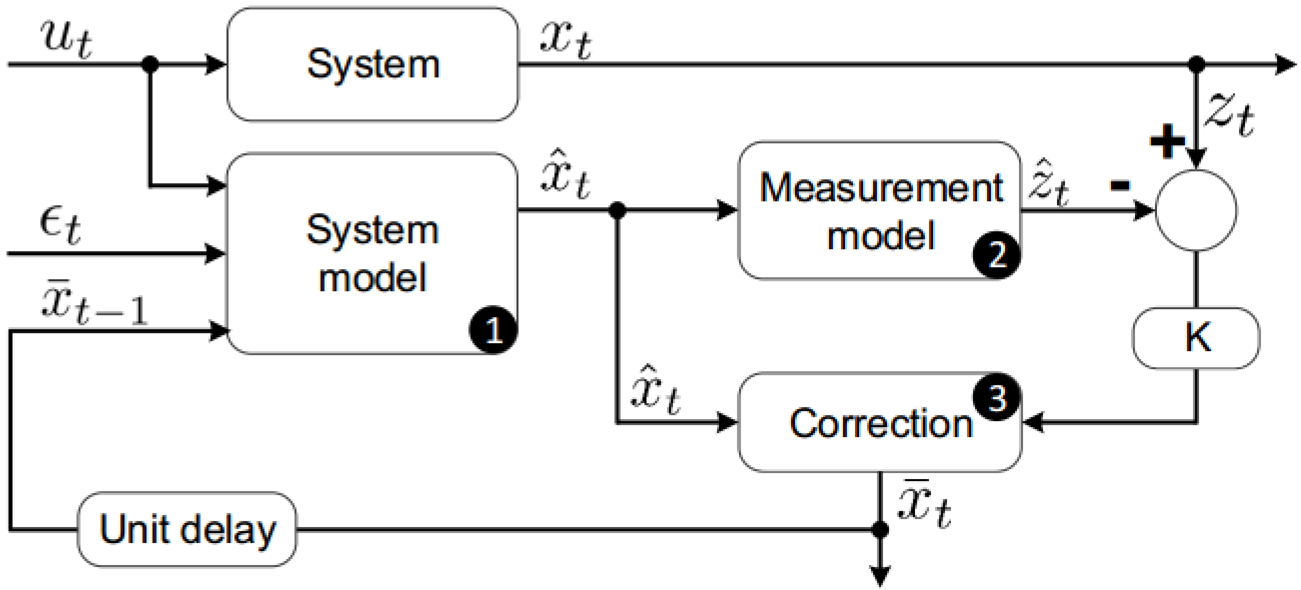

Fig. 1. Kalman filter block diagram.