Sensor Positioning and Selection in Sensor Networks for Target Tracking

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1. Introduction

Framework

- The Network Centric Warfare (NCW) systems concept consists of a sensor, an information and a shooter grid.
- Sensor grid nodes (platforms) contain different sensors with multiple operational modes.
- To realize the NCW capabilities, coordination between various naval units will have to be increased and sensor management (SM) will have to be applied across ships.
- In this paper sensor coordination is extended to a group of moving platforms for single target tracking.

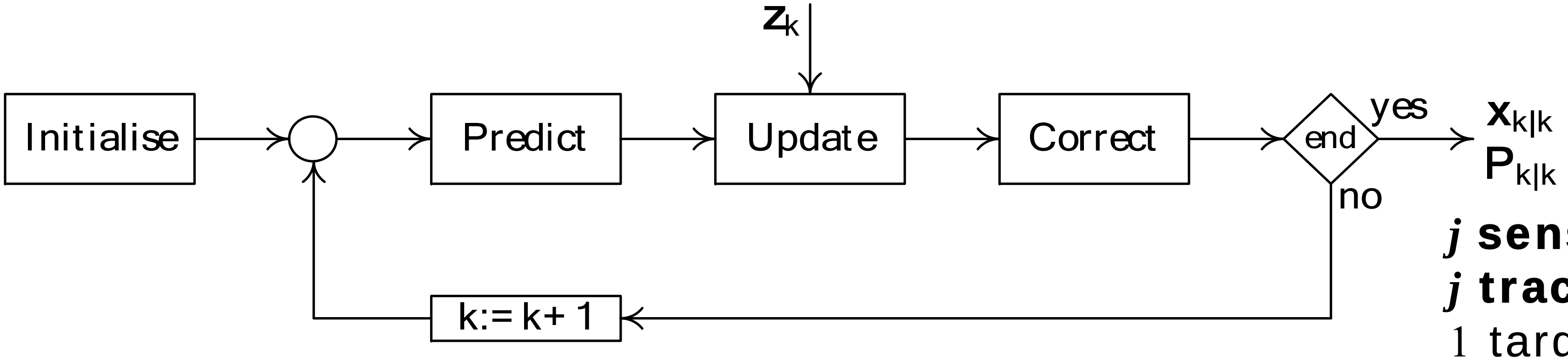
1. Introduction

Research Objectives

- The goal is to optimize the target track estimate accuracy.
- SM is divided into sensor selection and sensor positioning.
- The outcome of the sensor selection process is the appropriate sensor for doing an observation.
- Sensor positioning will place the platforms such, that they can best deploy their sensor capabilities in the near future.
- The result is one target track composed of a sequence of measurements from (possibly) different sensors.

Target Tracking

- Target tracking: a sequence of sensor observations is used to estimate the target state vector.
- State estimation is done with the Kalman Filter (KF), a recursive algorithm with a predictor, update and a corrector step.
- The KF output is a target state estimate $\mathbf{x}_{k|k}$ with a corresponding error covariance matrix $\mathbf{P}_{k|k}$.
- The target state is estimated using measurement data $\mathbf{z}_k$ in polar coordinates (range, Doppler and bearing).



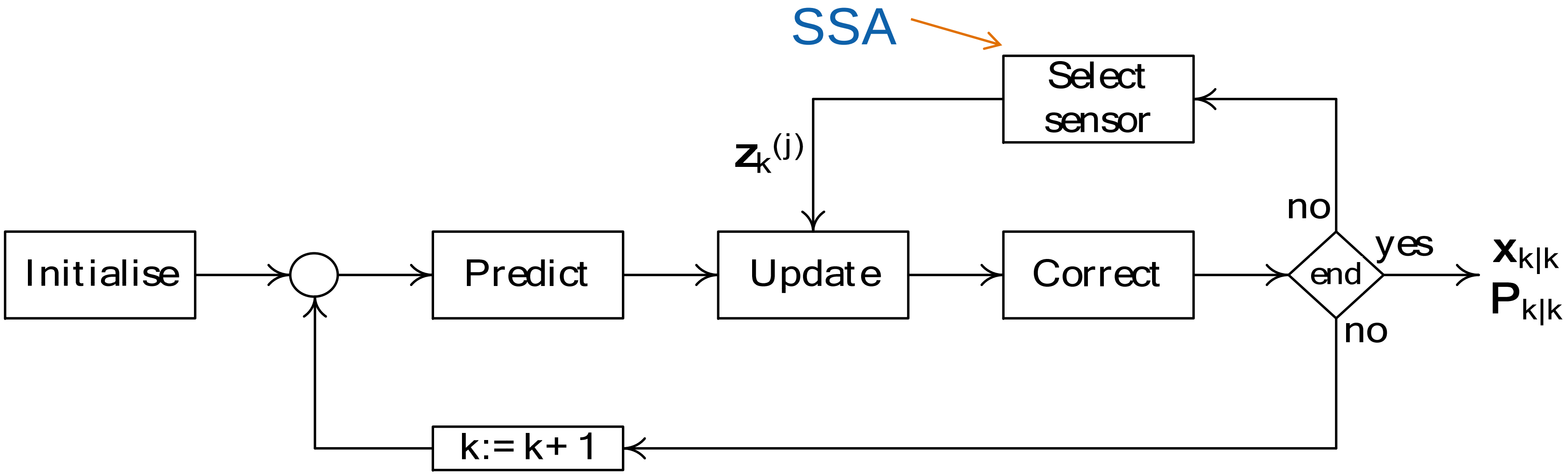
j **sensors** → *j* **tracks** for 1 target

Sensors

- There are three different radar-like sensors, $s^{(1)}$, $s^{(2)}$ and $s^{(3)}$, each located on a moving platform:
    - $s^{(1)}$: measures bearing only.
    - $s^{(2)}$: measures bearing and range.
    - $s^{(3)}$: measures bearing, range and Doppler.
- Since the detection probability $0 \leq p_d^{(j)} \leq 1$, it is possible that no measurement is obtained at a certain time step.
- In case of no measurement update: the KF update and corrector steps are skipped.

Sensor Selection

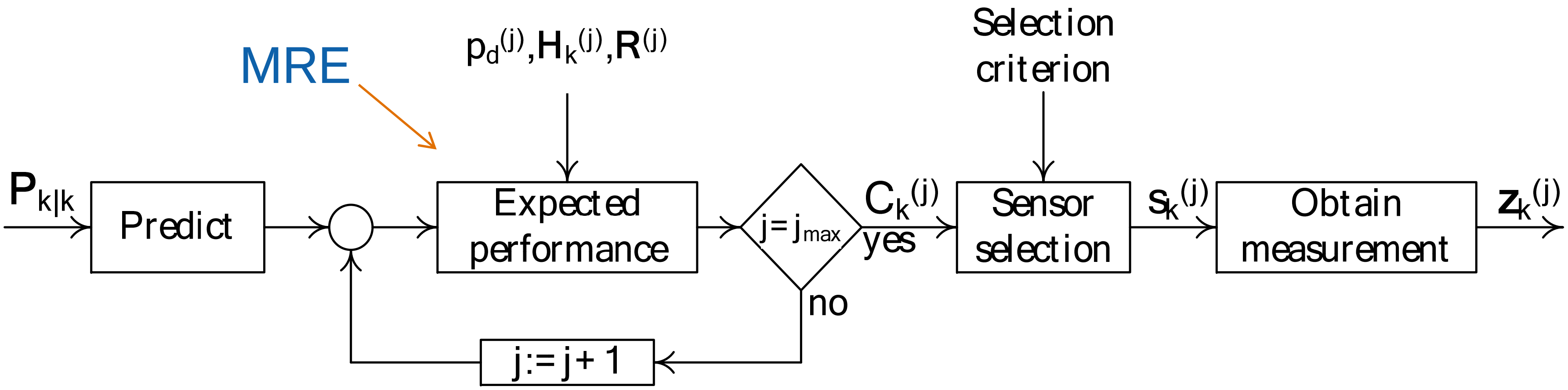
- The Sensor Selection Algorithm (SSA) compares the available sensors with respect to the best expected performance.
- The sensor with the best expected performance is selected to obtain a measurement at time k.



- Now, for a single target **j sensors** will yield **one target track**.

Sensor Selection Algorithm

- The Modified Riccati Equation (MRE) is used for performance evaluation. It includes for each sensor the p_d and measurement accuracies.
- The cost function is based on the MRE and the best expected target position accuracy selection criterion (i.e., minimum positional variance in Cartesian coordinates).
- For every sensor the expected performance is computed.



MRE

$p_d^{(j)}, H_k^{(j)}, R^{(j)}$

Selection criterion

$P_{k|k}$

Predict

Expected performance

$j = j_{max}$

$C_k^{(j)}$

yes

no

Sensor selection

$s_k^{(j)}$

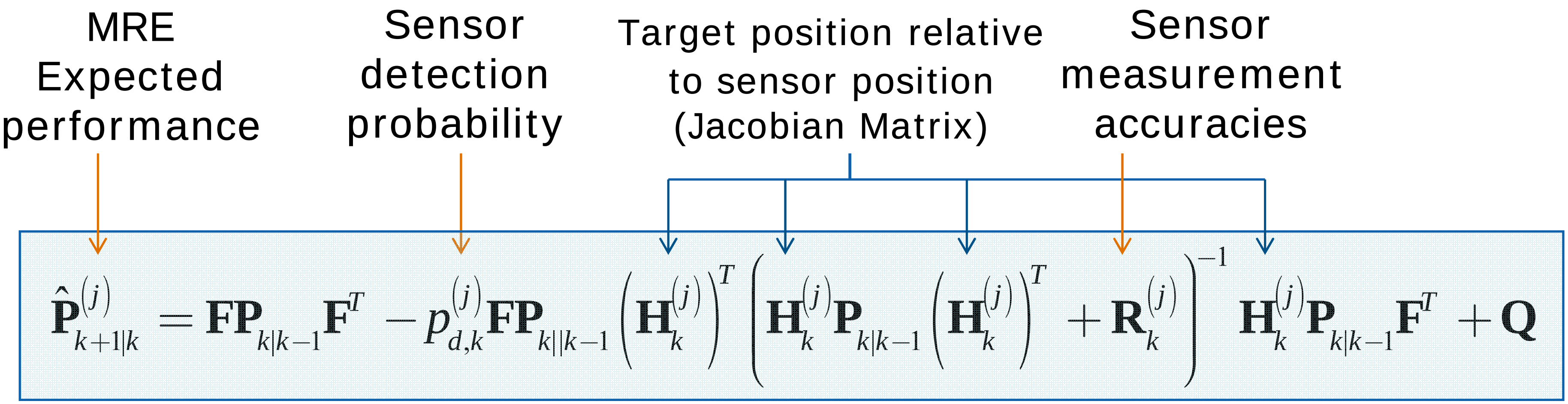
Obtain measurement

$z_k^{(j)}$

$j := j + 1$

3. Sensor Selection

Expected Performance



MRE Expected performance

Sensor detection probability

Target position relative to sensor position (Jacobian Matrix)

Sensor measurement accuracies

$$\hat{\mathbf{P}}^{(j)}_{k+1|k} = \mathbf{F}\mathbf{P}_{k|k-1}\mathbf{F}^{T} - p^{(j)}_{d,k}\mathbf{F}\mathbf{P}_{k||k-1}\left(\mathbf{H}^{(j)}_{k}\right)^{T}\left(\mathbf{H}^{(j)}_{k}\mathbf{P}_{k|k-1}\left(\mathbf{H}^{(j)}_{k}\right)^{T}+\mathbf{R}^{(j)}_{k}\right)^{-1}\mathbf{H}^{(j)}_{k}\mathbf{P}_{k|k-1}\mathbf{F}^{T}+\mathbf{Q}$$

Sensor selection criterion: best expected target position accuracy

$$C^{(j)}_{k} = \det\left\{\left[\begin{bmatrix}\hat{\mathbf{P}}^{(j)}_{k+1|k}(1,1) & \hat{\mathbf{P}}^{(j)}_{k+1|k}(1,3)\\ \hat{\mathbf{P}}^{(j)}_{k+1|k}(3,1) & \hat{\mathbf{P}}^{(j)}_{k+1|k}(3,3)\end{bmatrix}\right]\right\}$$

$\hat{\mathbf{P}}^{(j)}_{k|k+1}$ = expected error covariance matrix

$\mathbf{P}_{k|k-1}$ = predicted error covariance matrix

$\mathbf{H}^{(j)}_{k}$ = Jacobian of the measurement matrix

$\mathbf{R}^{(j)}_{k}$ = measurement accuracy matrix

$p^{(j)}_{d,k}$ = detection probability

$\mathbf{F}$ = state transition matrix

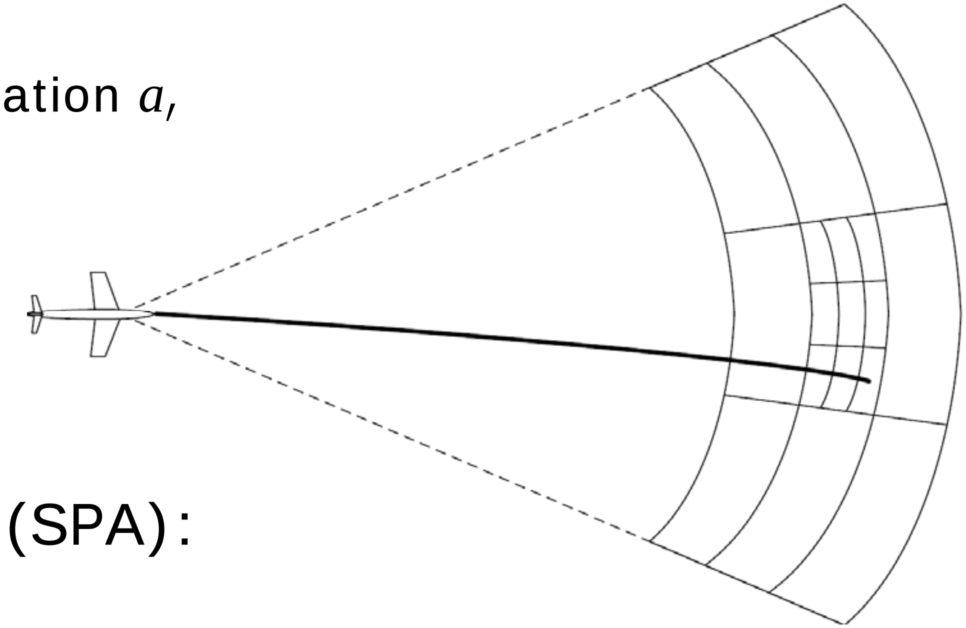
$\mathbf{Q}$ = process noise covariance matrix

(j) = index sensor

Sensor Positioning

The future sensor position envelope is divided into nine sectors. This envelope is constrained by:

1) the platform speed v and
2) the platform maneuverability:
    - maximum longitudinal acceleration a,
    - the heading change α.



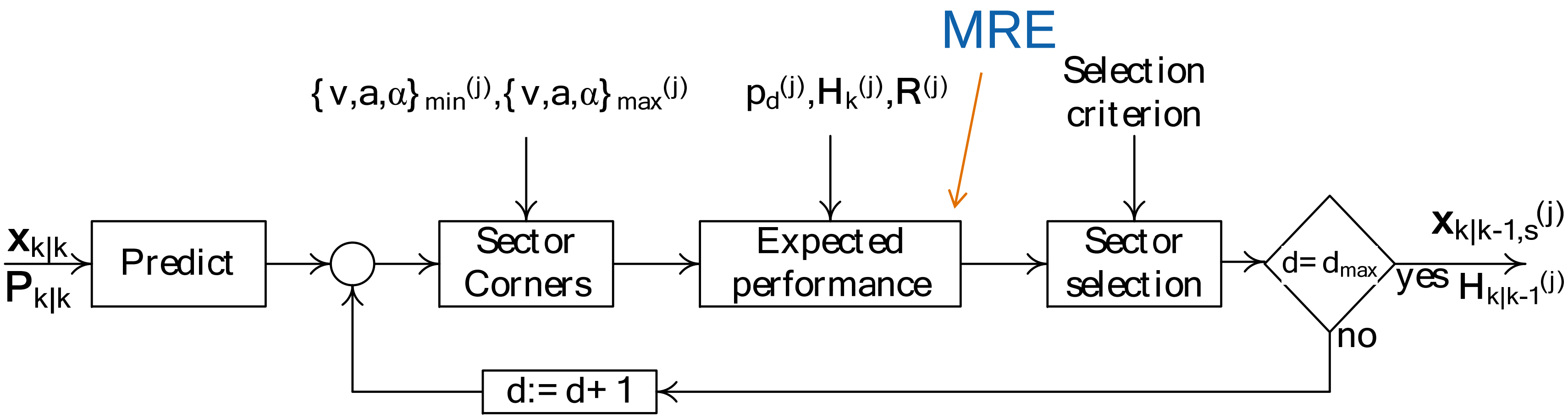
Two iteration steps are depicted (2 levels).

Sensor positioning algorithm (SPA):

- fast convergence,
- reduced computational requirements.

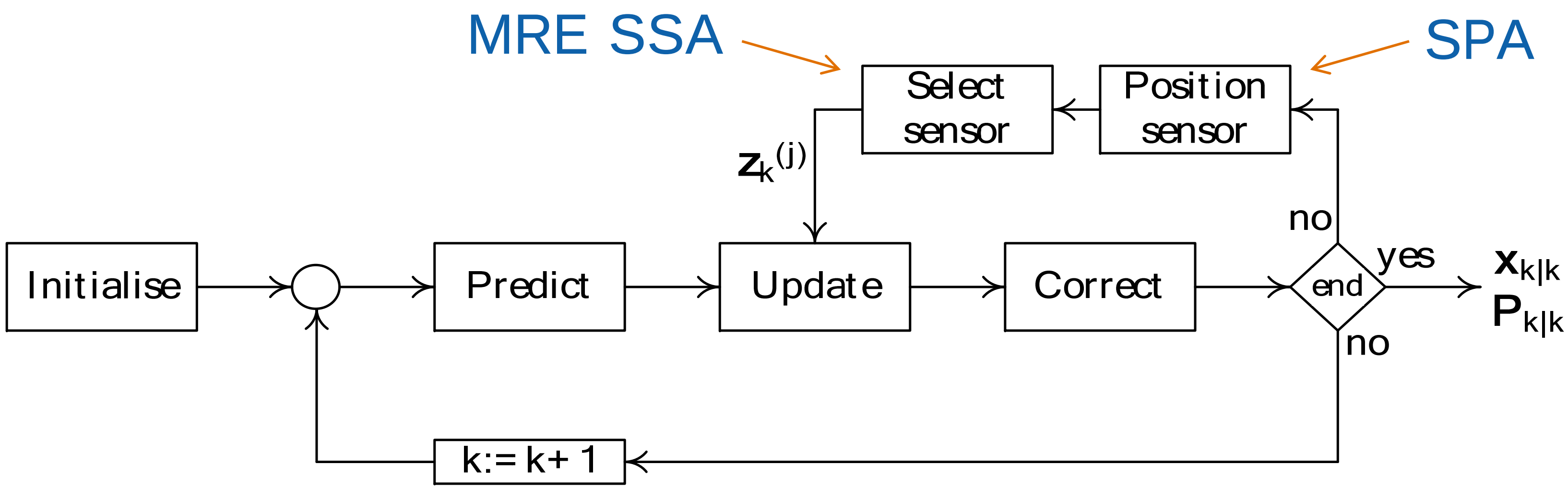
Sensor Positioning Algorithm

- For each corner point of the 9 sectors the cost is computed based on the MRE expected performance.
- The sector that minimizes the MRE-based cost function is selected and divided again into 9 sectors, until $d_{\max}$ is reached.
- The center of the last selected sector is the future position.



Sensor Positioning and Selection

- A schematic representation of the SPA and MRE SSA, in relation to the target tracking algorithm:
  1) search with the SPA for every sensor the position that will yield the lowest tracking error (best sensor positions),
  2) select with the MRE SSA the sensor that maximizes the target track accuracy (best available sensor) for measuring at time k.

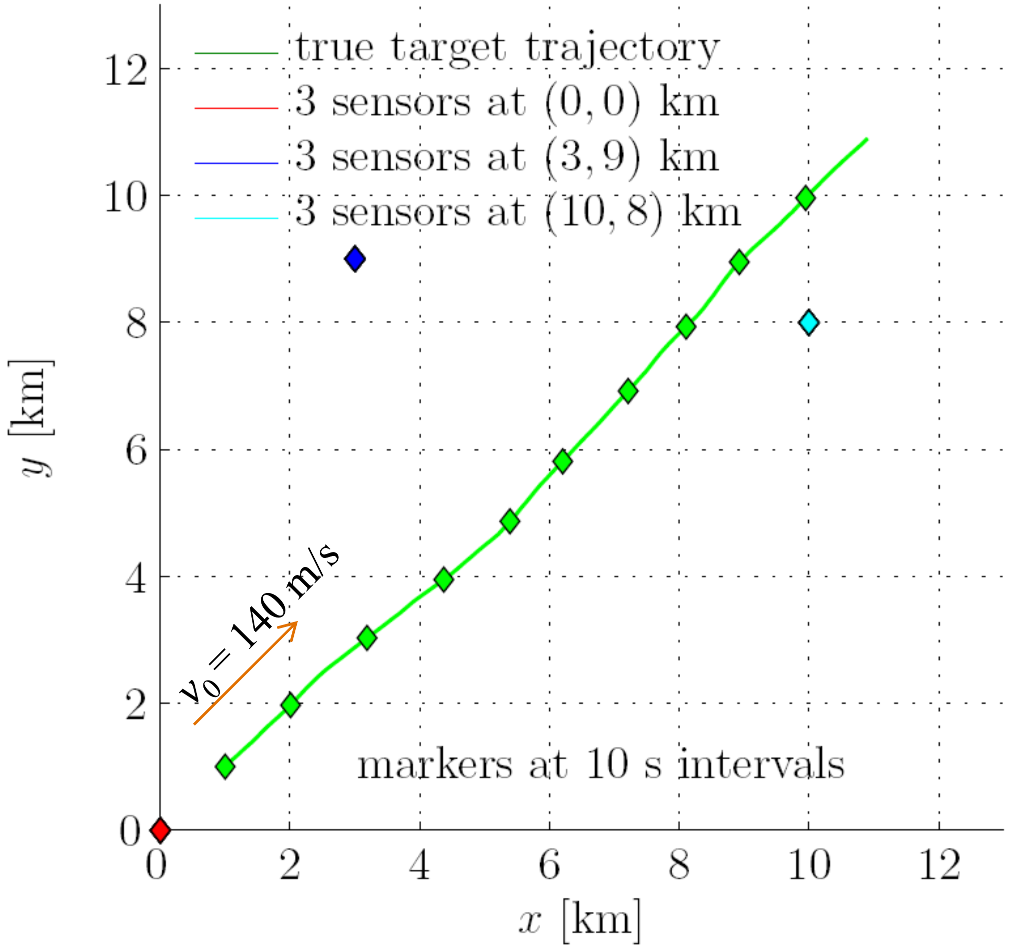


Simulations

- Goal: demonstrate the benefits of the SPA and SSA whilst maximizing the target track accuracy.
- Performance evaluation: the real performance (positional variance) after the KF corrector step: $\det(\mathbf{P}_{k|k})_{pos}$.
- Three positioning cases:
  - Case 1: stationary co-located sensors (at three positions),
  - Case 2: a distributed sensor network (stationary) and
  - Case 3: moving sensors (positioning with the SPA).
- Sensor properties:
  - $s^{(1)}$: $p_d^{(1)} = 1$; bearing: 0.09° (accuracy standard deviation, σ).
  - $s^{(2)}$: $p_d^{(2)} = 1$; bearing: 0.09°, range: 31.6 m.
  - $s^{(3)}$: $p_d^{(3)} = 1$; bearing: 0.9°, range: 7.7 m, Doppler: 10 m/s.
- Platform properties: $50 \leq v \leq 200$ m/s, $a_{\max} = 10$ m/s^2, $\alpha_{\max} = \pi/20$ rad/s.

5. Simulation Results

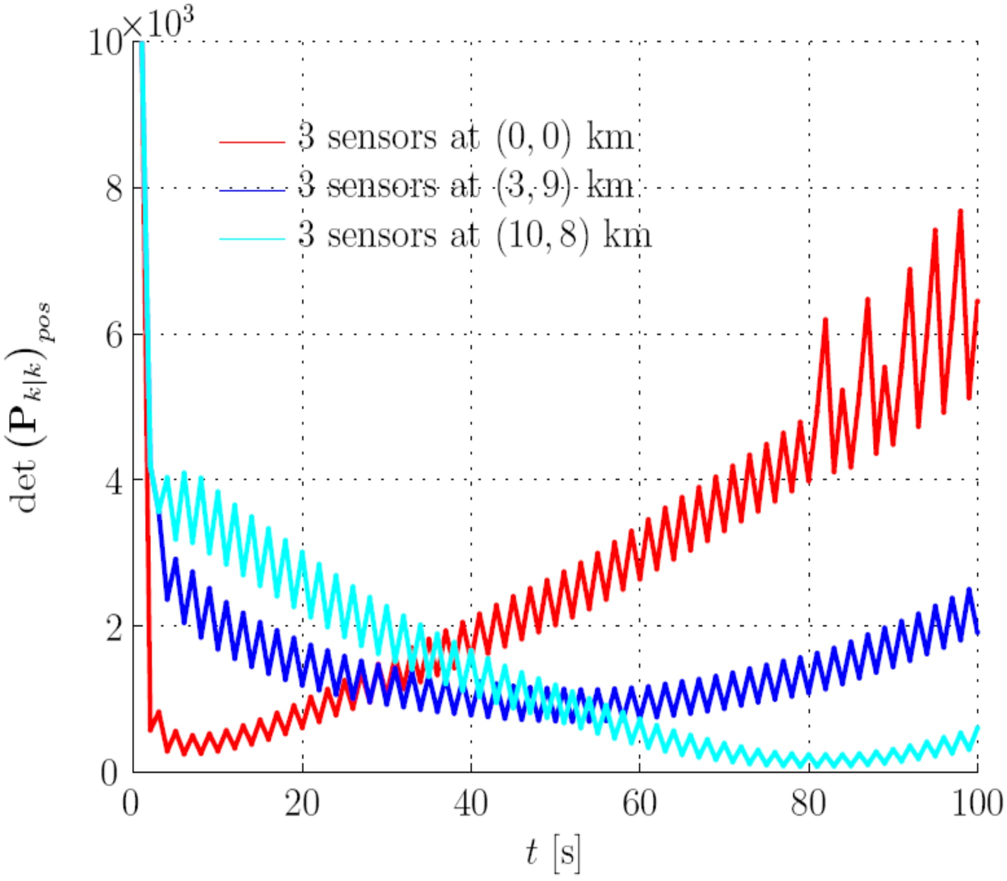
Case 1: Stationary Co-located Sensors



- The opening true target track (with respect to (0,0)).
- Three co-located sensors positions for Case 1.
- The relative position between the sensors is always the same for each co-located set.
- The line-of-sight (LOS) angle between the sensors and the target is the same.

5. Simulation Results

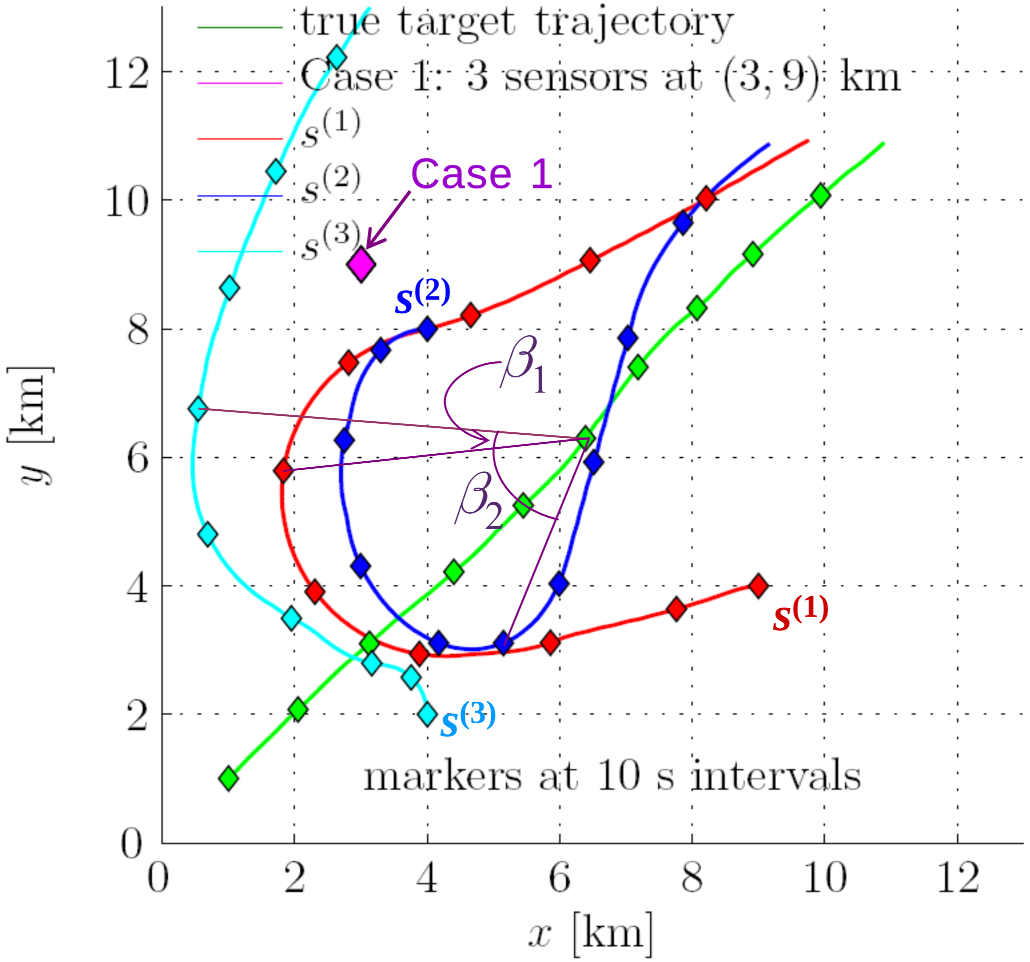
Case 1: Stationary Co-located Sensors



- The real performance $\det(\mathbf{P}_{k|k})_{pos}$.
- For sensors at $(0{,}0)$ km the $\det(\mathbf{P}_{k|k})_{pos}$ increases due to the increasing distance between sensors and target.
- The $\det(\mathbf{P}_{k|k})_{pos}$ will decrease for a closing target, (e.g., sensors placed at $(10{,}8)$ km).
- Although the parameters and selection strategies are equal, the performance strongly depends on the sensor position.

5. Simulation Results

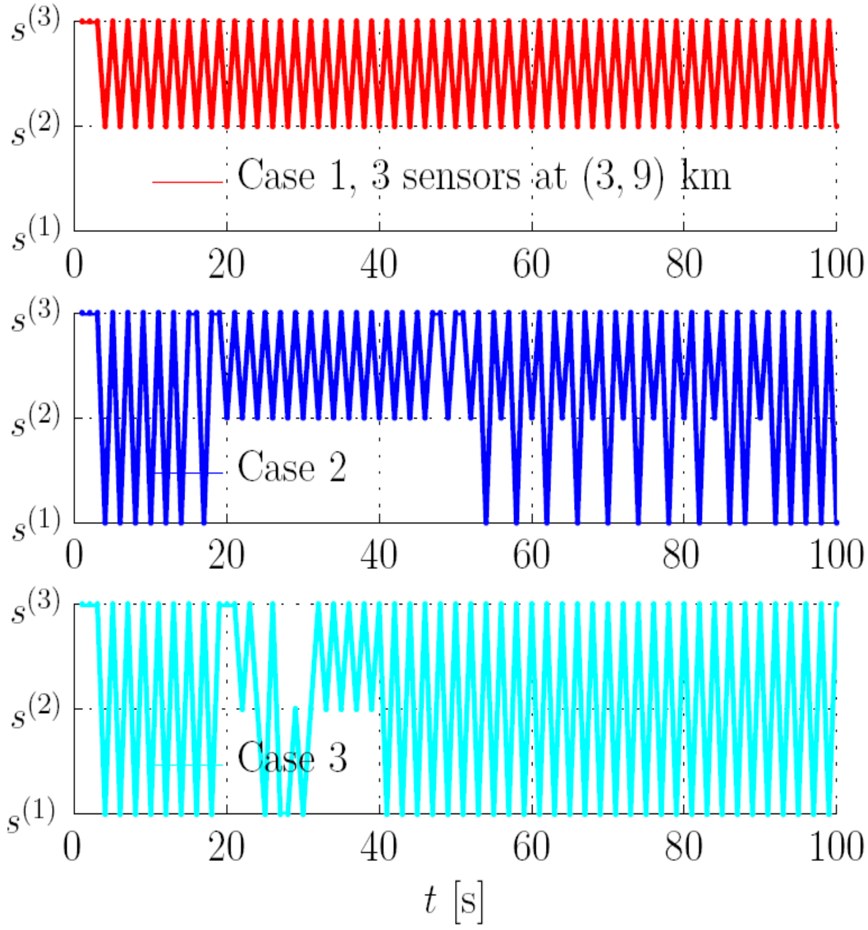
Comparison between Case 1, 2 and 3



- The true target track and sensor positions (trajectories for Case 3) for all three cases.
- Same initial sensor positions for Case 2 and Case 3.
- Sensor positioning for Case 3 is based on the SPA.
- For Case 3 the future sensor position also depends on the past performance of the other sensors.
- β_1: LOS-angle between $s^{(1)}$ and $s^{(3)}$ at $t=50$ s; β_2: LOS-angle between $s^{(2)}$ and $s^{(3)}$.

5. Simulation Results

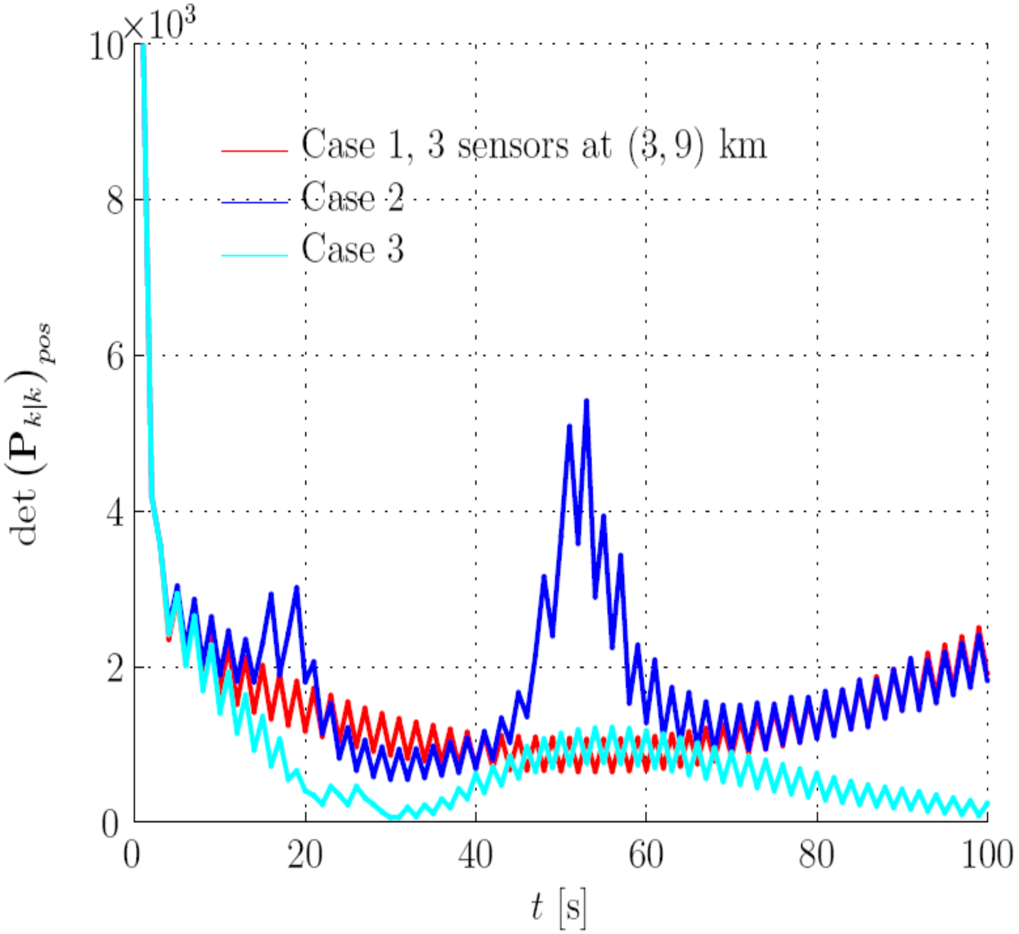
Comparison between Case 1, 2 and 3



- Sensor selection strategies.
- For Case 1 an alternating preference for $s^{(2)}$ and $s^{(3)}$ is the optimal selection strategy to minimize $\det(\mathbf{P}_{k|k})_{pos}$.
- For Case 2 and Case 3, the LOS-angle between sensors and target is not the same.
- Now, in general, the sensor will be selected that alternates with $s^{(3)}$ and has the smallest LOS-angle difference with $s^{(3)}$.
- For Case 3 a same reasoning holds, only now the sensor positions change every time step.

5. Simulation Results

Comparison between Case 1, 2 and 3



- The real performance $\det(\mathbf{P}_{k|k})_{pos}$.
- The 2 humps for Case 2 are due to multiple successive selections of $s^{(3)}$.
- The hump for Case 3 is due to the increasing distance between $s^{(3)}$ and the target.
- Stationary distributed sensors do not necessarily yield better performance compared to co-located sensors.
- Overall, Case 3 yields the lowest $\det(\mathbf{P}_{k|k})_{pos}$ (i.e., best performance).

Conclusions

- A combination of sensor positioning and selection is used to minimize the target track error.
- The outcome of both the SPA and the SSA is based on the expected target state accuracy, which is computed with the MRE and the best expected position accuracy criterion.
- The results show that a distributed moving sensor network (based on the SPA and MRE SSA) yields the best performance.
- In general, the sensor preference alternates between a sensor with good range and Doppler measurements, but a poor bearing accuracy and a sensor with a good bearing accuracy, but poor or no range measurements.
- The performance is optimized when the sensors have the same (or a small difference in) line-of-sight-angle between sensor and target.

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