Multiple Mobile Target Tracking in Wireless Sensor Networks

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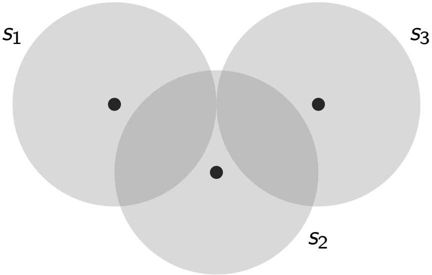
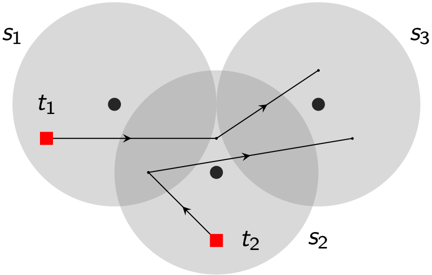
Initial data

- A set of m **static sensors** $I = \{1, \ldots, m\}$.
- Position of sensors : $(x_i, y_i) \in \mathbb{R}^2$, $i \in I$.



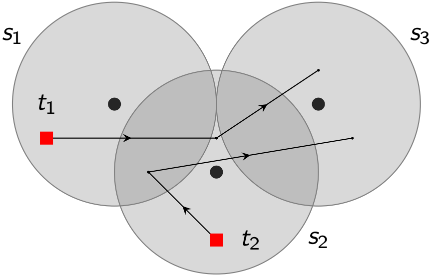
Initial data

- A set of m **static sensors** $I = \{1, \ldots, m\}$.
- Position of sensors : $(x_i, y_i) \in \mathbb{R}^2$, $i \in I$.
- A set of n **moving targets** $J = \{1, \ldots, n\}$.
- Trajectory of targets : $\mathcal{T}_j(t) \in \mathbb{R}^2$, $j \in J$.



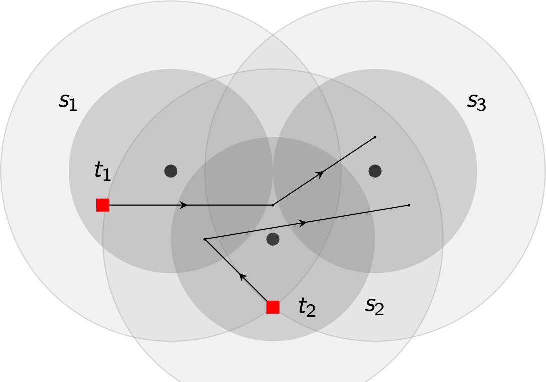
Initial data

- Sensing radius of sensors : R_i^S.
- Energy consumption for sensing : e_i^S.



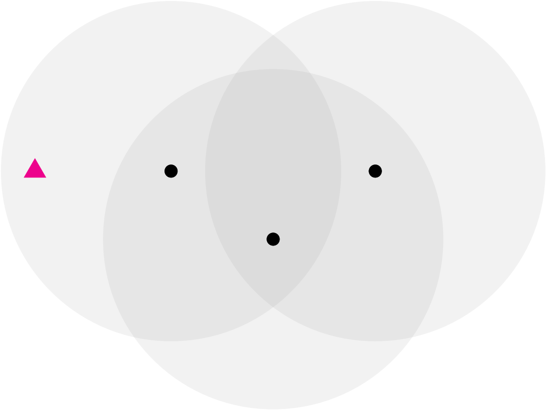
Initial data

- Sensing radius of sensors : R_i^S.
- Energy consumption for sensing : e_i^S.
- Communication radius of sensors : R_i^C.
- Energy consumption for communication : e_i^T and e_i^R.



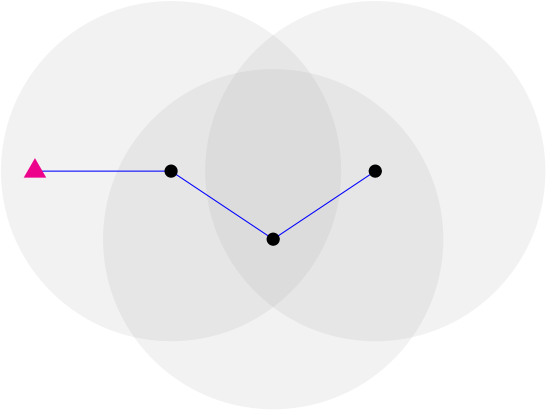
Initial data

- A base station receiving data.



Initial data

- A base station receiving data.
- A communication graph (to build).



Problem

Missions

- **Monitoring** the targets.
- **Reporting** the sensing data.

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- Minimize total energy consumption.
- Maximize network lifetime.

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- **Route** the sensing data to a *base station*.

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- Minimize total energy consumption.
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Constraints

- Every sensor has a limited battery lifetime E_i.
- Every target must be covered by at least one sensor.

Two-step method

Two steps

- Discretization.
- Scheduling and routing.

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Discretization

- Goal : Transform the problem to make it solvable as a LP.
- Split the time into a set of time windows using geometric intersections.

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Discretization

- Goal : Transform the problem to make it solvable as a LP.
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Scheduling and routing

- Solve the LP
- Then, in each time window :
  - Decide which sensors are in *active* state to cover the targets.
  - Decide which sensors send their data to which sensors.

Computing time windows

The monitored area can be seen as a *planar graph* [BCSZ04, SP01].

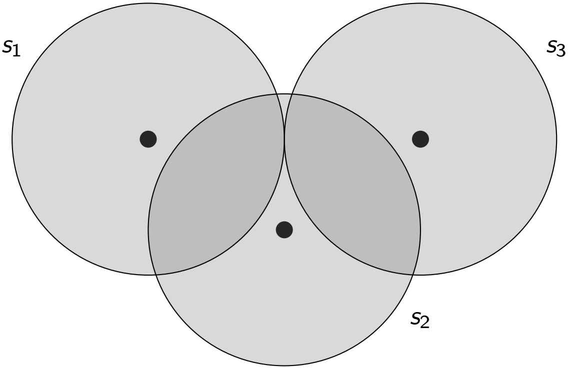

Figure: An example with $n = 3$ sensors.

Computing time windows

To each face is associated a set of covering sensors.
Example : face 2 is covered by $\{s_1, s_2\}$.

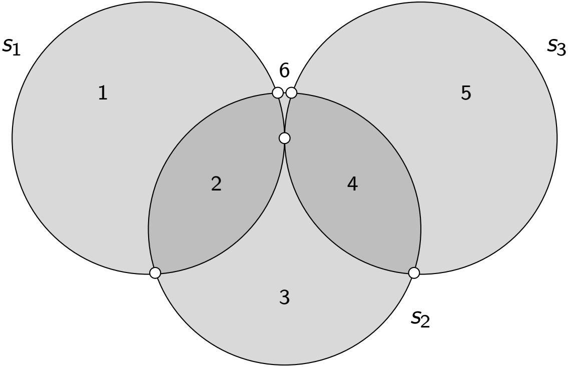

Figure: A planar graph example with $n = 3$ sensors, resulting in 6 faces.

Computing time windows

For each target, compute the geometric intersections between sensing area of sensors and its trajectory.

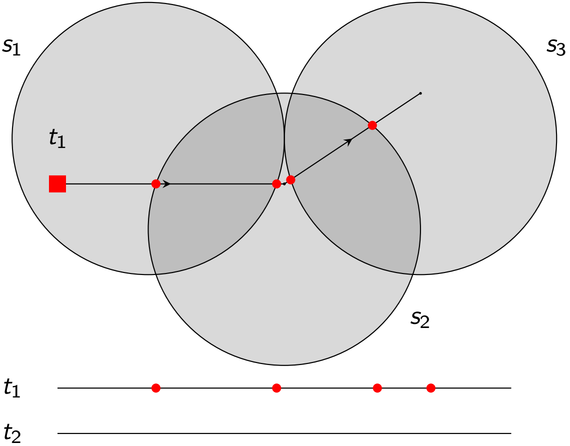

Figure: Temporal discretization of target 1

Computing time windows

For each target, compute the geometric intersections between sensing area of sensors and its trajectory.

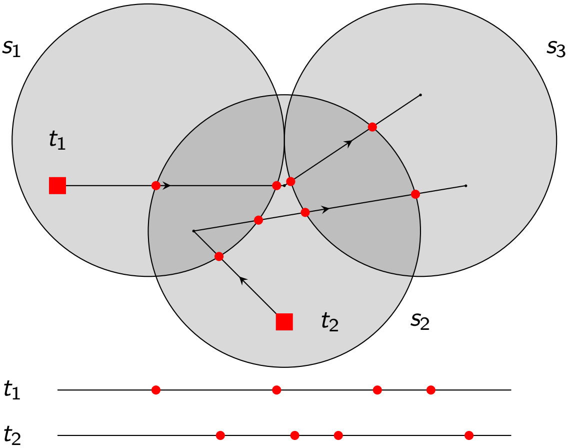

Figure: Temporal discretization of target 2

Computing time windows

Finally, merge all computed times in the same set T.

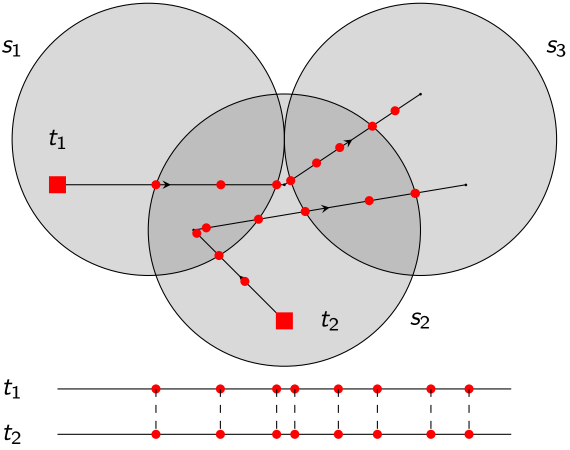

Figure: Temporal discretization of all targets

Computing time windows

Computing time windows

- Compute intersections for each target.
- Suppose sensing area of a sensor is a circle of radius R and center γ, then we solve : $\left(\mathcal{T}_{j_x}(t) - \gamma_x\right)^2 + \left(\mathcal{T}_{ky}(t) - \gamma_y\right)^2 = R^2.$
- $\implies$ Result is a sequence of time values ("ticks").
- Finally, merge all ticks in a set T.
- $\implies$ Result is a set of p time windows.

Computing sets

Computing $S^k(j)$

For each time window $k \in \{1, \ldots, p\}$ and each target $j \in \{1, \ldots, n\}$:
Compute $S^k(j)$: set of candidate sensors covering the target j during the time window k.

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Computing $T^k(i)$

For each time window $k \in \{1, \ldots, p\}$ and each sensor $i \in \{1, \ldots, m\}$:
Compute $T^k(i)$: set of targets that can be covered by the sensor i during the time window k.

Computing sets

Computing $N^T(i)$

For each sensor $i \in \{1, \ldots, n\}$:
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Computing $N^R(i)$

For each sensor $i \in \{1, \ldots, n\}$:
Compute $N^R(i)$: set of sensors that have the sensor i in their communication radius.

Problem data

- I : Set of sensors $\{1, \ldots, m\}$.
- J : Set of targets $\{1, \ldots, n\}$.
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- $N^T(i)$: set of sensors in the communication radius of sensor i.
- $N^R(i)$: set of sensors that have the sensor i in their communication radius.
- e_i^S : Energy consumption for sensing.
- e_i^T and e_i^R : Energy consumption for transmission/reception.
- E_i : Battery lifetime of sensor i.
- Δ^k : Duration of time window k ($\Delta^k = T_{k+1} - T_k$).

Problem data

Decision

- $d_{ij}^k \geq 0$: duration of active state for sensor i during the time window k to watch target j.
- $f_{ij}^k \geq 0$: amount of data transmitted from sensor i to j during the time window k.

Problem data

Decision

- $d_{ij}^k \geq 0$: duration of active state for sensor i during the time window k to watch target j.
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Additional variables (for max-lifetime)

- $y^k \in \{0, 1\}$
- $\delta^k \geq 0$

Remark

- LP model inspired from a model involving static targets [LCL+09].

Minimize energy consumption

$$\min E = \sum_{i \in I} \sum_{k \in K} \left(\sum_{j \in T^{k}(i)} e_i^S d_{ij}^k + \sum_{j \in N^{T}(i)} e_i^T f_{ij}^k + \sum_{j \in N^{R}(i)} e_i^R f_{ji}^k \right) \qquad (1)$$

(6)

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$$\sum_{j \in T^{k}(i)} d_{ij}^k + \sum_{j \in N^{R}(i)} f_{ji}^k = \sum_{j \in N^{T}(i)} f_{ij}^k \ , \qquad \forall k \in K, i \in I \tag{3}$$

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$$d_{ij}^k \geq 0 \ , \qquad \forall k \in K \ , i \in I \ , j \in T^k(i) \quad (5)$$

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$$\max L = \sum_{k \in K} \Delta^k y^k + \sum_{k \in K} \delta^k \quad (7)$$

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$$\delta^k \leq \Delta^k \left(y^{k-1} - y^k \right) \ , \qquad \forall k \in K \ (y^0 = 1) \tag{11}$$

$$y^{k-1} \geq y^k \ , \qquad \forall k \in K \setminus \{1\} \tag{12}$$

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$$y^k \in \{0, 1\} \ , \quad \delta^k \geq 0 \ , \qquad \forall k \in K \tag{13}$$

$$d_{ij}^k \geq 0 \ , \qquad \forall k \in K \ , i \in I \ , j \in T^k(i) \tag{14}$$

$$f_{ij}^k \geq 0 \ , \qquad \forall k \in K \ , i \in I \ , j \in N^T(i) \tag{15}$$

Result of LP

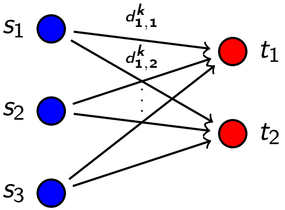
Result of LPs

- Durations : $D^k = \begin{pmatrix} d^k_{1,1} & d^k_{1,2} & \cdots & d^k_{1,n} \\ d^k_{2,1} & d^k_{2,2} & \cdots & d^k_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ d^k_{m,1} & d^k_{m,2} & \cdots & d^k_{m,n} \end{pmatrix}$
- Data flows : $F^k = \begin{pmatrix} f^k_{1,1} & f^k_{1,2} & \cdots & f^k_{1,m} \\ f^k_{2,1} & f^k_{2,2} & \cdots & f^k_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ f^k_{m,1} & f^k_{m,2} & \cdots & f^k_{m,m} \end{pmatrix}$

Scheduling

Bipartite graph and matching problems

- Each matrix D^k can be expressed as a bipartite graph [LCL+09], connecting sensors to targets, where each $d^k_{i,j}$ corresponds to an edge.
- Solve successive perfect matching problems to decompose D^k as a sum of cover matrices [LCL+09].
- $D^k = c_1 \begin{pmatrix} 0 & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & \cdots & 0 \end{pmatrix} + c_2 \begin{pmatrix} 0 & 1 & \cdots & 0 \\ 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} + \cdots + c_N \begin{pmatrix} 0 & 0 & \cdots & 1 \\ 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 1 & \cdots & 0 \end{pmatrix}.$



Routing

Iterative flow filling

- Successively fill the edges as the data comes.
- When an edge is saturated, use others.

Remarks

Advantages

- *Linear* models (continuous for energy minimization).
- Easily extensible to adjustable sensing ranges, flow limitations, Q-coverage [LCL+11]...

Drawbacks

- Many variables.
- A sensor i watching several targets consumes several times e_i^S units of energy (not suitable in some situations).

Example (min energy)

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- $m = 3$ sensors.
- $n = 2$ targets moving during 10 units of time.
- $E_i = 40 \ , \forall i \in I$
- $e_i^S = e_i^T = e_i^R = 1 \ , \forall i \in I$
- Optimal objective value : 70.5542 units of energy

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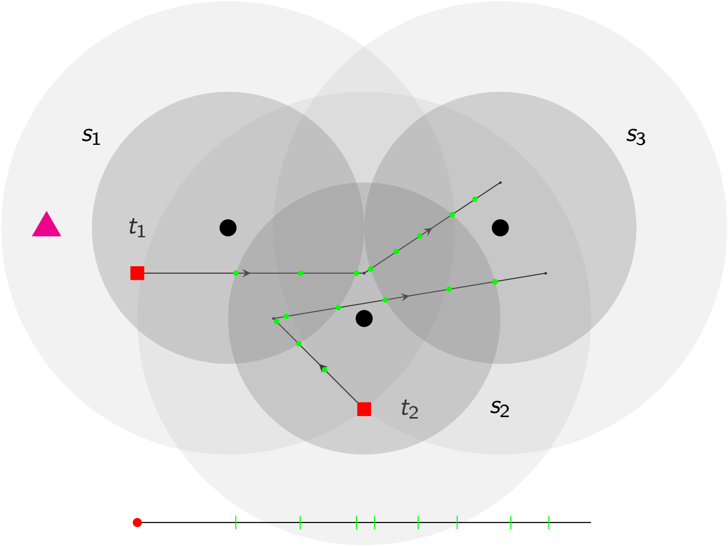

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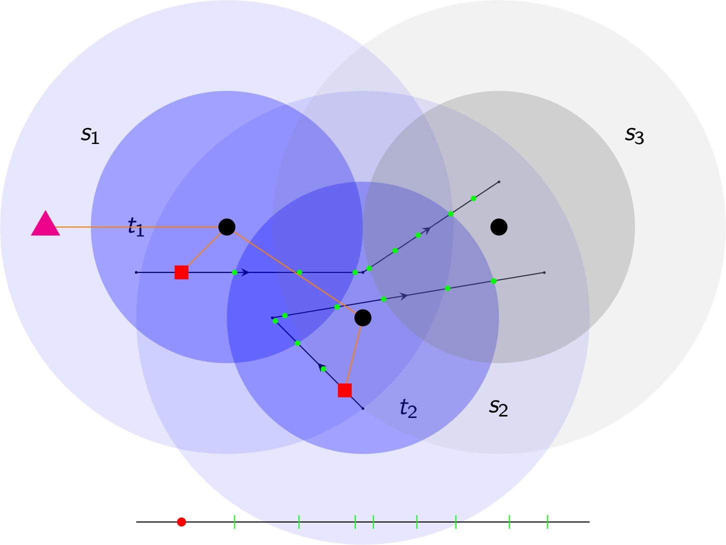

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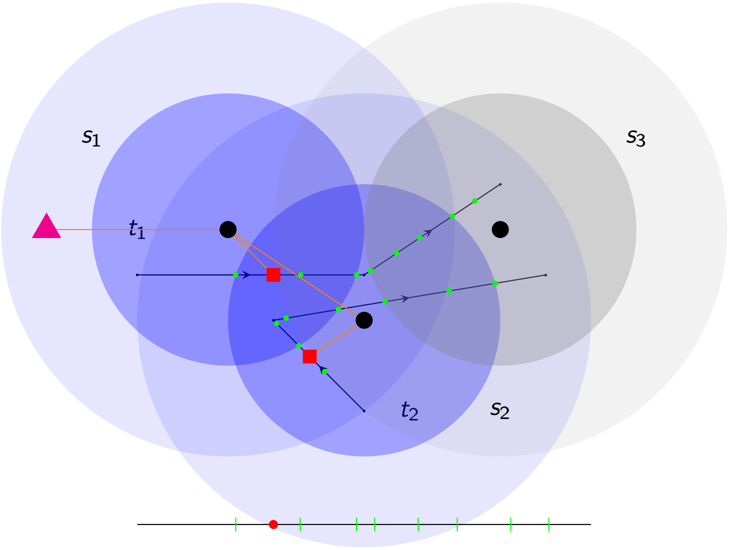

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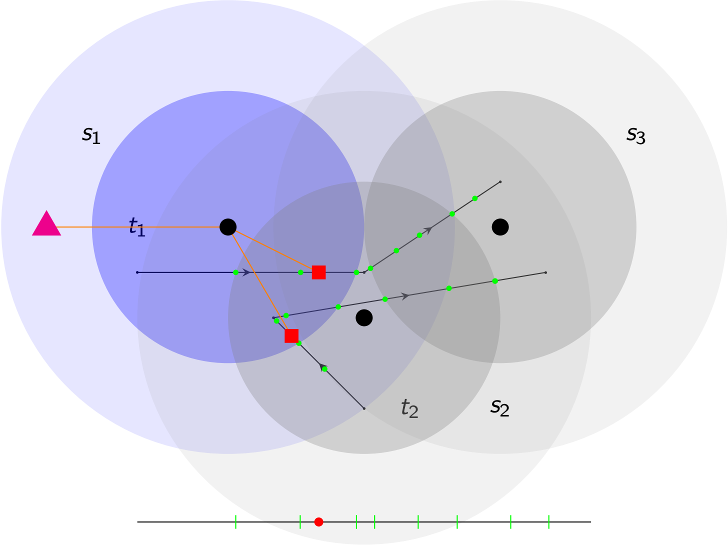

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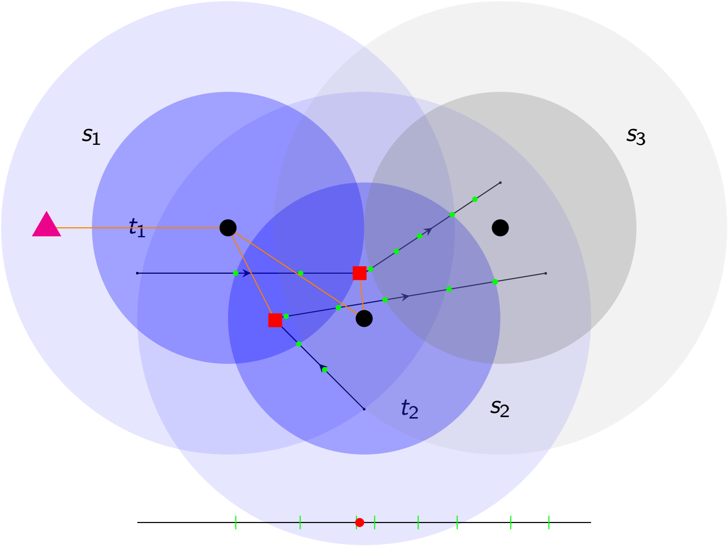

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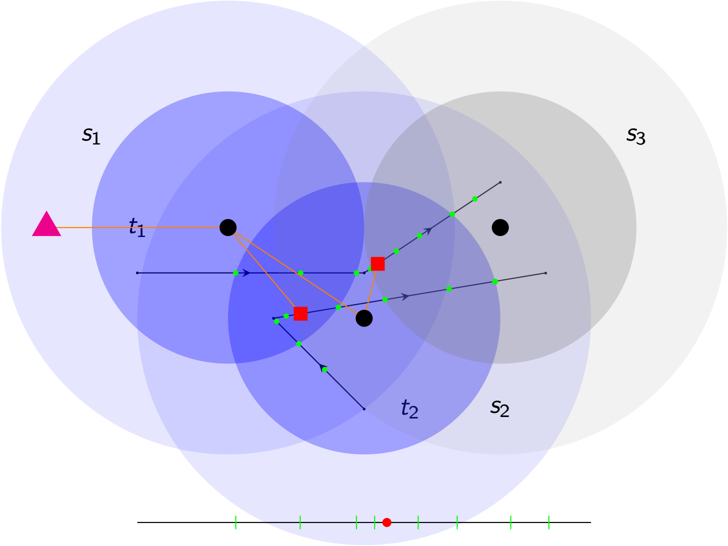

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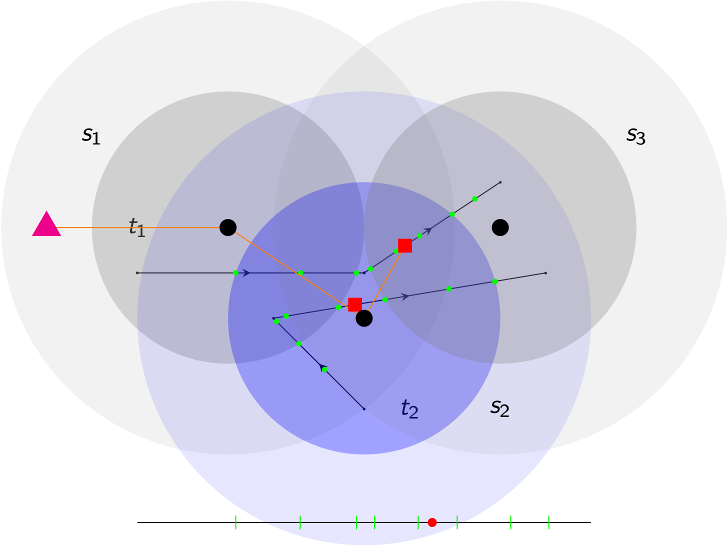

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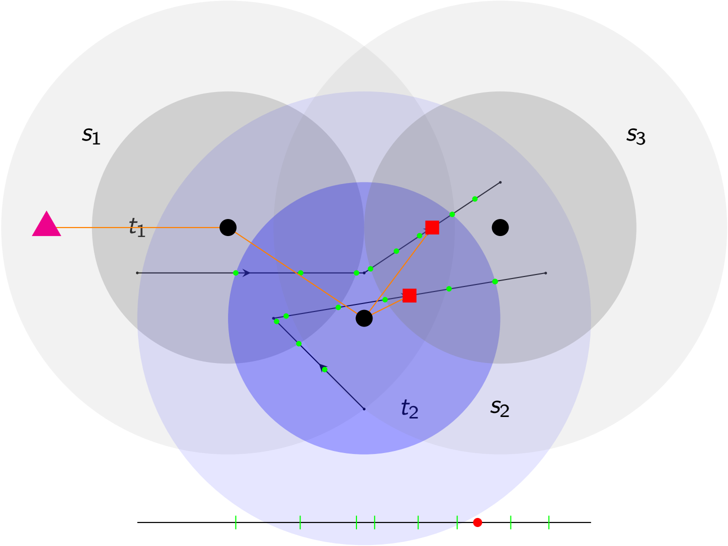

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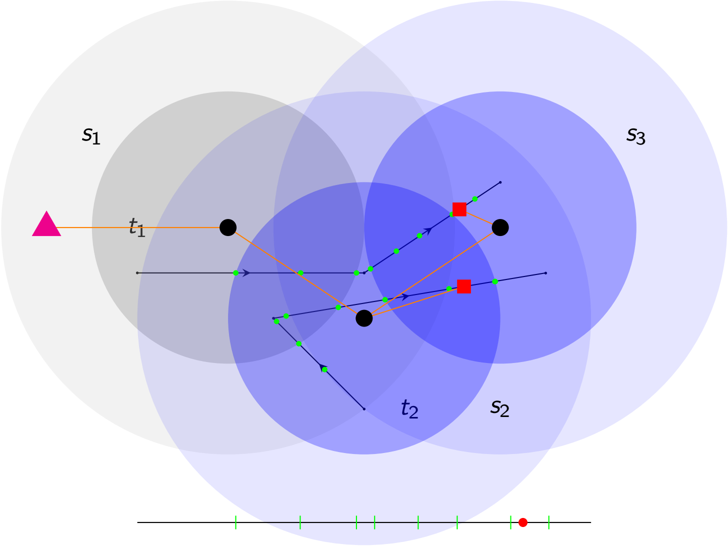

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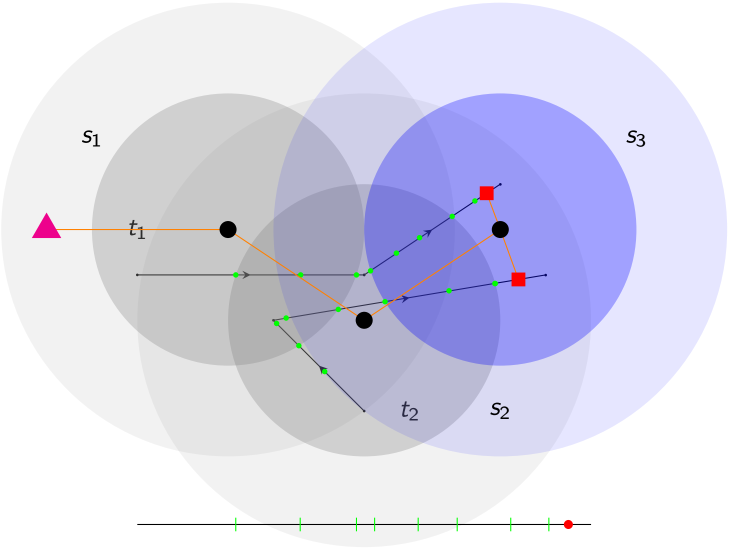

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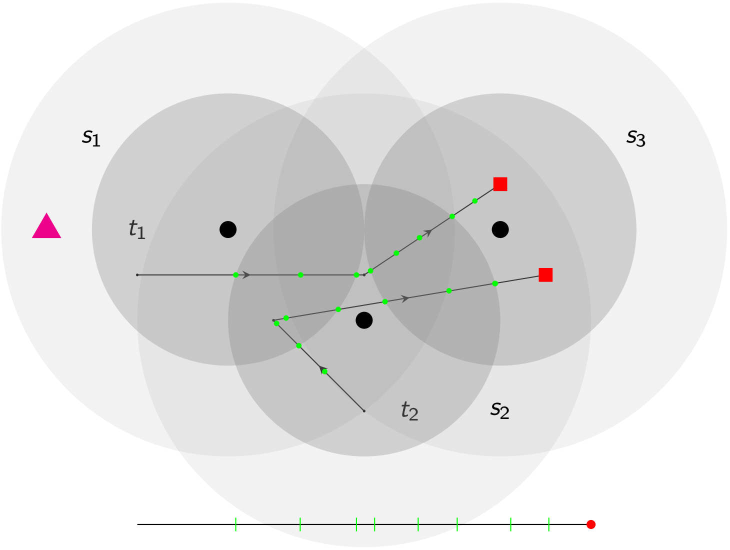

Example (max lifetime)

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- $m = 3$ sensors.
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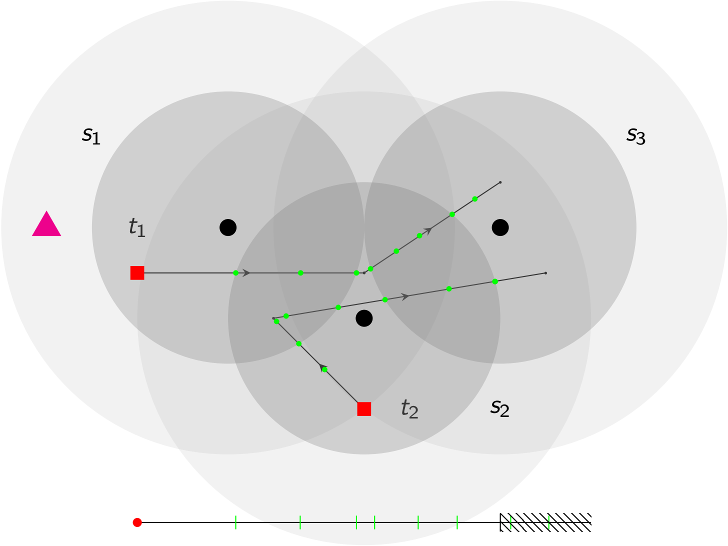
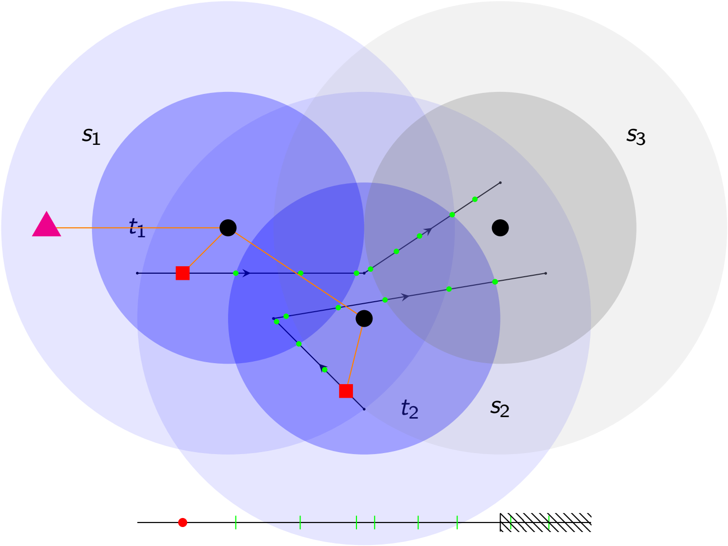
- $E_i = 32$, $\forall i \in I$
- $e_i^S = e_i^T = e_i^R = 1$, $\forall i \in I$
- Optimal objective value : 8 units of time

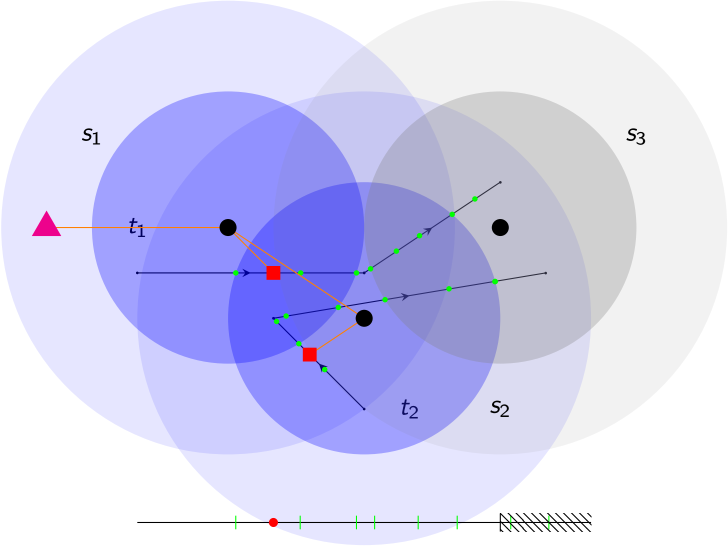
Example (max lifetime)



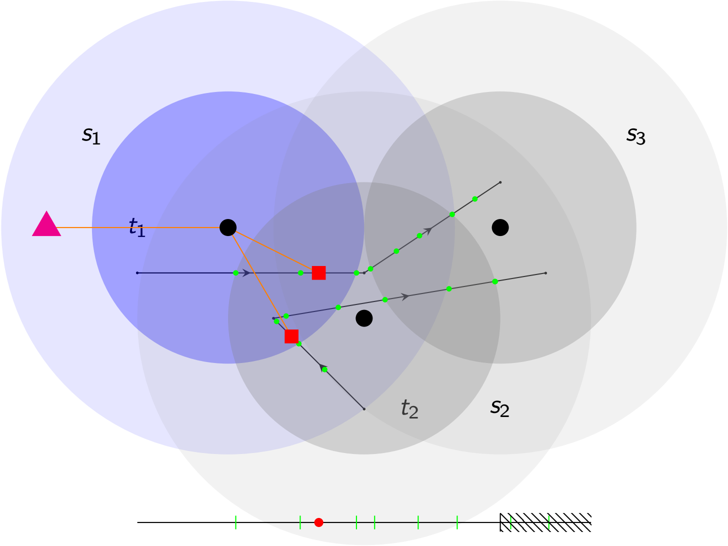
Example (max lifetime)



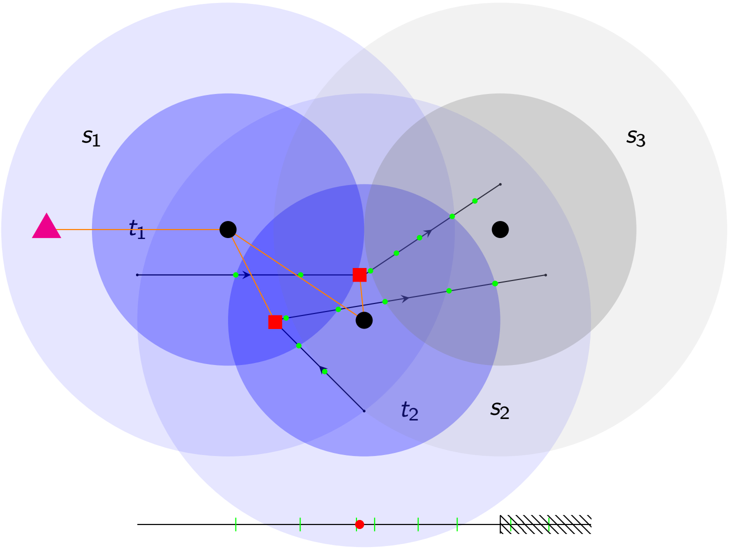
Example (max lifetime)



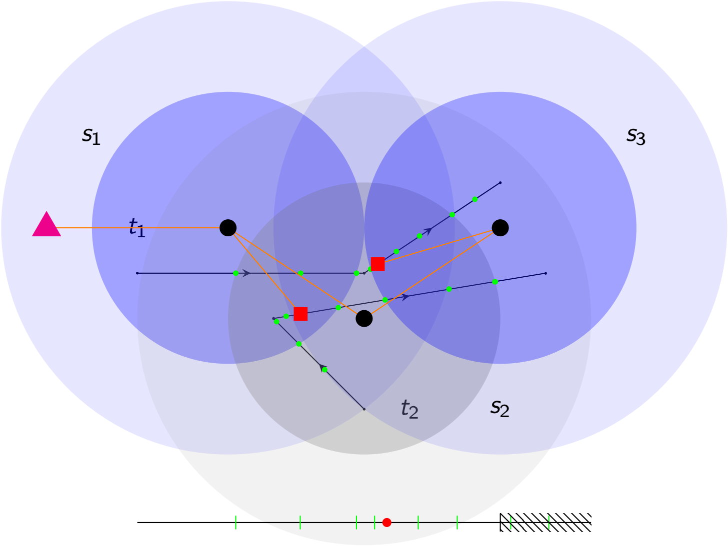
Example (max lifetime)



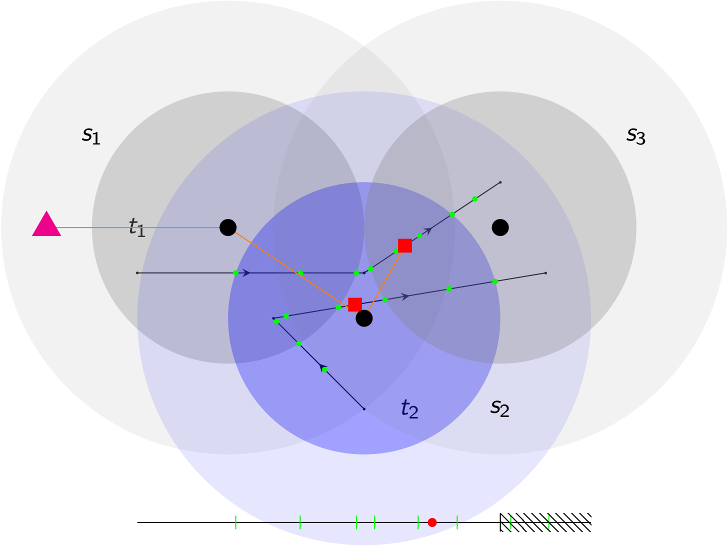
Example (max lifetime)



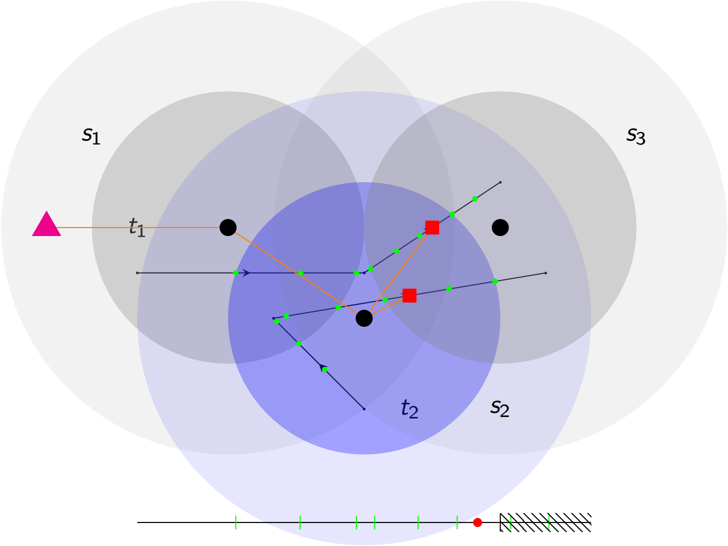
Example (max lifetime)



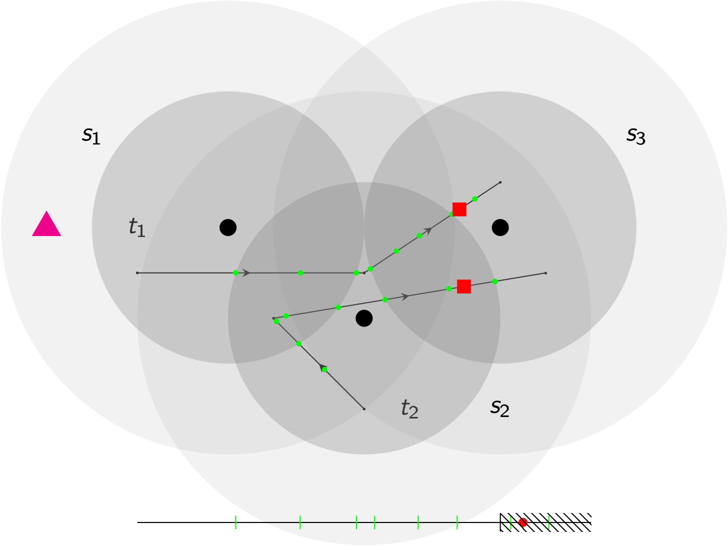
Example (max lifetime)



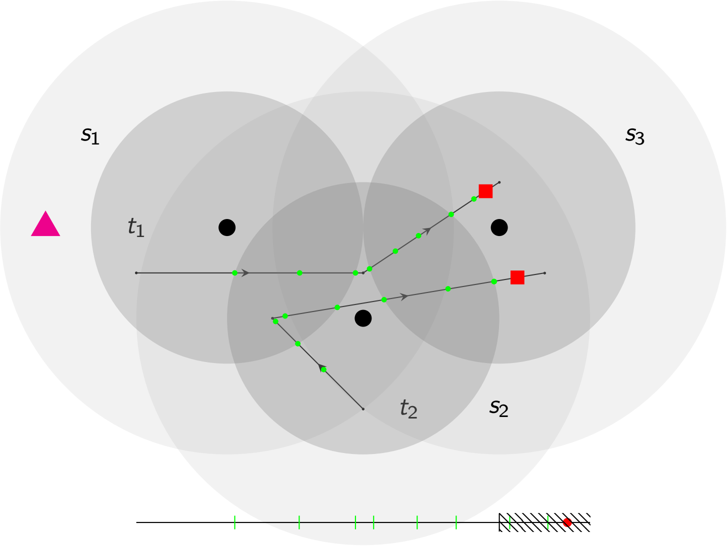
Example (max lifetime)



Example (max lifetime)



Example (max lifetime)



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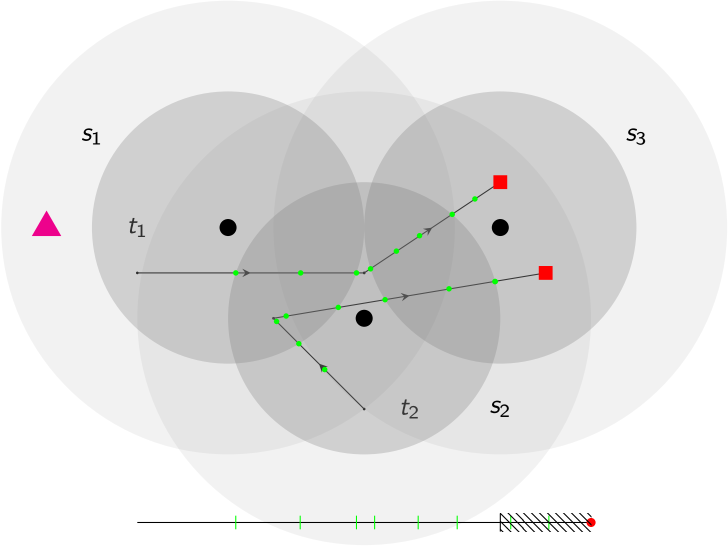

Conclusion

Conclusion

- Exact optimal solution for basic multi-target tracking.
- Linear models proposed.
- Two objectives handled :
  - Minimize energy consumption.
  - Maximize network lifetime.
- Base problem for multiple variants.

Further research

- Coping with large problems (exponential number of variables).
- Handle uncertainty (speed or trajectory not known).
- Evaluation of performance of target tracking protocols in WSN.

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