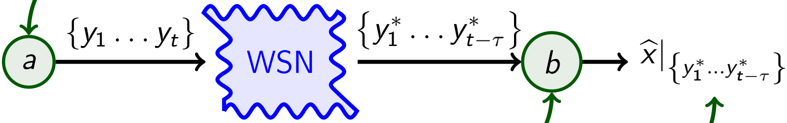
Performance analysis of different routing protocols in wireless sensor networks for real-time estimation

Damiano Varagnolo*, Phoebus Chen#, Luca Schenato*, Shankar S. Sastry#

* Department of Information Engineering - University of Padova
# EECS Department - University of California at Berkeley

Aim of the work

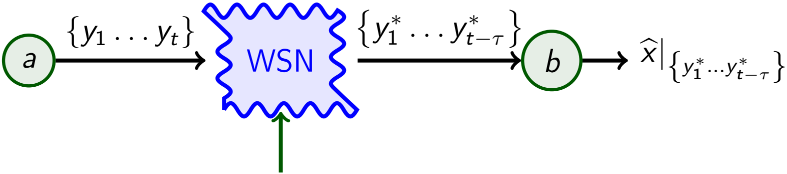
sensor node sensing: $\begin{cases} x_{t+1} = Ax_t + w_t \\ y_t = Cx_t + v_t \end{cases}$



estimator node estimating

Aim of the work

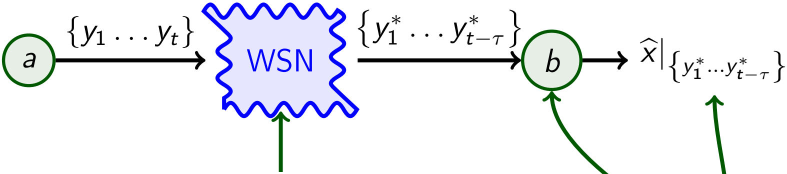
Questions:



1) how should we choose the protocol?

Aim of the work

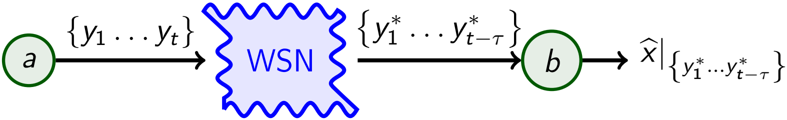
Questions:



1) how should we choose the protocol?

2) how should we project the estimation strategy?

Aim of the work



In this talk we will:

- propose some protocols for R.T.E.;
- propose an efficient R.T.E. strategy.

Communication protocols: outline

i.e. what kind of protocols do we consider?

We will focus on TCP- and UDP-like protocols

Brief scheme of properties:

	communications kind	acknowl.	retransm.
TCP-like	point-to-point	yes	yes
UDP-like	broadcast	no	no

Similarities between our protocols

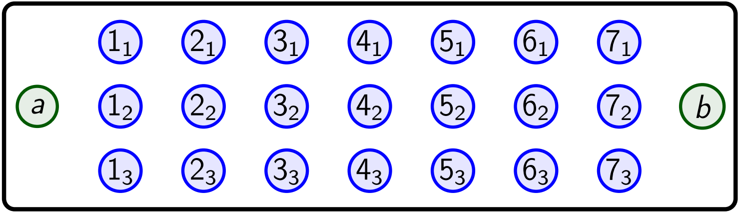
WSN is composed by

Similarities between our protocols

WSN is composed by the sensor and the estimator,

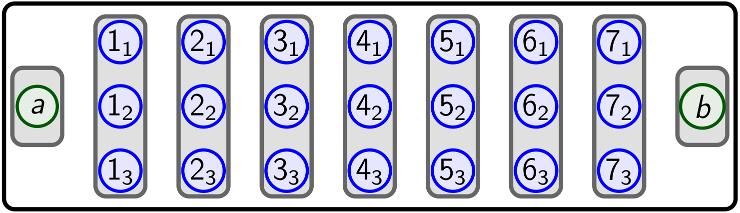
Similarities between our protocols

WSN is composed by the sensor and the estimator, several nodes



Similarities between our protocols

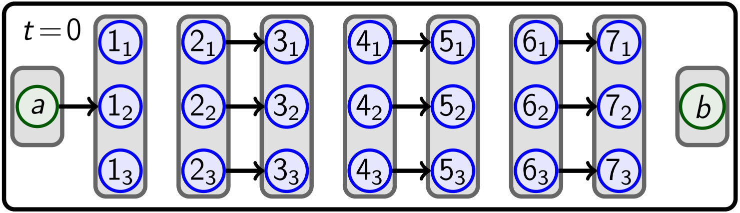
WSN is composed by the sensor and the estimator, several nodes divided in stages. Note that communications will happen between consequent stages.



Unicast Path Diversity protocol

our TCP-like communication protocol

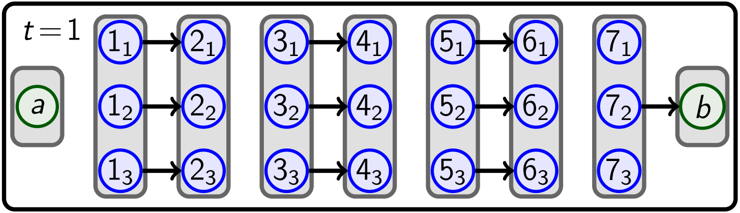
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Unicast Path Diversity protocol

our TCP-like communication protocol

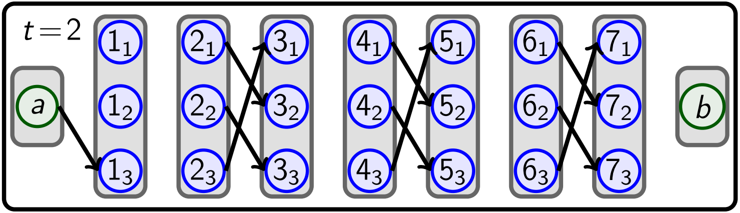
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Unicast Path Diversity protocol

our TCP-like communication protocol

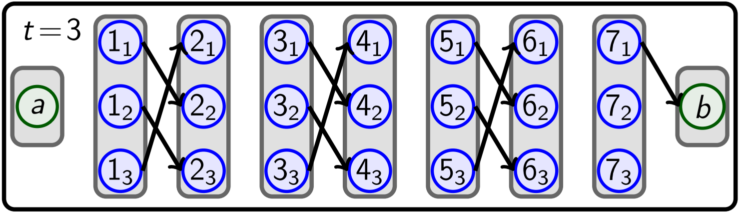
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Unicast Path Diversity protocol

our TCP-like communication protocol

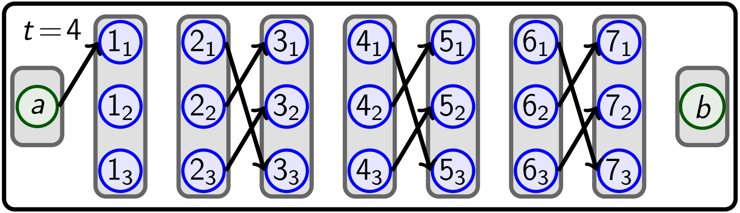
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Unicast Path Diversity protocol

our TCP-like communication protocol

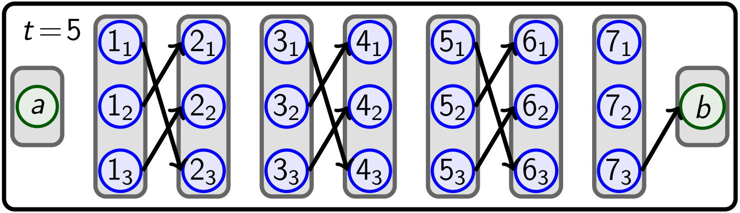
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Unicast Path Diversity protocol

our TCP-like communication protocol

WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Unicast Path Diversity protocol

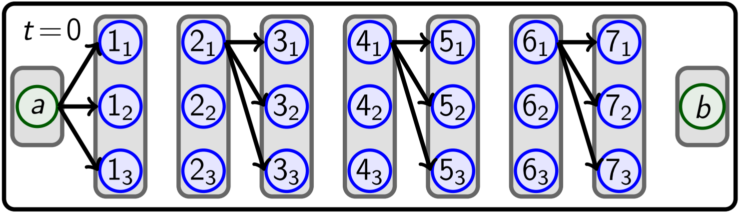
our TCP-like communication protocol

WSN is divided in stages, each stage contains several nodes, communications happen between stages:

Directed Staged Flooding protocol

our UDP-like communication protocol

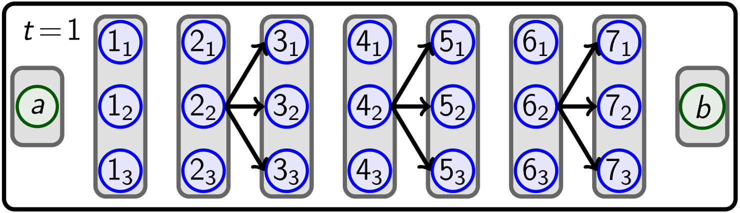
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Directed Staged Flooding protocol

our UDP-like communication protocol

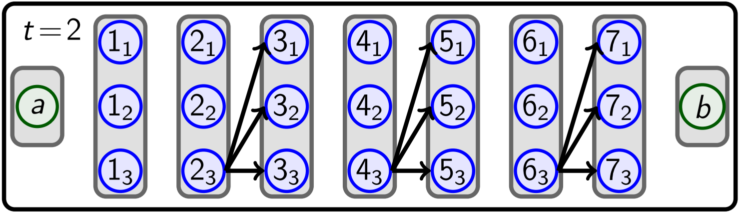
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Directed Staged Flooding protocol

our UDP-like communication protocol

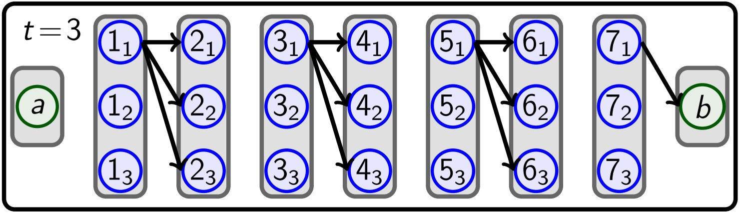
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Directed Staged Flooding protocol

our UDP-like communication protocol

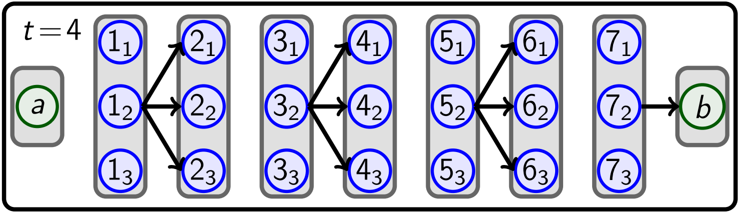
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



Directed Staged Flooding protocol

our UDP-like communication protocol

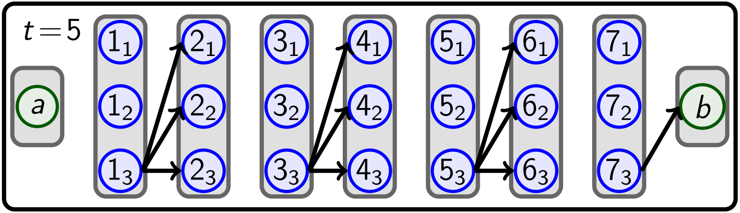
WSN is divided in stages, each stage contains several nodes, communications happen between stages:



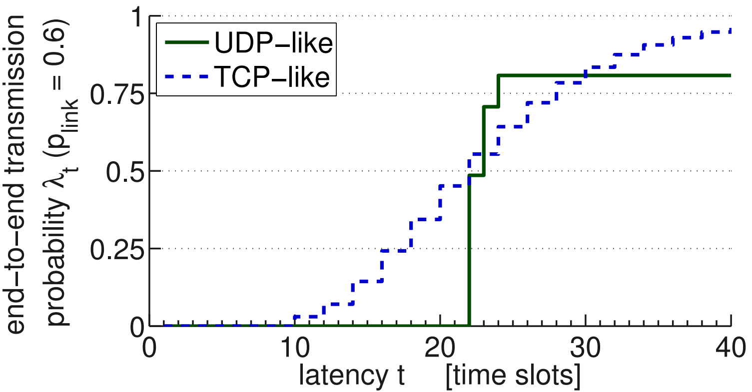
Directed Staged Flooding protocol

our UDP-like communication protocol

WSN is divided in stages, each stage contains several nodes, communications happen between stages:



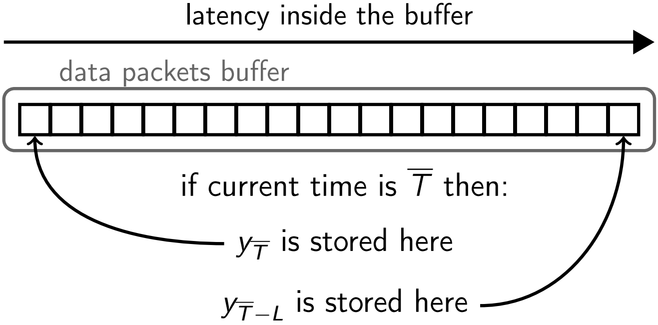
Comparison between protocols



	pros	*cons*
TCP-like	$\lambda_t \to 1$ for $t \to +\infty$	difficult to implement
UDP-like	easy to implement	low λ_t

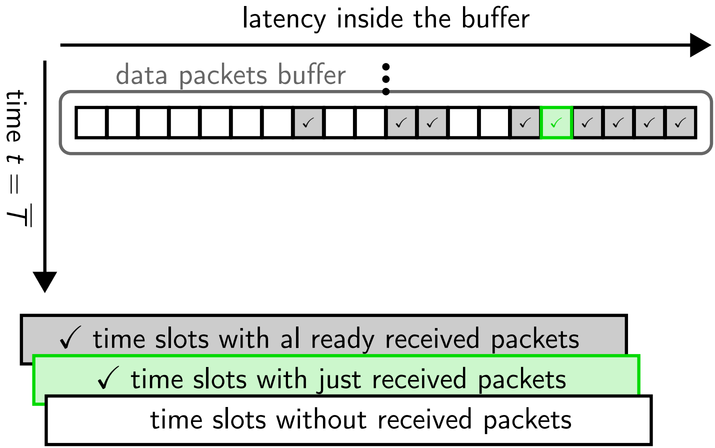
Example of a packets arrival process

how can the packets sent by the sensor arrive to the estimator node?



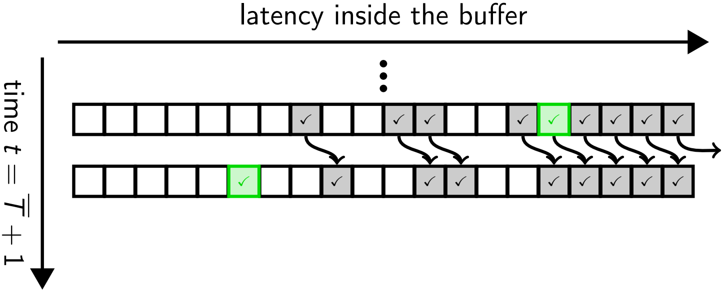
Example of a packets arrival process

how can the packets sent by the sensor arrive to the estimator node?



Example of a packets arrival process

how can the packets sent by the sensor arrive to the estimator node?



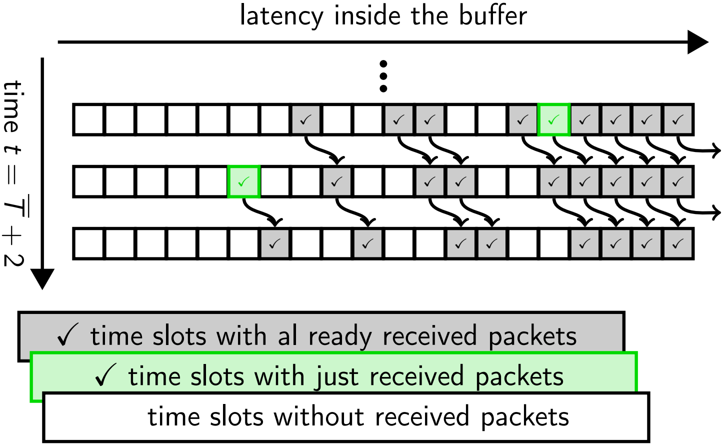
✓ time slots with al ready received packets

✓ time slots with just received packets

time slots without received packets

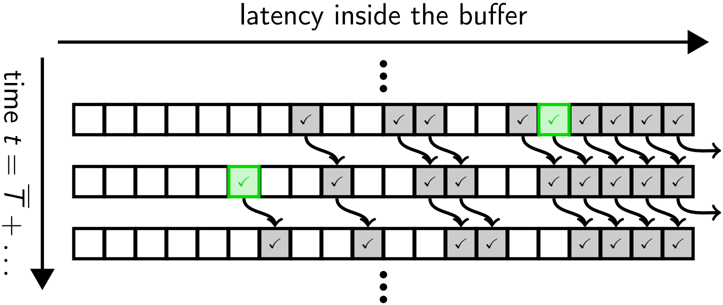
Example of a packets arrival process

how can the packets sent by the sensor arrive to the estimator node?



Example of a packets arrival process

how can the packets sent by the sensor arrive to the estimator node?



✓ time slots with al ready received packets

✓ time slots with just received packets

time slots without received packets

Definition of optimal estimation

which kind of optimality are we looking for?

We want to find an estimation strategy $\hat{x}$ that minimizes the variance of its estimation error

Definition of optimal estimation

which kind of optimality are we looking for?

We want to find an estimation strategy $\hat{x}$ that minimizes the variance of its estimation error

Following [Schenato 2006] *Optimal estimation in networked control systems subject to random delay and packet loss* (Proc. 45th IEEE CDC):

- the optimal strategy generally satisfies $\hat{x}^t_{t|t} = \mathbb{E}[x_t \,|\, \text{arrived measurements}]$;

Definition of optimal estimation

which kind of optimality are we looking for?

We want to find an estimation strategy $\hat{x}$ that minimizes the variance of its estimation error

Following [Schenato 2006] *Optimal estimation in networked control systems subject to random delay and packet loss* (Proc. 45th IEEE CDC):

- the optimal strategy generally satisfies $\hat{x}_{t|t}^{t} = \mathbb{E}[x_t \,|\, \text{arrived measurements}]$;
- for linear systems the optimal estimation strategy is Kalman-like;

Definition of optimal estimation

which kind of optimality are we looking for?

We want to find an estimation strategy $\hat{x}$ that minimizes the variance of its estimation error

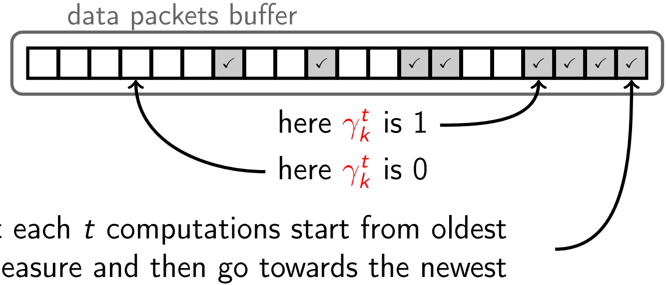
Following [Schenato 2006] *Optimal estimation in networked control systems subject to random delay and packet loss* (Proc. 45th IEEE CDC):

- the optimal strategy generally satisfies $\hat{x}^t_{t|t} = \mathbb{E}[x_t \mid \text{arrived measurements}]$;
- for linear systems the optimal estimation strategy is Kalman-like;
- the estimator gains depend on packets arrival processes.

Optimal estimation problem solution

For linear systems optimality is a buffered time-variant Kalman Filter:

$$\begin{cases} P^t_{k+1|k} = A P^t_{k|k-1} A^T + Q - \gamma^{\mathbf{t}}_{\mathbf{k}} A K^t_k C P^t_{k|k-1} A^T \\ K^t_k = P^t_{k|k-1} C^T \left(C P^t_{k|k-1} C^T + R \right)^{-1} \\ \hat{x}^t_{k|k} = A \hat{x}^t_{k-1|k-1} + \gamma^{\mathbf{t}}_{\mathbf{k}} K^t_k \left(\tilde{y}^t_k - C A \hat{x}^t_{k-1|k-1} \right) \end{cases}$$



Optimal estimation problem solution

For linear systems optimality is a buffered time-variant Kalman Filter:

$$\begin{cases} P^t_{k+1|k} & = & AP^t_{k|k-1}A^T + Q - \gamma^{\mathbf{t}}_{\mathbf{k}} AK^t_k CP^t_{k|k-1}A^T \\ K^t_k & = & P^t_{k|k-1}C^T\left(CP^t_{k|k-1}C^T + R\right)^{-1} \\ \hat{x}^t_{k|k} & = & A\hat{x}^t_{k-1|k-1} + \gamma^{\mathbf{t}}_{\mathbf{k}} K^t_k\left(\tilde{y}^t_k - CA\hat{x}^t_{k-1|k-1}\right) \end{cases}$$

Main drawbacks:

- computational complexity (inversion of lots of matrices at each time-step);
- length of the used buffer.

Could be too expensive or even infeasible!

Concepts of the suboptimal estimation strategy

how can we semplify the optimal strategy?

Natural semplifications are:

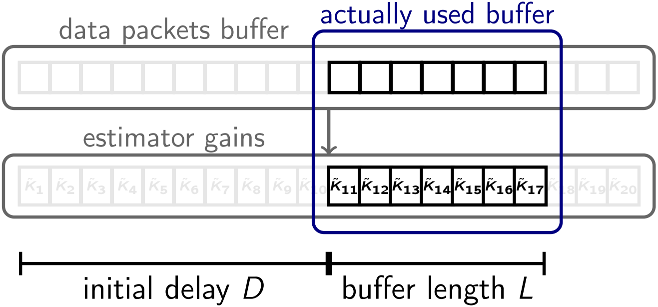
- computational complexity $\Rightarrow$ use constant gains!
- length of the used buffer $\Rightarrow$ use a subset of the buffer!

Concepts of the suboptimal estimation strategy

how can we semplify the optimal strategy?

Natural semplifications are:

- computational complexity ⇒ use constant gains!
- length of the used buffer ⇒ use a subset of the buffer!



Implementation of the suboptimal strategy

what are the equations of the filter?

Filter design parameters:

- the initial delay D;
- the length of the buffer L;
- the constant gains $\tilde{K}_{D+1}, \ldots, \tilde{K}_{D+L}$.

Implementation of the suboptimal strategy

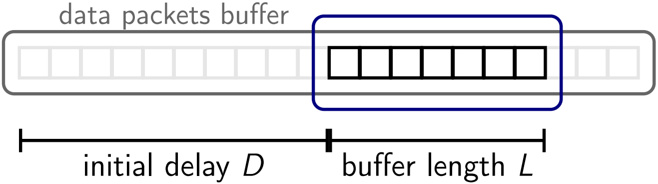
what are the equations of the filter?

Filter design parameters:

- the initial delay D;
- the length of the buffer L;
- the constant gains $\tilde{K}_{D+1}, \ldots, \tilde{K}_{D+L}$.

Equations are given by:

$$\begin{cases} \tilde{x}^t_{k|k} = A\tilde{x}^t_{k-1|k-1} + \gamma^{\mathbf{t}}_{\mathbf{k}} \tilde{K}_{t-k} \left(\tilde{y}^t_k - CA\tilde{x}^t_{k-1|k-1} \right) \\ \tilde{x}^t_{t|t} = A^D \tilde{x}^t_{t-D|t-D} \end{cases}$$



Suboptimal estimation problem solution

which is the numerical solution of the problem?

Considering the *stochastic process* of prediction error covariances:

$$\tilde{P}_{t+1|t} = \mathbb{E}\left[\left(x_{t+1} - A\tilde{x}^{t}_{t|t}\right)\left(x_{t+1} - A\tilde{x}^{t}_{t|t}\right)^{T}\right];$$

Suboptimal estimation problem solution

which is the numerical solution of the problem?

Considering the *stochastic process* of prediction error covariances:

$$\tilde{P}_{t+1|t} = \mathbb{E}\left[\left(x_{t+1} - A\tilde{x}^{t}_{t|t}\right)\left(x_{t+1} - A\tilde{x}^{t}_{t|t}\right)^{T}\right];$$

the filter is characterized by:

$$\tilde{K}^{*}, D^{*} \longleftarrow \arg\min_{\tilde{K}, D} \mathbb{E}\left[\tilde{P}^{t}_{t+1|t}\right]$$

Suboptimal estimation problem solution

which is the numerical solution of the problem?

Considering the *stochastic process* of prediction error covariances:

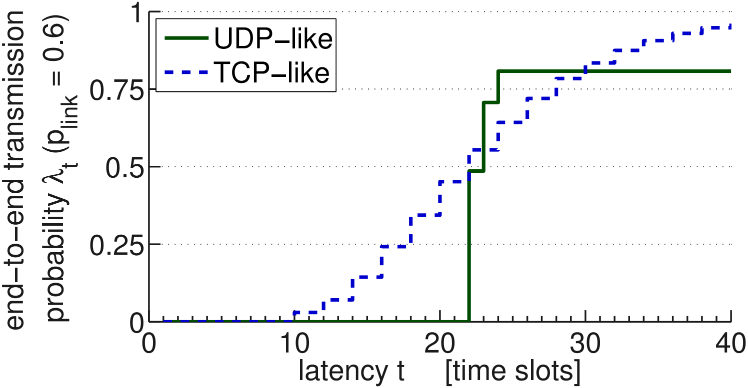
$$\tilde{P}_{t+1|t} = \mathbb{E}\left[\left(x_{t+1} - A\tilde{x}_{t|t}^{t}\right)\left(x_{t+1} - A\tilde{x}_{t|t}^{t}\right)^{T}\right];$$

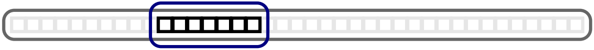
the filter is characterized by:

$$\tilde{K}^{*}, D^{*} \longleftarrow \arg\min_{\tilde{K}, D} \mathbb{E}\left[\tilde{P}_{t+1|t}^{t}\right]$$

Note: $\min_{\tilde{K},D}$ is usually a matrix norm in order to assure the existence of the minimum

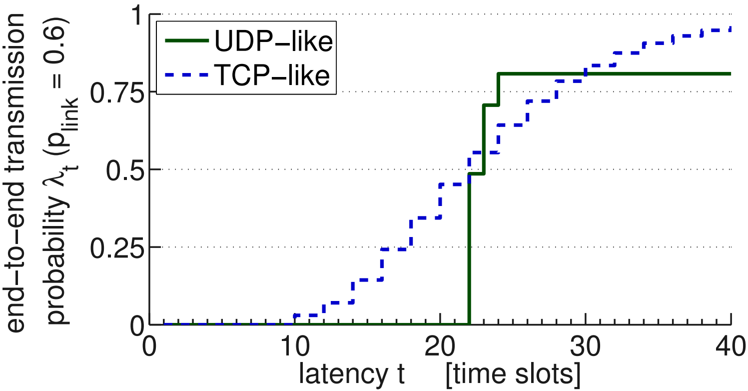
Graphical interpretation of the numerical solution

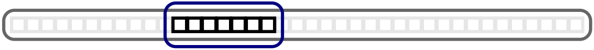




Set the lenght L,

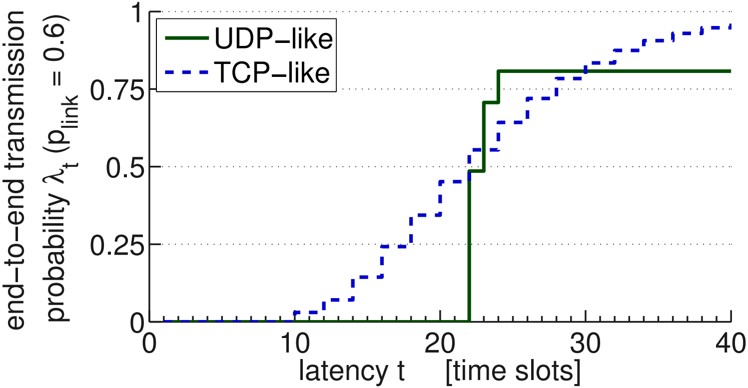
Graphical interpretation of the numerical solution

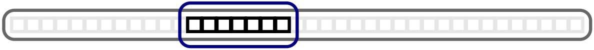




Set the lenght L, for each delay D compute the performances,

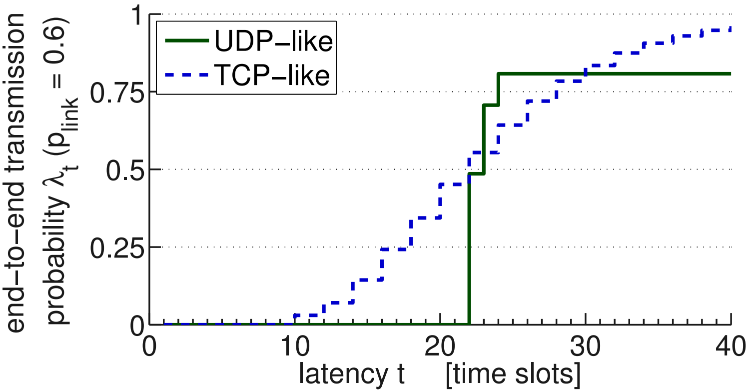
Graphical interpretation of the numerical solution

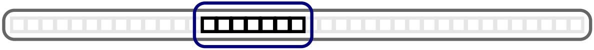




Set the lenght L, for each delay D compute the performances,

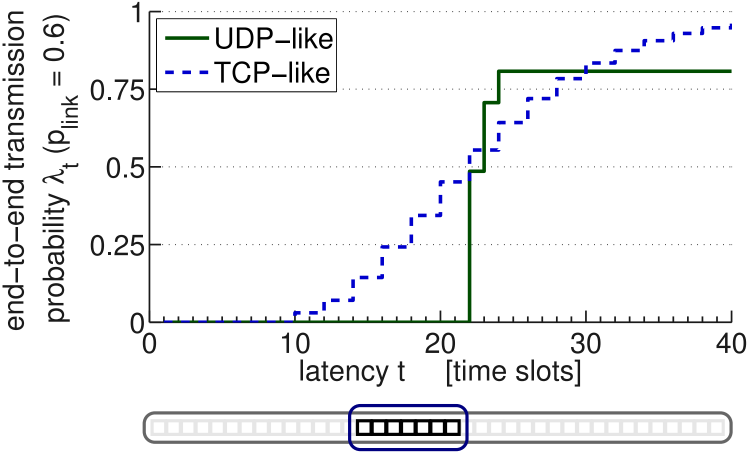
Graphical interpretation of the numerical solution





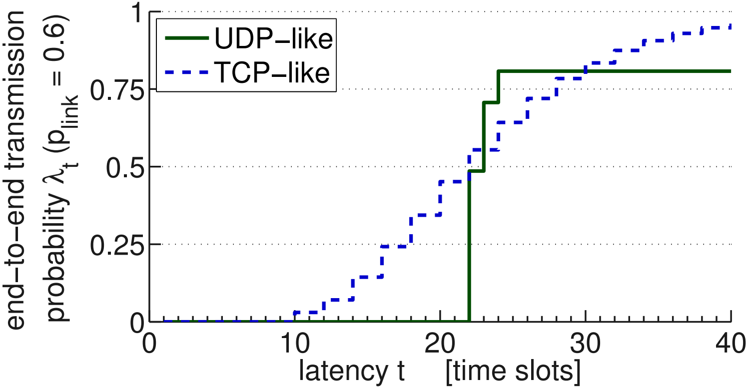
Set the lenght L, for each delay D compute the performances,

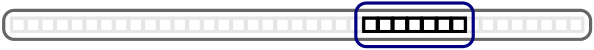
Graphical interpretation of the numerical solution



Set the lenght L, for each delay D compute the performances,

Graphical interpretation of the numerical solution





Set the lenght L, for each delay D compute the performances, then select the optimal one

Application used for the evaluations

i.e. what does the following charts refers to

Simulations on 2D target tracking application:

- state dynamic governed by:

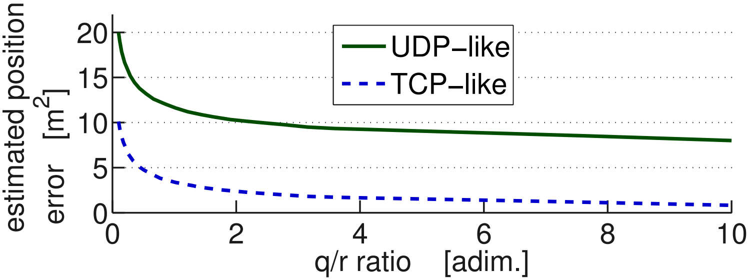
$$x_{t+1} = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix} x_t + w_t \qquad Q = q \begin{bmatrix} \frac{T^3}{3} & \frac{T^2}{2} & 0 & 0 \\ \frac{T^2}{2} & T & 0 & 0 \\ 0 & 0 & \frac{T^3}{3} & \frac{T^2}{2} \\ 0 & 0 & \frac{T^2}{2} & T \end{bmatrix}$$

- measure process given by:

$$y_t = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x_t + v_t \qquad R = r \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

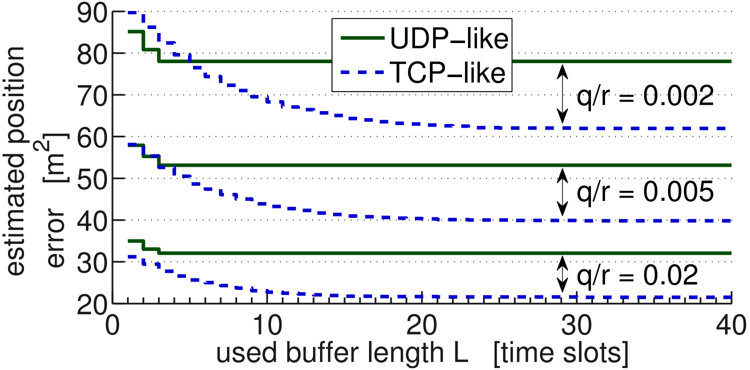
Performances of suboptimal filters when using the whole buffer

Results for the shown topology with $q = 1$, $p_l = 0.6$ and the suboptimal filter using the whole data buffer indicate that TCP-like protocol generally behaves better:



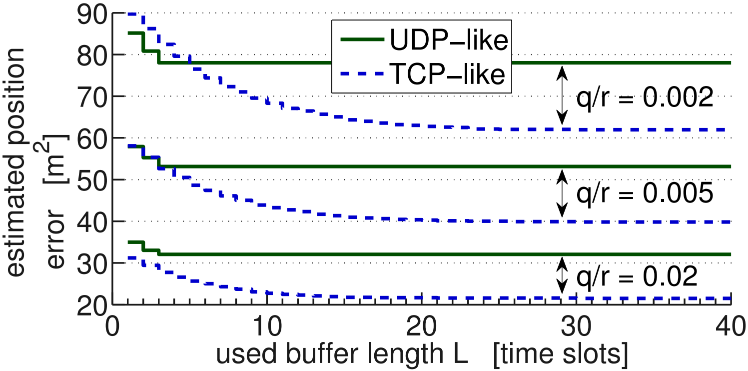
Performances of suboptimal filters when using shifted buffers

Results for the same WSN with varying buffer length L and q/r ratio indicate that there's no best protocol:



Performances of suboptimal filters when using shifted buffers

Results for the same WSN with varying buffer length L and q/r ratio indicate that there's no best protocol:



Note that it is unuseful to use the whole data buffer!

Conclusions

- We proposed and evaluated two protocols for Real Time Estimation;
- we proposed a suboptimal estimation strategy (which make possible a kind of evaluation of protocols);
- we shown some tradeoffs between protocols and estimation strategies complexity and performances.

Thank you for your attention

damiano.varagnolo@dei.unipd.it

www.dei.unipd.it/∼varagnolo