Università di Pisa
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
Sant'Anna Scuola Universitaria Superiore Pisa

Dynamic Quality Estimation of Wireless Links with Autonomous Agents

Master's Thesis Defense

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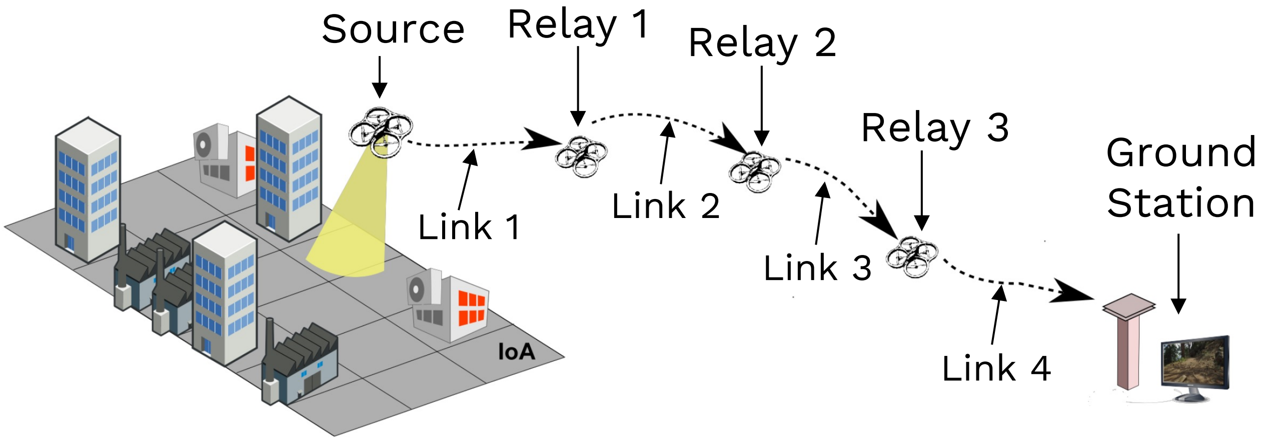
Candidate:
Livio Bisogni

Supervisors:
Prof. Giorgio Carlo Buttazzo
Prof. Luis Almeida

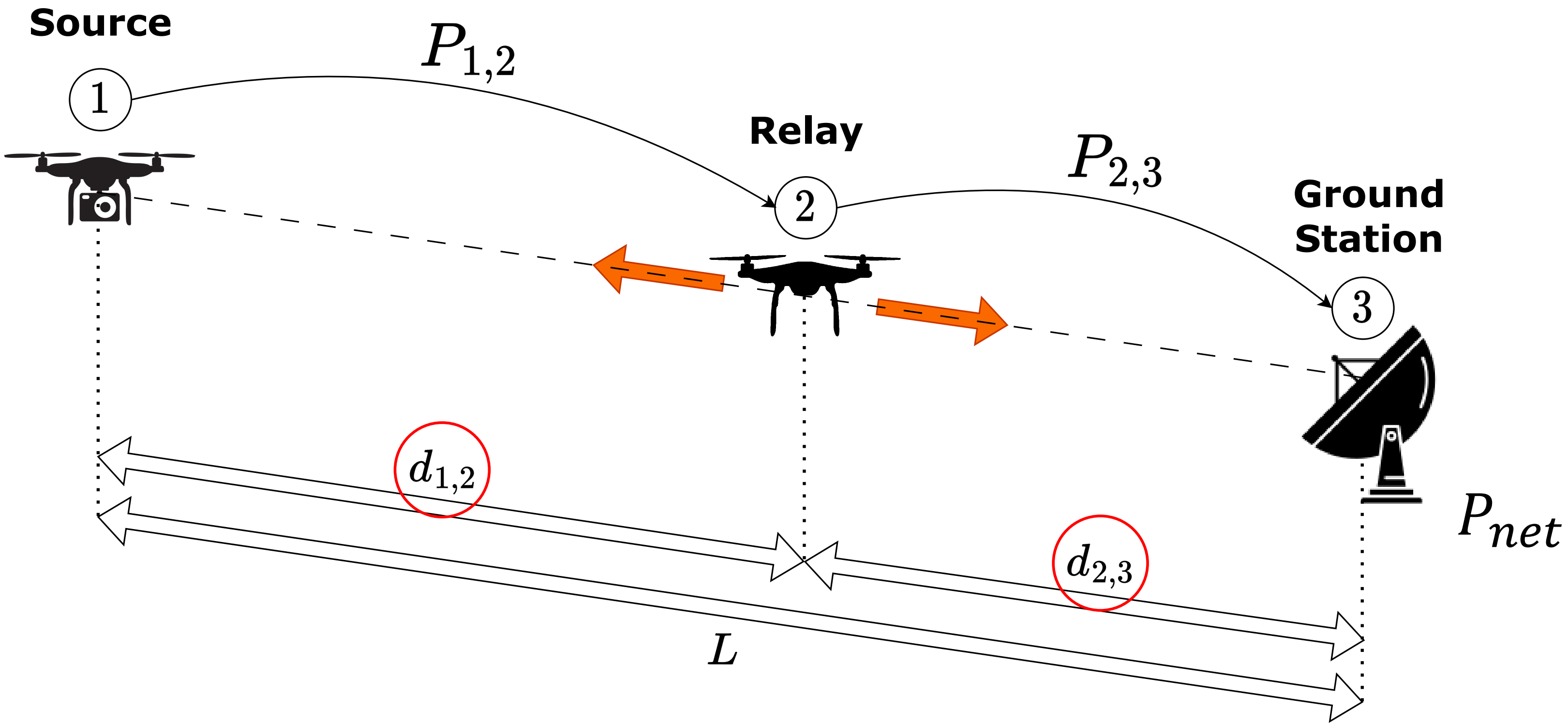
Context and Problem



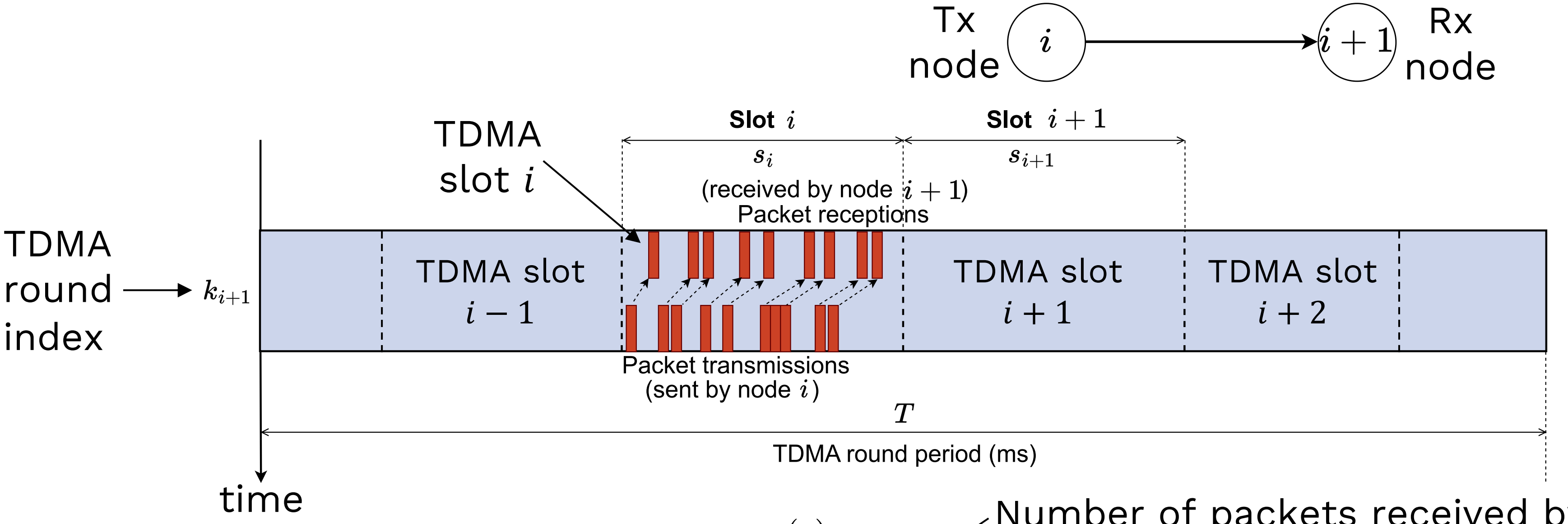
1. **Multi-hop communication**, information is relayed from source to ground station
2. The nodes communicate on the same channel and need to coordinate transmission to avoid mutual interference → **Time-Division Multiple Access (TDMA)**
3. There can be **packet losses**, which depends on:
   1. **Distance**
   2. **Environmental parameters** (interference, obstacles): change *dynamically*

Problem: Relay Placement

Objective: *Continuously* determine the positions of the relay drones that maximize the Packet Delivery Ratio of the entire network



TDMA & Packet Delivery Ratio (PDR)



$$P_{i,i+1}(k_{i+1}) = \frac{N_{i+1}^{(r)}(k_{i+1})}{N_i^{(s)}(k_{i+1})}, \quad i \in \{1, \ldots, n\}$$

Number of packets received by $i+1$

Number of packets sent by i

- **PDR** is the **communication quality metric** in our problem

Related Works

- **Model**:
  - Zhao and Govindan (2003) and Jia et al. (2010)
    Show the impact of distance as the main factor of Packet Delivery Ratio (PDR)
  - Henkel and Brown (2008)
    Found relations between distance and performance
  - Pinto et al. (2017)
    Proposed a model to estimate PDR as a function of distance
- **Relay Placement** (to improve communication):
  - Magán-Carrión et al. (2016)
    Provides optimal (static) relay placement (not focused on UAVs)
  - Lu et al. (2020)
    Proposes ERNetC, relays aligned between source and ground station
  - Pinto and Almeida (2022)
    Proposes a dynamic relay positioning to optimize PDR

Contributions

- **Estimation of** link PDR **model parameters with dynamic channels conditions**
  - Design of a **model change detector**
  - Proposal of an **estimation error index**
- **Implementation of** three **relay placement strategies** in a distributed fashion:
  - Equidistant
  - Equal-PDR (new proposed strategy)
  - DRP (optimal)
- **Comparison of** relay placement **strategies**
- A new **C software framework** for dynamic relay placement

Wireless Link PDR Model

- **Link PDR** as a function of the distance d and depending on (R, α):

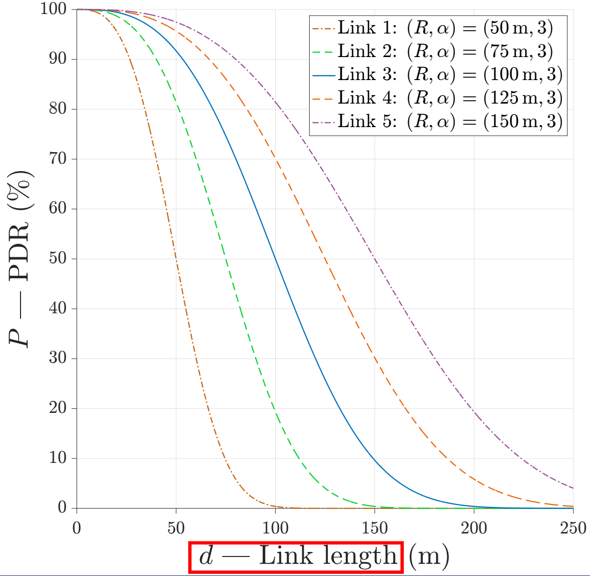
Pinto et al. (2017)

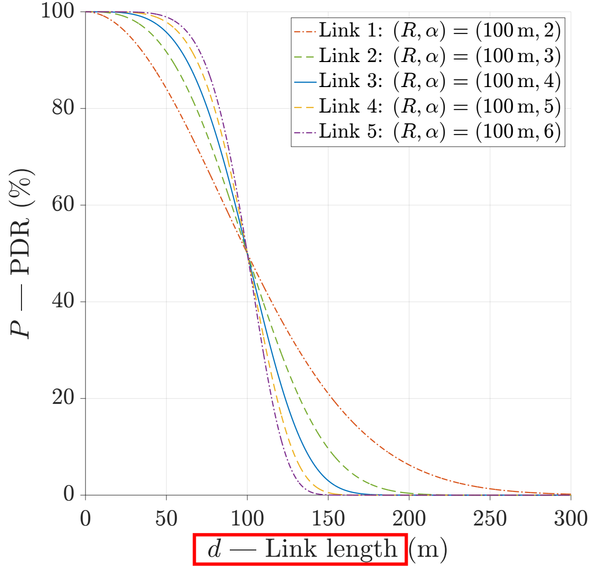
Link length

$$P_{i,j}(\boxed{d_{i,j}}) = e^{-\log(2)\left(\frac{d_{i,j}}{\boxed{R_{i,j}}}\right)^{\boxed{\alpha_{i,j}}}}, \quad i,j \in \{1,\dots,n\}$$

Distance at which PDR is 50%

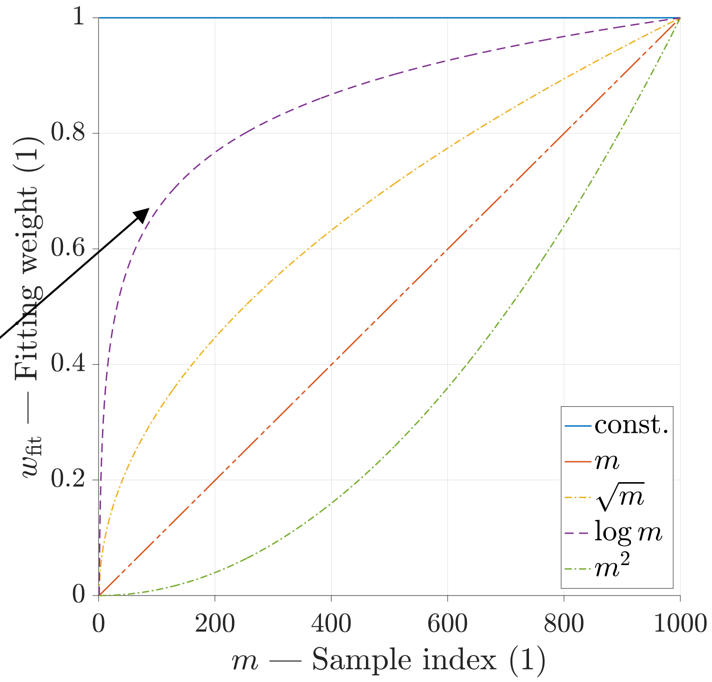
Steepness of the curve





Estimating Link PDR Model

- PDR link models **estimated online**
- Parameters obtained by **fitting** with **non-linear least squares** method
- **Sample size** constantly **increasing** with new PDR samples (*until link change detected*)
- **Samples** are weighted by **age**
  - older samples count less (according to logarithmic decrease)



(age)

Detecting Changes in PDR Model

- **Detection indicator**:

$$D_i(k_i) = \begin{cases} 1\,, & \text{if } |\boxed{\bar{\hat{R}}_i(k_i')} - \hat{R}_i(k_i')| > \rho \cdot \boxed{\mathrm{WRMSE}_{\hat{R}_i}(k_i')} \\ & \vee\ |\boxed{\bar{\hat{\alpha}}_i(k_i')} - \hat{\alpha}_i(k_i')| > \rho \cdot \boxed{\mathrm{WRMSE}_{\hat{\alpha}_i}(k_i')}, \quad \forall k_i' \in \{k_i - \tau + 1, k_i\} \\ 0\,, & \text{otherwise} \end{cases}$$

Weighted averages of $\hat{R}_i$ and $\hat{\alpha}_i$

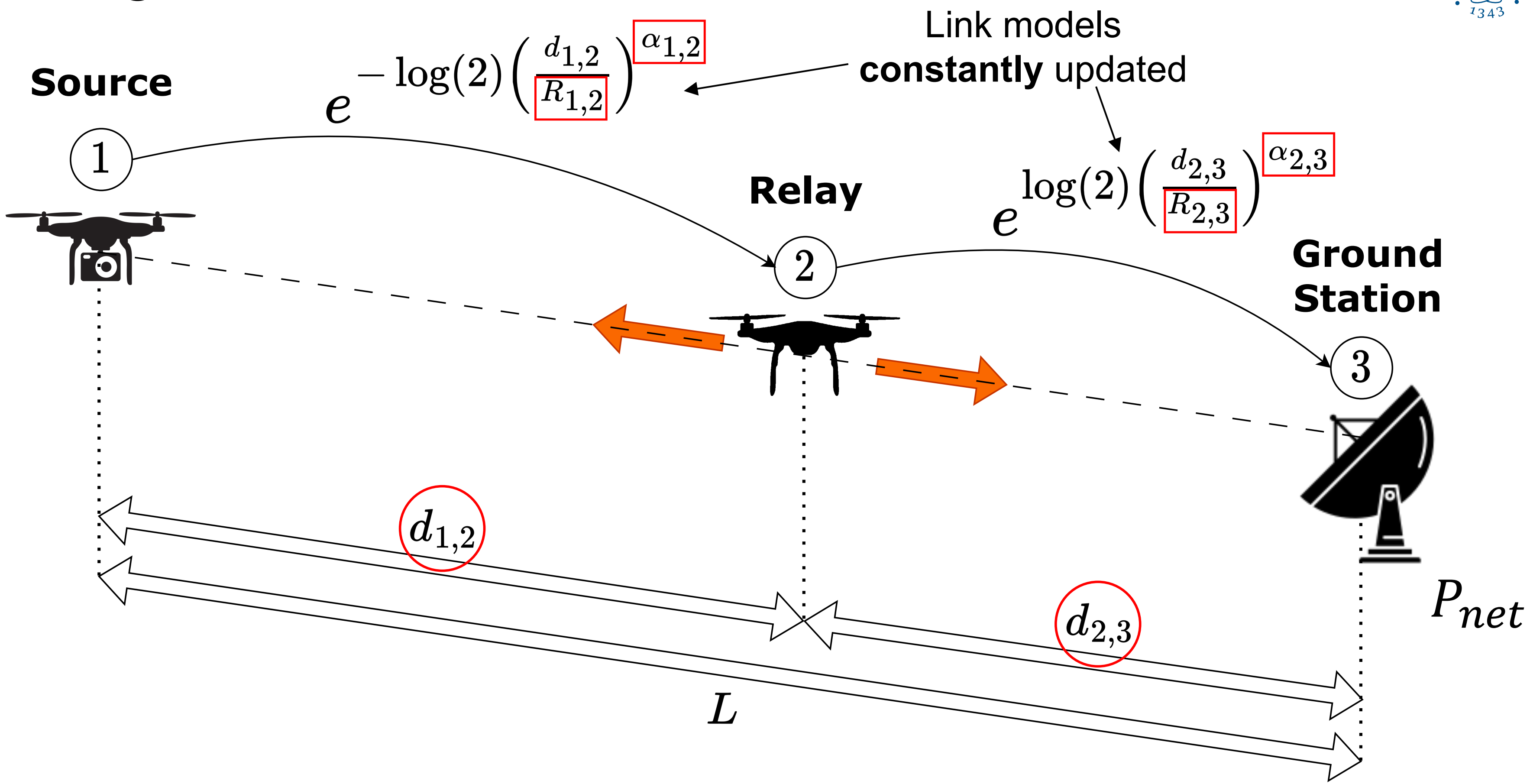
Weighted Root Mean Square Errors (**WRMSEs**) of $\hat{R}_i$ and $\hat{\alpha}_i$

- $\bar{\hat{R}}_i$, $\bar{\hat{\alpha}}_i$ and $\mathrm{WRMSE}_{\hat{R}_i}$, $\mathrm{WRMSE}_{\hat{\alpha}_i}$ depend on the **sample size**:

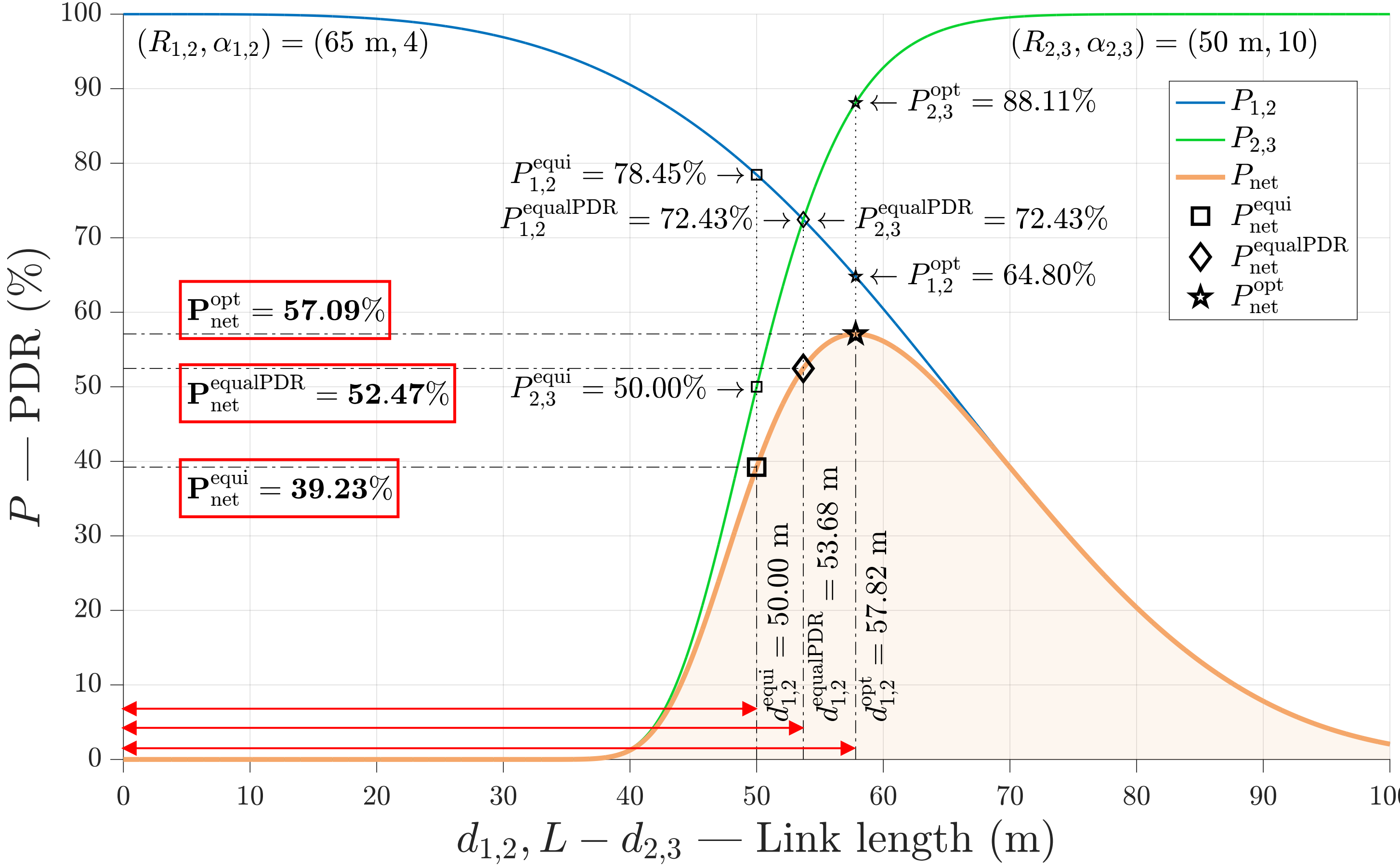
$$N_i(k_i) = \begin{cases} \lceil (1-\eta_N) N_i(k_i - 1) \rceil\,, & \text{if } \boxed{D_i}(k_i) = 1 \\ N_i(k_i - 1) + 1\,, & \text{otherwise} \end{cases}$$

When model change detected, older samples are removed

Relay Placement Problem

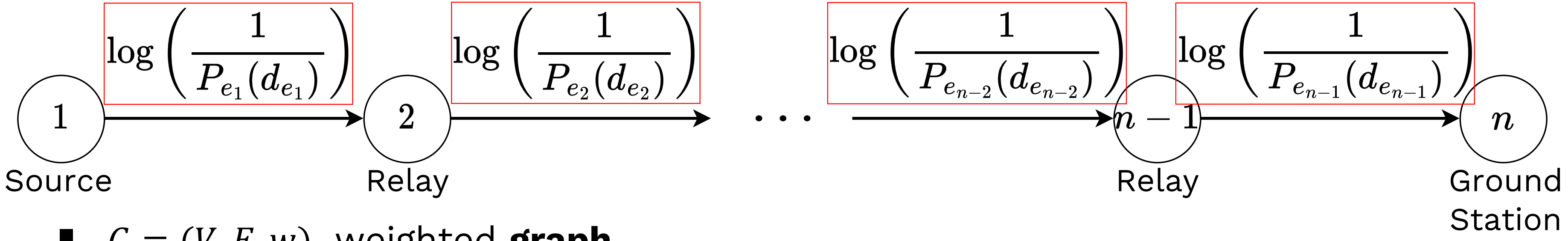


Relay Placement: Different Strategies



Maximizing Network PDR

- **Line network** with n nodes:



- $G = (V, E, w)$, weighted **graph**
  - $V = \{1,2,\dots,n\}$, vertex set
  - $E = \{\{1,2\},\dots,\{n-1,n\}\}$, edge set
  - $w: E \to \mathbb{R}_{\geq 0}$, **weight** function:

$$w_{i,i+1} = \log\left(\frac{1}{P_{i,i+1}(d_{i,i+1})}\right)$$

Find the relay **positions** that maximize the network PDR

- **Network PDR**:

$$P_{\text{net}}(\mathbf{d}) = \prod_{i=1}^{n-1} P_{i,i+1}(d_{i,i+1}) = \left(\exp\left(\sum_{i=1}^{n-1} w_{i,i+1}\right)\right)^{-1}$$

Estimation Error

- **Estimation error index**:

$$\xi = \mathrm{dist}(P, \hat{P}) = \int_0^L \left| P(d) - \hat{P}(d) \right| \, \mathrm{d}d = \int_0^L \left| e^{-\log(2)\cdot\left(\frac{d}{R}\right)^{\alpha}} - e^{-\log(2)\cdot\left(\frac{d}{\hat{R}}\right)^{\hat{\alpha}}} \right| \, \mathrm{d}d$$

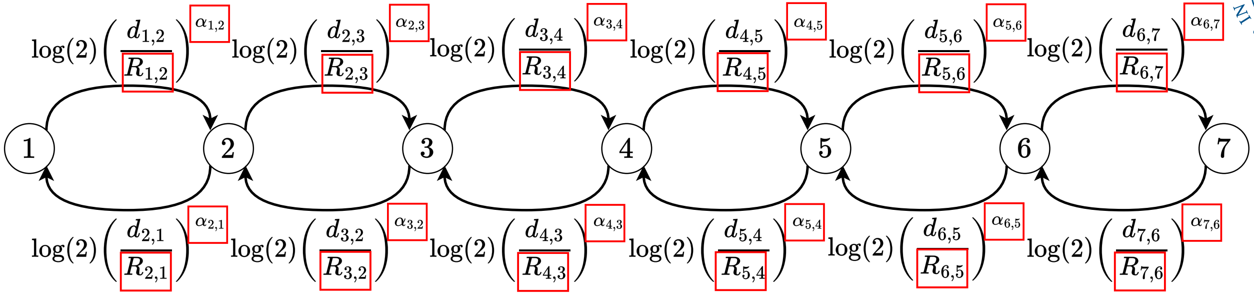
- **Average estimation error index**:

$$\bar{\xi}([k_0..k]) = \frac{1}{k-k_0+1} \sum_{k'=k_0}^{k} \xi(k') = \frac{1}{k-k_0+1} \sum_{k'=k_0}^{k} \int_0^L |P(d,k') - \hat{P}(d,k')| \, \mathrm{d}d =$$

$$= \frac{1}{k-k_0+1} \sum_{k'=k_0}^{k} \int_0^L \left| e^{-\log(2)\cdot\left(\frac{d}{R(k')}\right)^{\alpha(k')}} - e^{-\log(2)\cdot\left(\frac{d}{\hat{R}(k')}\right)^{\hat{\alpha}(k')}} \right| \, \mathrm{d}d$$

Simulation

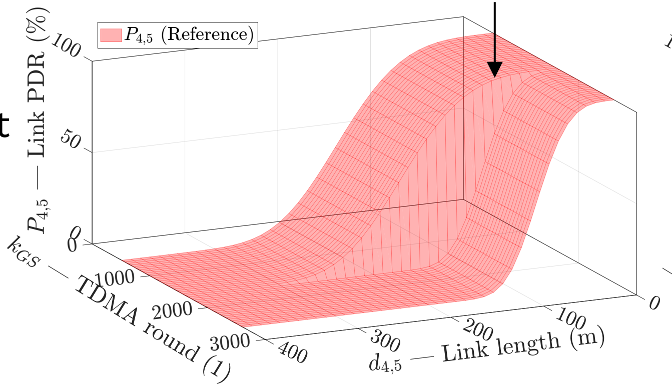
- **Network** ($n = 7$):
  - 1 source
  - (up to) 5 relays
  - 1 ground station



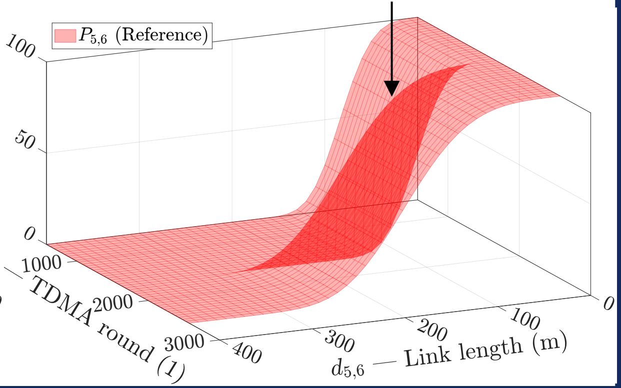
- Three **Relay Placement Strategies**:
  - Equidistant
  - Equal-PDR
  - DRP

- Four **simulated scenarios**:
  - <u>Scenario 'a' </u>(unchanged parameters)
  - <u>Scenario 'b'</u> (small abrupt parameters change)
  - <u>Scenario 'c'</u> (large abrupt parameters change)
  - *<u>Scenario 'd'</u>* (incremental parameters change)

Link {4,5} degrades



Link {5,6} improves

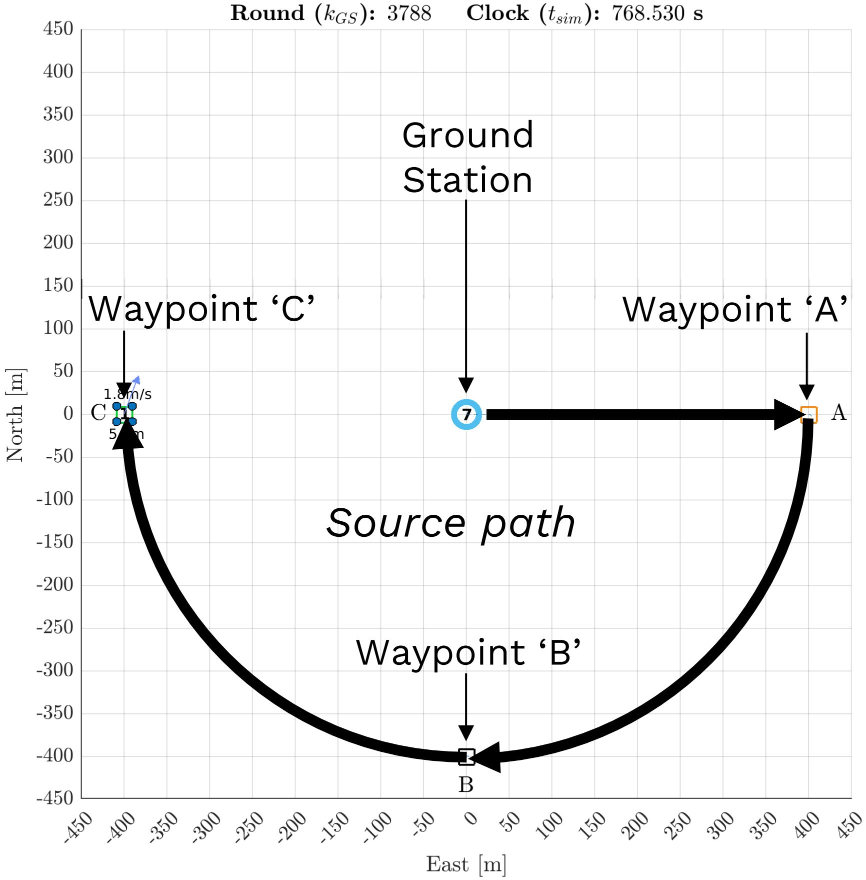


Waypoints

- Source path:
  1. Starts at the ground station
  2. Goes to **waypoint 'A'** (at time k^A)
  3. Goes to **waypoint 'B'** (at time k^B)
  4. Goes to **waypoint 'C'** (at time k^C)

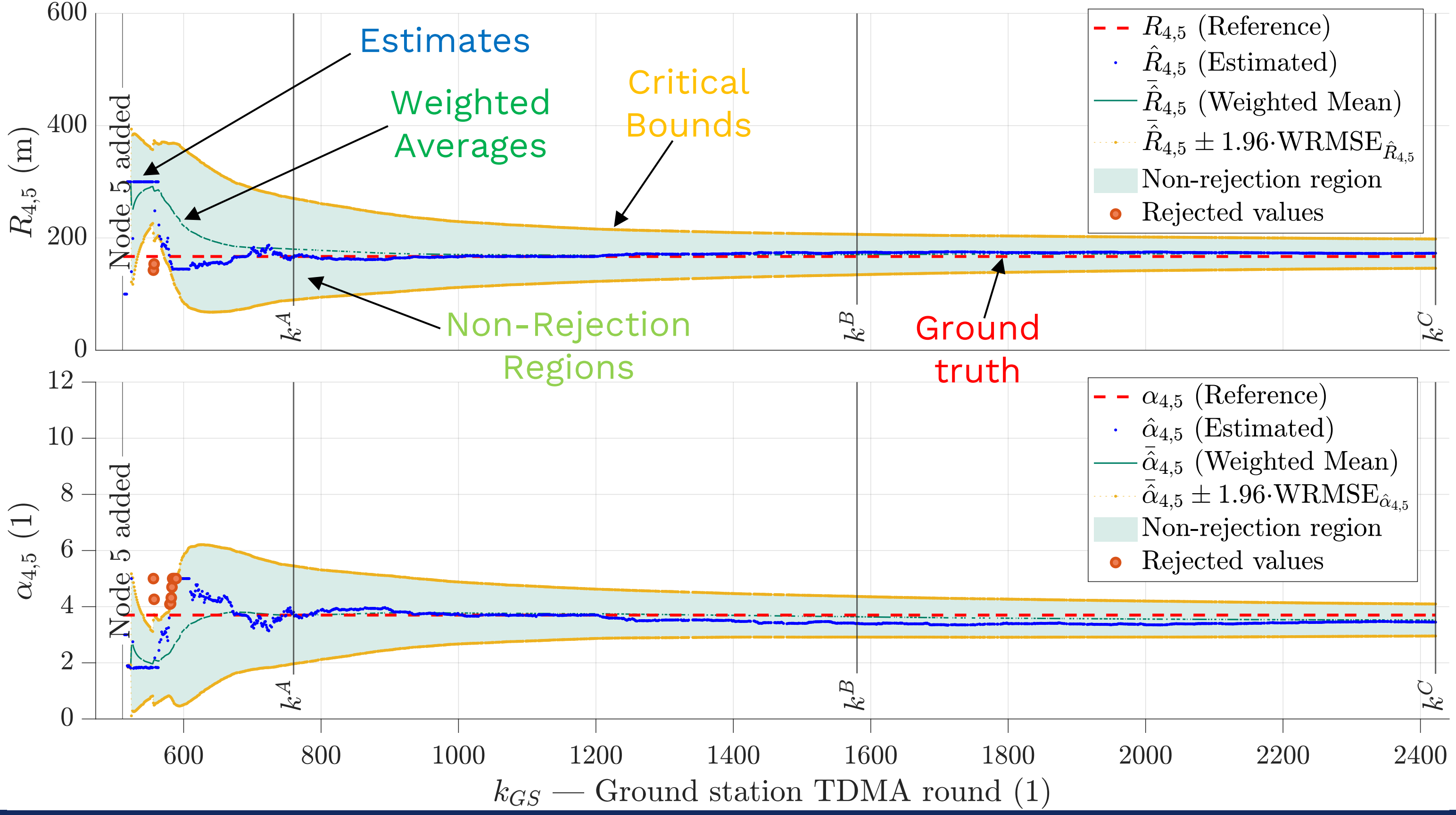
- **Average network PDR** is measured in $[k^A..k^C]$:

$$\bar{P}_{\text{net}}([k^{\text{A}}..k^{\text{C}}]) = \frac{\sum\limits_{k\in[k^{\text{A}}..k^{\text{C}}]} N_n^{\text{r,data}}(k)}{\sum\limits_{k\in[k^{\text{A}}..k^{\text{C}}]} N_1^{\text{s,data}}(k)}$$



Results: Scenario ‘a’, DRP

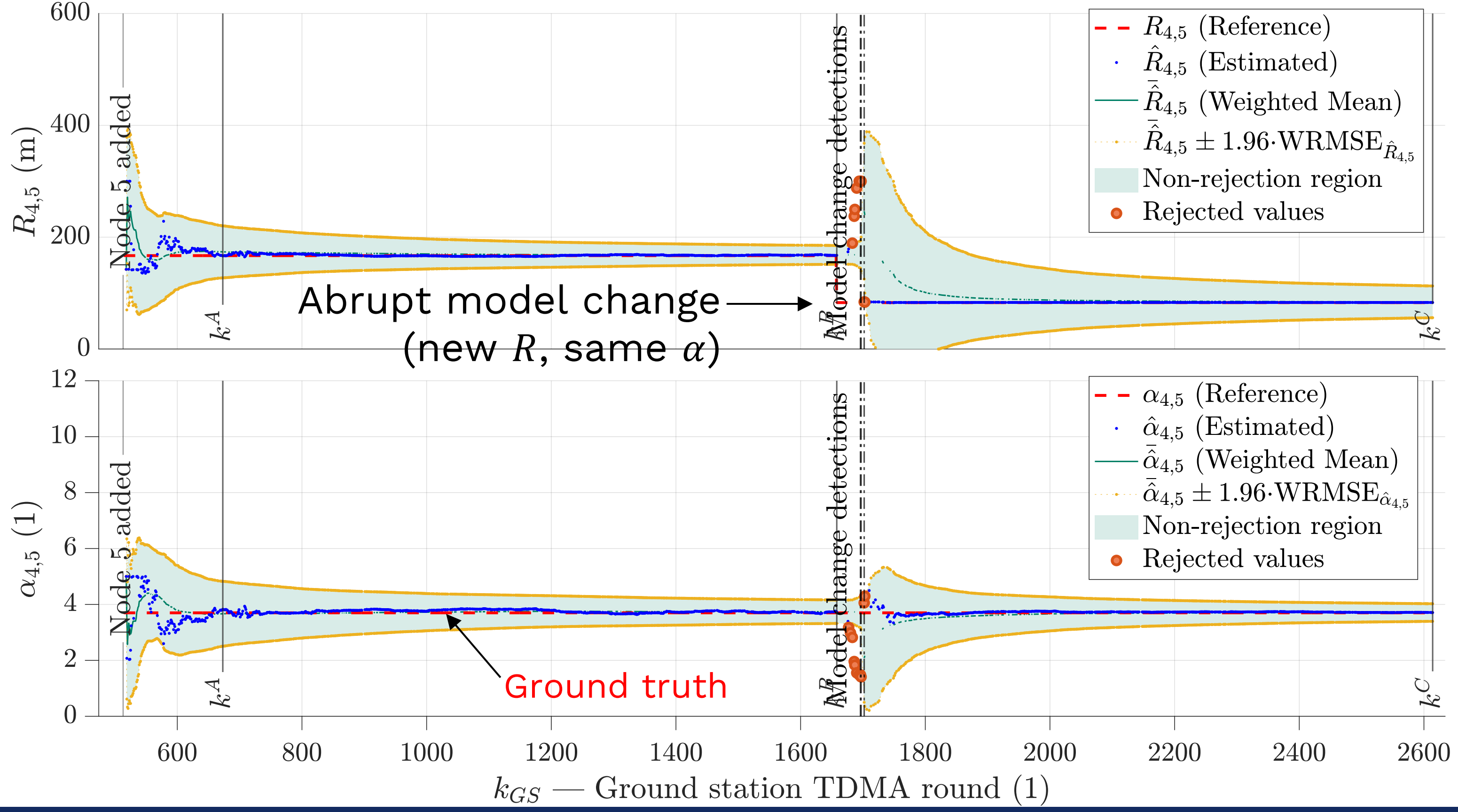
- Time evolution of the **estimated parameters** $(\hat{R}, \hat{\alpha})$:



Link $\{4, 5\}$

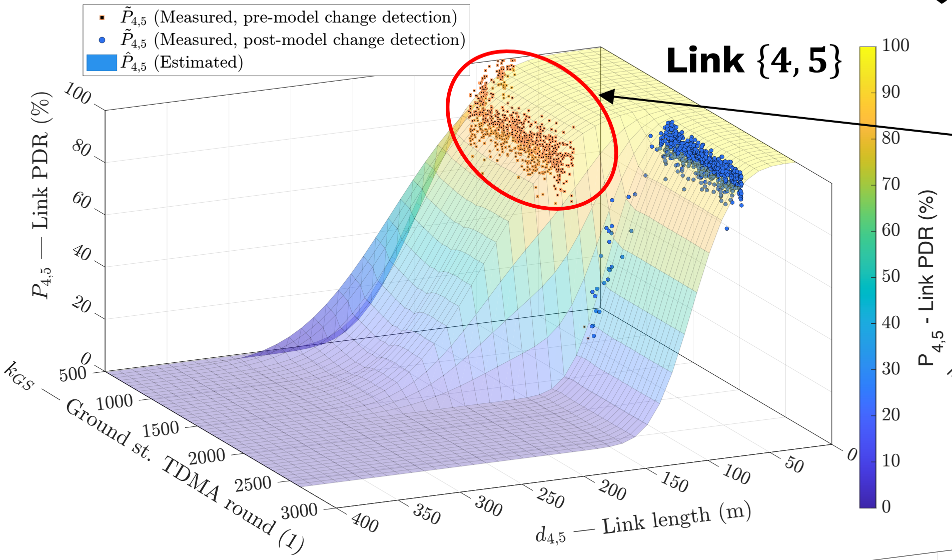
Results: Scenario ‘c’, DRP

- Time evolution of the **estimated parameters** $(\hat{R}, \hat{\alpha})$:

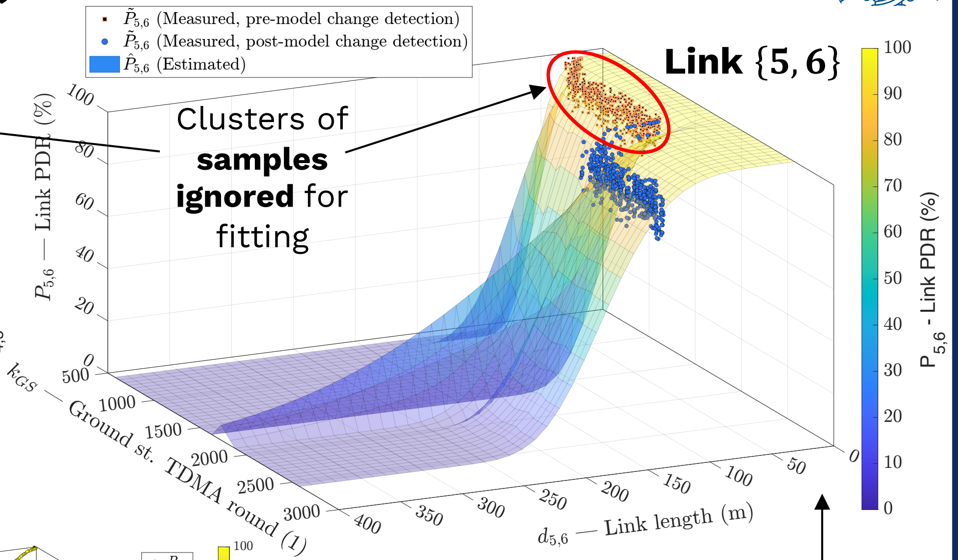


Link $\{4, 5\}$

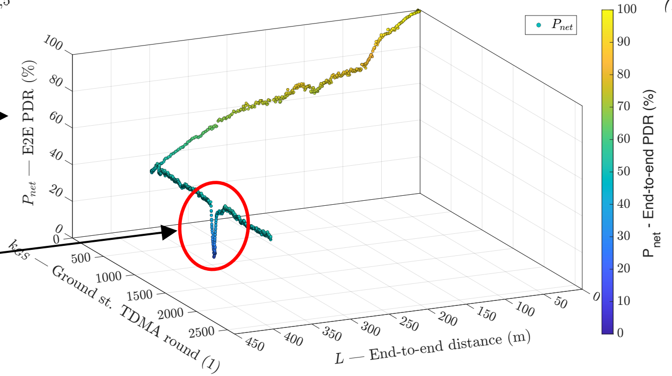
Results: Scenario ‘c’, DRP



Clusters of **samples ignored** for fitting



- **Time evolution** of P_{net}



Transitory decrease in P_{net} at k^B

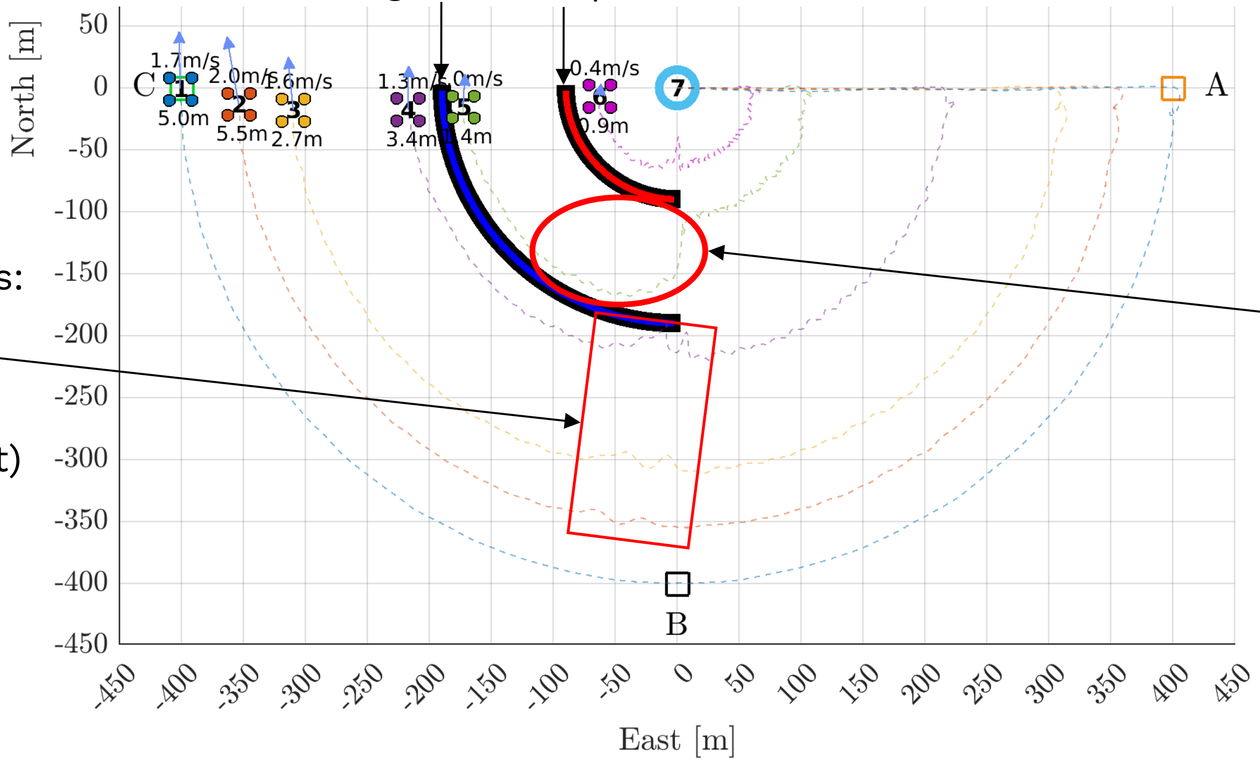
- **Time evolution** of (P, d) measurements and model estimates:

Results: Scenario ‘c’, DRP

- UAVs **Trajectories**:

Link {4,5} degrades

Link {5,6} improves



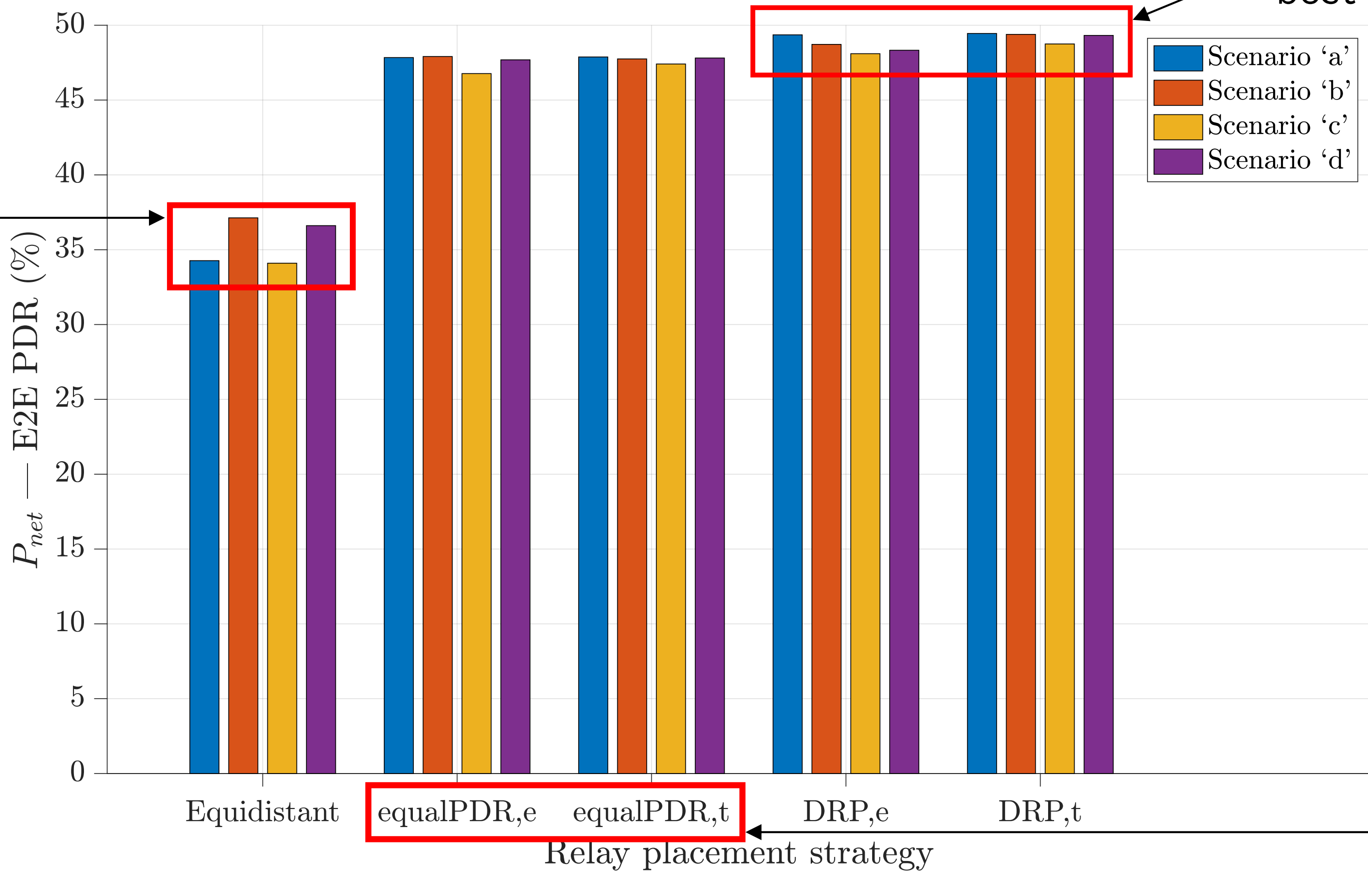
All other nodes: trajectories <u>un</u>changed (except for a short transient)

Node 5 (in green): trajectory changed!

Results: Average Network PDRs

Equidistant strategy: worst results

DRP: best results



Equal-PDR: proposed strategy

Conclusions

- **Good estimates of** network **parameters** (scenario ‘a’), …
- …, **even with small and large abrupt model changes** (scenarios ‘b’, ‘c’), …
- …, except with incremental model change (scenario ‘d’): **we recommend improving the model change detector for incremental-change scenarios**
- **Relays moved as expected** in all distributed relay placement strategies
- In all scenarios, both **DRP and equal-PDR outperformed** the **equidistant** strategy by ~40%
- The **DRP strategy** is highly **recommended for any wireless line network**

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