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Switching in the Rain: Predictive Wireless x-haul Network Reconfiguration

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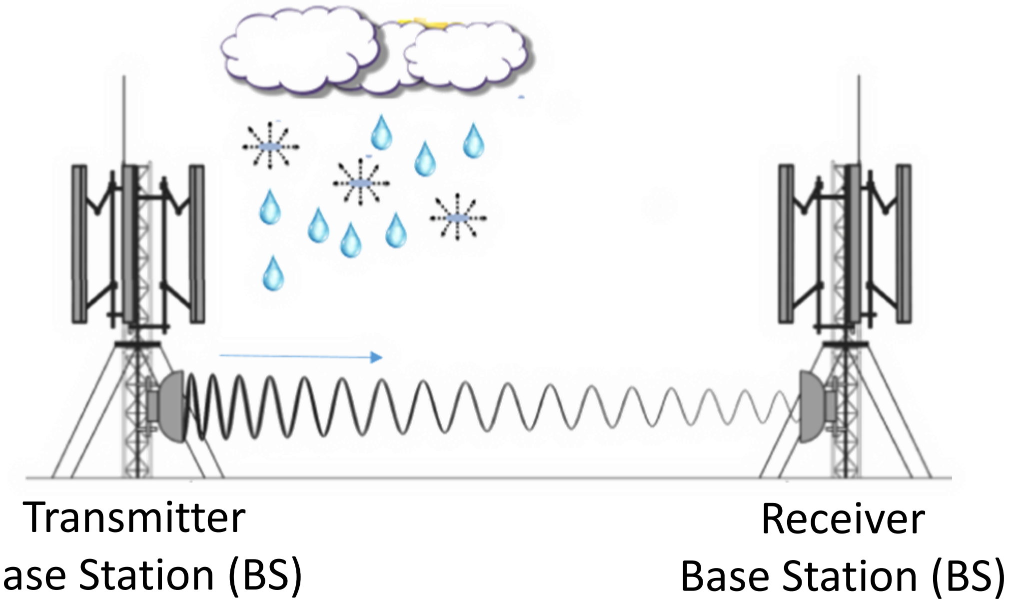
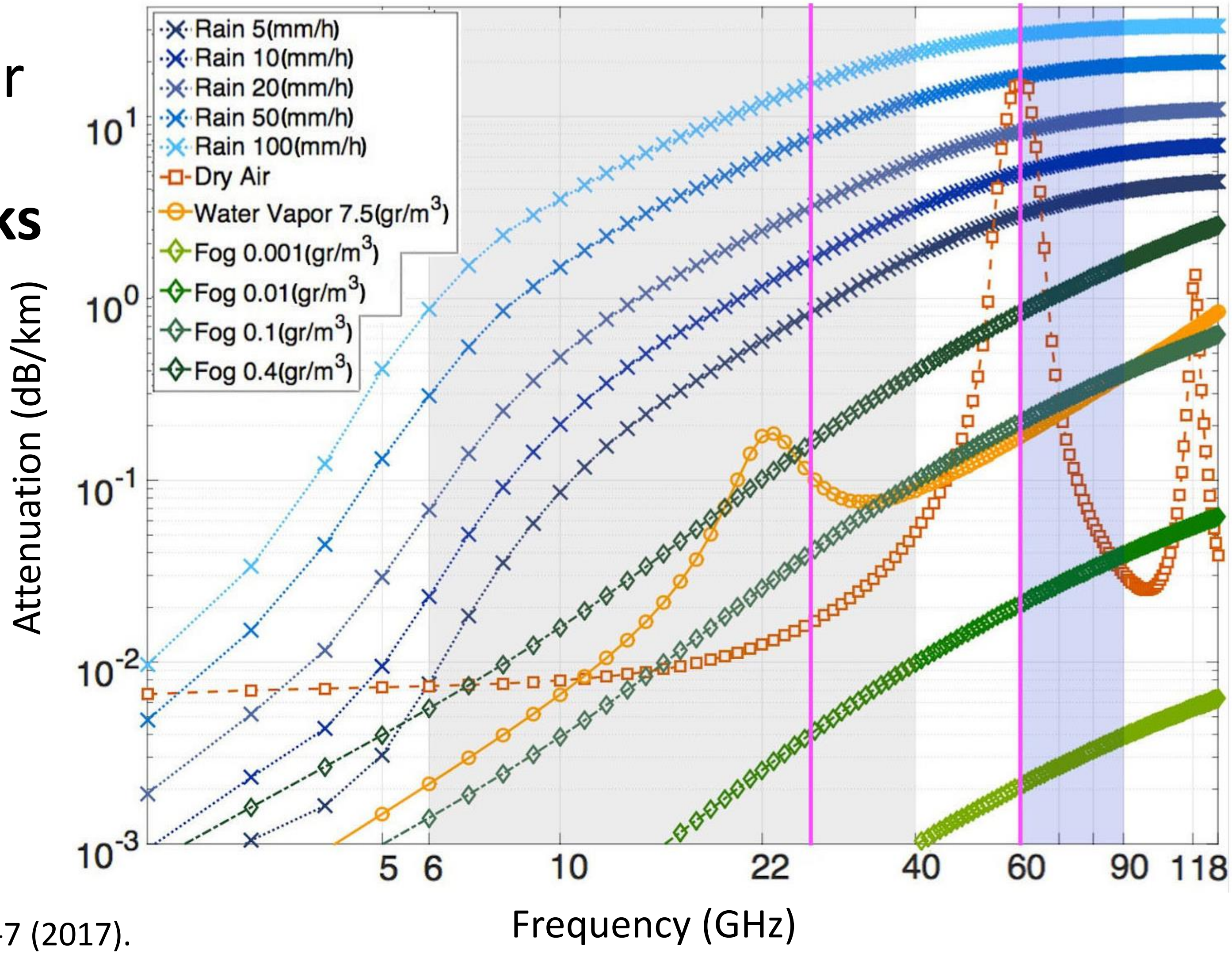
*Both authors contributed equally to this research

US Patent Application No. 17/551,643. Dec. 2021

Motivation

Different atmospheric and weather phenomena can cause **severe attenuation to high frequency links**





[21] ITU-R P.840. 2017. Attenuation due to clouds and fog. ITU 840-7 (2017).

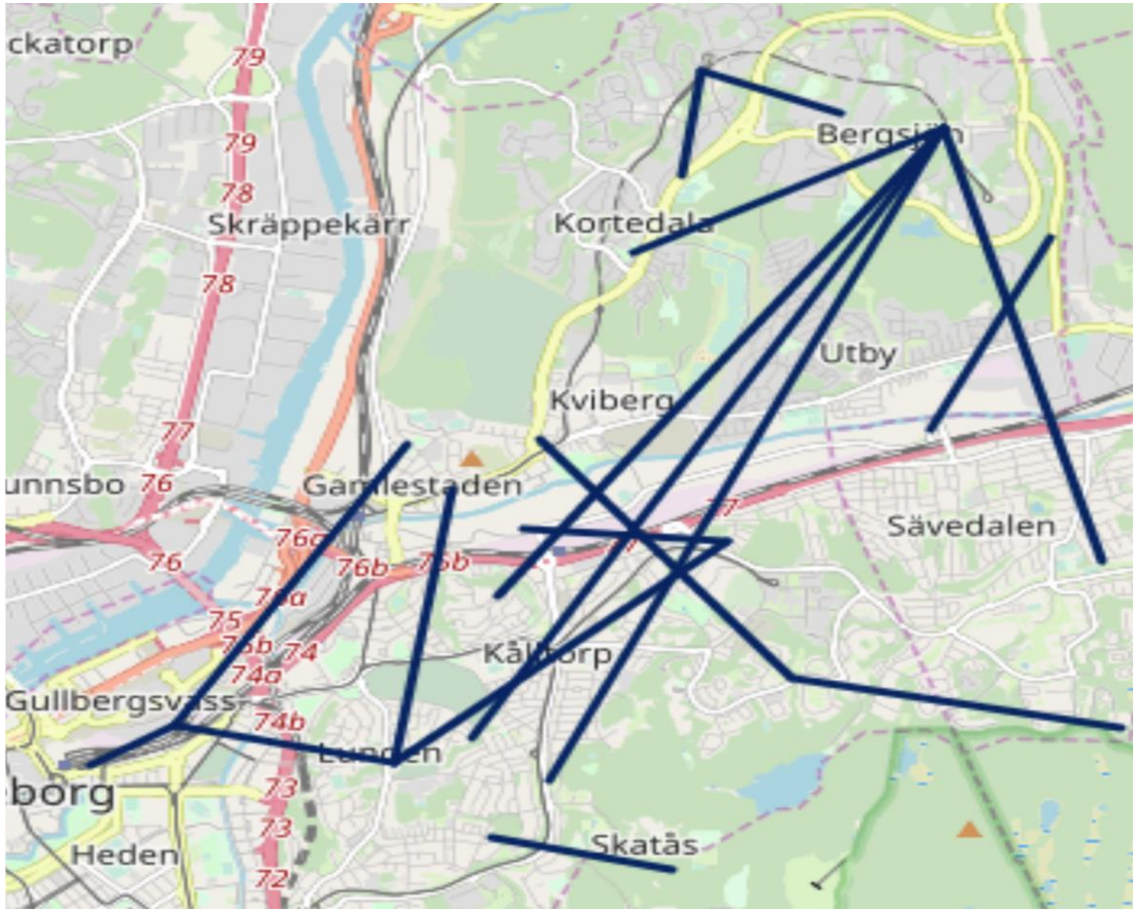
[22] ITU-R P.676. 2016. Attenuation by atmospheric gasses. ITU 676-11 (2016).

[23] ITU-R P.530. 2017. Propagation data and prediction methods required for the design of terrestrial line-of-sight systems. ITU 530-17 (2017).

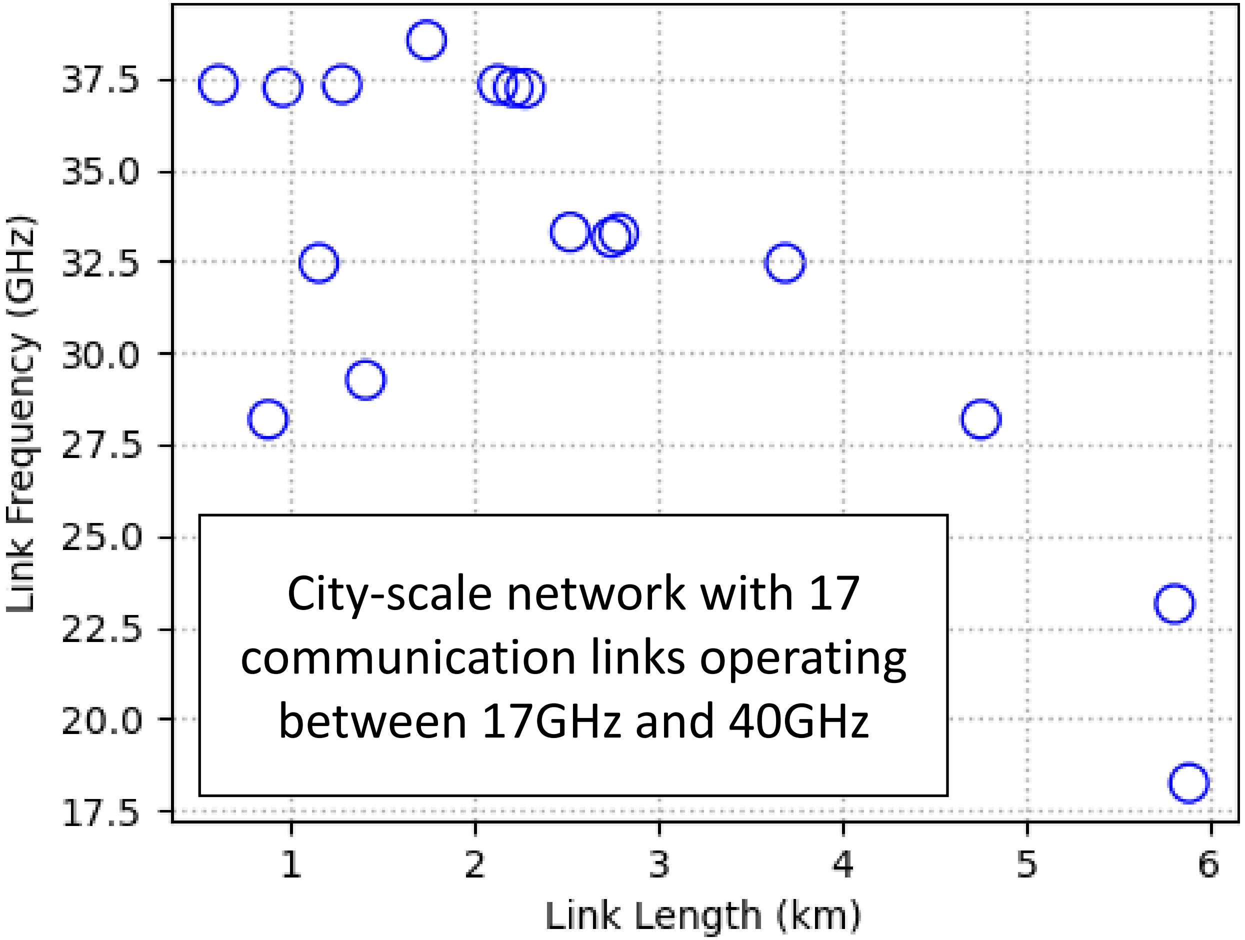
[24] ITU-R P.838. 2005. Specific attenuation model for rain for use in prediction methods. ITU 838-3, 1992-1999-2003-2005 (2005).

Motivation

Real-world city-scale wireless backhaul network in Gothenburg, Sweden



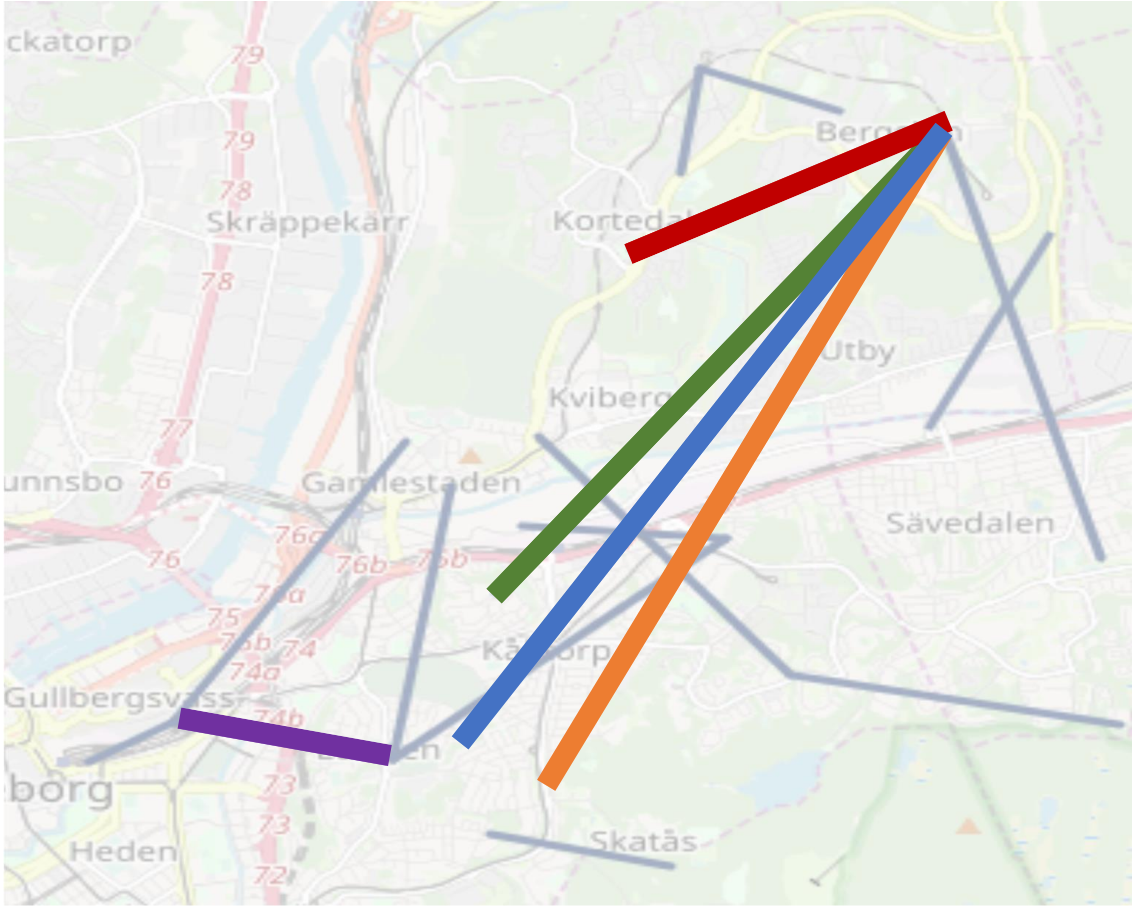
map area is of approximately 10x10 km^2

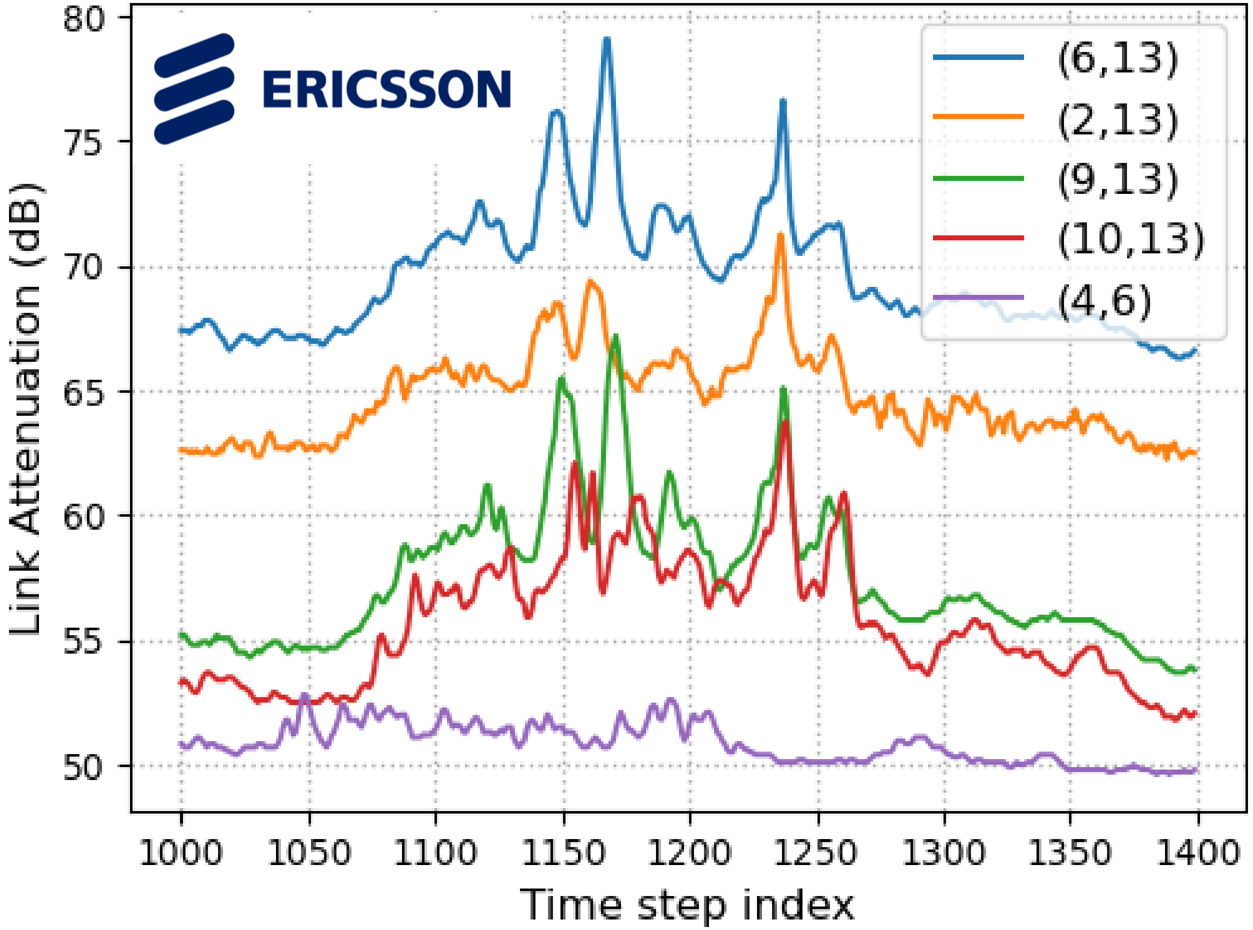


City-scale network with 17 communication links operating between 17GHz and 40GHz

Motivation

Ericsson collects link attenuation measurements [6] in time steps of 10sec





[6] L. Bao, C. Larsson, M. Mustafa, J. Selin, J. Andersson, J. Hansryd, M. Riedel, and H. Andersson. 2017. A brief description on measurement data from an operational microwave network in Gothenburg, Sweden. In Proc. CEST

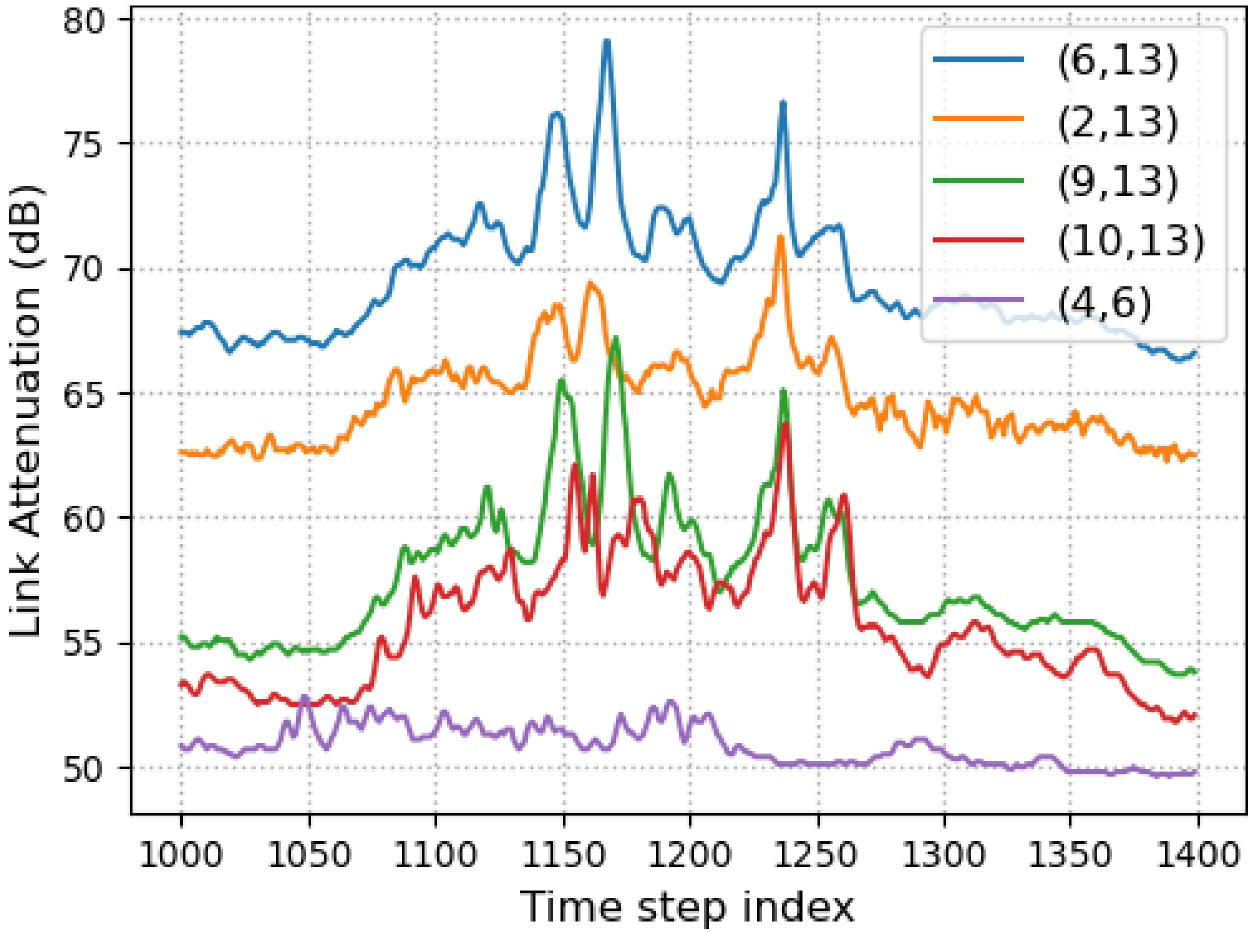
Motivation

Motivation: Need for a high-capacity wireless x-haul network that is **robust**

Challenge: **Link degradation varies** over time, geographical location, rain intensity, and **can be severe**.

Existing Solution:

- Global (**reactive**) NET layer mechanisms
  - NEC's SDN-based backhaul solution [40]



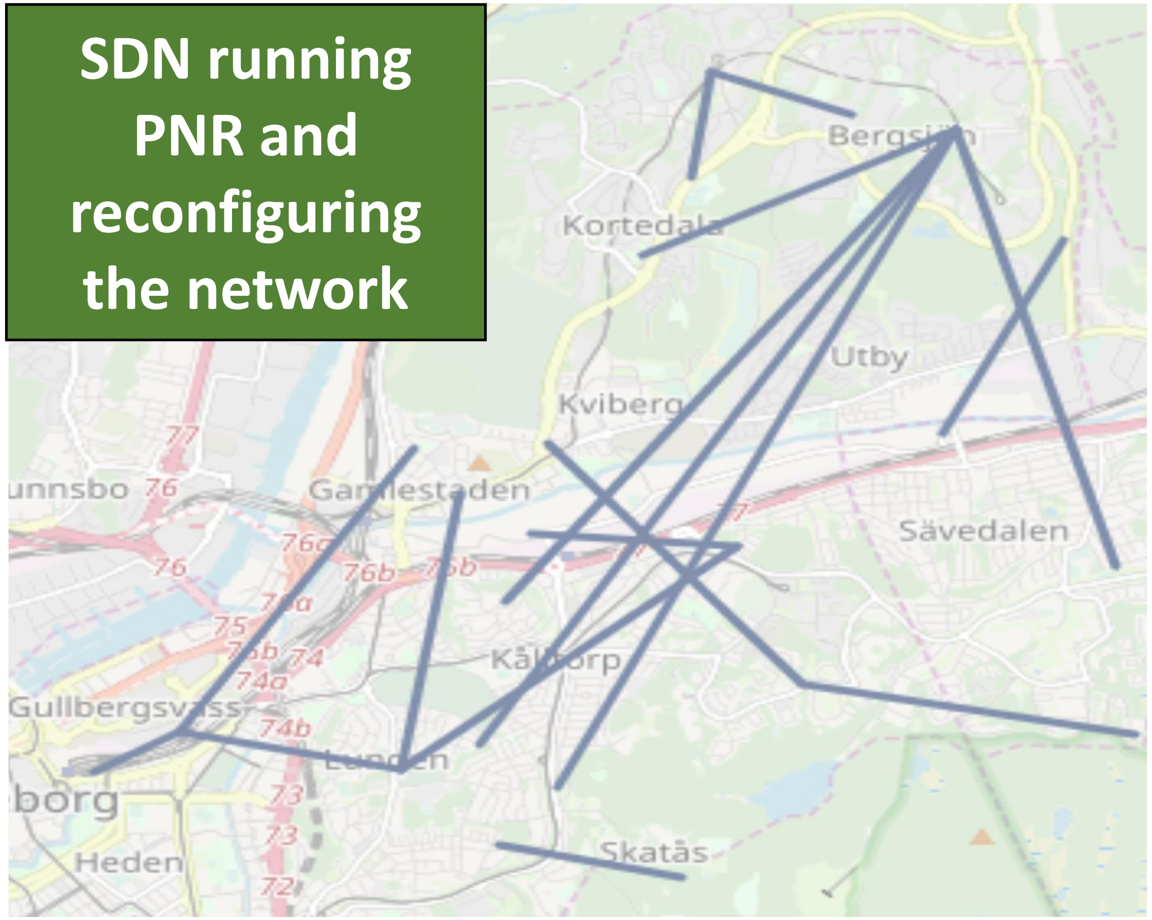
[40] NEC iPASOLINK Series. Intelligent and high-capacity wireless transport solution.

Related Work on Predictive Weather-Aware Reconfig.

Reference	Attenuation Prediction Mechanism			Routing Algorithm	Maximizes Throughput	Achieves Fair Allocation	Prevents Transient Congestion
	Weather Radar Measurements	Temporal Correlation	Spatial Correlation				
[25] 2009 A. Jabbar	X			Distributed (OSPF)			
[29] 2013 N. Javed		X		Distributed (OSPF)			
[45] 2016 J. Rak	X			Distributed (OSPF)			
[59] 2018 F. Yaghoubi		X		Centralized (SDN)	X		
This paper		X	X	Centralized (SDN)	X	X	X

J. Ostrometzky, G. Zussman, H. Messer, D. Jacoby, and I. Kadota. Predictive Weather-Aware Communication Network Management. US Patent Application No. 17/551,643. December 2021.

Predictive Network Reconfiguration (PNR)



SDN running PNR and reconfiguring the network

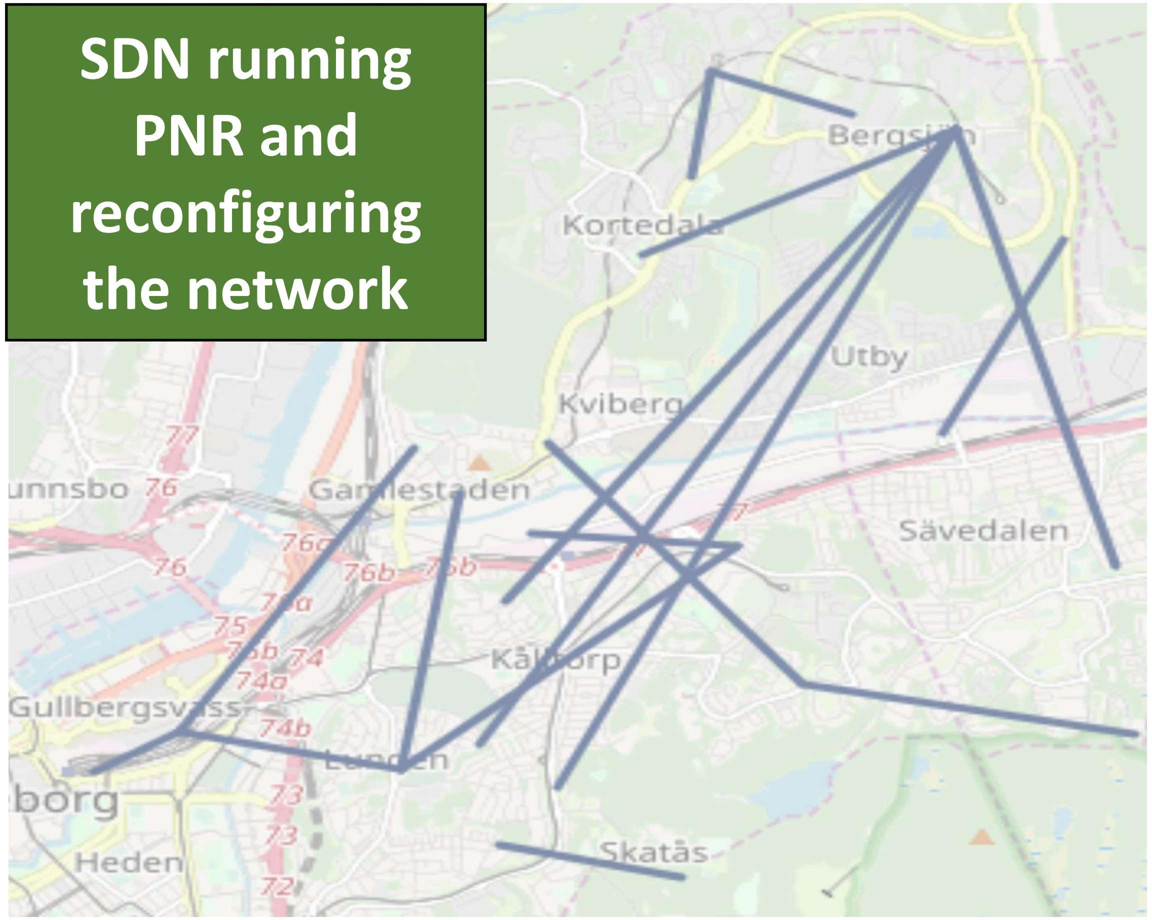
(Existing) Data Collection System [6]

Attenuation Prediction (AP) Mechanism

Multi-Step Network Reconfiguration (MSNR) Algorithm

[6] L. Bao, C. Larsson, M. Mustafa, J. Selin, J. Andersson, J. Hansryd, M. Riedel, and H. Andersson. 2017. A brief description on measurement data from an operational microwave network in Gothenburg, Sweden. In Proc. CEST

Outline



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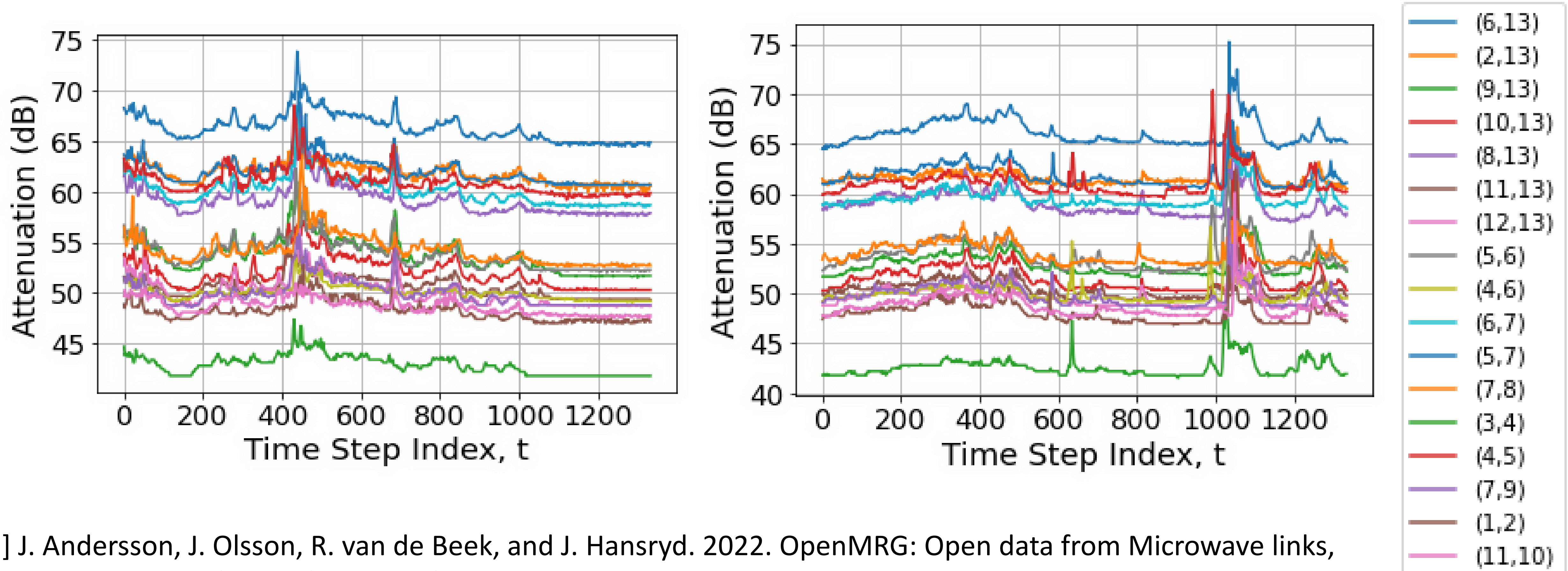
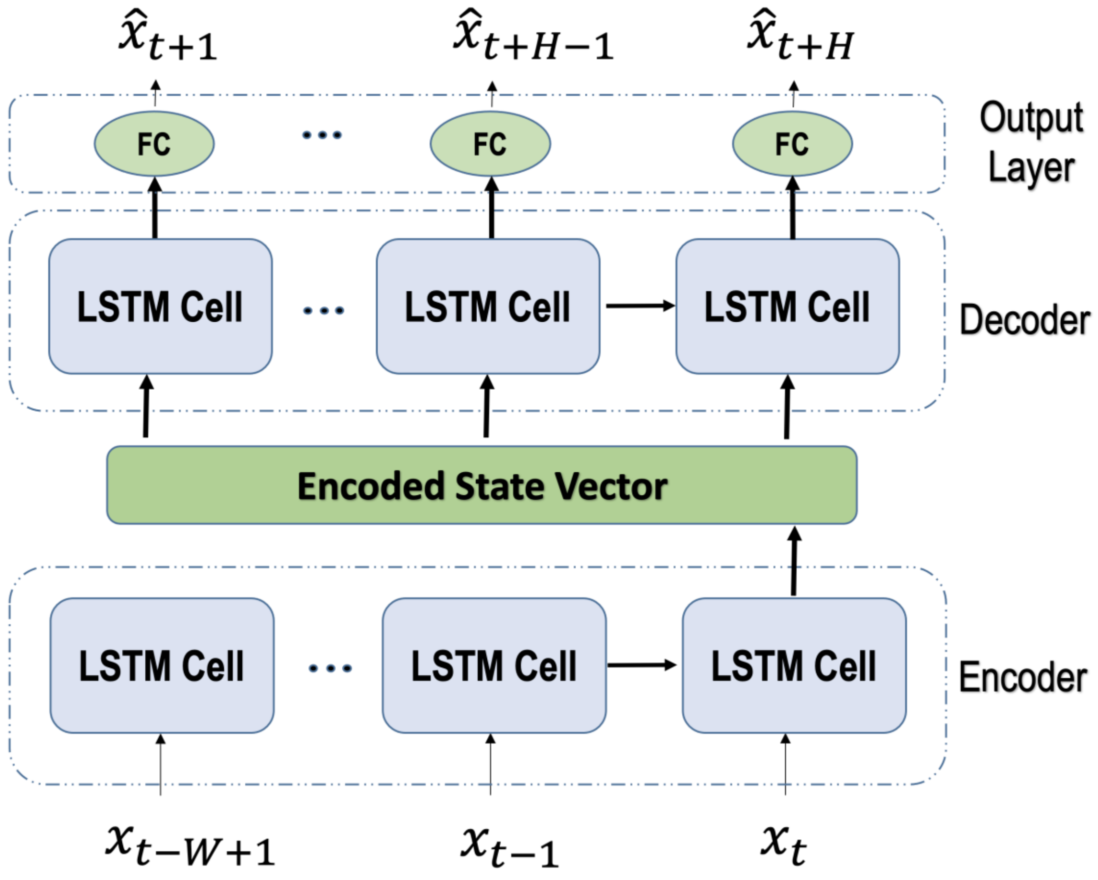
Dataset

- 2,295,000 measurements of link attenuation levels $x_t^{(k,l)}$ for each of the 17 links, in intervals of $\Delta t = 10$ sec, containing both dry and rainy periods.



[3] J. Andersson, J. Olsson, R. van de Beek, and J. Hansryd. 2022. OpenMRG: Open data from Microwave links, Radar, and Gauges for rainfall quantification in Gothenburg, Sweden. *Earth System Science Data Discussions*.

Encoder-Decoder LSTM Model



$\hat{x}_{t+1}$ $\hat{x}_{t+H-1}$ $\hat{x}_{t+H}$

FC ··· FC FC

Output Layer

LSTM Cell ··· LSTM Cell → LSTM Cell

Decoder

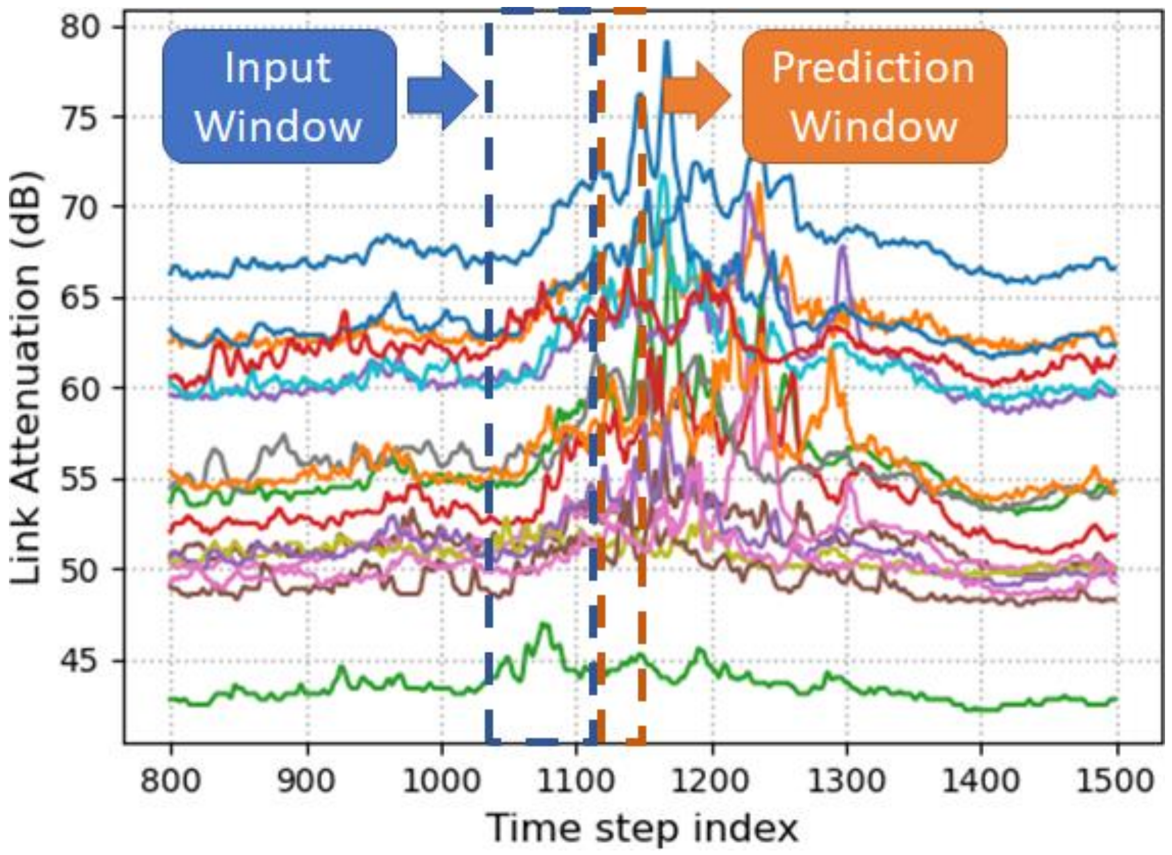
Encoded State Vector

LSTM Cell ··· LSTM Cell → LSTM Cell

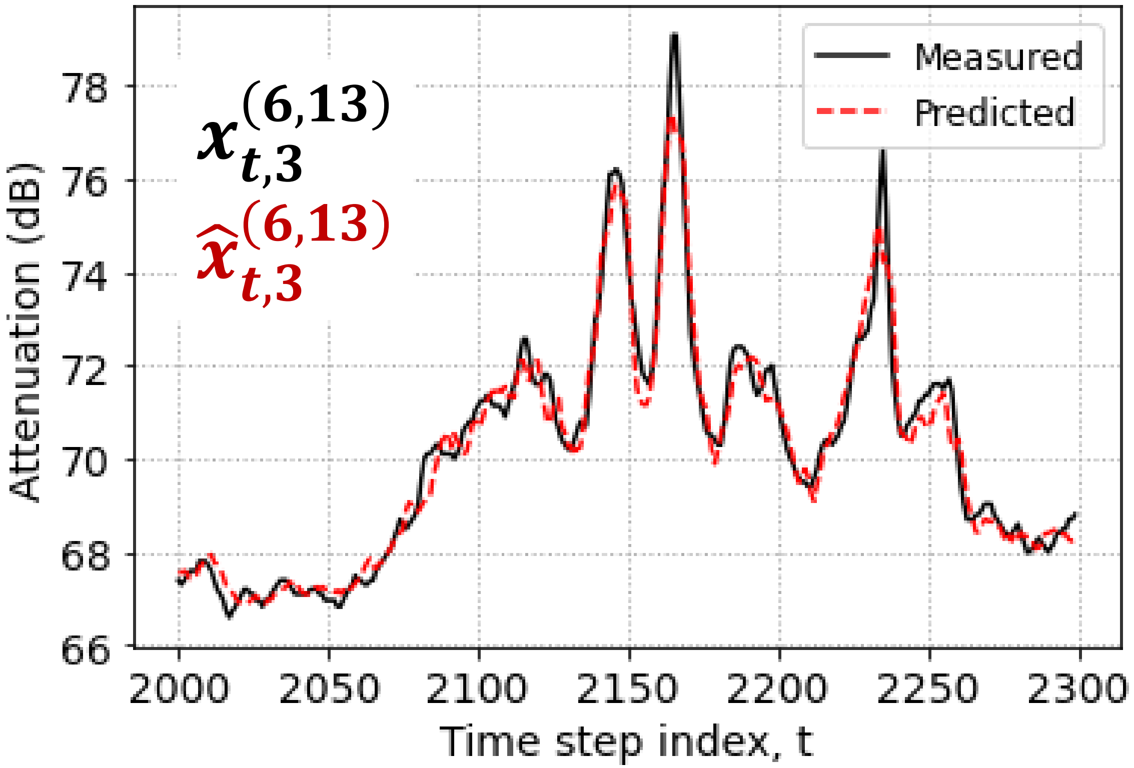
Encoder

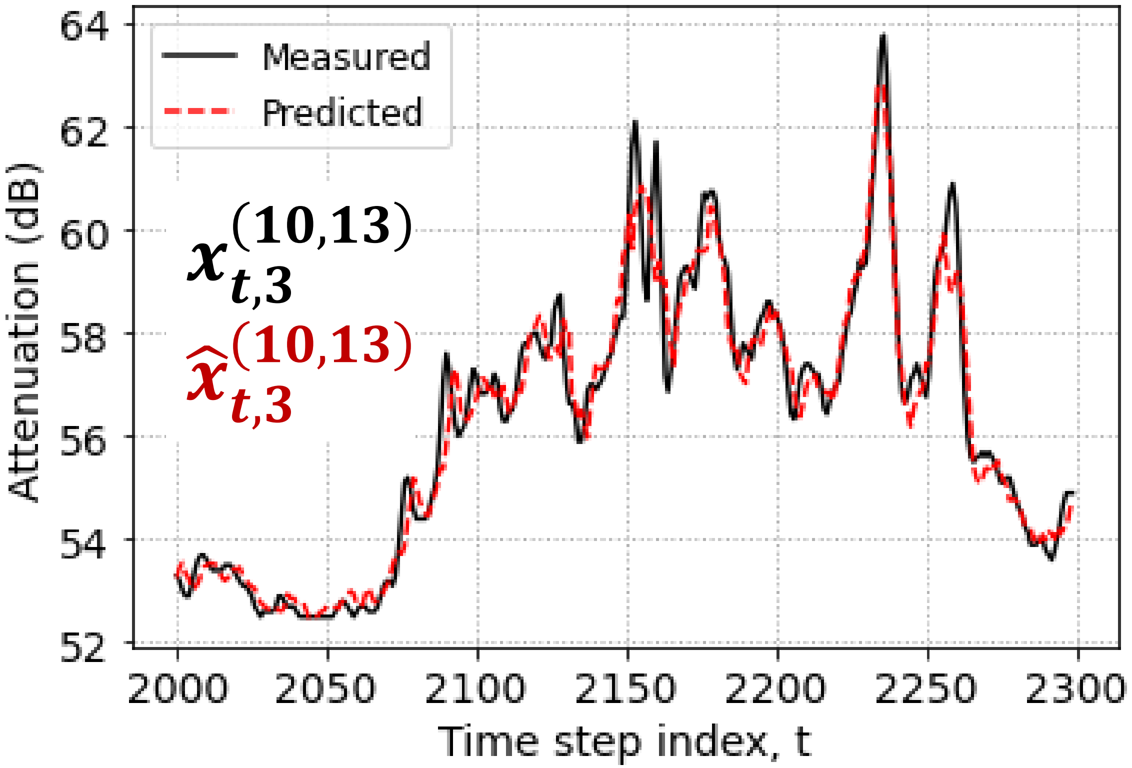
x_{t-W+1} x_{t-1} x_t

$$L(\theta) = \sum_{h=1}^{H} \sum_{\forall(k,l)} \left(x_{t+h}^{(k,l)} - \hat{x}_{t+h}^{(k,l)}(\theta)\right)^2$$



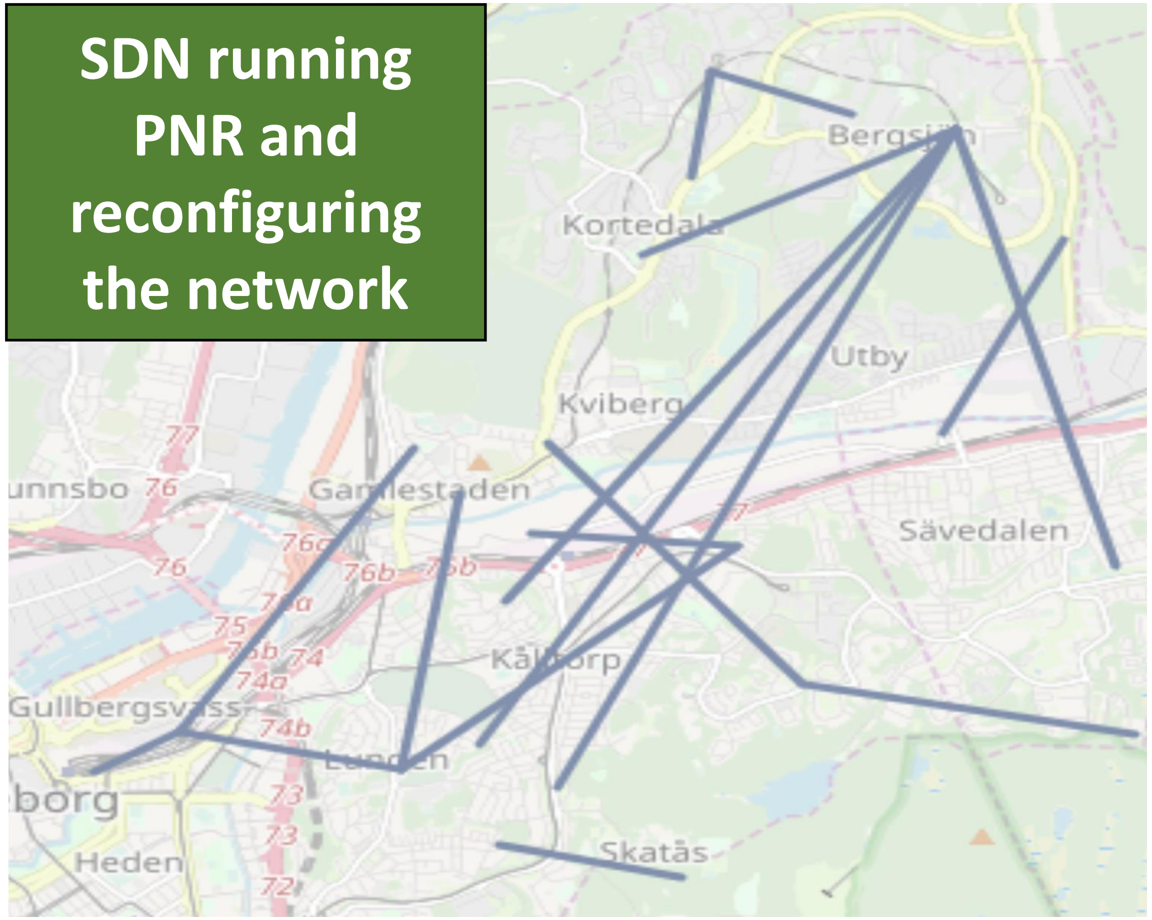
Evaluation of the AP Mechanism





Outline

SDN running PNR and reconfiguring the network



(Existing) Data Collection System

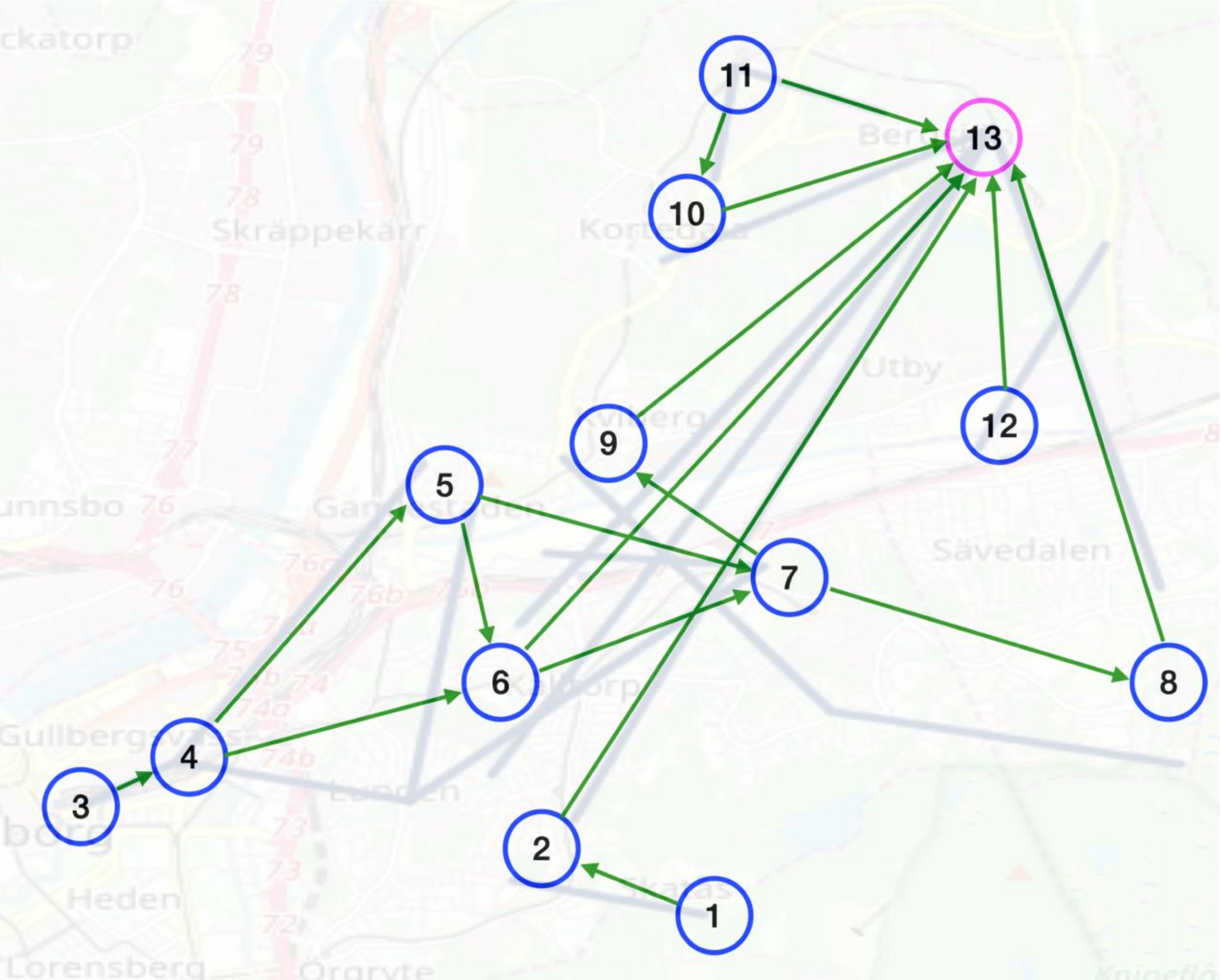
Attenuation Prediction (AP) Mechanism

Multi-Step Network Reconfiguration (MSNR) Algorithm

Evaluation of the Predictive Network Reconfiguration (PNR) framework

Network Model: Assumptions

- Neighboring link endpoints (up to 300m apart) form a Base Station (BS), also called a node
- Links are unidirectional
- Single destination BS (node $\boldsymbol{n = 13}$)
- Time is divided in time-steps with index $t \in \{1, \ldots, T\}$ and $\Delta t = 10\text{sec}$
- Admission Control and Routing decisions remain fixed between time-steps, e.g., t and $t + 1$.



Multi-Step Network Reconfiguration Problem

Goal: dynamically optimize **admission control** and **routing** decisions, i.e.:

$$\underset{\boldsymbol{z_{n,t}},\boldsymbol{f_{n,t}^{(k,l)}}}{\text{maximize}} \sum_{t=1}^{T}\sum_{n=1}^{N-1} \boldsymbol{z_{n,t}}$$

such that:

$$\sum_{n=1}^{N-1} \boldsymbol{z_{n,t}} d_n \boldsymbol{f_{n,t}^{(k,l)}} \leq min\left\{c_t^{(k,l)}, \hat{c}_{t+1}^{(k,l)}\right\}, \forall (k,l) \in E, \forall t$$

$$\sum_{k=1}^{N} \boldsymbol{f_{n,t}^{(k,l)}} + \mathbb{I}_{\{l=n\}} = \sum_{m=1}^{N} \boldsymbol{f_{n,t}^{(l,m)}} + \mathbb{I}_{\{l=N\}}, \forall n \in V, \forall l \in V, \forall t$$

while guaranteeing that, **at every time-step t**, the selected $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$:

- achieves **max-min fairness** among the BSs sharing the network
- can be implemented **without inducing transient congestion**

Multi-Step Network Reconfiguration Problem

Max-min fairness: in order to maintain feasibility, ↑ $\boldsymbol{z_{n,t}}$ necessarily results in ↓ $\boldsymbol{z_{m,t}}$ for which $\boldsymbol{z_{m,t}} \leq \boldsymbol{z_{n,t}}$.

Transient congestion occurs when going from $\left\{\boldsymbol{z_{n,t-1}}, \boldsymbol{f_{n,t-1}^{(k,l)}}\right\}$ to $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$ results in the **violation of the capacity constraint of at least one link**.

while guaranteeing that, **at every time-step $\boldsymbol{t}$**, the selected $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$:

- achieves **max-min fairness** among the BSs sharing the network
- can be implemented **without inducing transient congestion**

Known **Solution** to the Static Single-Step Problem

Goal: for a fixed t, optimize **admission control** and **routing** decisions, i.e.:

$$\underset{\boldsymbol{z_{n,t}},\boldsymbol{f_{n,t}^{(k,l)}}}{\text{maximize}} \sum_{n=1}^{N-1} \boldsymbol{z_{n,t}}$$

such that:

$$\sum_{n=1}^{N-1} \boldsymbol{z_{n,t}} d_n \boldsymbol{f_{n,t}^{(k,l)}} \leq c_t^{(k,l)}, \forall (k,l) \in E$$

$$\sum_{k=1}^{N} \boldsymbol{f_{n,t}^{(k,l)}} - \sum_{m=1}^{N} \boldsymbol{f_{n,t}^{(l,m)}} = \mathbb{I}_{\{l=N\}} - \mathbb{I}_{\{l=n\}}, \forall n \in V, \forall l \in V$$

while guaranteeing that, the selected $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$:

- achieves **max-min fairness** among the BSs sharing the network

[2] M. Allalouf and Y. Shavitt. 2008. Centralized and distributed algorithms for routing and weighted max-min fair bandwidth allocation. *IEEE Trans. Netw. Service Manag.* 16, 5 (2008), 1015–1024.

[49] F. Shahrokhi and D. Matula. 1990. The maximum concurrent flow problem. *Journal of the ACM* 37, 2 (1990), 318–334.

Known **Solution** to the Static Single-Step Problem

Intuition of the solution [2,49] to the Maximum Concurrent Multi-Commodity Flow Problem:

- Iterative progressive filling ($\boldsymbol{z_{n,t}} \leftarrow \boldsymbol{z}$ for all unsaturated) & saturation test.

Potential Multi-Step Solution: at every time t, given the measured $c_t^{(k,l)}$, use the algorithm in [2] to obtain $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$.

Main Challenges:

- Reactive reconfiguration → Reconfigure after impairment
- Transient congestion

[2] M. Allalouf and Y. Shavitt. 2008. Centralized and distributed algorithms for routing and weighted max-min fair bandwidth allocation. *IEEE Trans. Netw. Service Manag.* 16, 5 (2008), 1015–1024.
[49] F. Shahrokhi and D. Matula. 1990. The maximum concurrent flow problem. *Journal of the ACM* 37, 2 (1990), 318–334.

Proposed Multi-Step Algorithm: Key Elements

Cost of re-routing:

- to **guarantee zero transient congestion**, the SDN needs **scratch capacity**.
- at time t, when **not planning** to re-route at $t+1$, the optimization should use the constraint : $\sum_{n=1}^{N-1} \boldsymbol{z_{n,t}} d_n \boldsymbol{f_{n,t}^{(k,l)}} \leq min\left\{c_t^{(k,l)}, \hat{c}_{t+1}^{(k,l)}\right\}, \forall (k,l) \in E$
- at time t, when **planning** to re-route at $t+1$, the optimization should use the constraint: $\sum_{n=1}^{N-1} \boldsymbol{z_{n,t}} d_n \boldsymbol{f_{n,t}^{(k,l)}} \leq min\left\{c_t^{(k,l)}, \underbrace{(\boldsymbol{1}-\boldsymbol{s})}_{\text{Cost of re-routing}}\hat{c}_{t+1}^{(k,l)}\right\}, \forall (k,l) \in E$

Proposed Multi-Step Algorithm: Key Elements

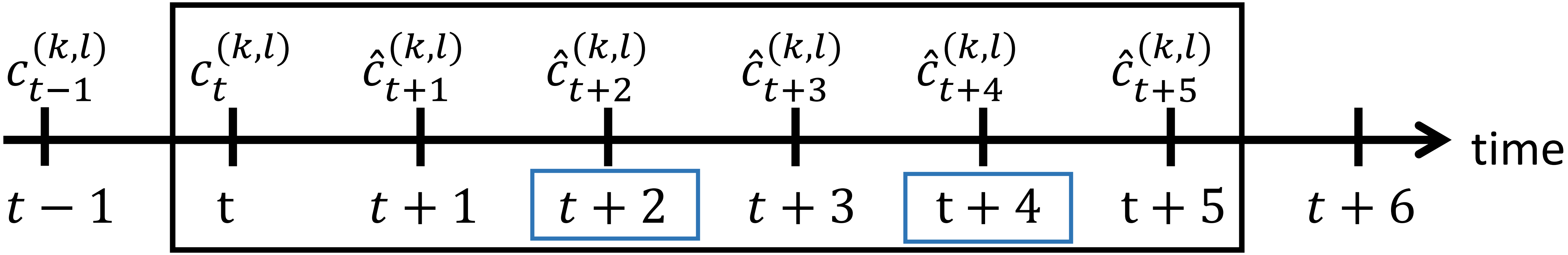
Joint Optimization over Multiple Time-Steps:

- Input: measured and predicted capacities $\{c_t^{(k,l)}, \hat{c}_{t+1}^{(k,l)}, \dots, \hat{c}_{t+H}^{(k,l)}\}$
- Output: sequence of $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$ that maximizes $\sum_{h=0}^{H} \sum_{n=1}^{N-1} \boldsymbol{z_{n,t+h}}$

Proposed Multi-Step Algorithm: Key Elements

Joint Optimization over Multiple Time-Steps:

- Input: measured and predicted capacities $\{c_t^{(k,l)}, \hat{c}_{t+1}^{(k,l)}, \ldots, \hat{c}_{t+H}^{(k,l)}\}$
- Output: sequence of $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$ that maximizes $\sum_{h=0}^{H}\sum_{n=1}^{N-1}\boldsymbol{z_{n,t+h}}$
- MPC-based solution: consider every possible "**re-routing plan**" and select the plan that maximizes $\sum_{h=0}^{H}\sum_{n=1}^{N-1}\boldsymbol{z_{n,t+h}}$. There are $\geq 2^H$ possible plans.
- One of these plans is illustrated below for $H = 5$:

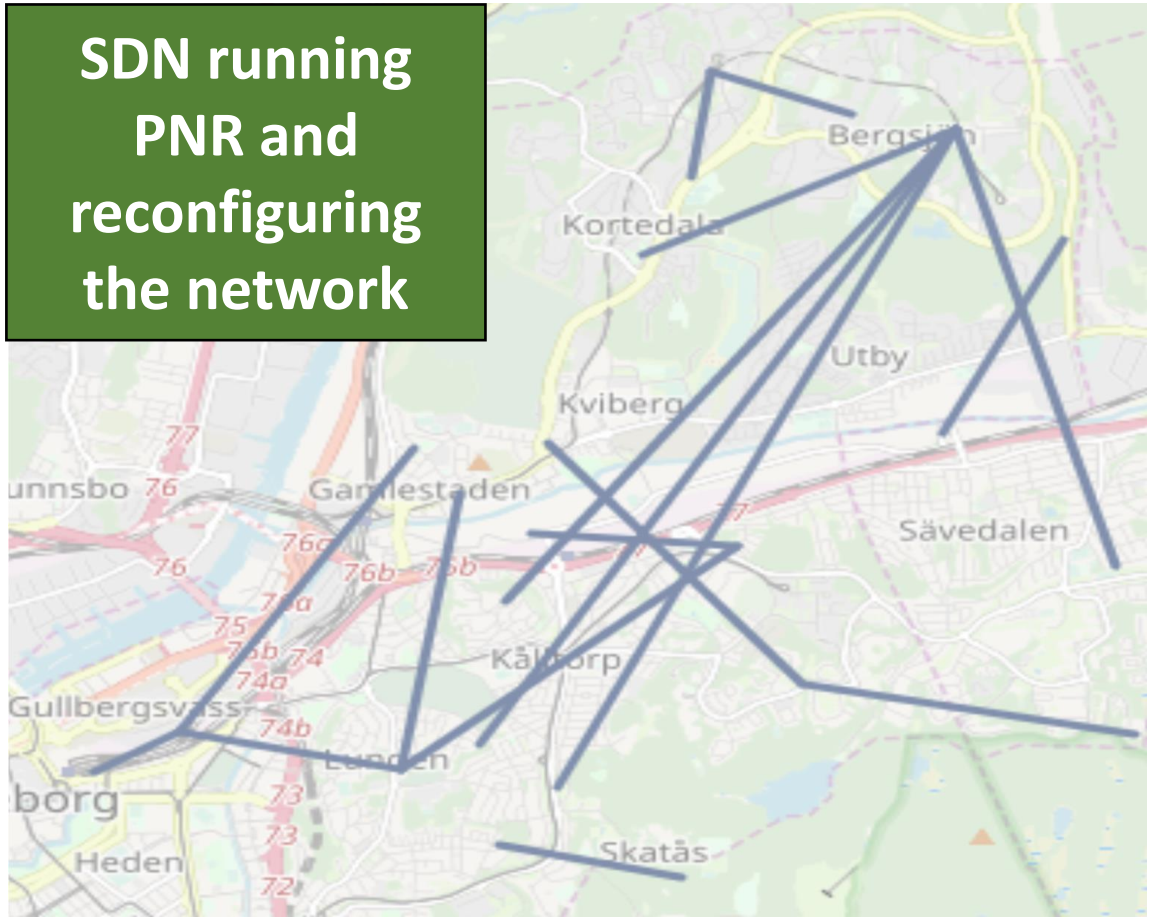


Proposed Multi-Step Algorithm: Key Elements

Joint Optimization over Multiple Time-Steps:

- Input: measured and predicted capacities $\{c_t^{(k,l)}, \hat{c}_{t+1}^{(k,l)}, \dots, \hat{c}_{t+H}^{(k,l)}\}$
- Output: sequence of $\left\{\boldsymbol{z_{n,t}}, \boldsymbol{f_{n,t}^{(k,l)}}\right\}$ that maximizes $\sum_{h=0}^{H}\sum_{n=1}^{N-1}\boldsymbol{z_{n,t+h}}$
- MPC-based solution: consider every possible "**re-routing plan**" and select the plan that maximizes $\sum_{h=0}^{H}\sum_{n=1}^{N-1}\boldsymbol{z_{n,t+h}}$. There are $\geq 2^H$ possible plans.
- Remark: using backward induction, we can reduce complexity from $O(2^H)$ to $O(H^4)$.
- Proposition: $\left\{\boldsymbol{z_{n,t+h}}, \boldsymbol{f_{n,t+h}^{(k,l)}}\right\}$ is max-min fair $\forall h$

Outline



SDN running PNR and reconfiguring the network

(Existing) Data Collection System

Attenuation Prediction (AP) Mechanism

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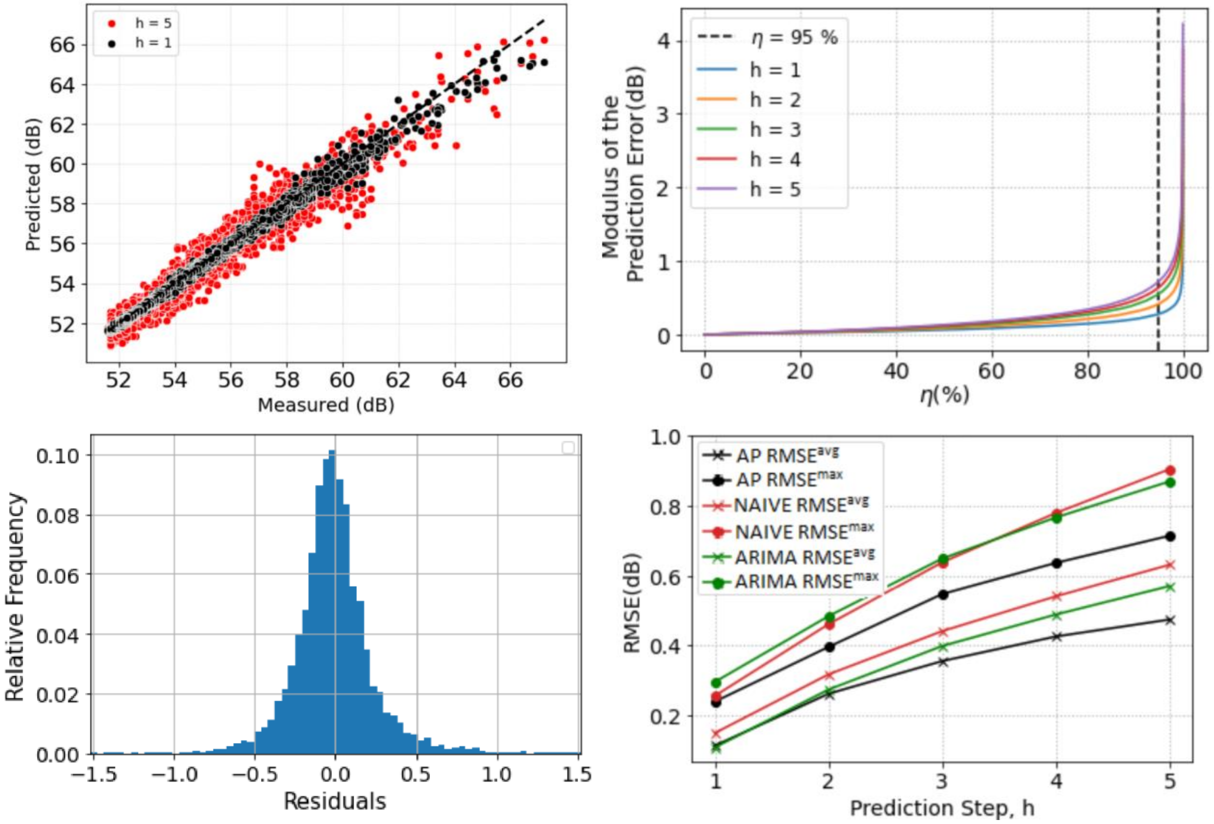
Evaluation of the Predictive Network Reconfiguration (PNR) framework

Performance Evaluation

Attenuation Prediction

- Comparison with Naïve and ARIMA



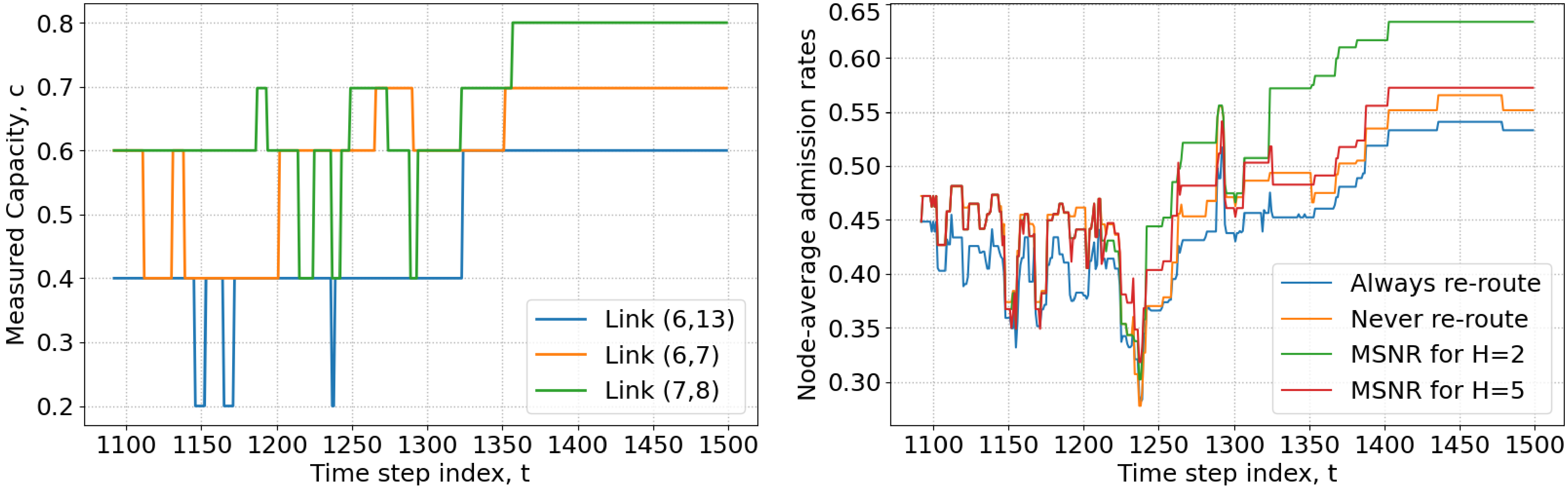
Predictive Network Reconfiguration

- Comparison with two reactive reconfiguration algorithms:
    - Always re-route with Adm Ctrl
    - Never re-route with Adm Ctrl
- Small network with synthetic data and tunable accuracy of attenuation predictions.
- **Large network with measurements is discussed in the next slides…**

Evaluation of PNR using measurements

Challenging scenario with a period of high $c_t^{(k,l)}$ variability due to a rain event.

Node-average admission rates are given by: $\sum_{n=1}^{N-1} z_{n,t} \,/(N-1)$



Evaluation of PNR using measurements

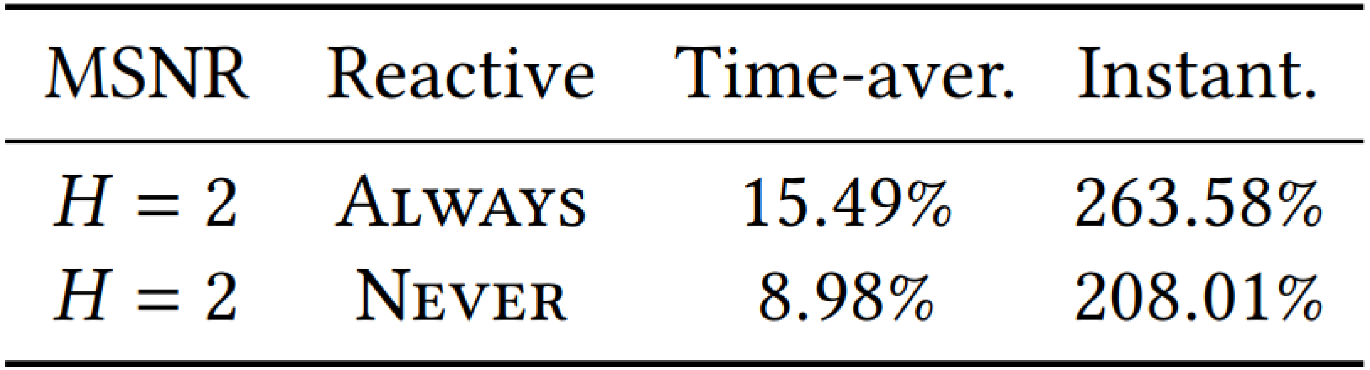
Challenging scenario with a period of high $c_t^{(k,l)}$ variability due to a rain event.

Time-average performance gain

$$\frac{\sum_{t=1}^{T}\sum_{n=1}^{N-1}\left(z_{n,t}^{MSNR} - z_{n,t}^{React}\right)}{\sum_{t=1}^{T}\sum_{n=1}^{N-1} z_{n,t}^{React}}$$

Max. Instant. performance gain

$$\max_{n,t}\left(\frac{z_{n,t}^{MSNR} - z_{n,t}^{React}}{z_{n,t}^{React}}\right)$$



MSNR	Reactive	Time-aver.	Instant.
$H = 2$	ALWAYS	15.49%	263.58%
$H = 2$	NEVER	8.98%	208.01%

Summary

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ERICSSON

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(Existing) Data Collection System

Attenuation Prediction (AP) Mechanism

(Existing) Adaptive Modulation Mechanism

Multi-Step Network Reconfiguration (MSNR) Algorithm

Evaluation of the Predictive Network Reconfiguration (PNR) framework