Time Synchronization for Large-Scale Mobile Optical Fiber Networks

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Project

- **Collaborative Project:** Time Delay Detection in Large-Scale Mobile Backhaul Networks
- **Collaborator:** Huawei (the 2023 Huawei Spark Award)

Mobile Communications

Mobile Optical Fiber Networks

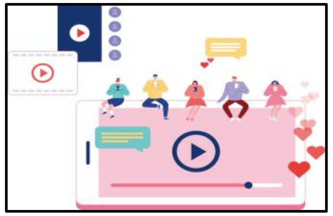
➢ Diverse Applications

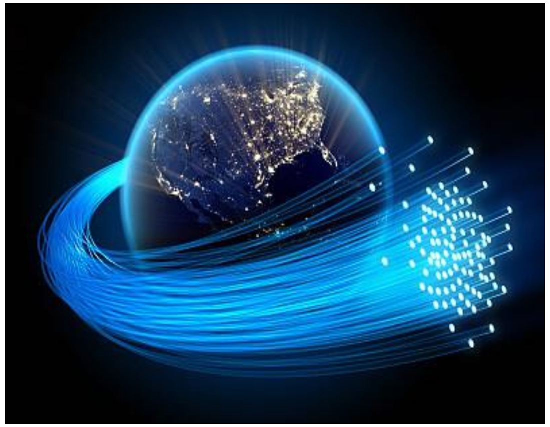
- Mobile Communication
- Online Meeting/Game
- High-Frequency Trading
- Intelligent Transportation System
- Video On Demand
- …

Mobile Optical Fiber Networks

Mobile Optical Fiber Networks

Time accuracy across exchanges





Alignment of both parties' time

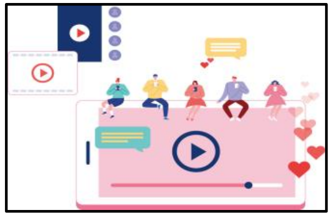
Mobile Optical Fiber Networks

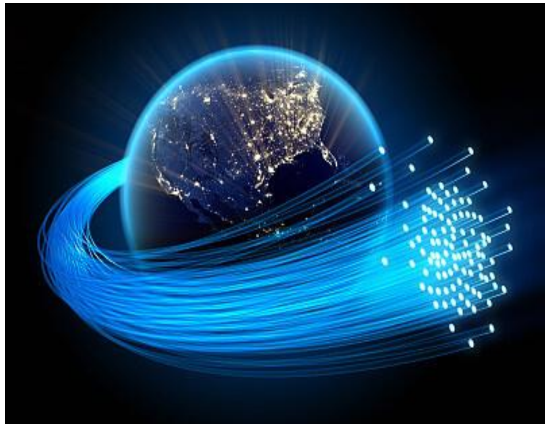
Mobile Optical Fiber Networks

Time Synchronization

Time accuracy across exchanges

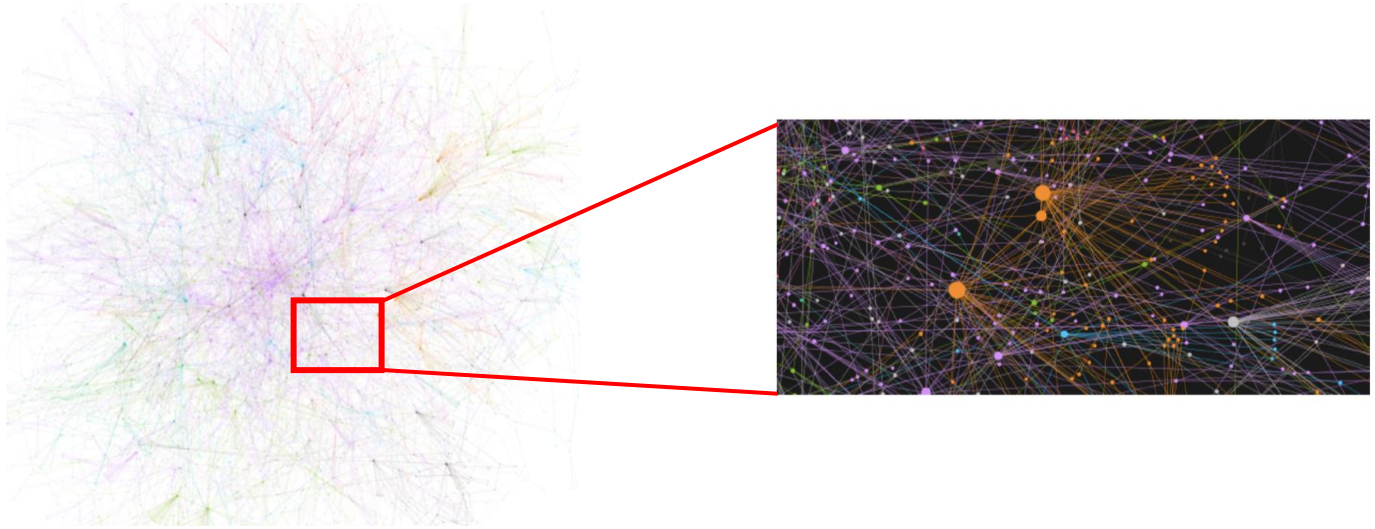
Alignment of both parties' time





Mobile Optical Fiber Networks

- **Large Scale Network**
  - Numerous Nodes



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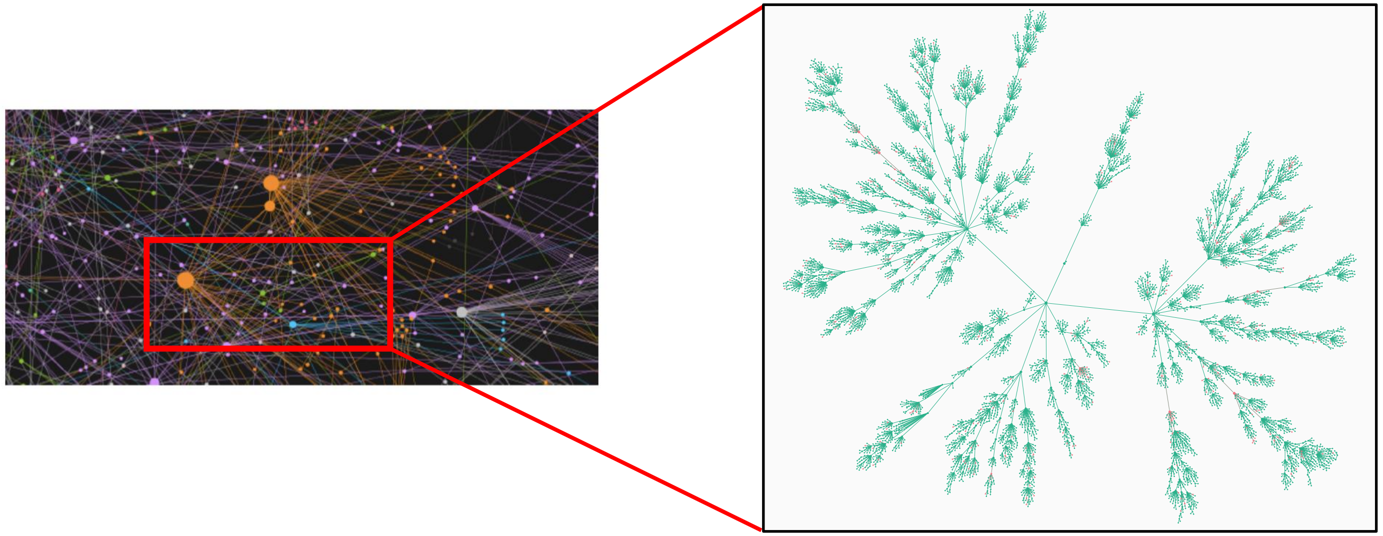
The Characteristic of Mobile Optical Fiber Networks

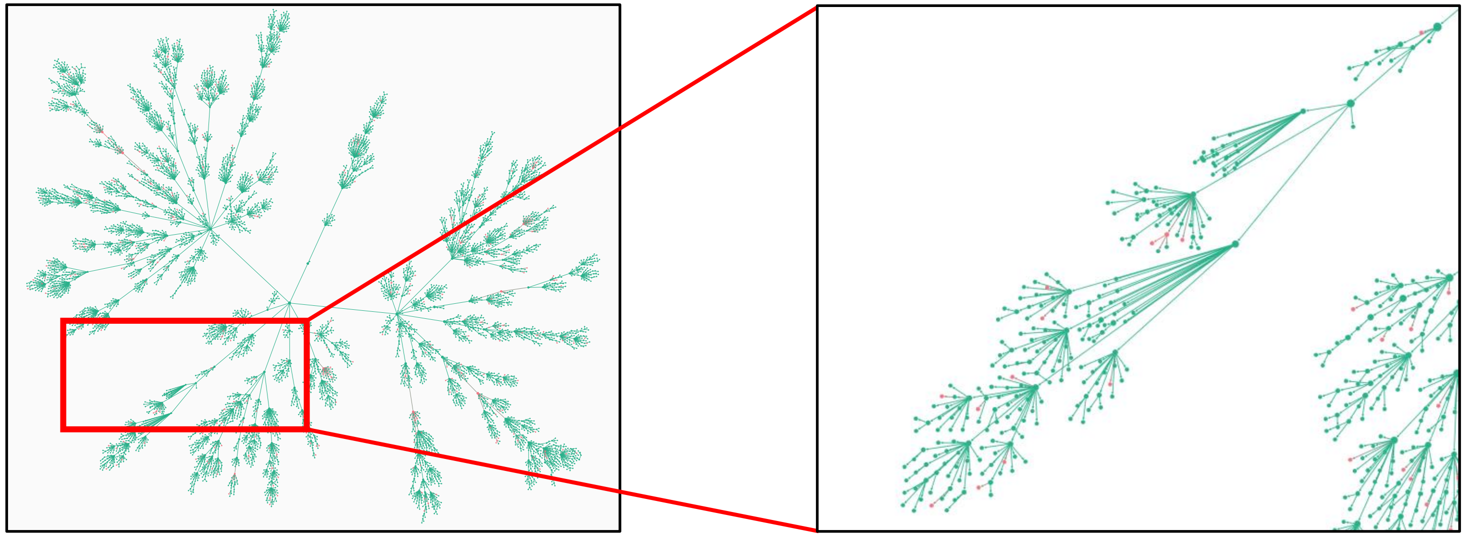
➢ Large Scale Network

- Numerous Nodes
  - Complex Structure



The Characteristic of Mobile Optical Fiber Networks

- Large Scale Network
  - Numerous Nodes
    - Complex Structure
      - Tree Topology



➢ Large Scale Network

- Numerous Nodes
  - Complex Structure
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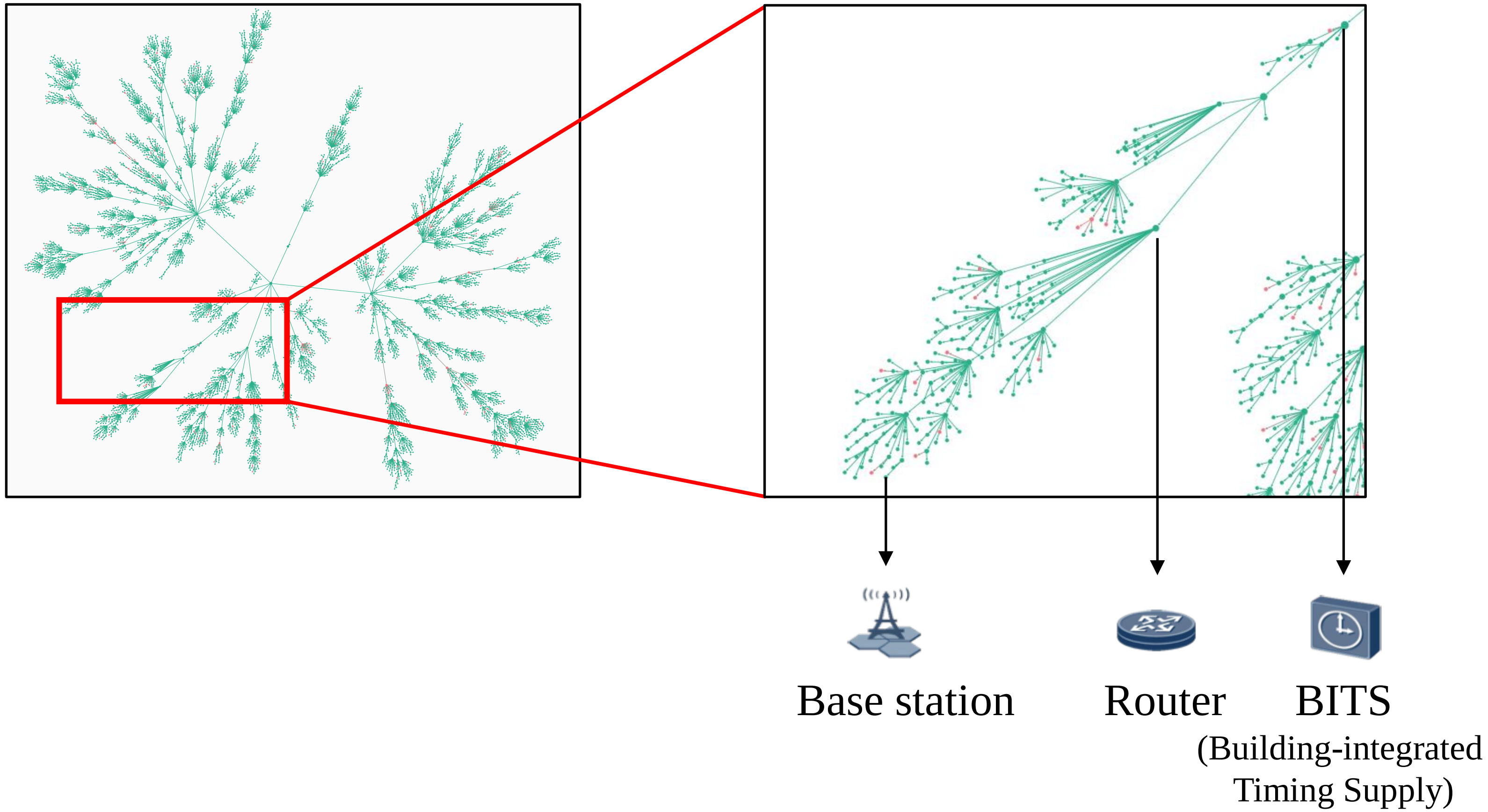
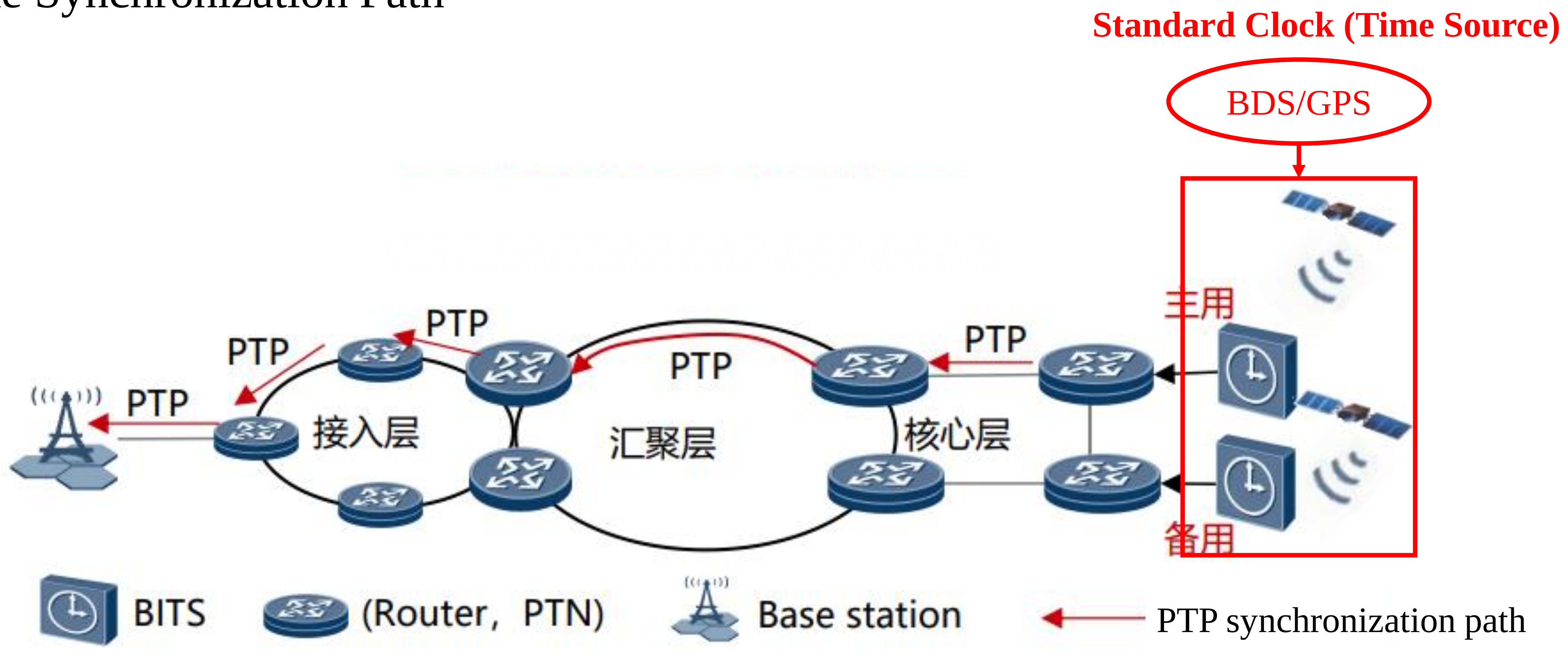


- PTP Time Synchronization Path



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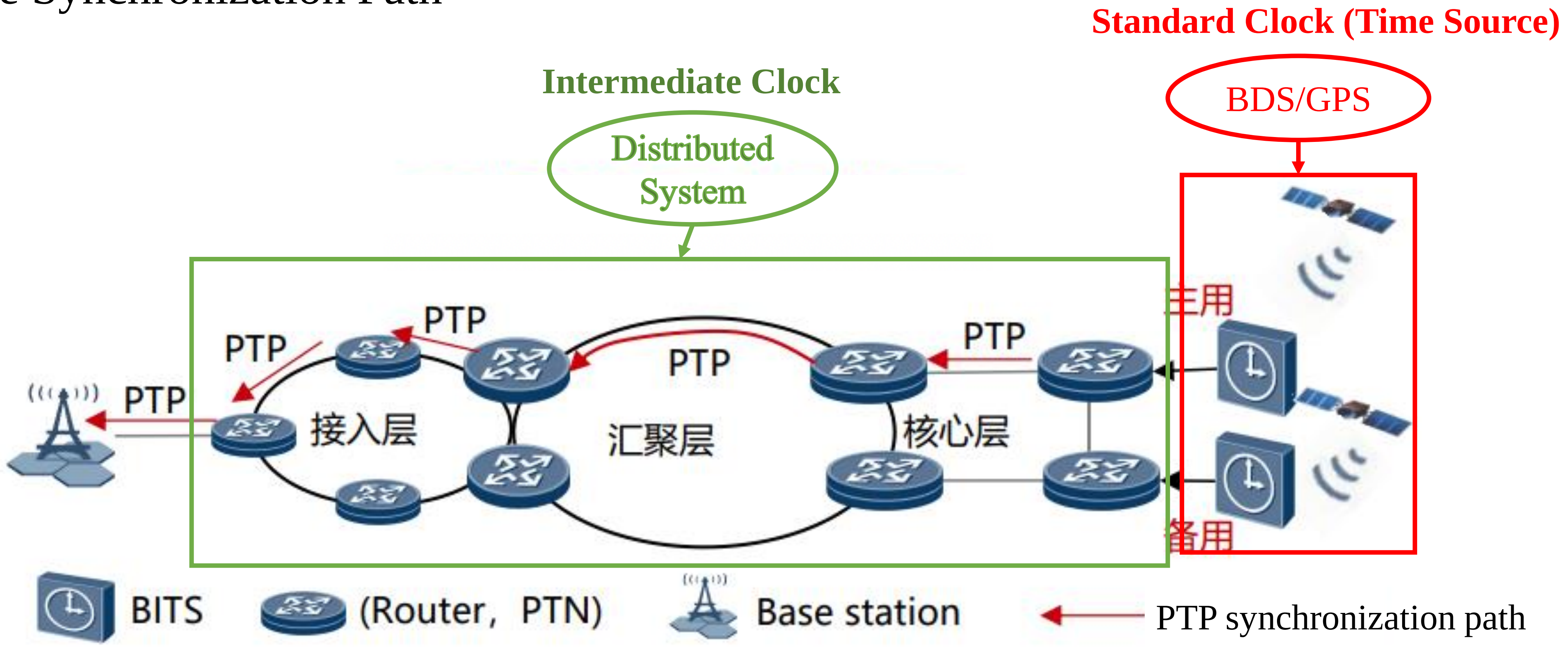
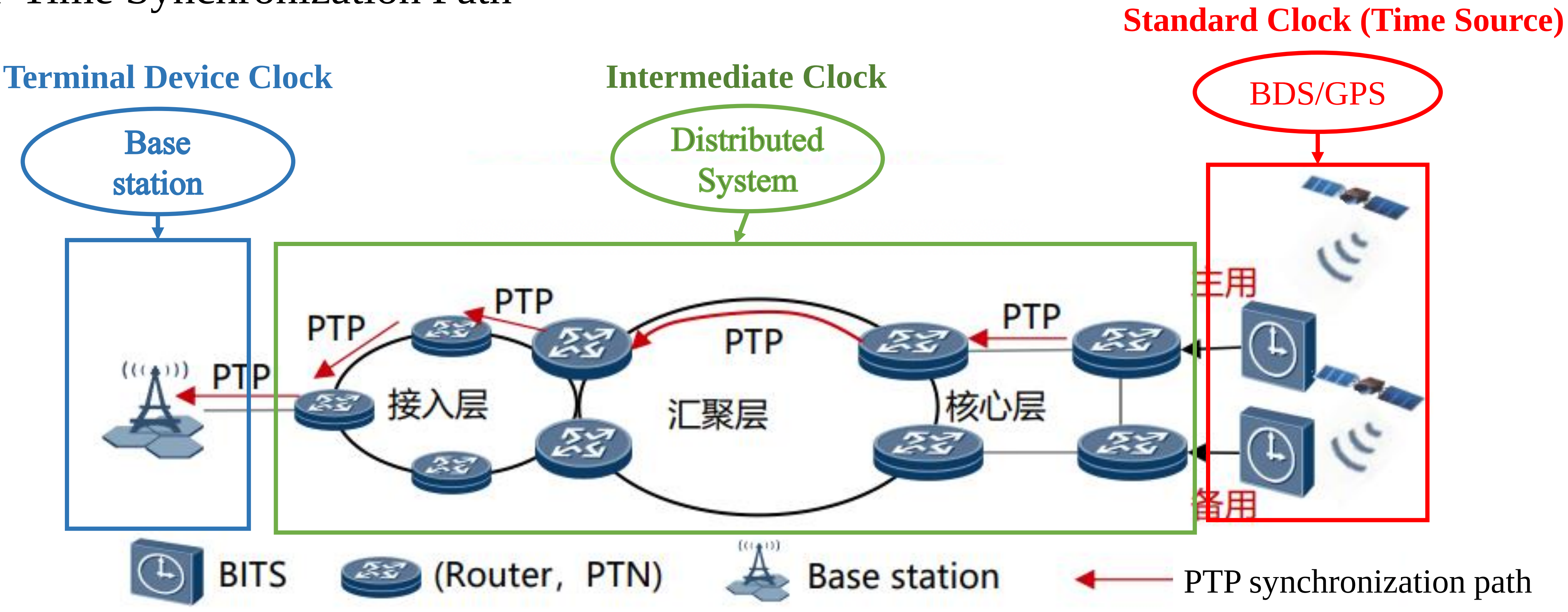


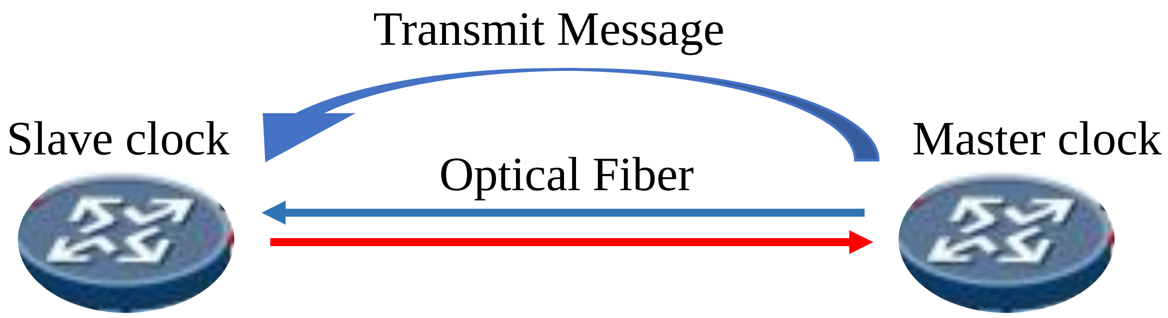
Precision Time Protocol (PTP)

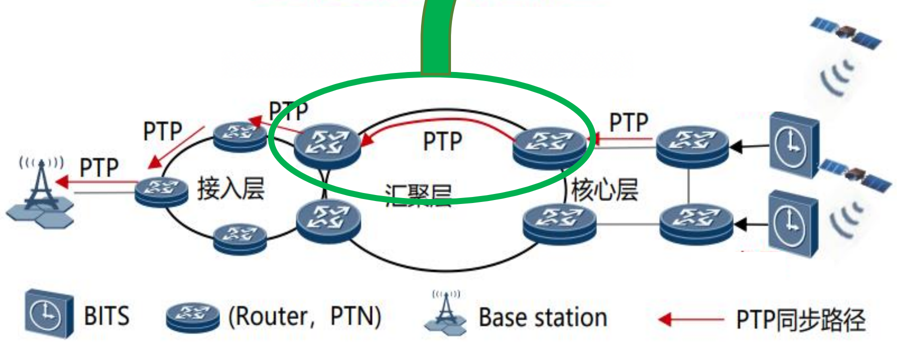
- PTP Time Synchronization Path



The Principal of PTP Time Synchronization

- Step 1: Transmit Message





$$T_2 - T_1 = \alpha_1 + \theta$$

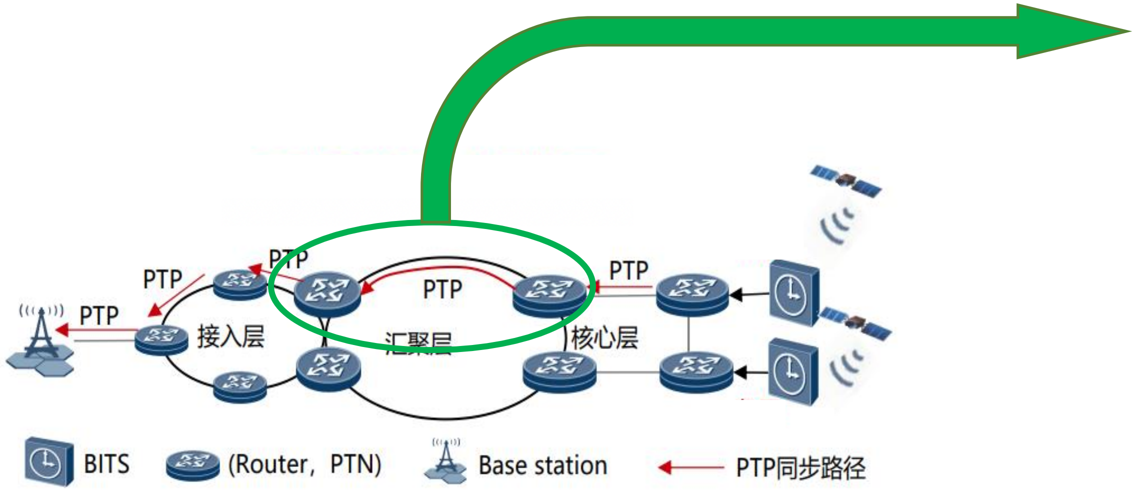
T_2: Reception Time

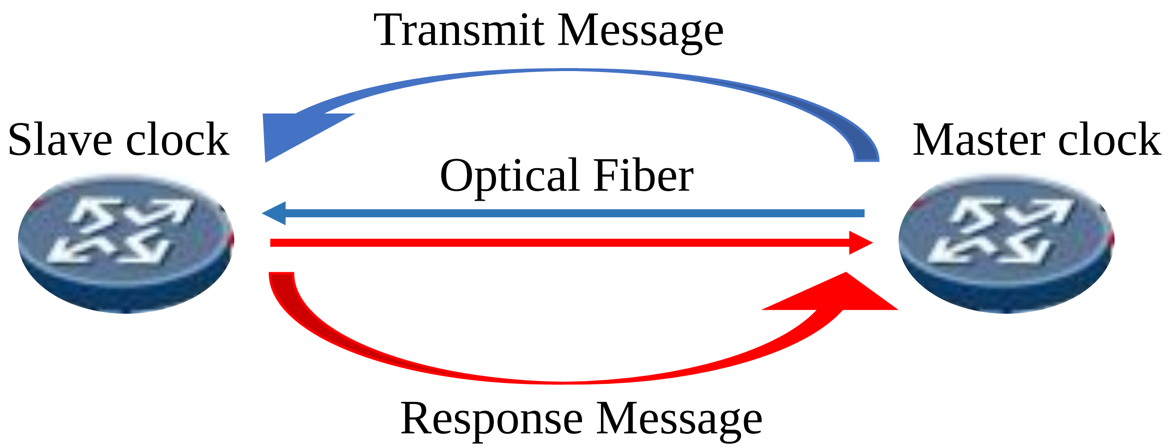
T_1: Transmission Time

α_1: Time Delay

θ: Offset

- Step 2: Reply Response Message





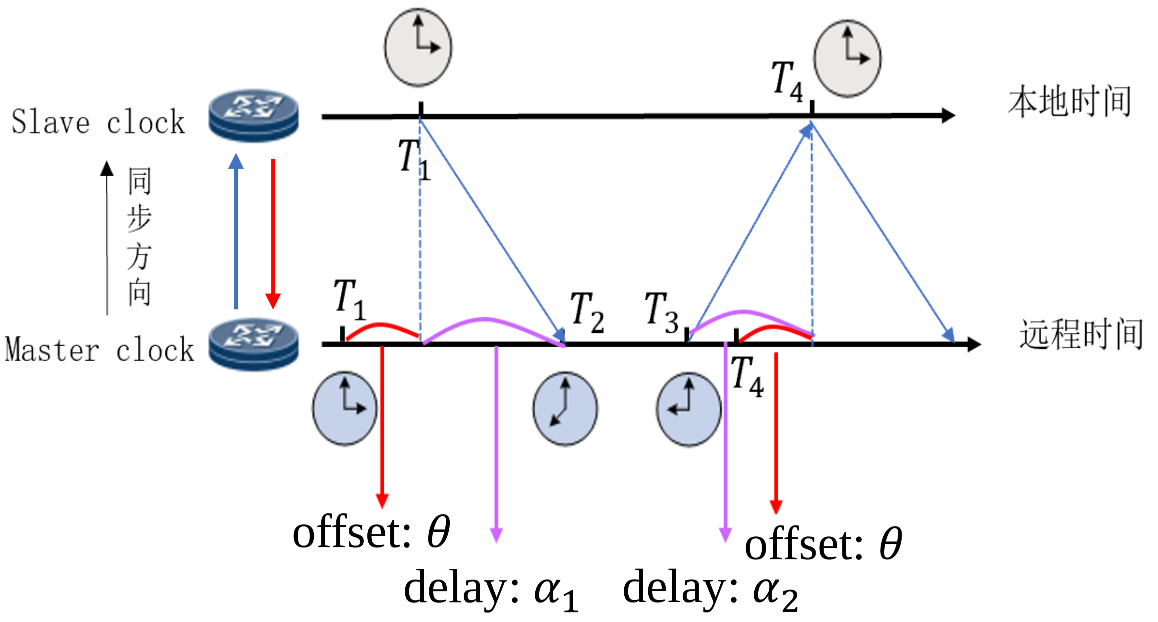
$$\mathrm{T}_4 - T_3 = \alpha_2 - \theta$$

T_4: Reception Time	T_3: Transmission Time	α_2: Time Delay	θ: Offset

The Principal of PTP Time Synchronization

➢ Step 3: Time Correction

$$\begin{cases} T_2 - T_1 & = \alpha_1 + \theta \\ T_4 - T_3 & = \alpha_2 - \theta \end{cases}$$



a) If $\alpha_1 = \alpha_2$, the offset can be solved, i.e.

$$\theta = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}$$

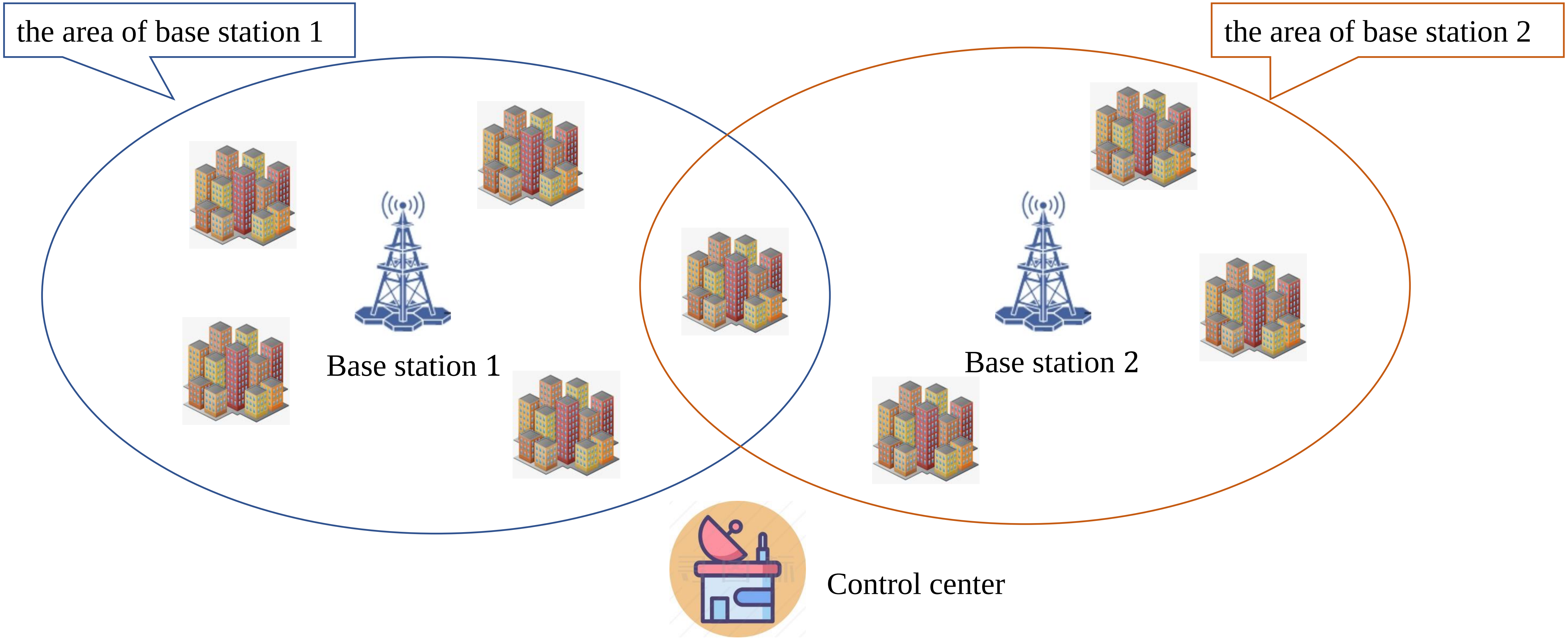
then correct the slave clock based on θ

b) If $\alpha_1 \neq \alpha_2$ (asymmetry), correction is not possible and there exists a time delay.

- Different fiber lengths
- Physical damage;
- Noise interference;

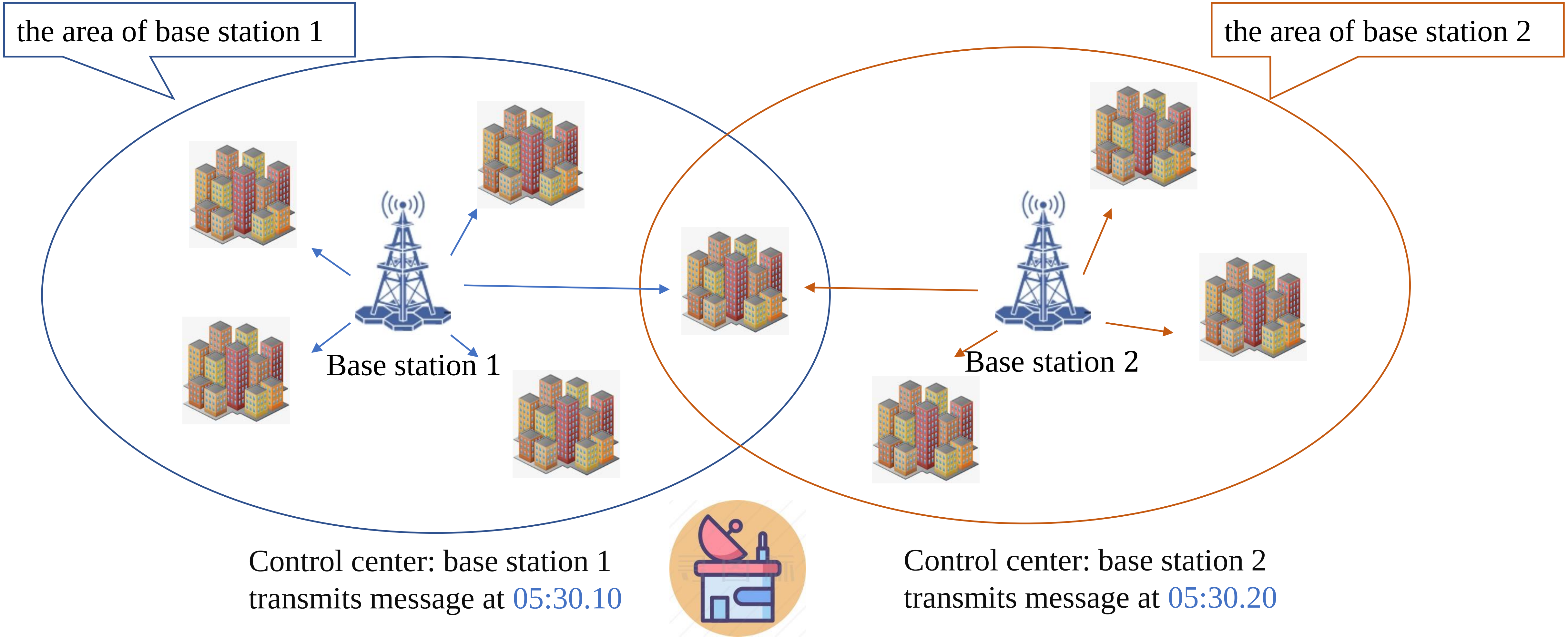
Impact of Time Delay: An example

- Control center: coordinate with base stations



Impact of Time Delay: An example

- Control center coordinates base stations to transmit at different times

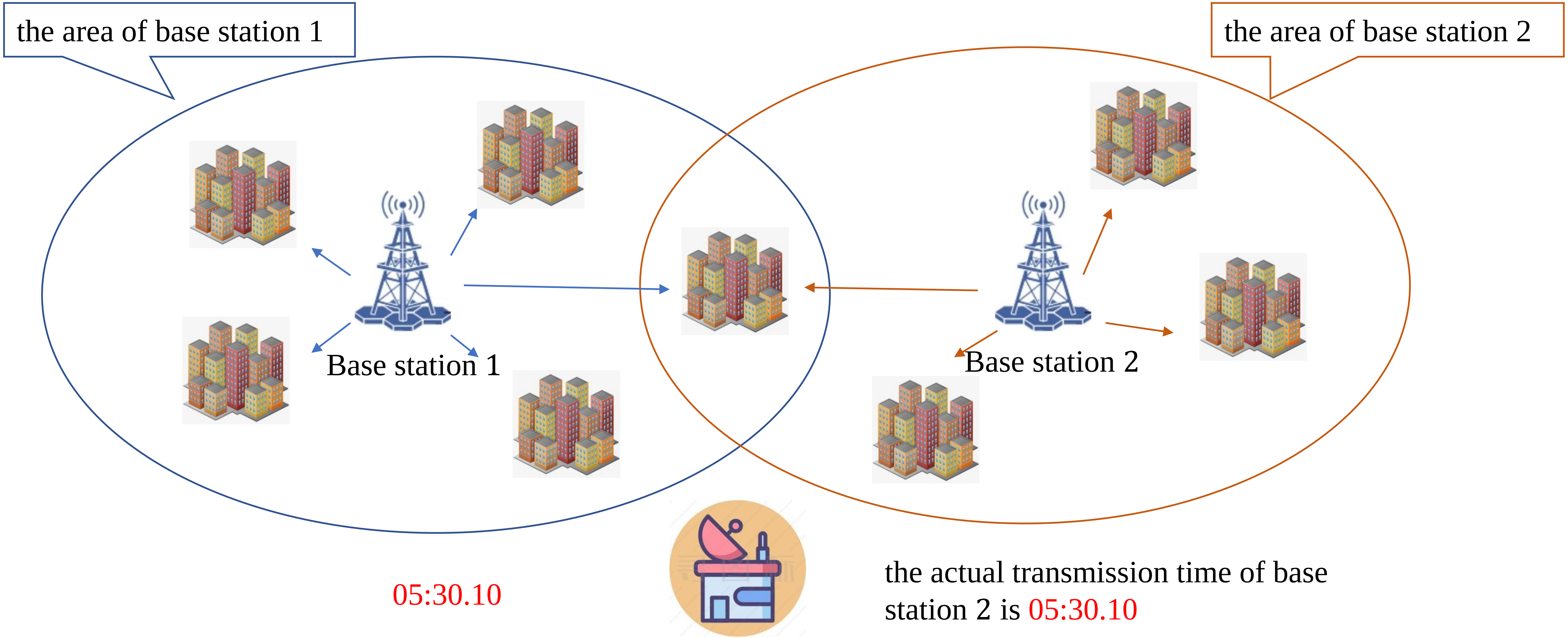


Control center: base station 1 transmits message at 05:30.10

Control center: base station 2 transmits message at 05:30.20

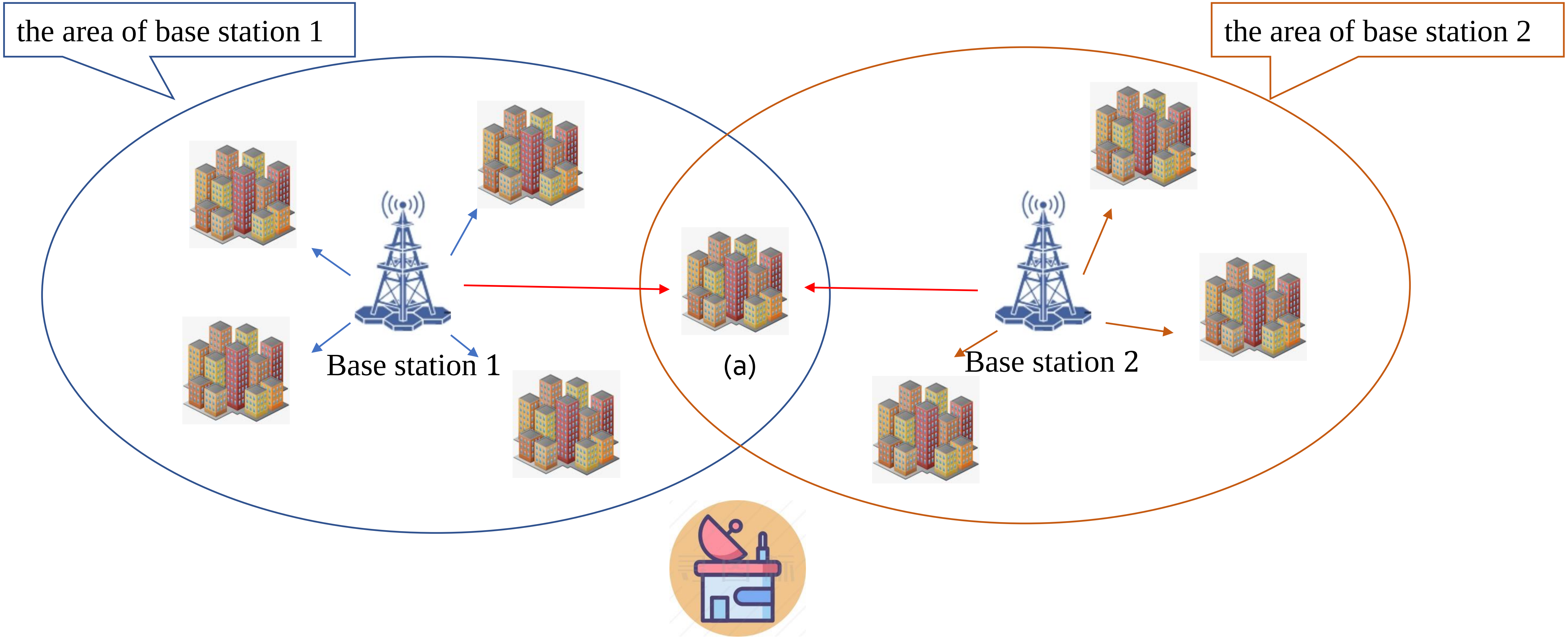
Impact of Time Delay: An example

- If base station 2 is 10 ms faster than base station 1;



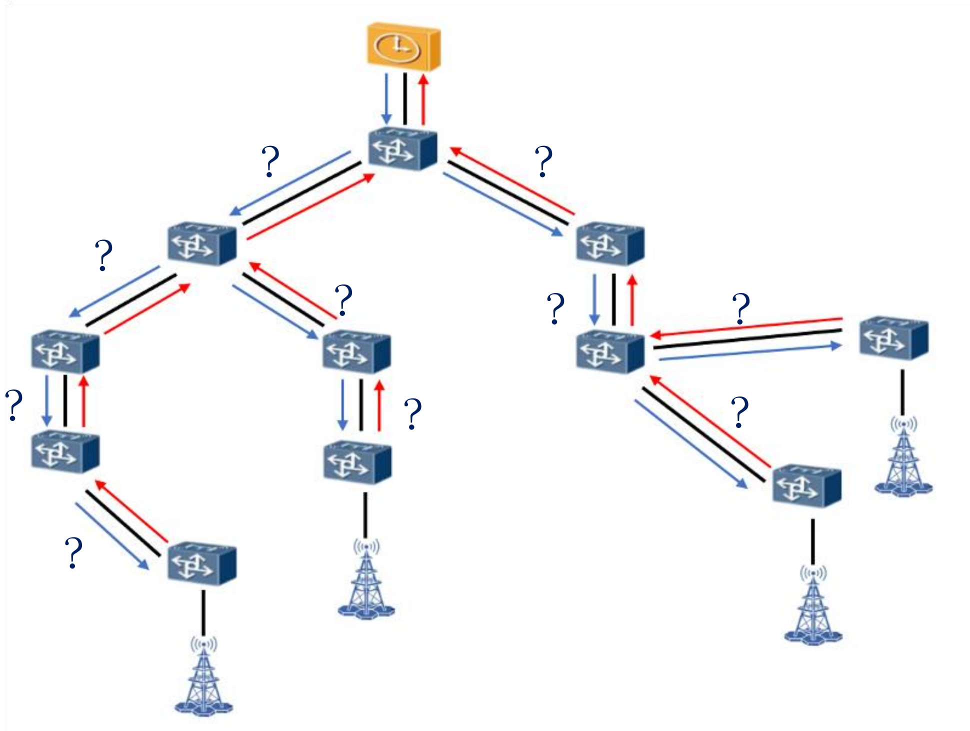
Impact of Time Delay: An example

- (a) receive two signals of the same frequency simultaneously; communication interference (e.g., noise, disruptions)



Problem

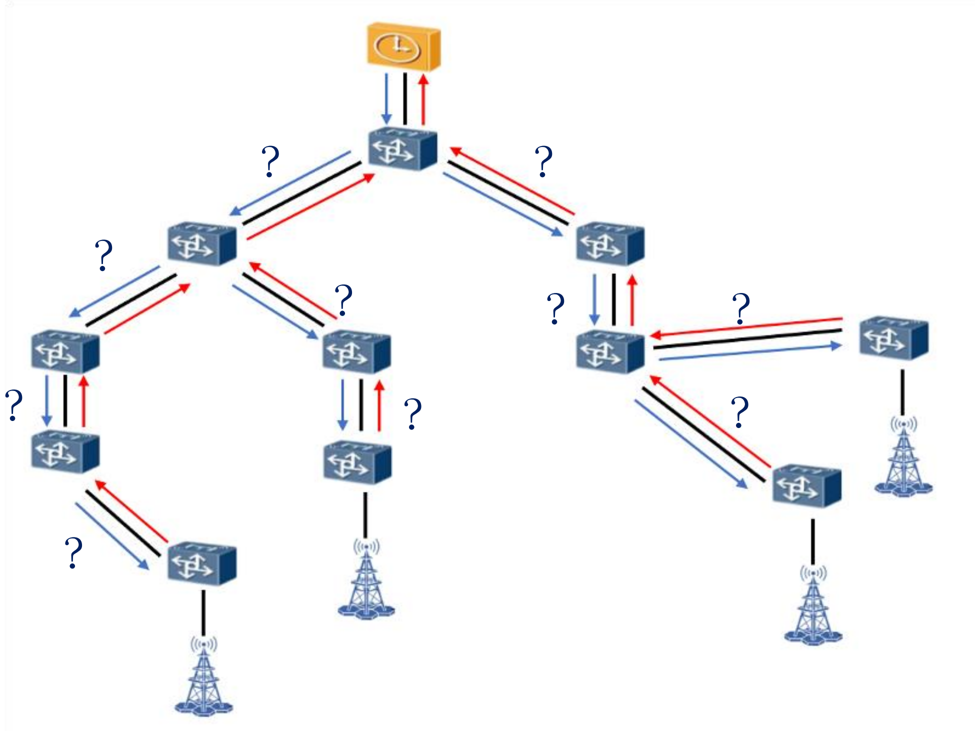
➢ How to detect the asymmetry/time delay locations?

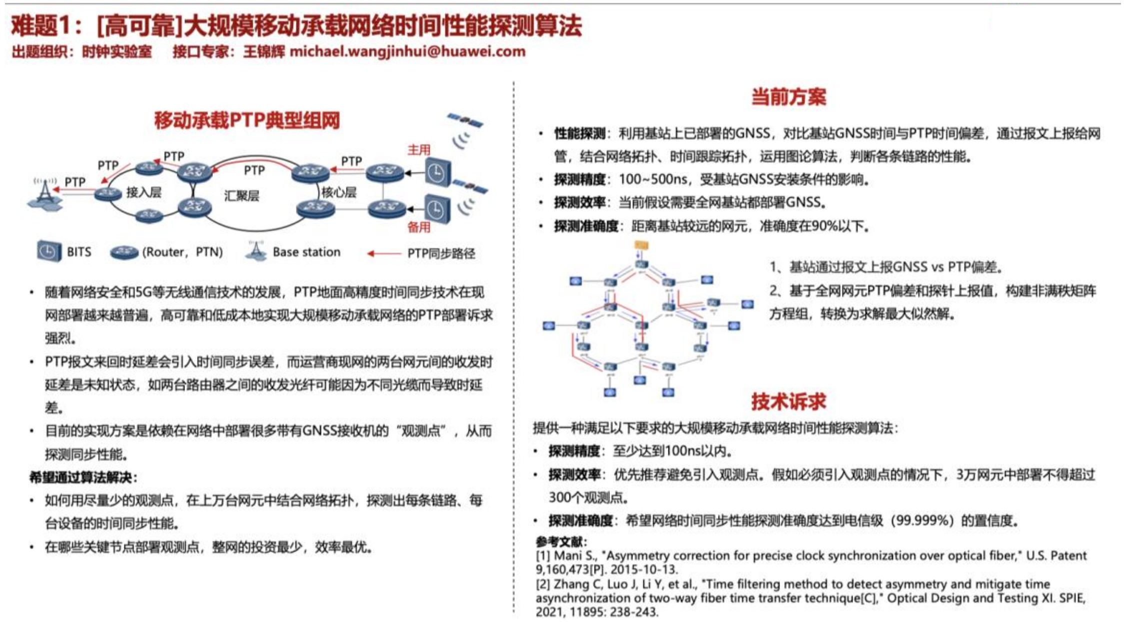


Problem

➢ How to detect the asymmetry/time delay locations?

(A challenging problem proposed by Huawei)





难题1：[高可靠]大规模移动承载网络时间性能探测算法

出题组织：时钟实验室　接口专家：王锦辉 michael.wangjinhui@huawei.com

移动承载PTP典型组网

- 随着网络安全和5G等无线通信技术的发展，PTP地面高精度时间同步技术在现网部署越来越普遍，高可靠和低成本地实现大规模移动承载网络的PTP部署诉求强烈。
- PTP报文来回时延差会引入时间同步误差，而运营商现网的两台网元间的收发时延差是未知状态，如两台路由器之间的收发光纤可能因为不同光缆而导致时延差。
- 目前的实现方案是依赖在网络中部署很多带有GNSS接收机的“观测点”，从而探测同步性能。

希望通过算法解决：

- 如何用尽量少的观测点，在上万台网元中结合网络拓扑，探测出每条链路、每台设备的时间同步性能。
- 在哪些关键节点部署观测点，整网的投资最少，效率最优。

当前方案

- **性能探测**：利用基站上已部署的GNSS，对比基站GNSS时间与PTP时间偏差，通过报文上报给网管，结合网络拓扑、时间跟踪拓扑，运用图论算法，判断各条链路的性能。
- **探测精度**：100~500ns，受基站GNSS安装条件的影响。
- **探测效率**：当前假设需要全网基站都部署GNSS。
- **探测准确度**：距离基站较远的网元，准确度在90%以下。

1、基站通过报文上报GNSS vs PTP偏差。

2、基于全网网元PTP偏差和探针上报值，构建非满秩矩阵方程组，转换为求解最大似然解。

技术诉求

提供一种满足以下要求的大规模移动承载网络时间性能探测算法：

- **探测精度**：至少达到100ns以内。
- **探测效率**：优先推荐避免引入观测点。假如必须引入观测点的情况下，3万网元中部署不得超过300个观测点。
- **探测准确度**：希望网络时间同步性能探测准确度达到电信级（99.999%）的置信度。

参考文献：

[1] Mani S., "Asymmetry correction for precise clock synchronization over optical fiber," U.S. Patent 9,160,473[P]. 2015-10-13.
[2] Zhang C, Luo J, Li Y, et al., "Time filtering method to detect asymmetry and mitigate time asynchronization of two-way fiber time transfer technique[C]," Optical Design and Testing XI. SPIE, 2021, 11895: 238-243.

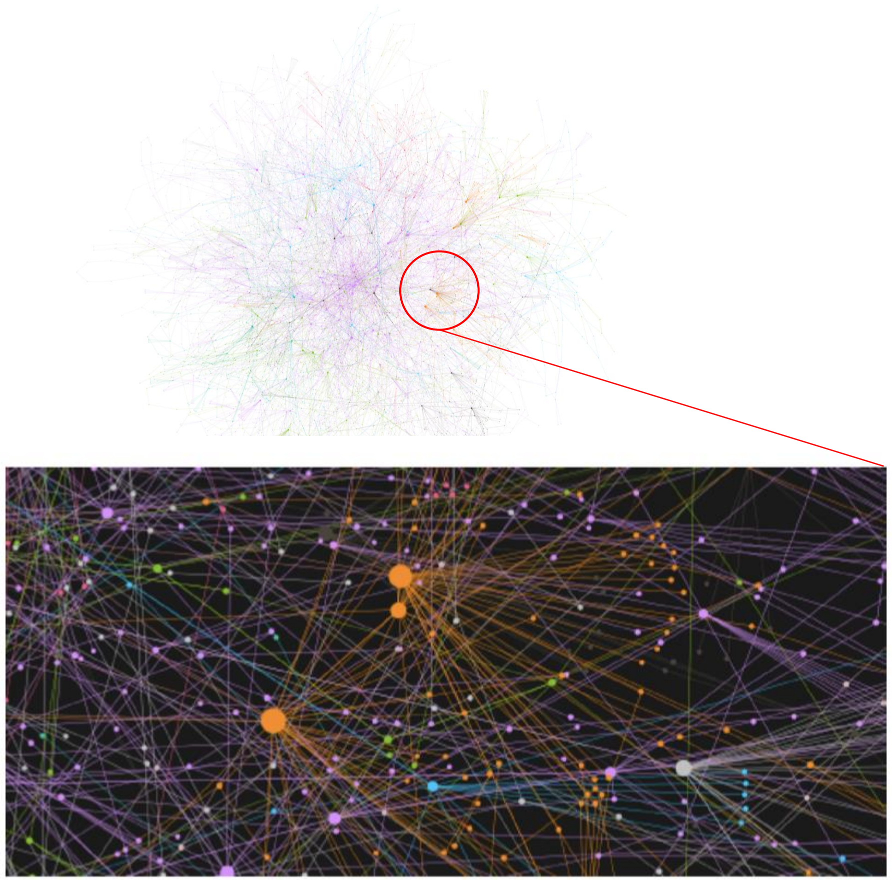
Challenges

➢ Large Scale Network

- Numerous Nodes;
- Complex Structure;
- Tree Topology;

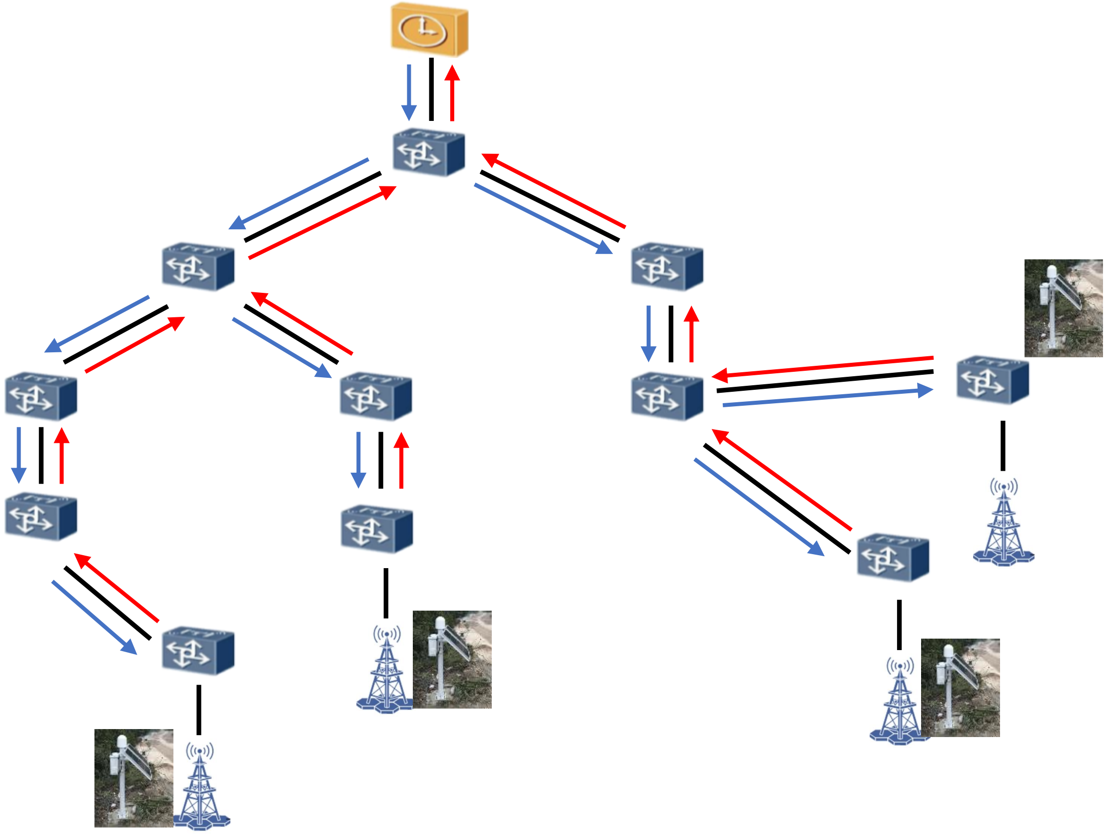
➢ Sparse Asymmetry Delay

- Only 1% to 10% of fibers exhibit significant asymmetry delay.



Mobile Optical Fiber Network

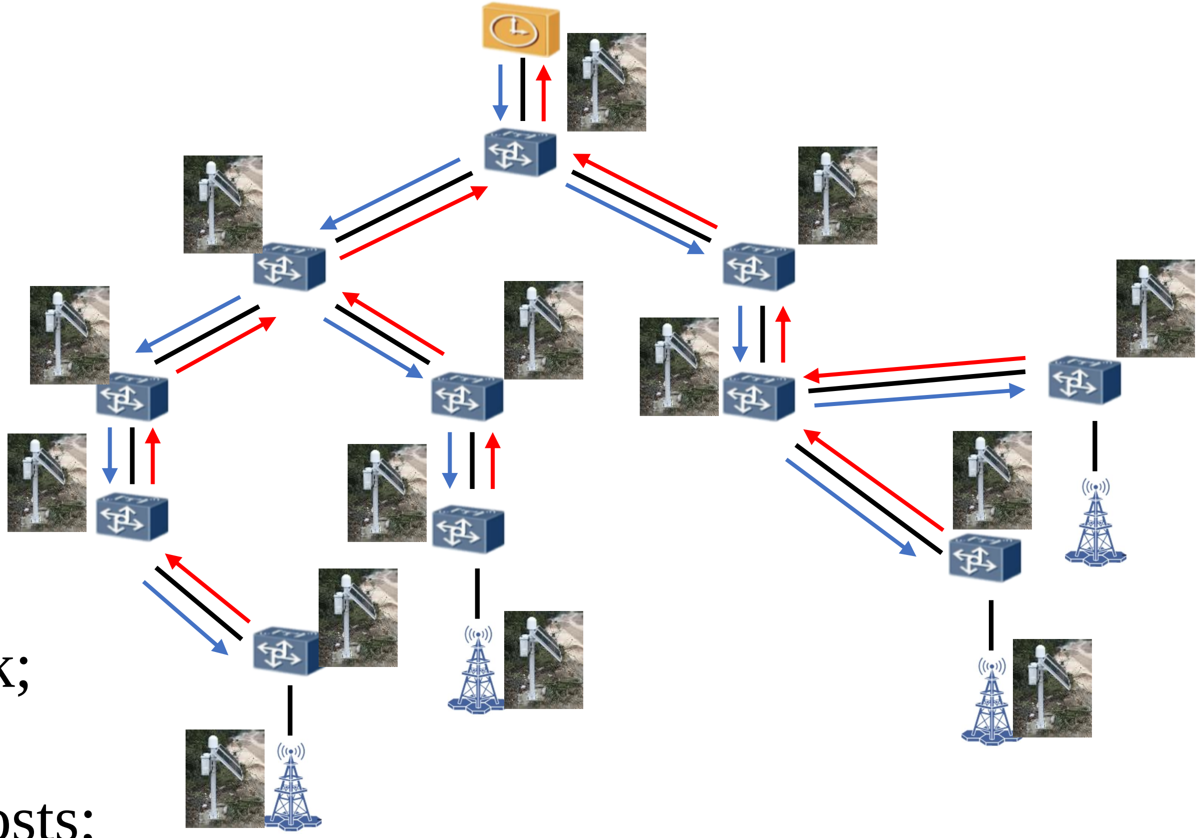
- Existing methods:
  - Cumulative time delay-based correction;
    - Disadvantage: lower accuracy;



GNSS: Global Navigation Satellite System

Existing Methods

- Existing methods:
  - Cumulative time delay-based correction;
    - Disadvantage: lower accuracy;
  - GNSS receivers
    - precision timing through receiving satellite signals
    - deploy GNSS across the whole network;
    - Disadvantages:
      - high equipment and maintenance costs;
      - environmental constraints;



GNSS: Global Navigation Satellite System

- **Task:**

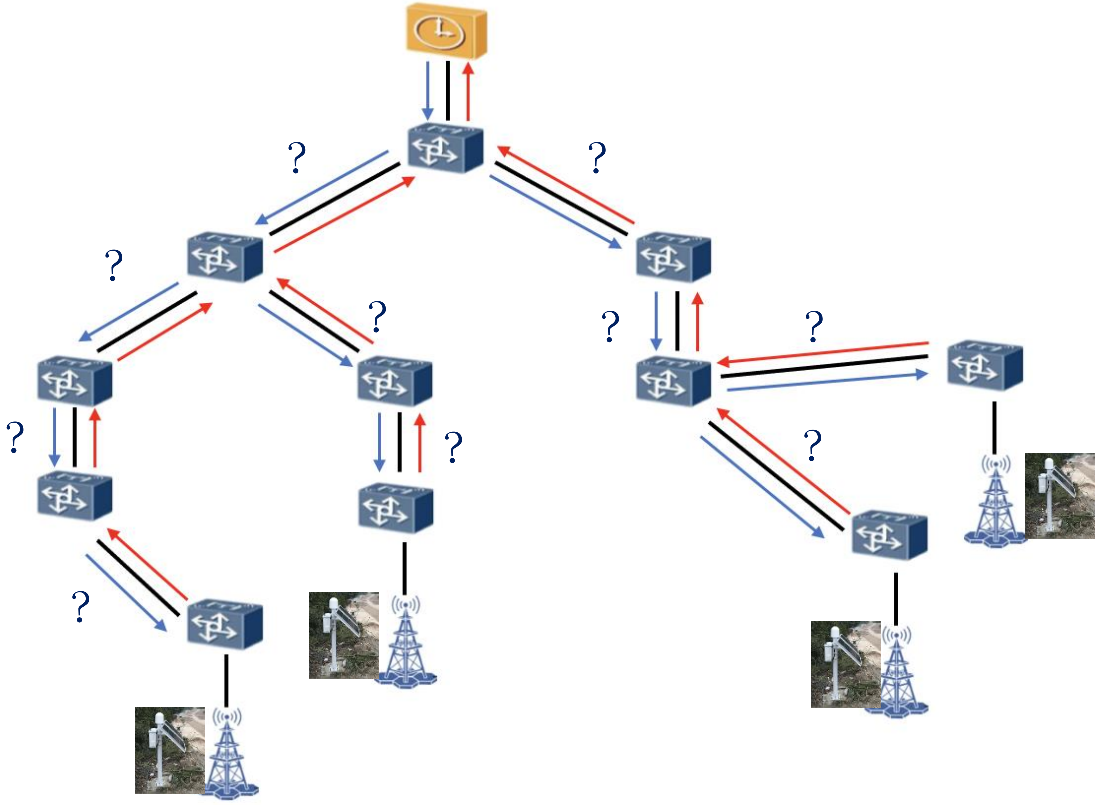
  Ensuring the accuracy of time delay detection with base station GNSS deployment;

- **Methodolgy:**

  Modeling as the Large-scale Sparse System of Linear Equations Solving Problem;

- **Result:**

  Accuracy 100% (perfect solution!)



① Background

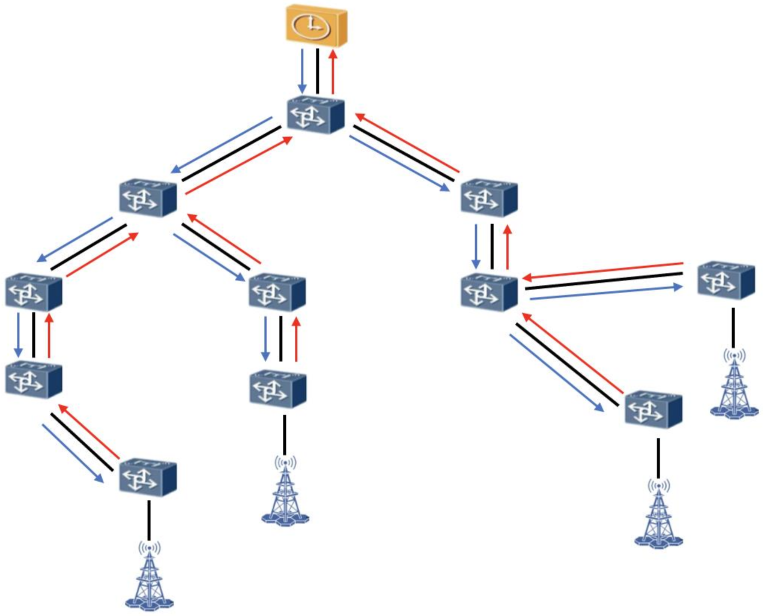
② Research Problem

③ Methodology

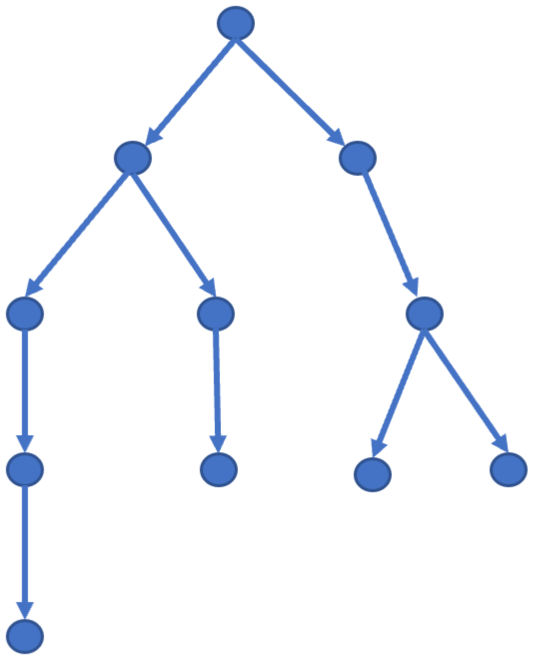
④ Further Exploration

Large-scale Sparse System of Linear Equations

- Mathematical Problem



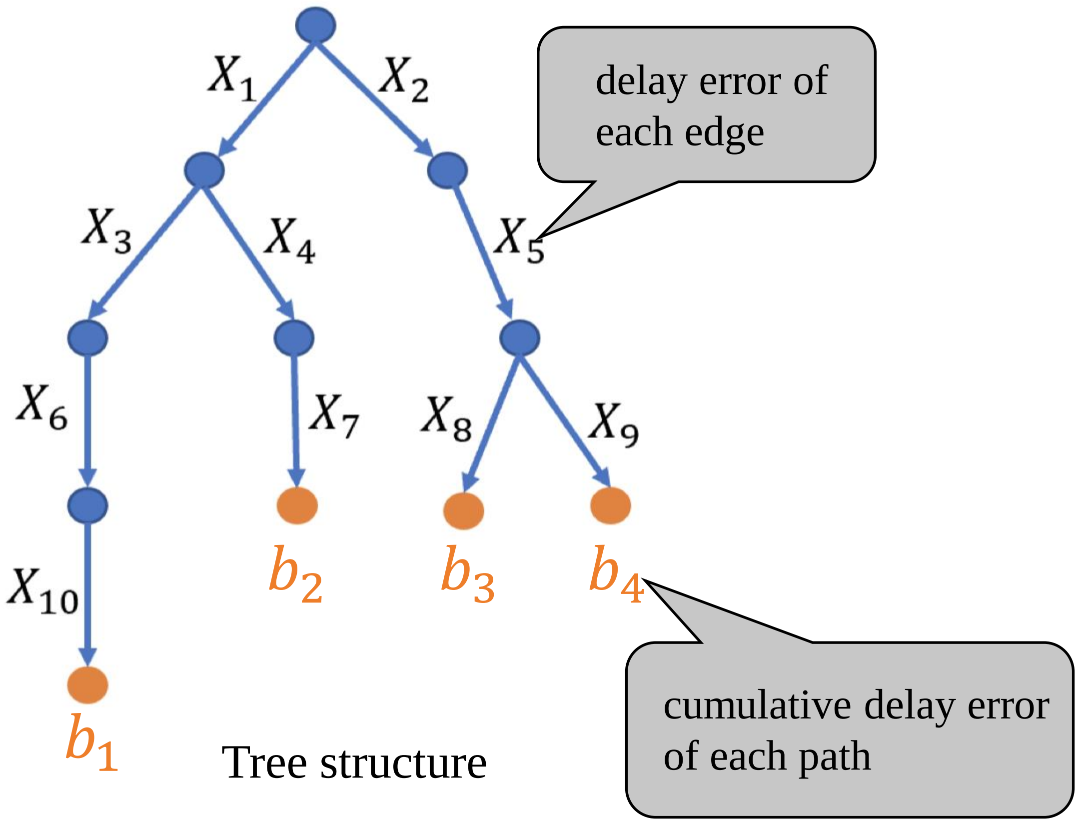
Optical Fiber Network example



Tree structure

Large-scale Sparse System of Linear Equations

- Mathematical Problem



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Large-scale Sparse System of Linear Equations

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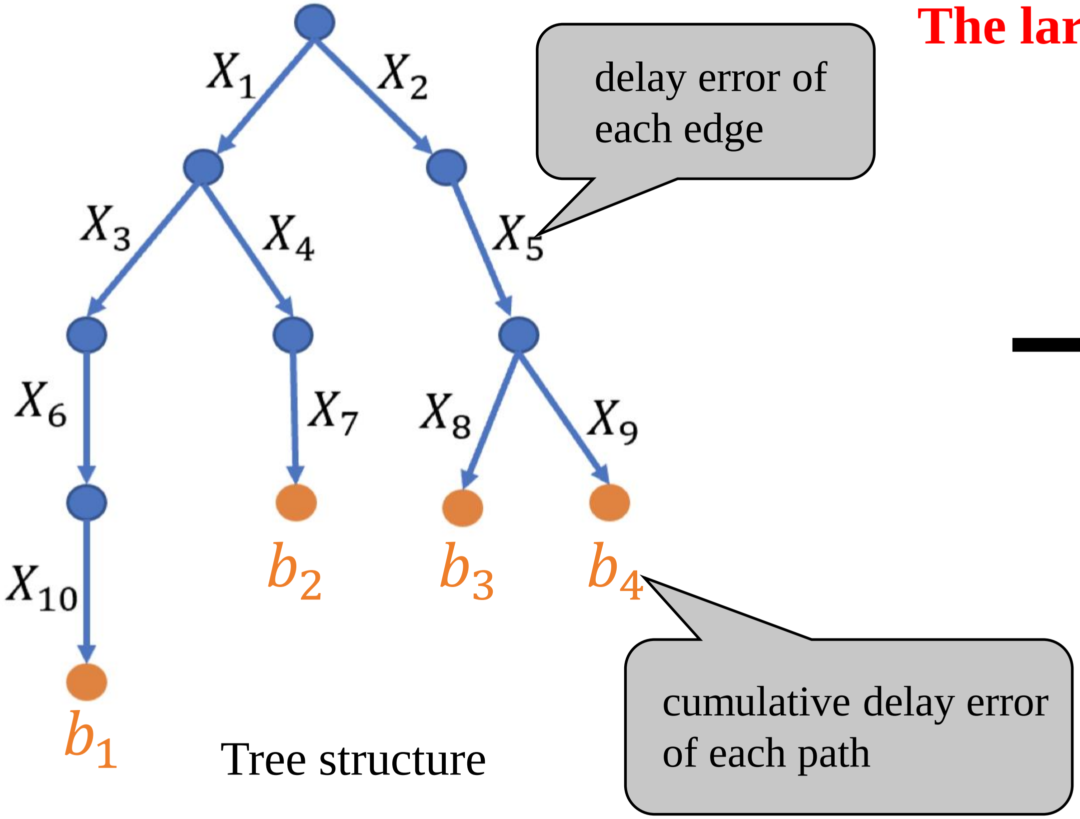


Tree structure

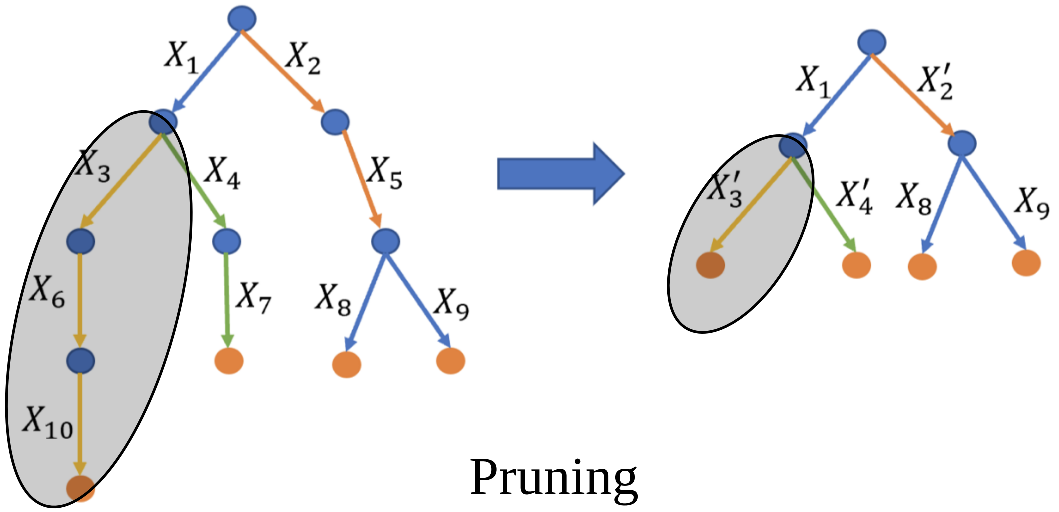
The large-scale sparse system of linear equations:

$$\begin{cases} x_1 + x_3 + x_6 + x_{10} & = b_1 \\ x_1 + x_4 + x_7 & = b_2 \\ x_2 + x_5 + x_8 & = b_3 \\ x_2 + x_5 + x_9 & = b_4 \end{cases}$$

Large-scale Sparse System of Linear Equations Solving Problem

(1) Pruning

- Continuous paths without branches cannot be accurately solved;
- Simplify the system of linear equations via pruning;



Pruning

Large-scale Sparse System of Linear Equations Solving Problem

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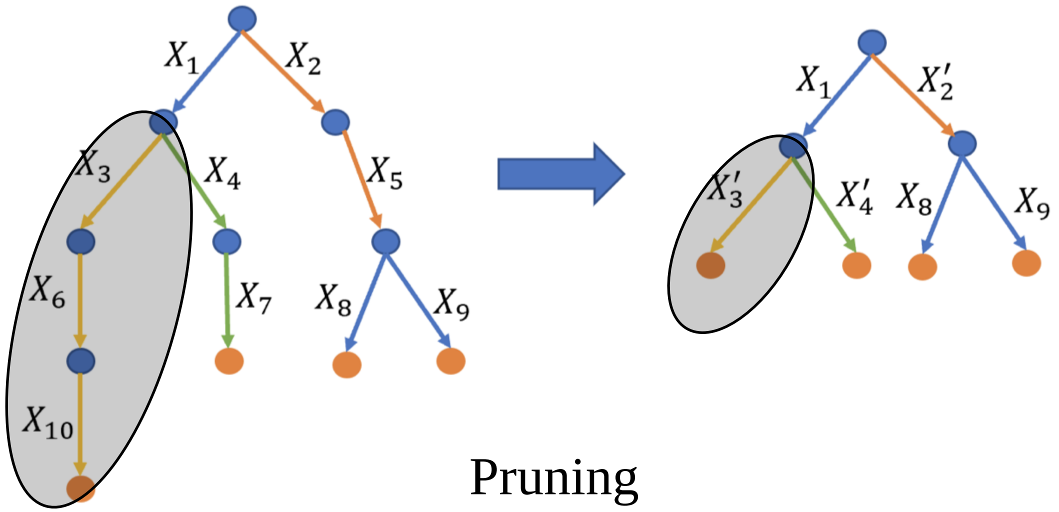


$$\begin{cases} x_1 + x_3' &= b_1 \\ x_1 + x_4' &= b_2 \\ x_2' + x_8 &= b_3 \\ x_2' + x_9 &= b_4 \end{cases} \Rightarrow \quad A = \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- The model can be described as $AX = b$, where A denotes the coefficient matrix.

Large-scale Sparse System of Linear Equations Solving Problem

(2) Objective function

Considering the sparsity of the delay errors, the L0 regularization term and convex penalty are introduced into the objective function:

$$J(X) = \frac{1}{2}\|b - AX\|^2 + \lambda_0\|X\|_0 + \lambda_q\|X\|_q^q,$$

$$\hat{X} = \arg\min_X J(X).$$

Where, q ∈ {1,2}, λ_0 controls the number of non-zero elements in X, and λq controls the degree of shrinkage caused by the $\|X\|_q^q$ regularization term.

Large-Scale Sparse Network Solution

(3) Problem Solving

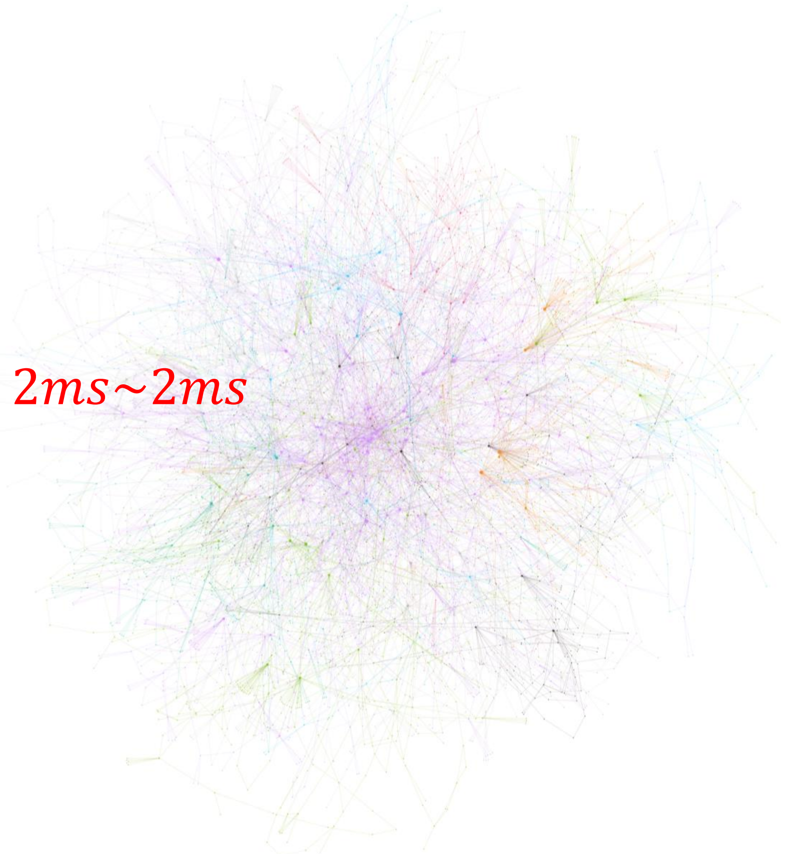
L0 minimization problem is NP-hard, consider the following methods :

- **Alternative problem:** L1 problem (convex approximation of L0 problem).
  - Lasso, MCP, SCAD;
- **Approximate algorithm:** Mixed Integer Optimization (MIP) method.
  - Proposed by Hussein Hazimeh (2020);
  - combination of cyclic coordinate descent (ccd) and local search algorithms;

Simulation Setting

Data generation:

- Dataset: 8720 leaf nodes, 10415 edges: $A \in \mathbb{R}^{8720\times10415}$
- $A(X+\epsilon_1) = b + \epsilon_2$
  - $X \sim N(0, 4\times10^{11})$:99.7% of generated data delay values within $-2ms \sim 2ms$
  - Ratio of asymmetric edges: $1\%, 5\%, 10\%, 20\%, 30\%$
  - $\epsilon_1 \sim N(0,\ \ 44)$
  - $\epsilon_2 \sim N(250,\ \ 1.4\times10^4)$
  - Repeated times: 500



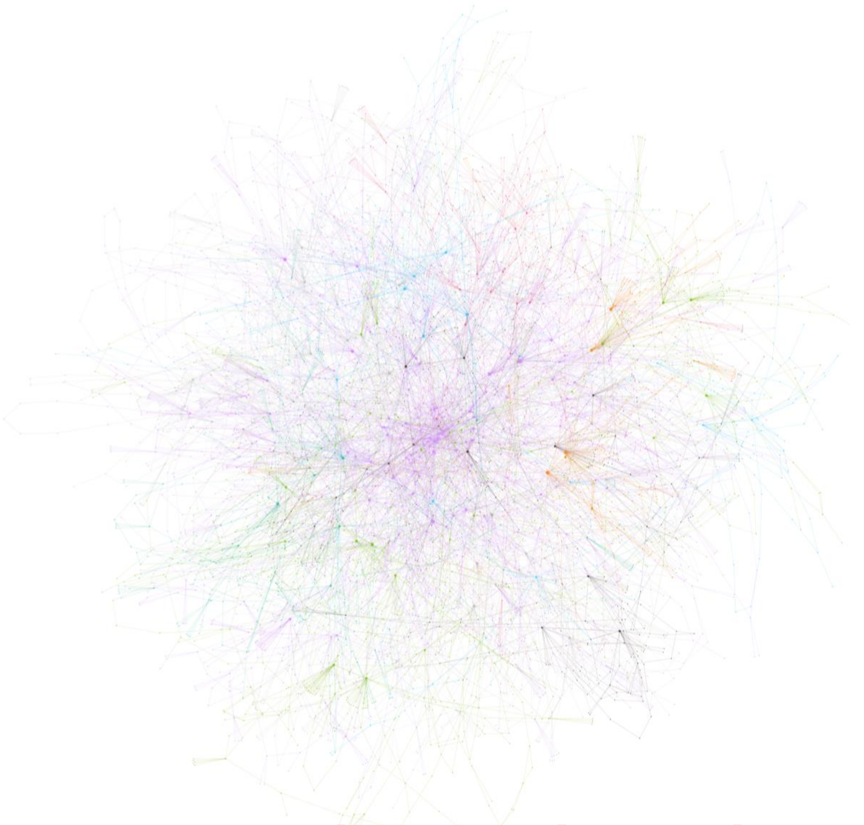
Foshan optical network

Simulation Setting

Correct predictions: $|\hat{x}_i - \mathrm{x}_i^*| < 5 \times 10^{-4}$;

Evaluation metrics:

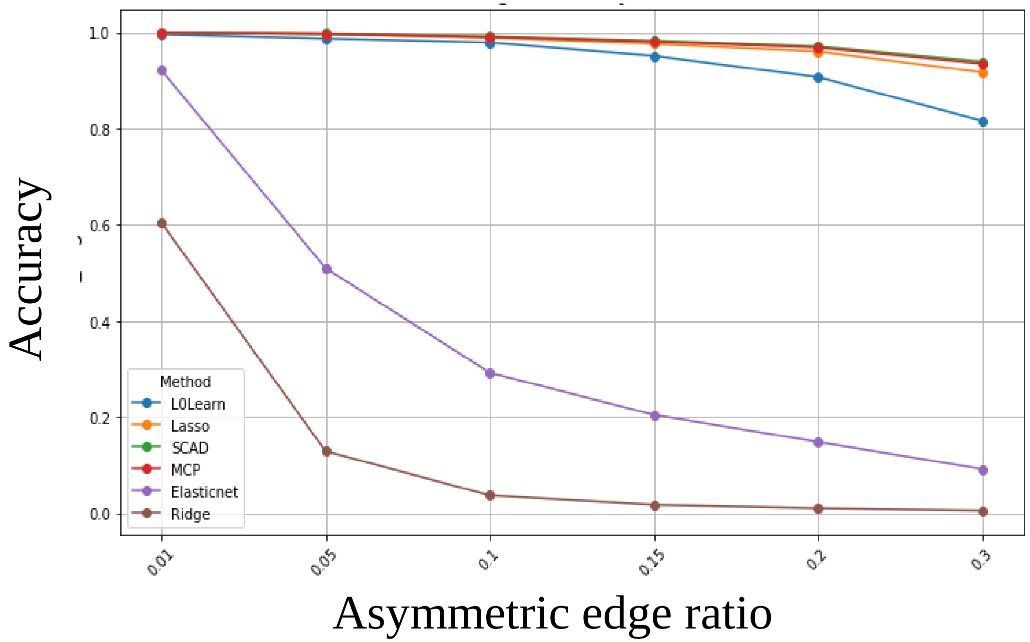
- Accuracy: $\frac{Correctly\ predicted\ number\ of\ edges}{Total\ number\ of\ edges} \times 100\%$
- Precision: $\frac{Correctly\ predicted\ number\ of\ asymmetric\ edges}{Number\ of\ predicted\ asymmetric\ edges} \times 100\%$



Foshan optical network

Simulation Results

Comparison of Different Methods:



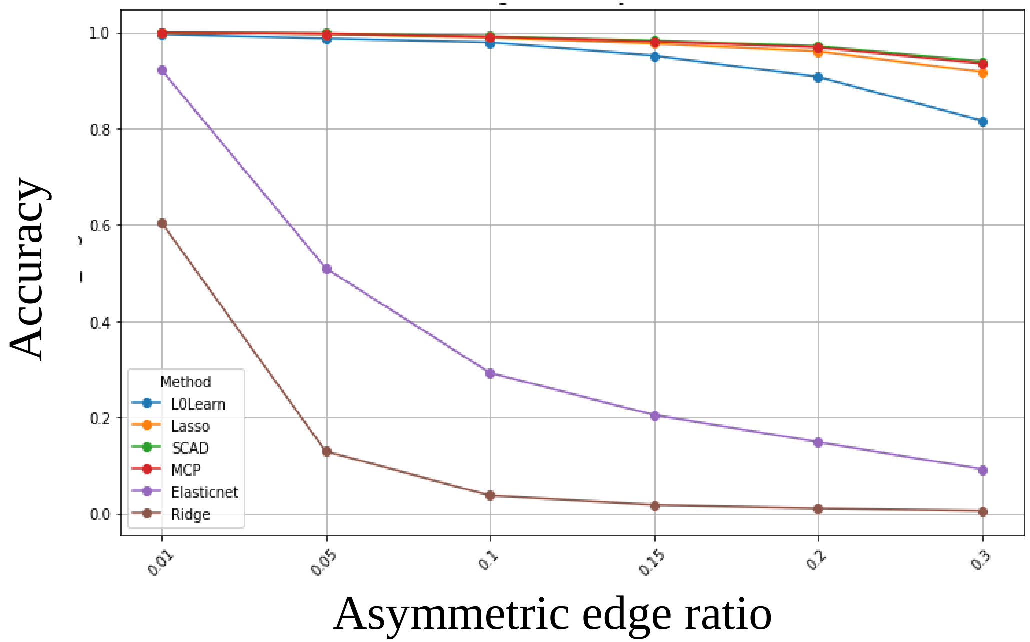
Conclusion:

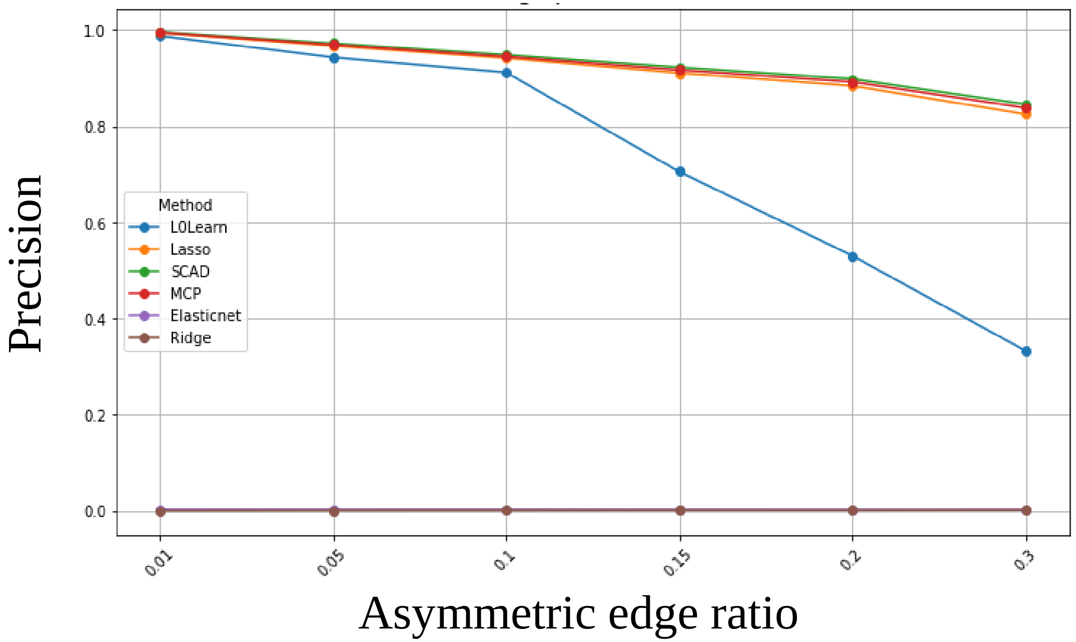
✓ SCAD outperforms other methods;

✓ **High accuracy:** Under sparse conditions (asymmetric edge ratio <10%), accuracy exceeds **95%**;

Simulation Results

Comparison of Different Methods:





Conclusion:

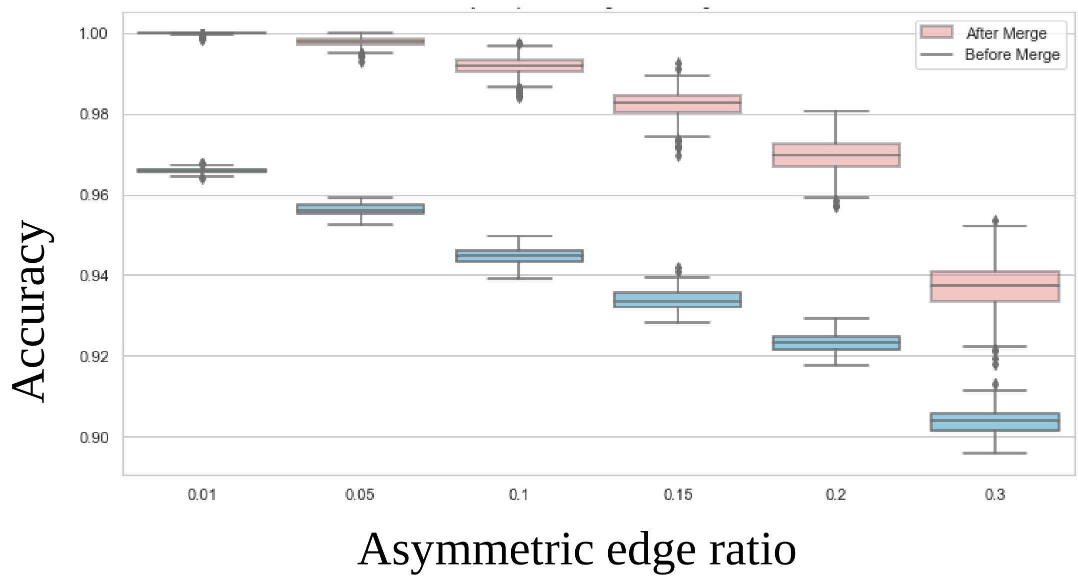
✓ SCAD outperforms other methods;

✓ **High accuracy:** Under sparse conditions (asymmetric edge ratio <10%), accuracy exceeds **95%**;

✓ **Robustness:** Under non-sparse conditions, the prediction accuracy remains above **84%**;

Simulation Results

Performance Before and After Pruning (SCAD):

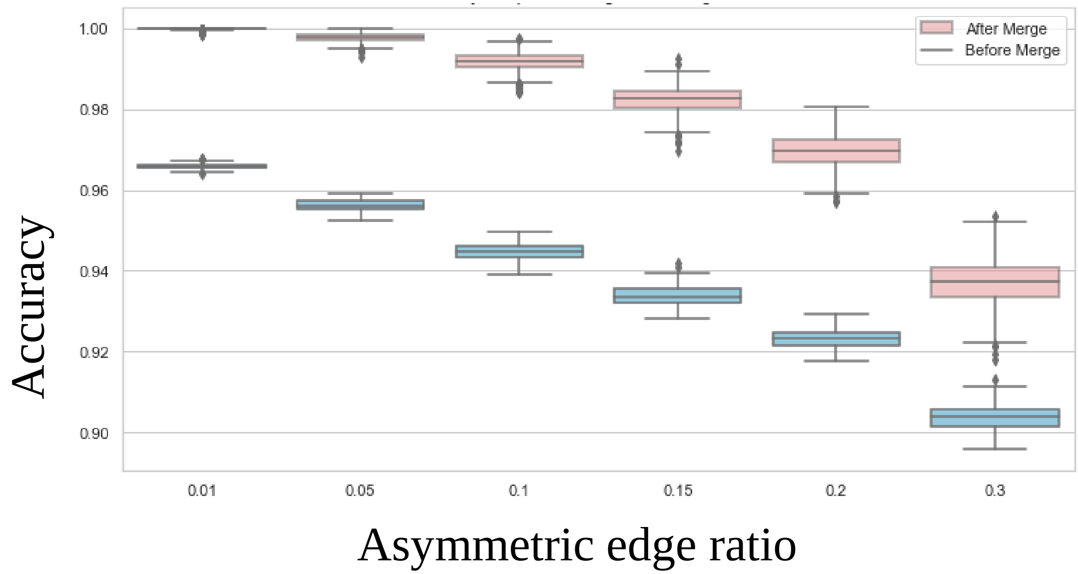


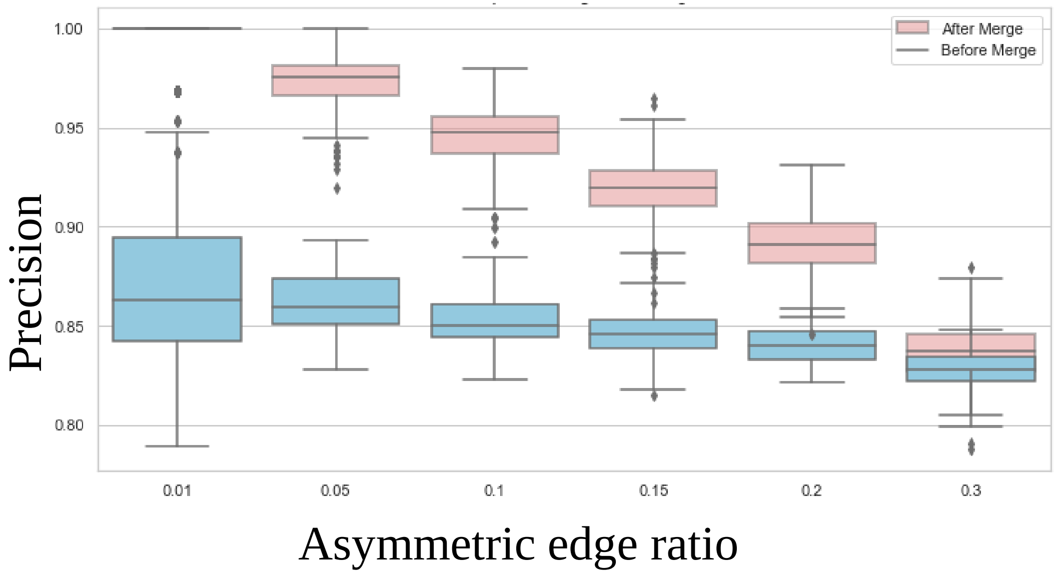
Conclusion:

✓ The accuracy and precision significantly improve after pruning;

Simulation Results

Performance Before and After Pruning (SCAD)：





Conclusion:

- ✓ The accuracy and precision significantly improve after pruning;
- ✓ The computation time is reduced by nearly 33%;

Simulation Results

Performance on Different Datasets (SCAD):

Cities	Asymmetric Edge Ratio	Accuracy (max/min/mean)	Precision (max/min/mean)
	1%	100% / 99.8% / 99.9%	100% / 93.8% / 99.9%
	5%	100% / 99.6% / 99.9%	100% / 96.9% / 99.8%
Beijing	10%	100% / 99.2% / 99.9%	100% / 95.7% / 99.5%
$A \in \mathbb{R}^{2964\times3260}$	20%	100% / 98.5% / 99.6%	100% / 95.2% / 98.7%
	30%	100% / 97.4% / 99.0%	100% / 94.2% / 97.7%
	1%	100% / 99.9% / 99.9%	100% / 96.9% / 99.6%
	5%	100% / 99.4% / 99.8%	100% / 93.9% / 97.3%
Foshan	10%	99.8% / 98.7% / 99.2%	99.7% / 90.8% / 94.8%
$A \in \mathbb{R}^{5052\times6495}$	20%	98.0% / 95.9% / 97.1%	97.9% / 86.2% / 89.8%
	30%	95.4% / 92.2% / 93.9%	95.4% / 79.9% / 84.7%
	1%	100% / 99.9% / 99.9%	100% / 95.7% / 99.5%
	5%	100% / 99.5% / 99.8%	100% / 94.3% / 97.7%
Guangzhou	10%	99.7% / 98.8% / 99.3%	97.9% / 92.7% / 94.5%
$A \in \mathbb{R}^{15431\times16582}$	20%	98.5% / 96.7% / 97.6%	94.5% / 88.3% / 90.2%
	30%	96.3% / 93.6% / 94.2%	90.0% / 83.2% / 86.3%

Conclusion:

✓ Under sparse conditions, accuracy exceeds 99% and precision exceeds 94% across different datasets.

Simulation Results

Performance on Different Datasets (SCAD):

Cities	Asymmetric Edge Ratio	Accuracy (max/min/mean)	Precision (max/min/mean)
	1%	100% / 99.8% / 99.9%	100% / 93.8% / 99.9%
	5%	100% / 99.6% / 99.9%	100% / 96.9% / 99.8%
Beijing	10%	100% / 99.2% / 99.9%	100% / 95.7% / 99.5%
$A \in \mathbb{R}^{2964\times3260}$	20%	100% / 98.5% / 99.6%	100% / 95.2% / 98.7%
	30%	100% / 97.4% / 99.0%	100% / 94.2% / 97.7%
	1%	100% / 99.9% / 99.9%	100% / 96.9% / 99.6%
	5%	100% / 99.4% / 99.8%	100% / 93.9% / 97.3%
Foshan	10%	99.8% / 98.7% / 99.2%	99.7% / 90.8% / 94.8%
$A \in \mathbb{R}^{5052\times6495}$	20%	98.0% / 95.9% / 97.1%	97.9% / 86.2% / 89.8%
	30%	95.4% / 92.2% / 93.9%	95.4% / 79.9% / 84.7%
	1%	100% / 99.9% / 99.9%	100% / 95.7% / 99.5%
	5%	100% / 99.5% / 99.8%	100% / 94.3% / 97.7%
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Conclusion:

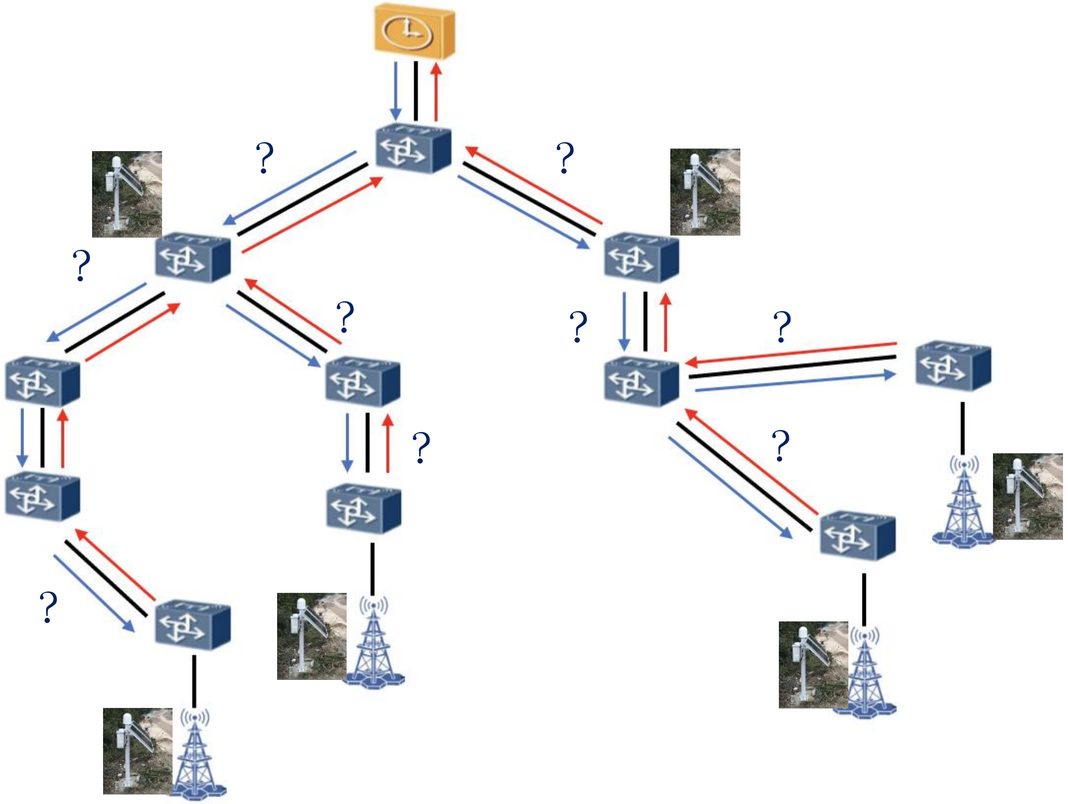
✓ Under sparse conditions, accuracy exceeds 99% and precision exceeds 94% across different datasets.

Question: How to further improve accuracy/precision?

Further exploration

How to further improve accuracy/precision?

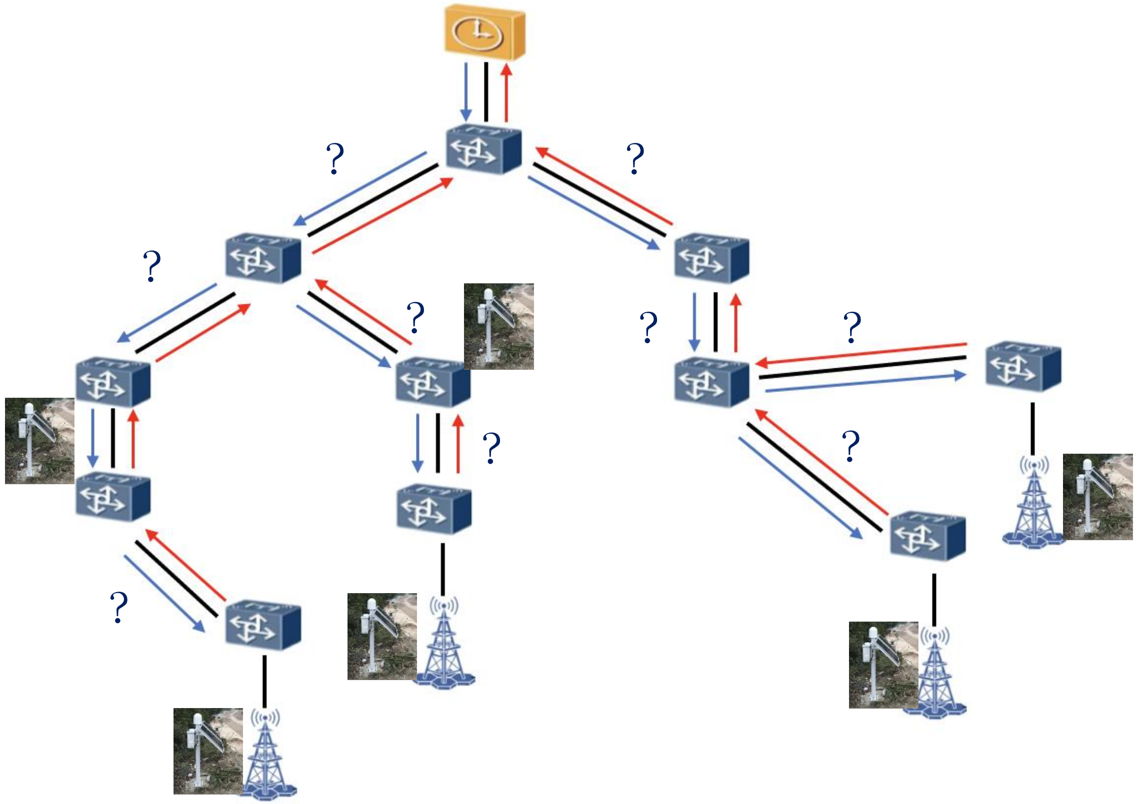
➢ Deploy more GNSS receivers;



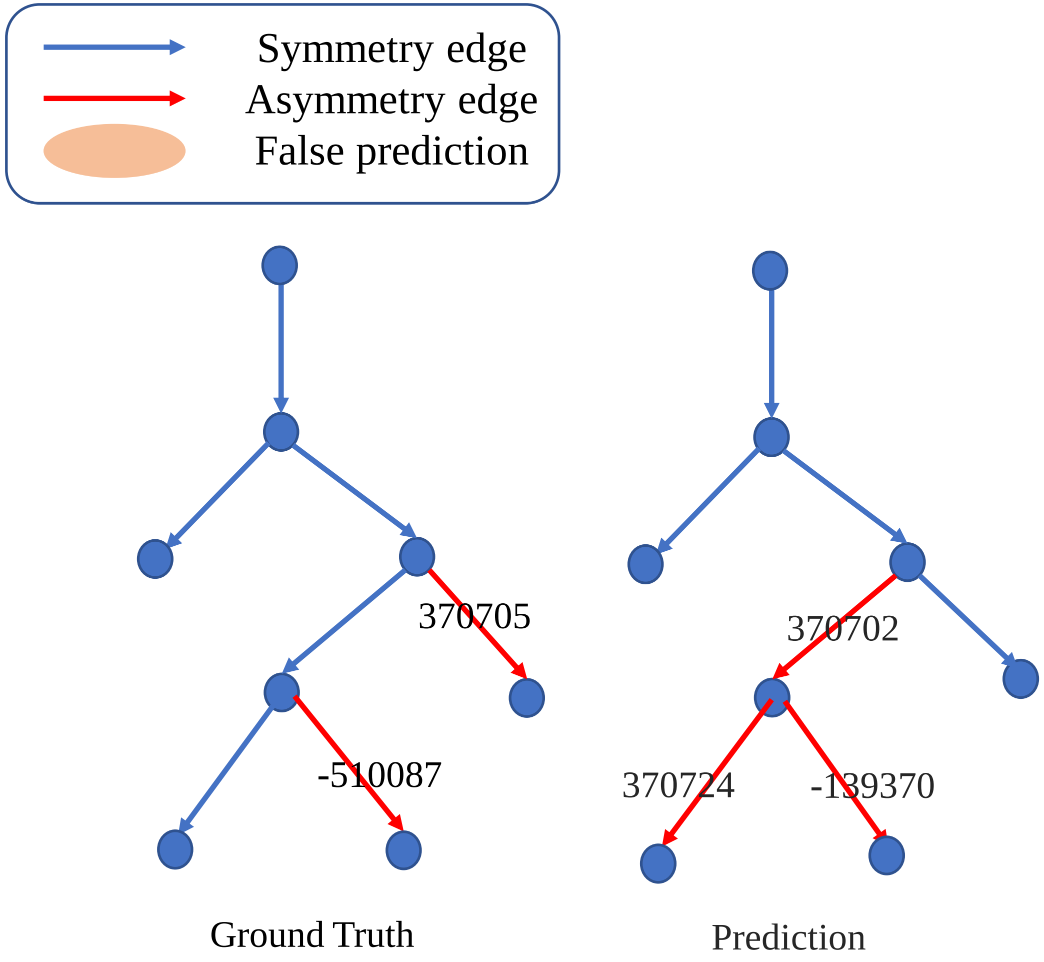
Further exploration

How to further improve accuracy/precision?

- Deploy more GNSS receivers;
- Where to deploy the additional GNSS receivers?
  (Determination of key node in the network)



Inspection of false predictions



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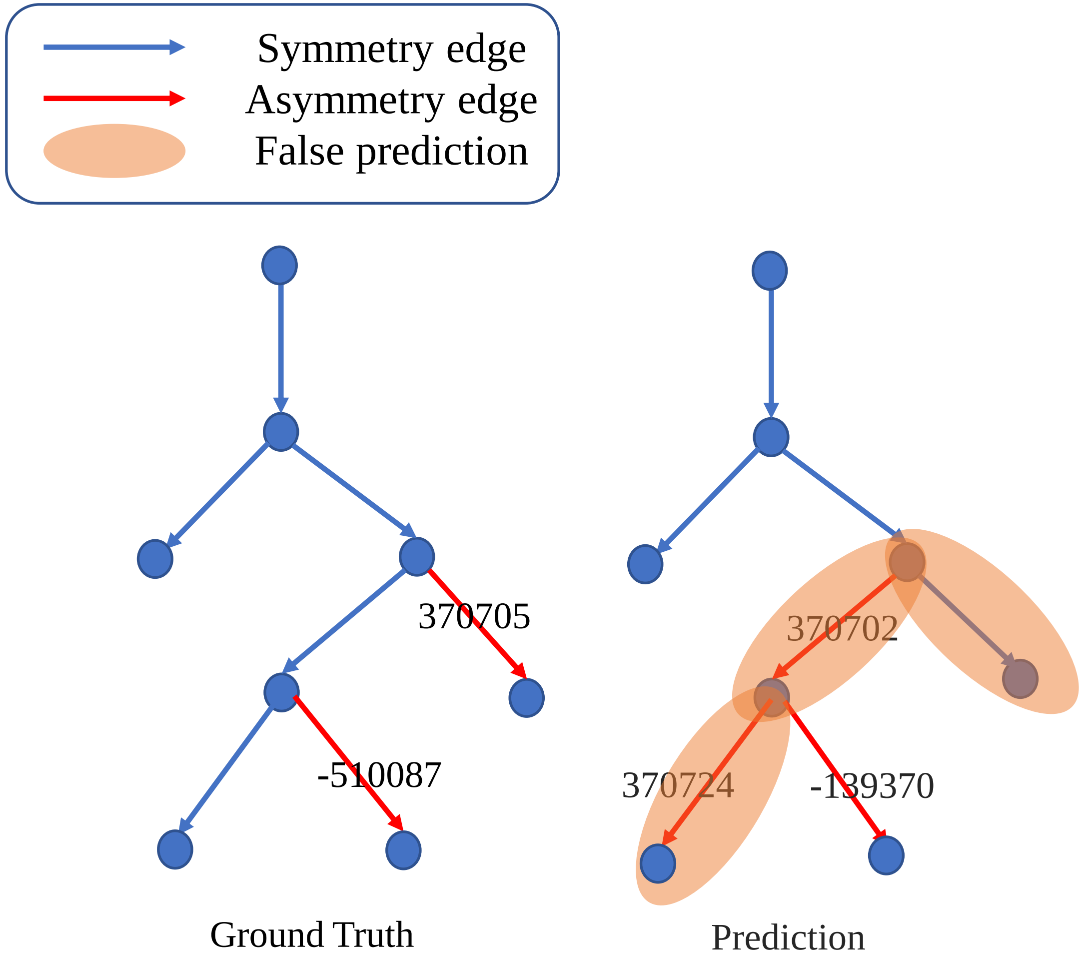

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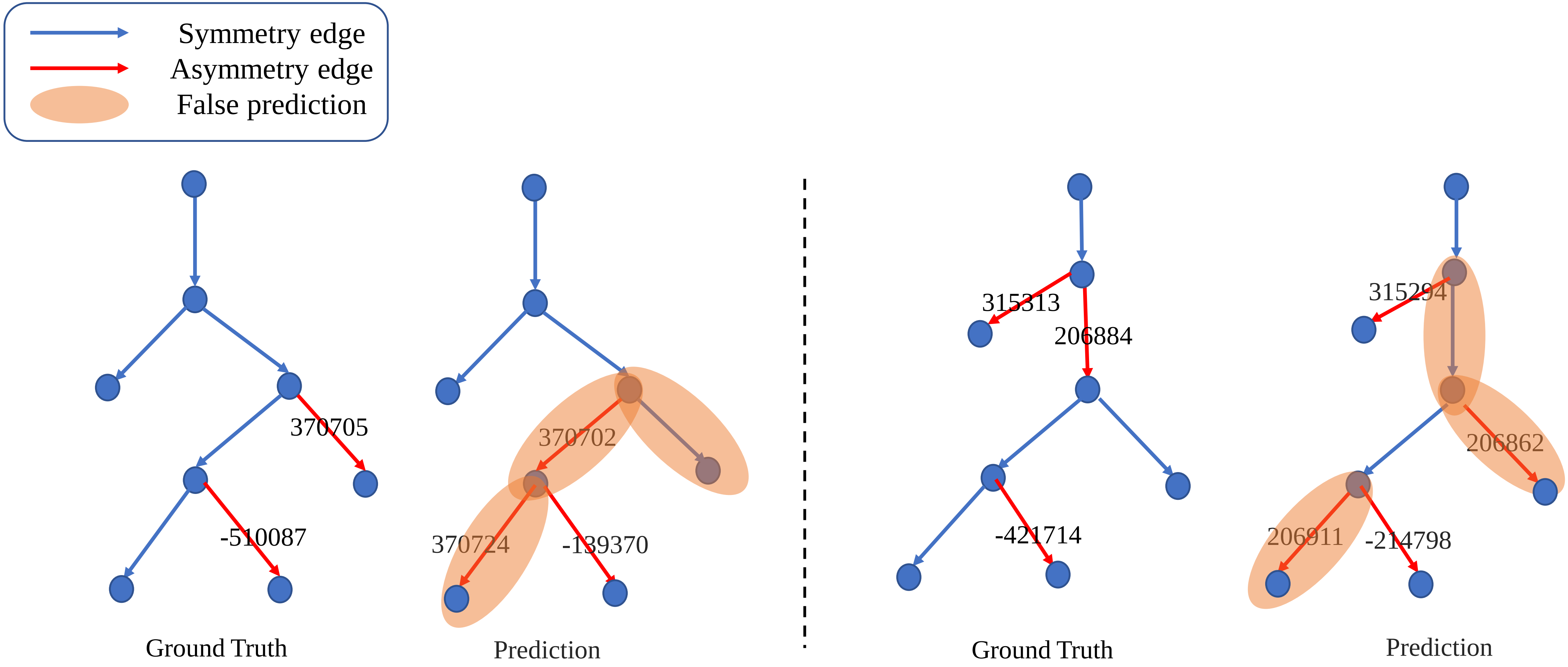
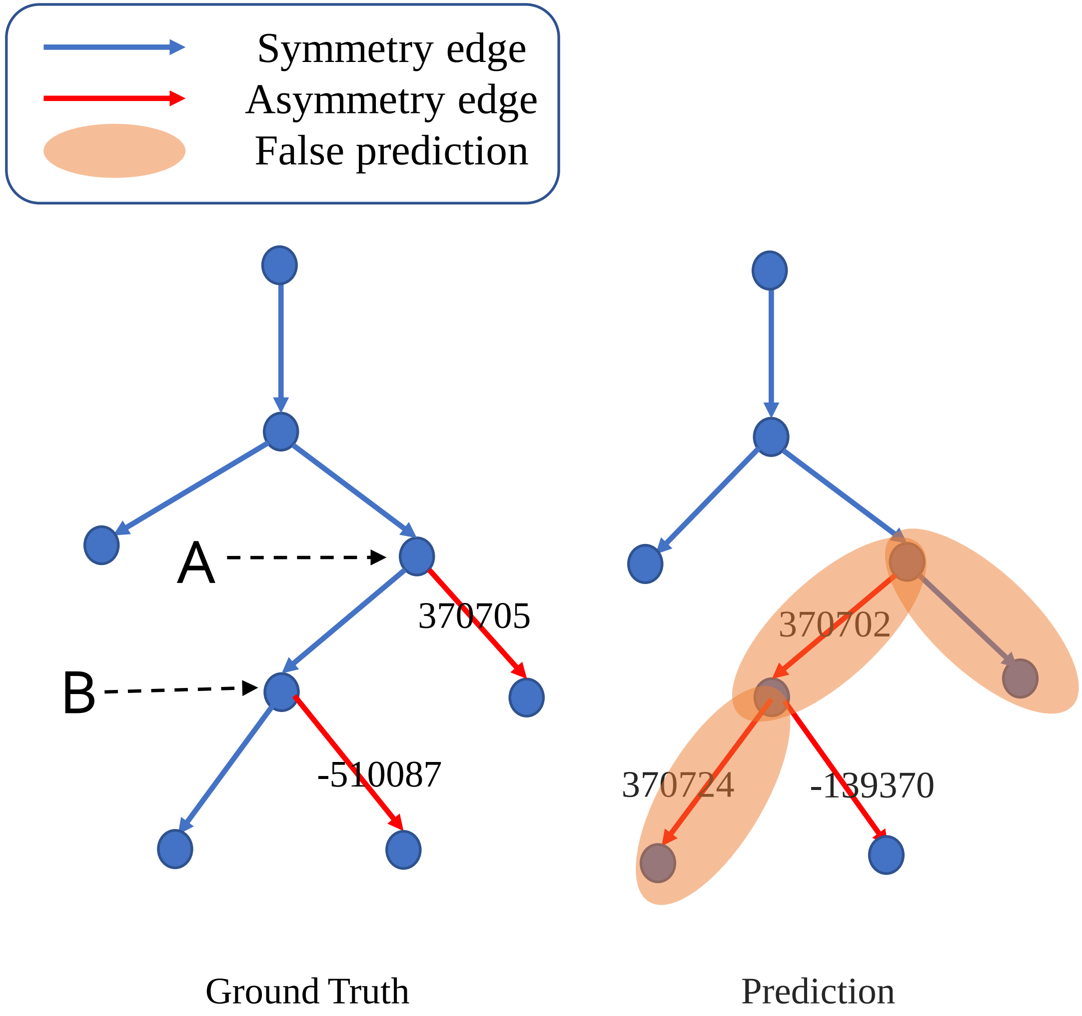


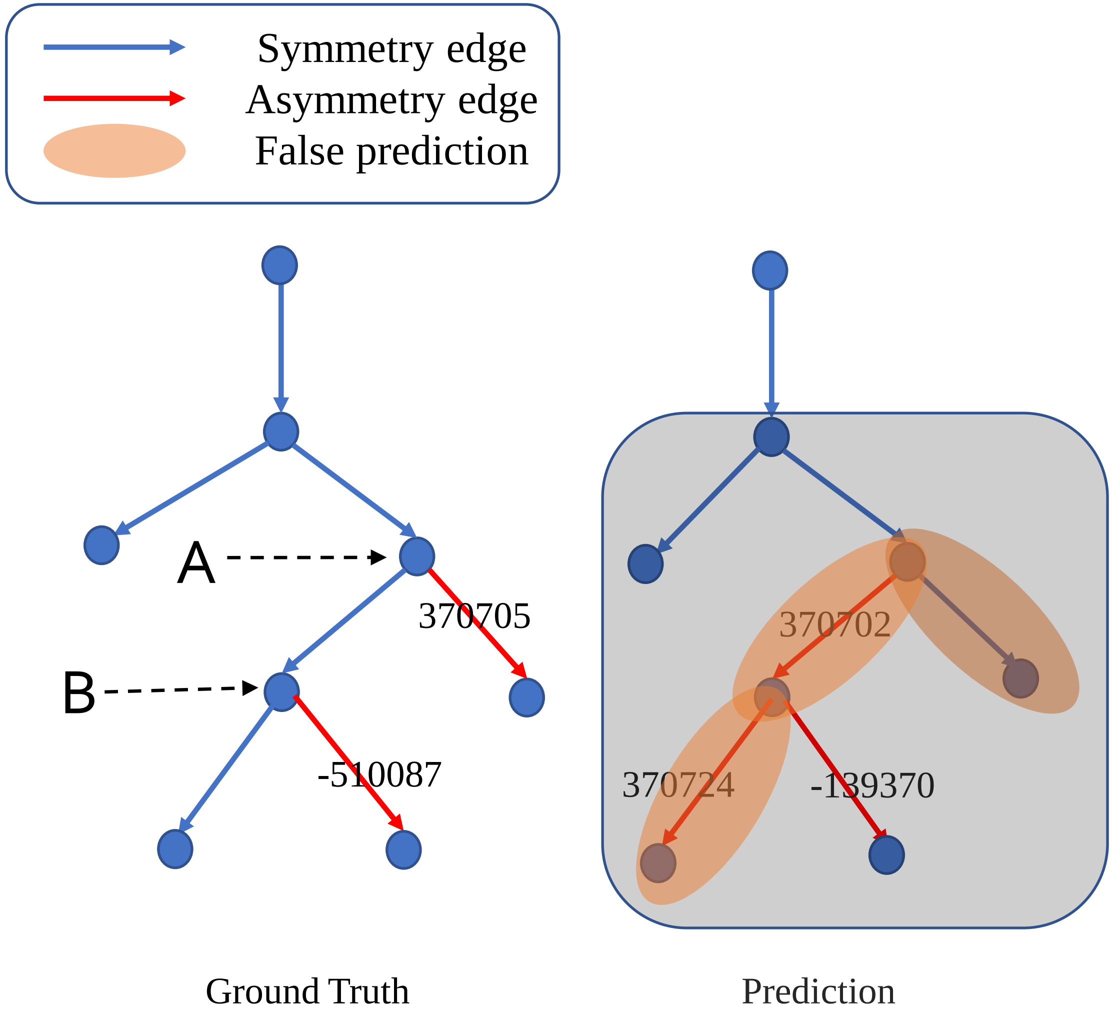
False predictions are likely to happen around nodes connected with more predicted asymmetry edges!

Inspection of false predictions

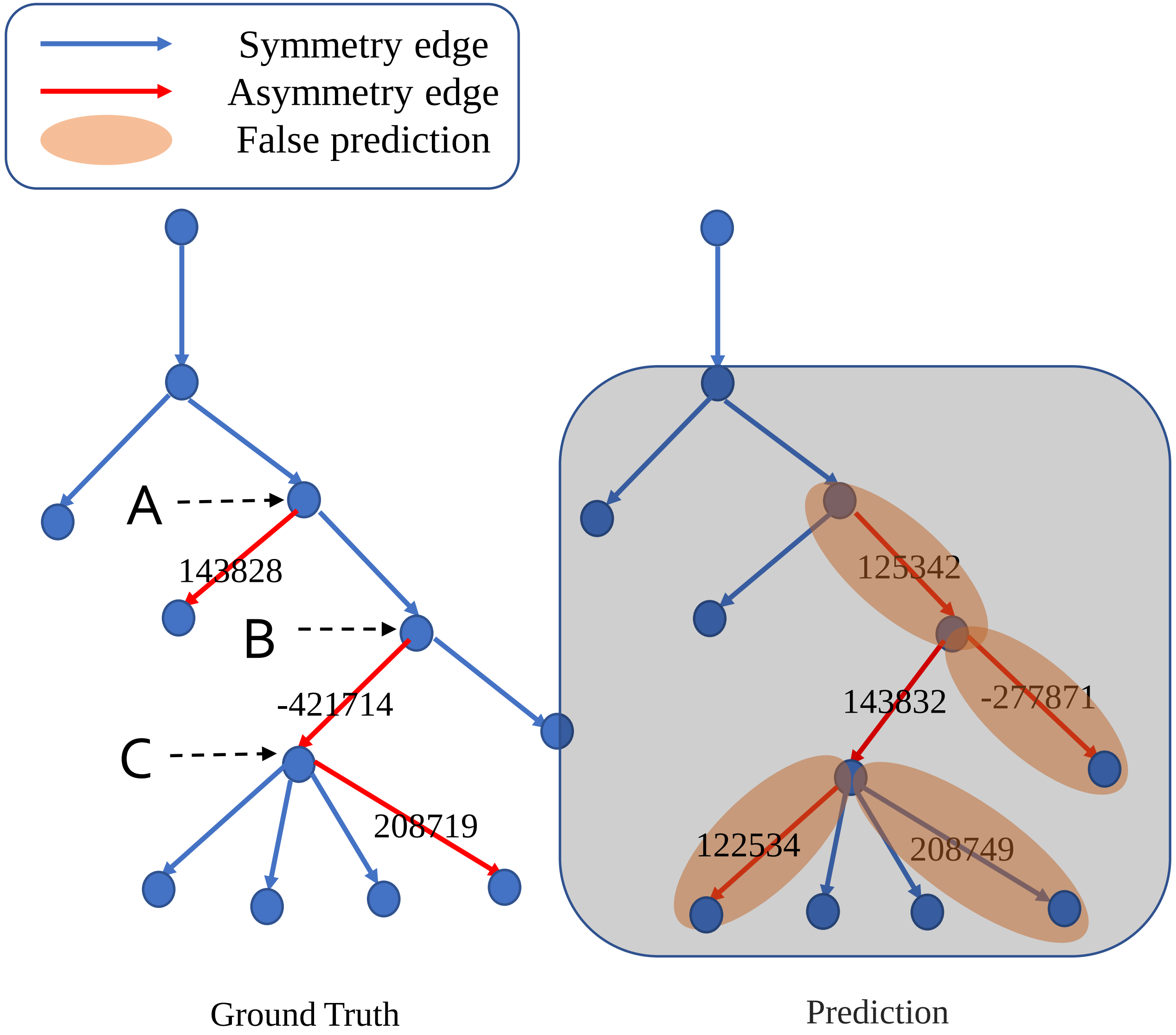


- **Asymmetry occurs at 2 connected nodes (A, B)**
  - False predictions around **(A, B)** ;

Inspection of false predictions



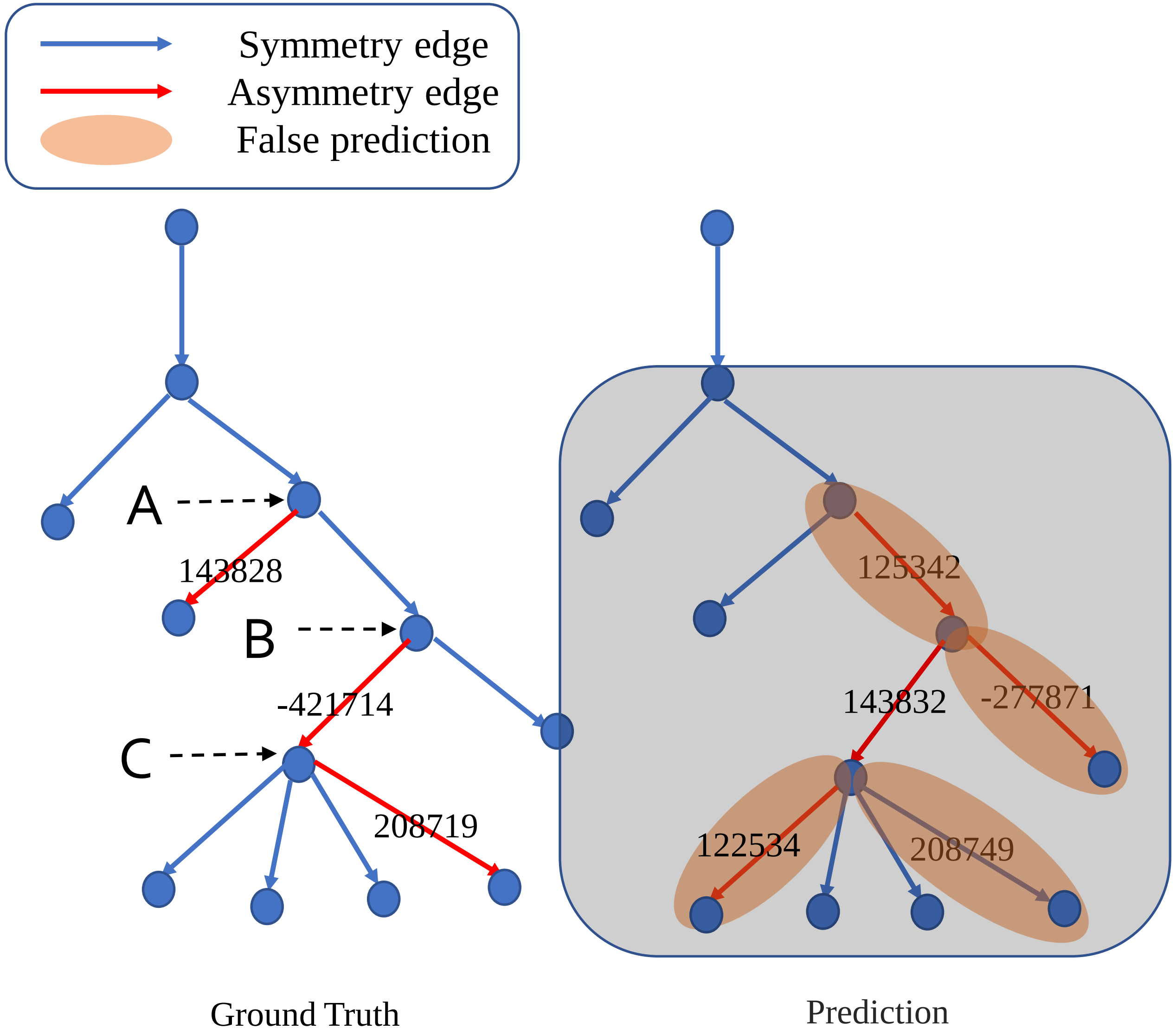
- **Asymmetry occurs at 2 connected nodes (A, B)**
  - False predictions around **(A, B)** ;
  - False prediction region including **(A, B)** ;



- **Asymmetry occurs at (A, B, C)**
  - ➢ False predictions around **(A, B, C)** ;
  - ➢ False prediction region including **(A, B, C)** ;

Identifying the false prediction region

Inspection of false predictions



- **Asymmetry occurs at (A, B, C)**
  - False predictions around **(A, B, C)** ;
  - False prediction region including **(A, B, C)** ;

Identifying the false prediction region

Perfectly detect the time delay

Theoretical Results

- Definition of the *False Prediction Region*

Consider a network $\mathcal{G}(V,E)$. For each node $l \in V$, let the degree of node l denoted by n_l and the edges that node l has to other nodes be denoted as $\mathcal{N}_l = \{x_1^{(l)}, x_2^{(l)}, \ldots, x_{n_l}^{(l)}\}$. For any subset of the vertices of $\mathcal{G}$, denoted as V', define the *False Prediction Region* $\mathcal{F}_{\mathrm{V}'}$ as follows:

$$\mathcal{F}_{\mathrm{V}'} = \begin{cases} \mathcal{G}(\mathrm{V}',\mathrm{E}') & \text{if } \forall\, l \in \mathrm{V}', \exists\, l' \in \mathrm{V}' \ s.t.\ (l,l') \in E \text{ and } \exists \text{ asymmetric edge } \hat{x}_k^{(l)} \in \mathcal{N}_l \text{ with } \mathrm{k} \in [n_l]\,; \\ \emptyset & \text{otherwise;} \end{cases}$$

where $\mathcal{G}(\mathrm{V}',\mathrm{E}')$ is the subgraph of $\mathcal{G}$ contains the nodes in V' and the edges between those nodes.

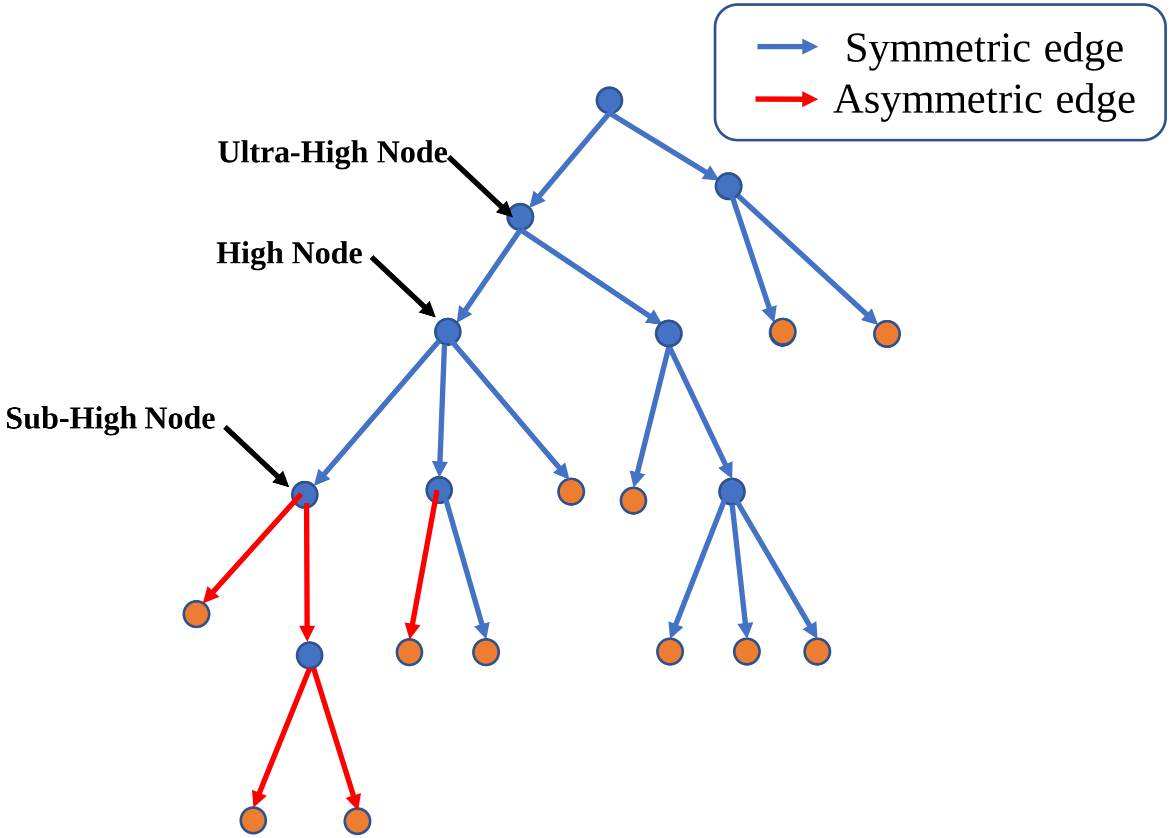
Theorem 1 (Accuracy of Detected Time Delays in Networks with False Prediction Regions)

Assume that $\mathcal{G}(V,E)$ *is a binary tree network, then f*alse predictions occur exclusively within the *False Prediction Regions* . i.e.

$$\hat{X} \equiv \mathrm{X}^*$$

where $\hat{X}$ is the detected time delay and X^* is the actual values, and " $\equiv$ " indicates that the asymmetric label assignments on both sides coincide up to the difference on false prediction regions.

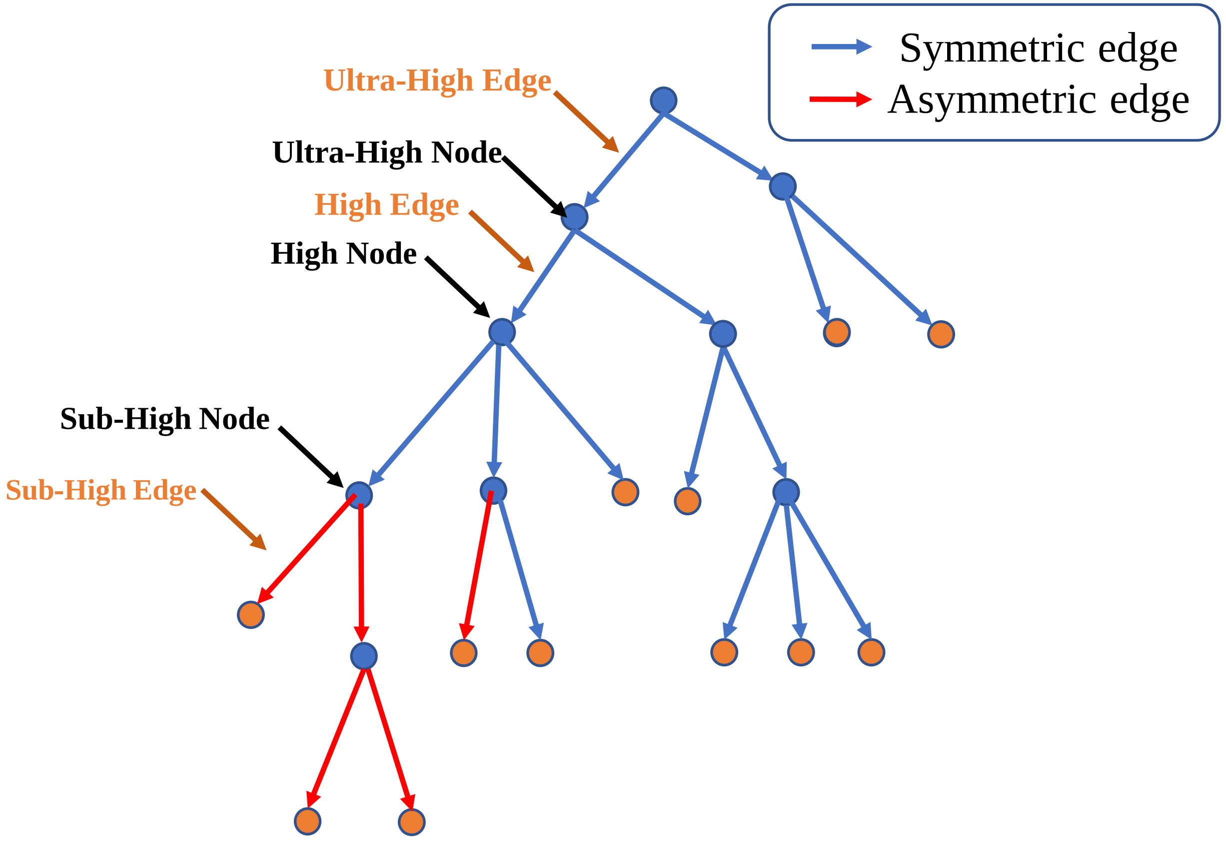
How to implement in engineering practice? → Partitioning algorithm



Node Confidence Classification:

- Sub-High Confidence Node:
  - Number of connected asymmetric edges ≥ 2 ;
  - Sub-High Confidence Edges
    (connected to Sub-High Confidence Nodes)
- High Confidence Node:
  - connected to Sub-High Confidence Nodes ;
  - High Confidence Edges
- Ultra-High Confidence Node:
  - Number of connected asymmetric edges ≤ 1 ;
  - Not connected to Sub-High Confidence Nodes ;
  - Ultra-High Confidence Edges

Partitioning algorithm



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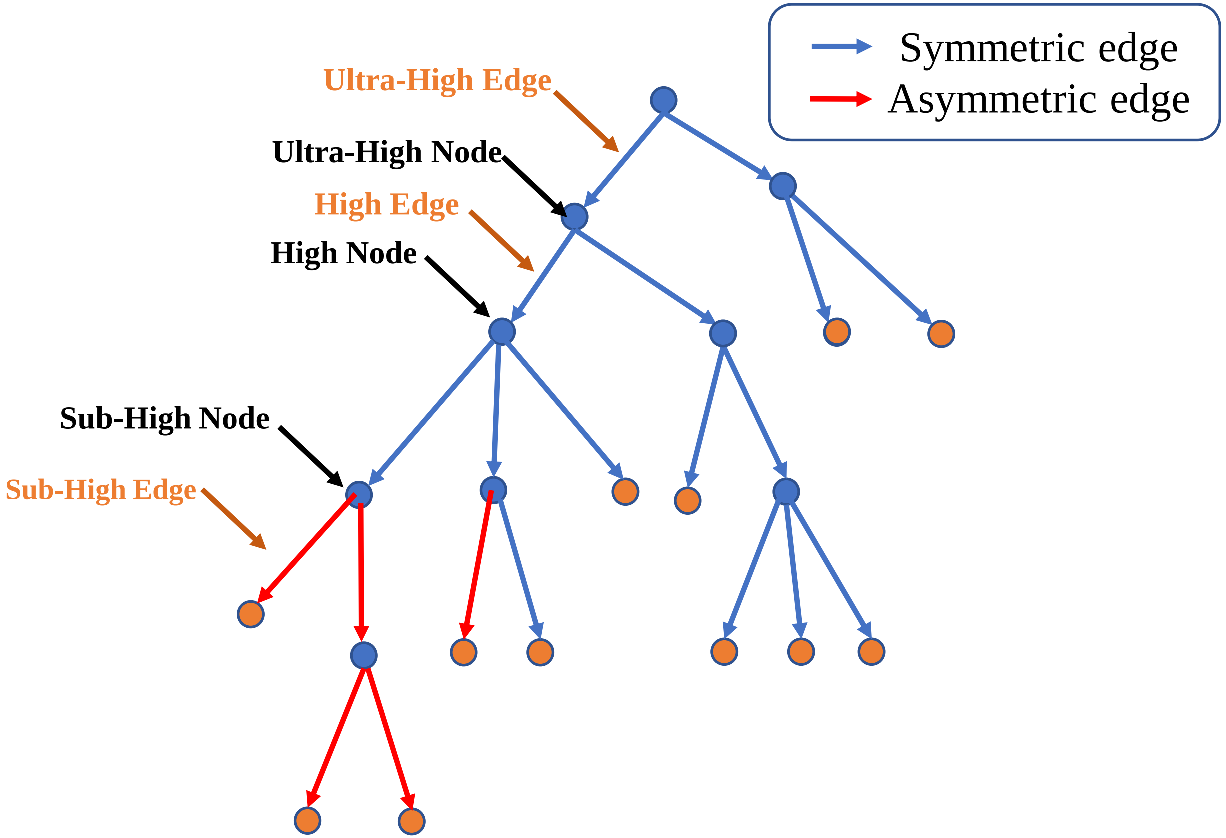
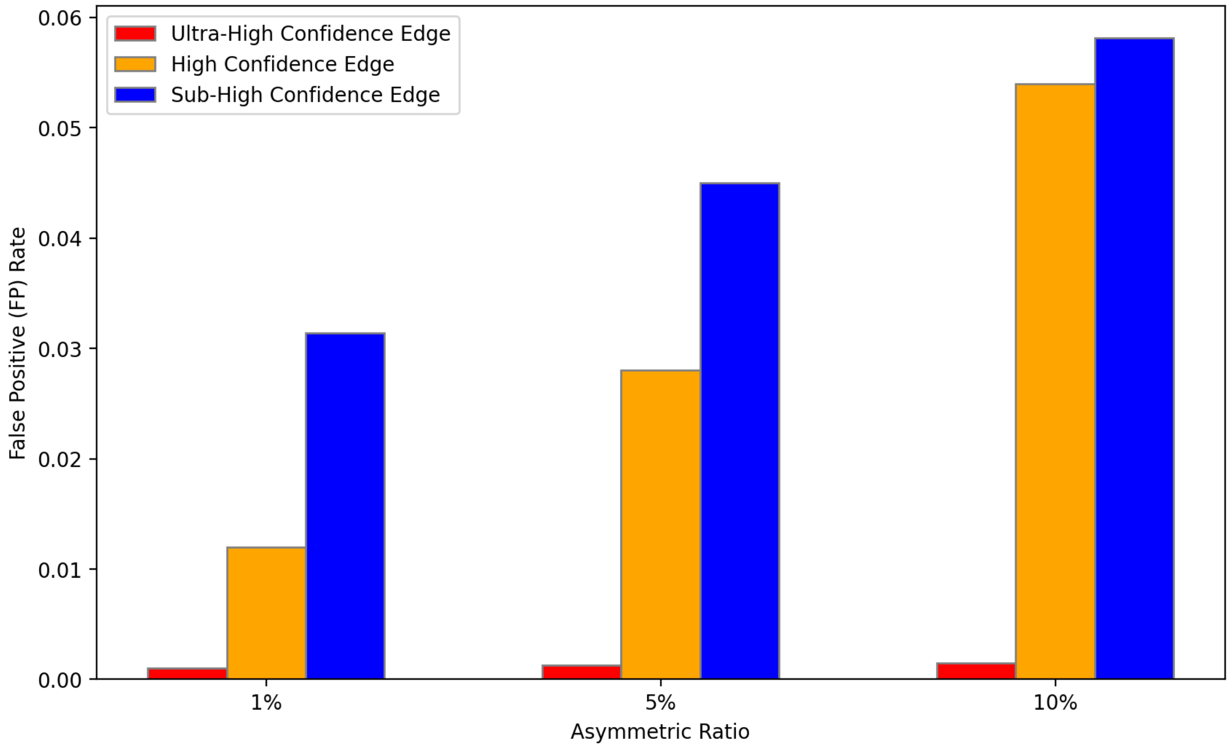


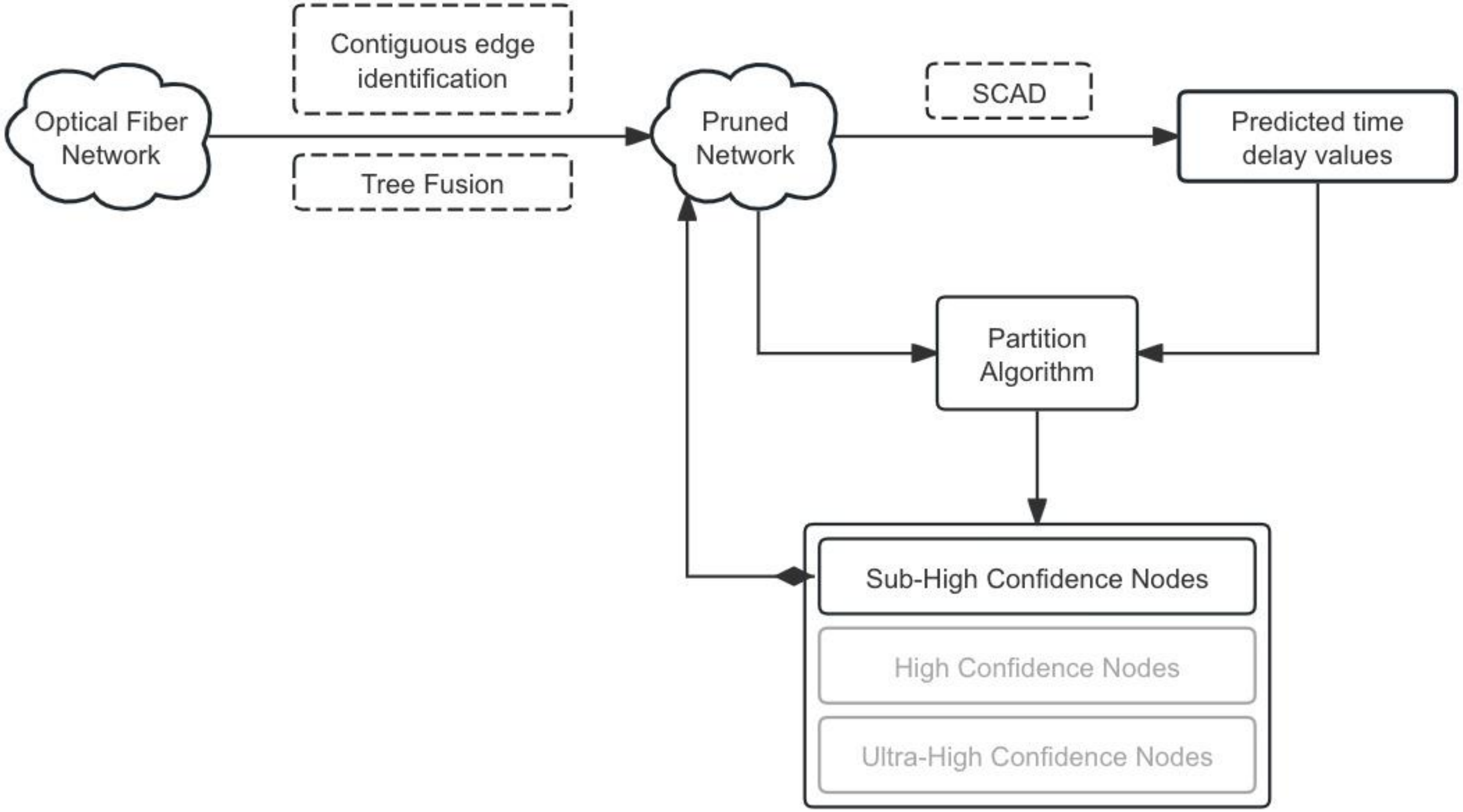


False Positive Rate (FPR) in different groups

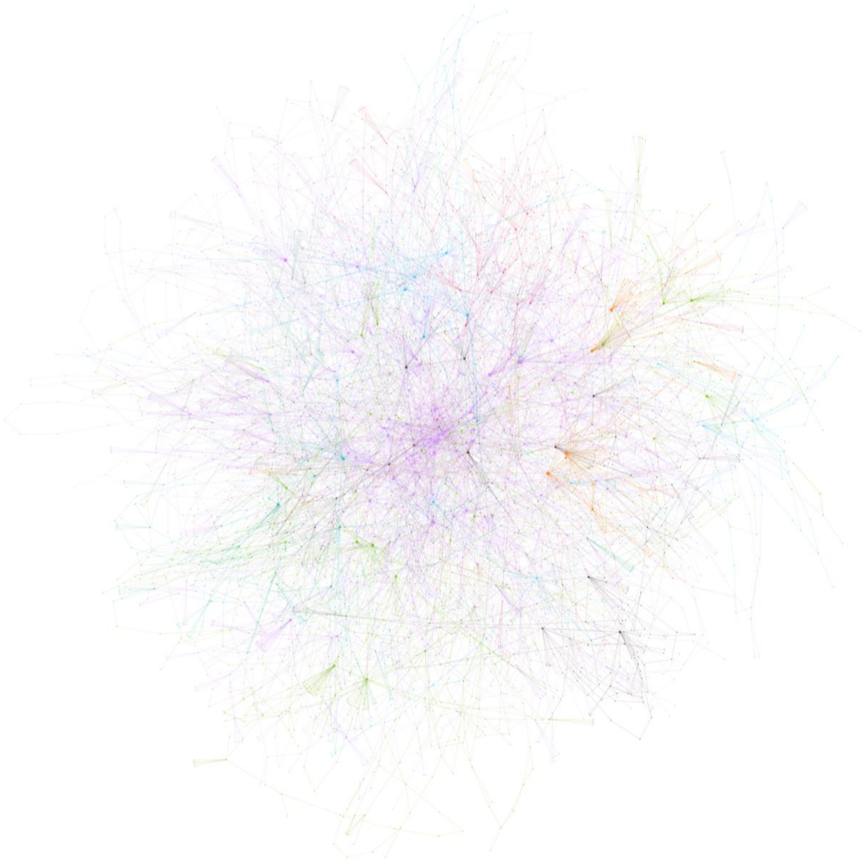
Conclusion:

- FRP is highest among Sub-High Confidence Edges;

The Flowchart of Delay Detection in Large-Scale Mobile Backhaul Networks



Results



Foshan optical network

Add 143 GNSS

Sub-High Confidence Node

	Before	After
Accuracy	99.03%	**99.84%**
Precision	94.14%	**99.17%**

Conclusion:

- The accuracy and precision significantly improved.

Summary

Detection of Time Delay in Large-Scale Optical Fiber Networks:

- Modeling as the Large-scale Sparse System of Linear Equations Solving Problem;
- Propose a pruning method to reduce computational complexity;
- Introduce a partitioning algorithm to select critical points;

Team Member

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Sai HAO

Ya WANG

Thanks!