Friedrich-Alexander-Universität
Technische Fakultät

Dynamic Reservation of Ultra-Reliable Real-Time Streams in Time-Sensitive Networking

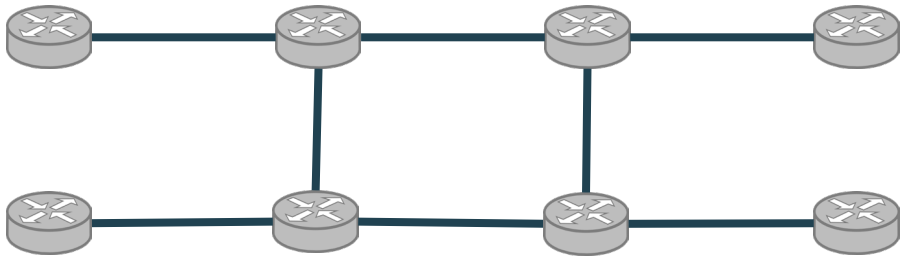
Lisa Maile

**Computer Networks and Communication Systems,
Friedrich-Alexander Universität, Erlangen-Nürnberg, Germany**

Academic Salon on High-Performance and Low Latency Networks and Systems 2023

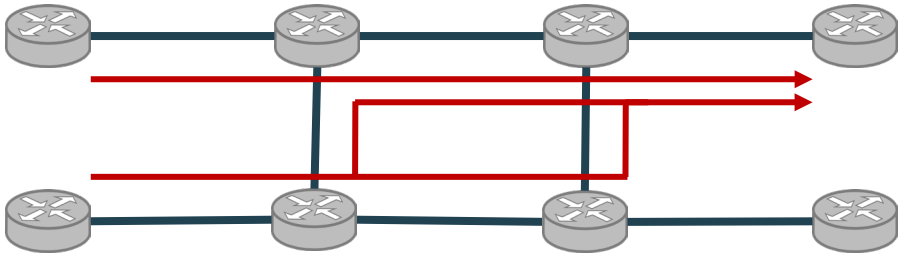
Network Flow Planning

Input



Flows
Source, Destination
Interval, Frame Size
Delay Requirement

Output



Ultra-Reliable Flows:

- Guaranteed max. End-To-End Delay
- No Packet/Frame Loss

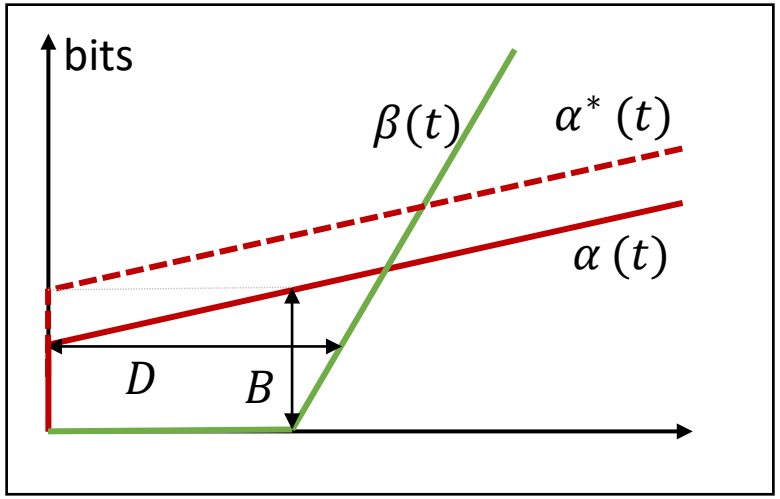
Non-trivial for, e.g.,
Deficit Round Robin and Credit-Based Shaper, …
because flows accumulate bursts over the path

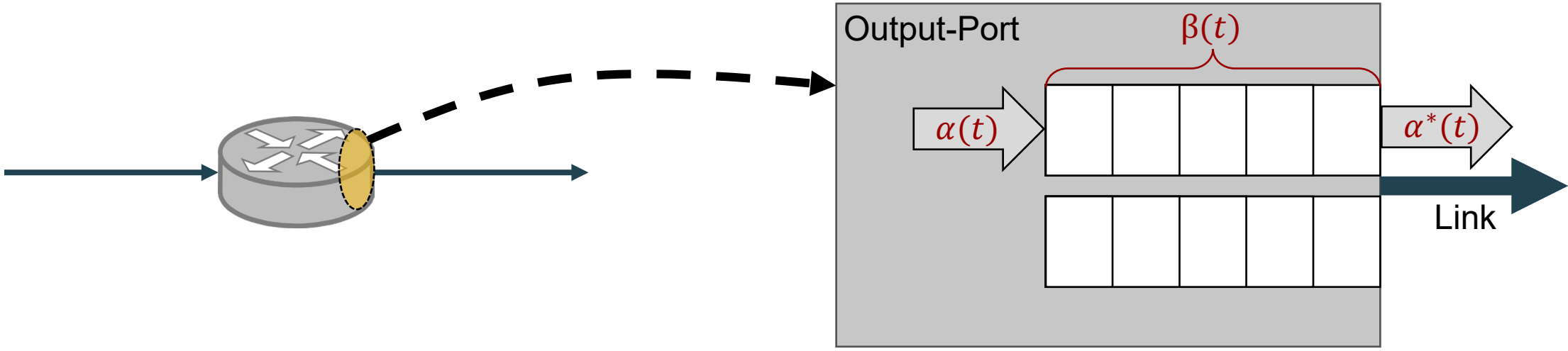
Delay Guarantees → Forwarding Parameters → No. of Priority Queues → Prioritization → Path Selection → Redundancy Configuration

Delay Analysis Framework

Network Calculus

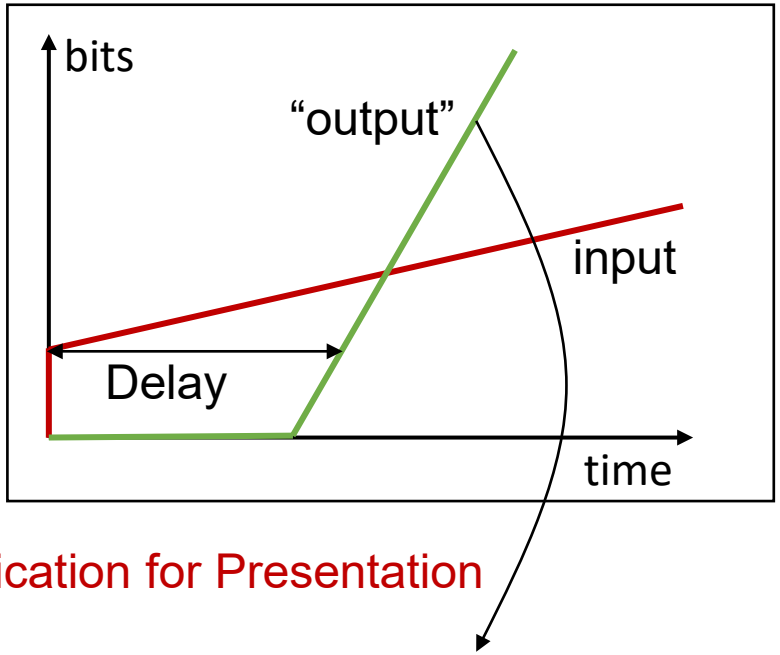
- Modeling of Communication Systems
- Worst-Case Performance Guarantees:
  max. Delays, max. Buffer Sizes, max. Output, …
- Cumulative Functions:
  max. Arrival Curve $\alpha(t)$ and min. Service Curve $\beta(t)$





Delay Guarantees

Effect on Network Delays

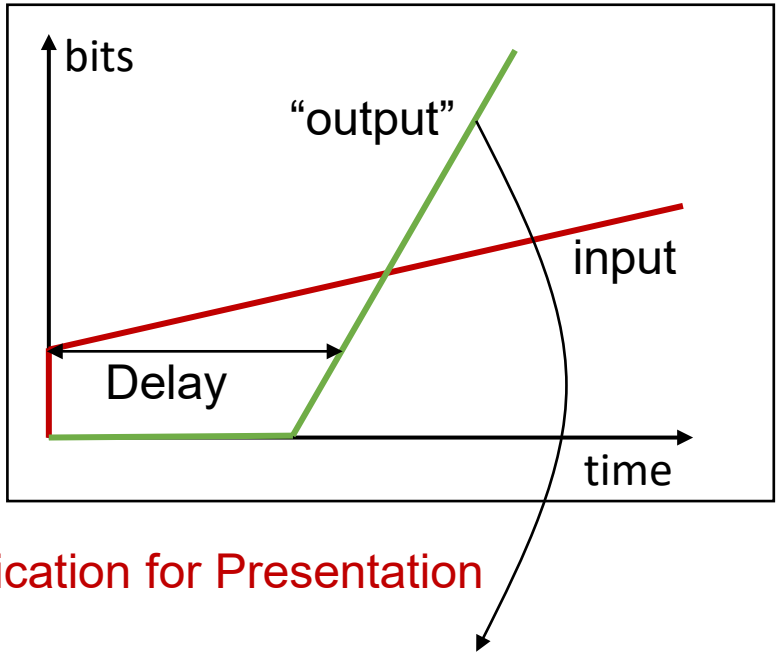


Simplification for Presentation

service curve / min. guaranteed forwarding:
defined, e.g., by idleSlopes, quantums, etc. of the queues

Delay Guarantees

Effect on Network Delays

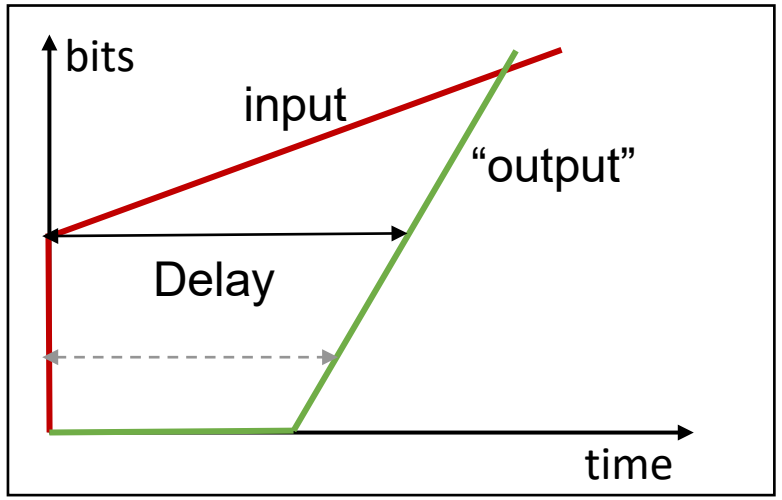


Simplification for Presentation

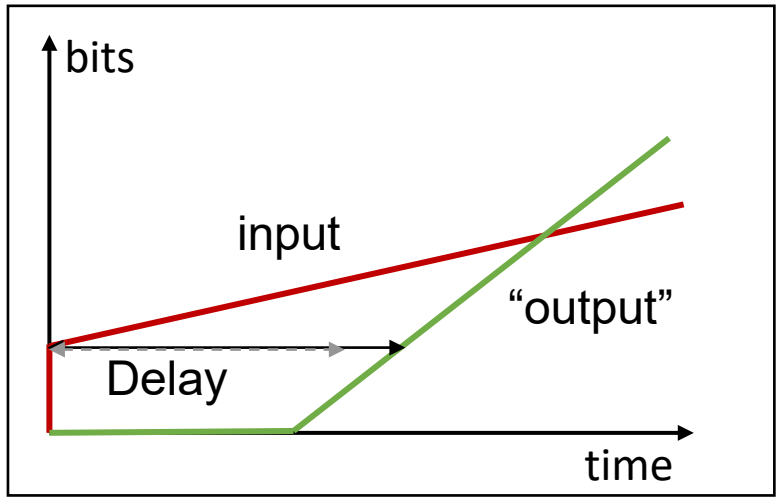
service curve / min. guaranteed forwarding:
defined, e.g., by idleSlopes, quantums, etc. of the queues

Delay Increase

More Traffic
≈
More Input



Less Resources /
Lower IdleSlope
≈
Less Output



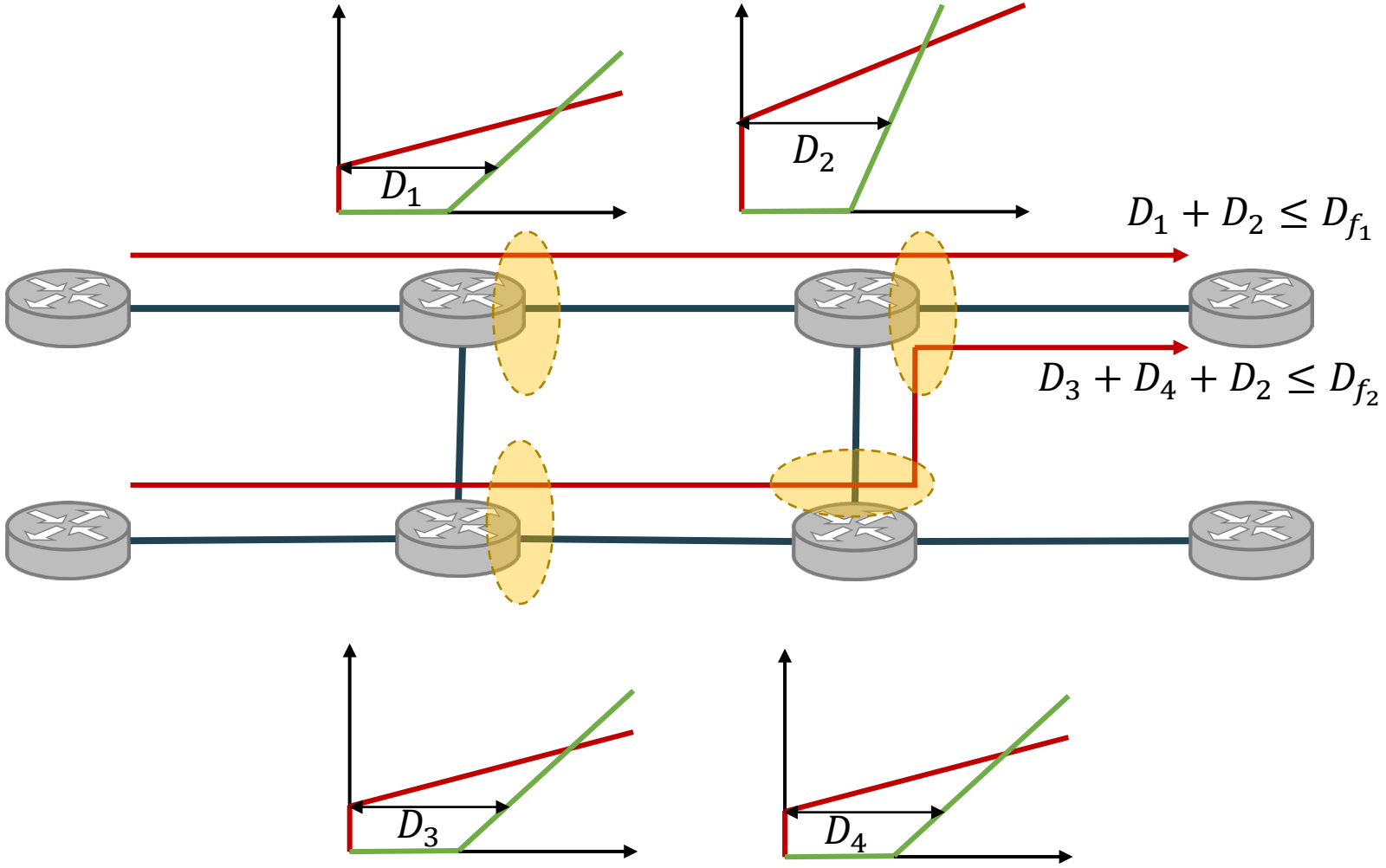
Offline vs. Online Network Flow Planning

Offline Optimization

Optimize the network in advance:

Offline Optimization

Delay Requirements fulfilled
+ optional objectives



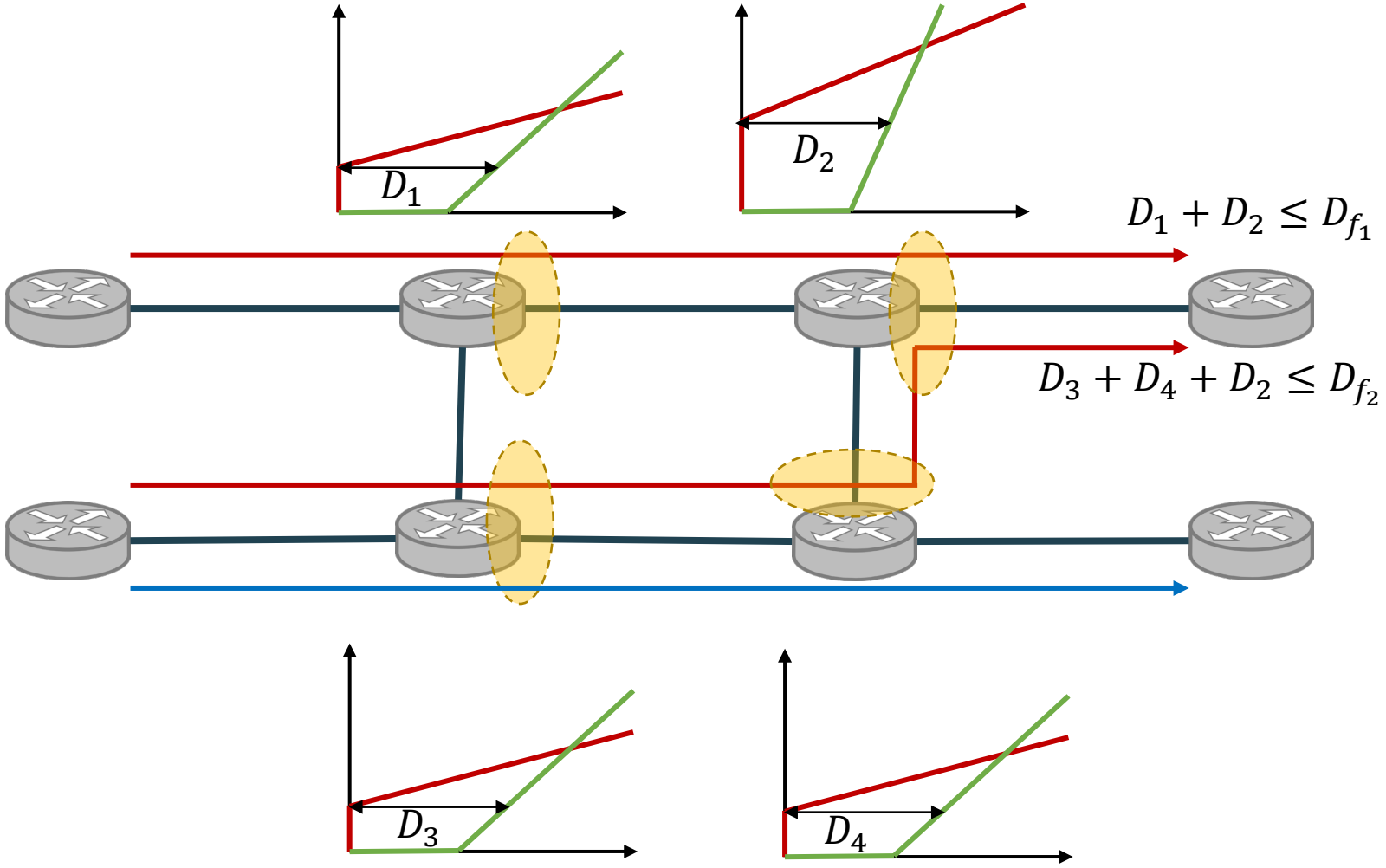
Offline vs. Online Network Flow Planning

Offline Optimization

Optimize the network in advance:

Offline Optimization

Delay Requirements fulfilled
+ optional objectives



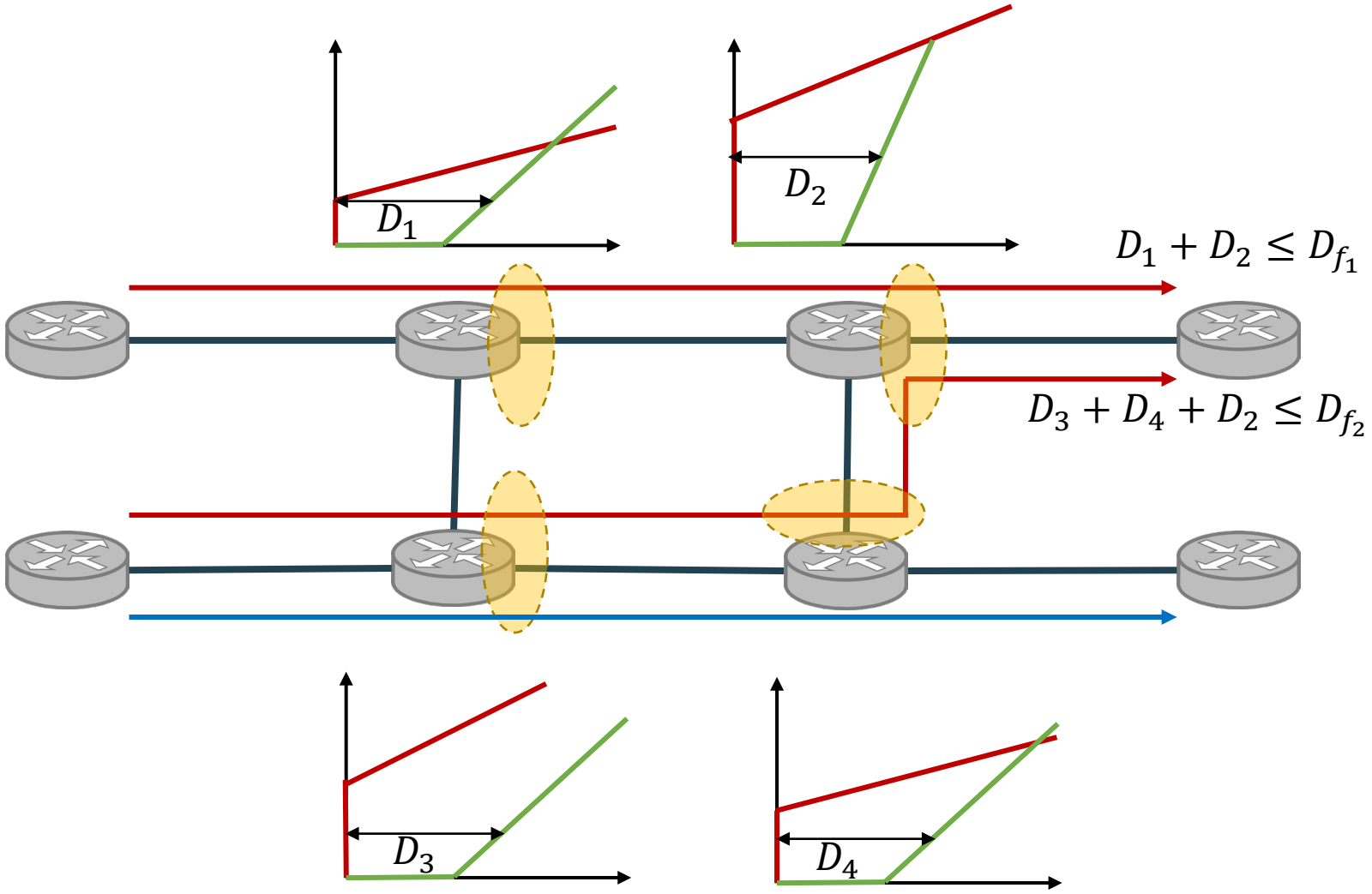
Offline vs. Online Network Flow Planning

Offline Optimization

Optimize the network in advance:

Offline Optimization

Delay Requirements fulfilled
+ optional objectives



Offline vs. Online Network Flow Planning

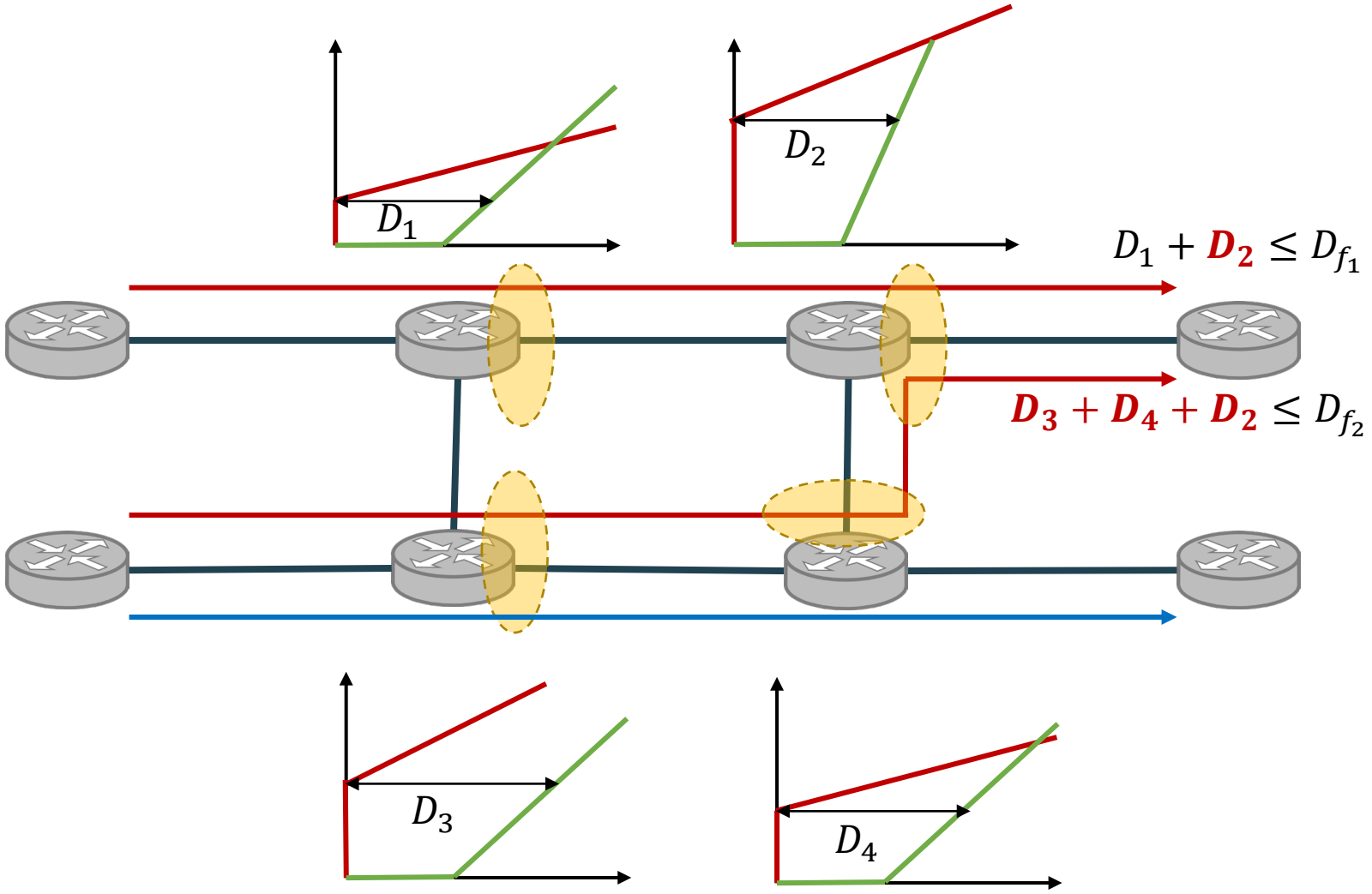
Offline Optimization

Optimize the network in advance:

Offline Optimization

Delay Requirements fulfilled
+ optional objectives

New Flows
→ Re-Validation of (whole) Network



Offline vs. Online Network Flow Planning

Offline Optimization

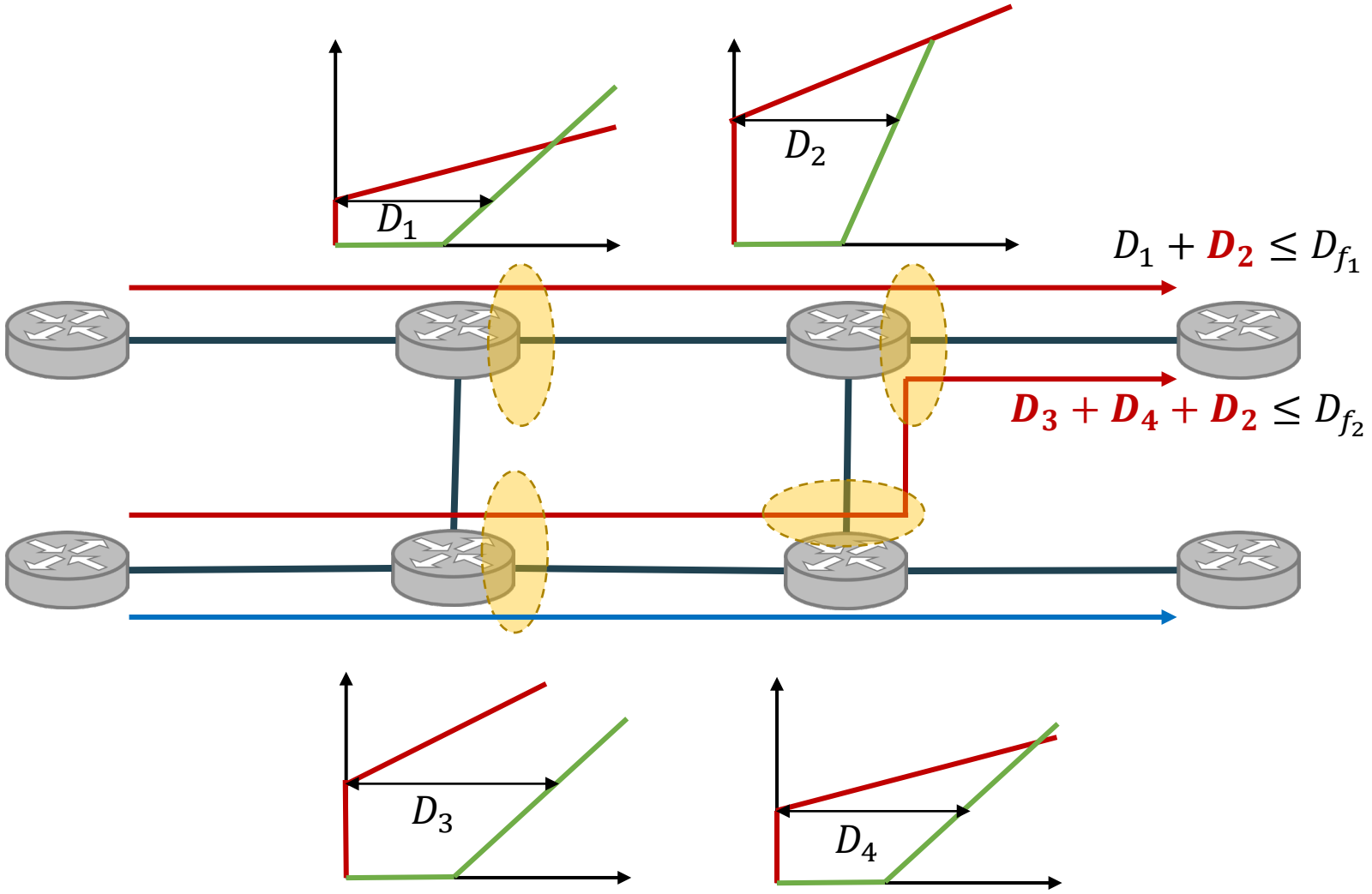
Optimize the network in advance:

Offline Optimization

Delay Requirements fulfilled
+ optional objectives

New Flows
→ Re-Validation of (whole) Network

Offline Optimization does not allow for new Flows during Runtime



Offline vs. Online Network Flow Planning

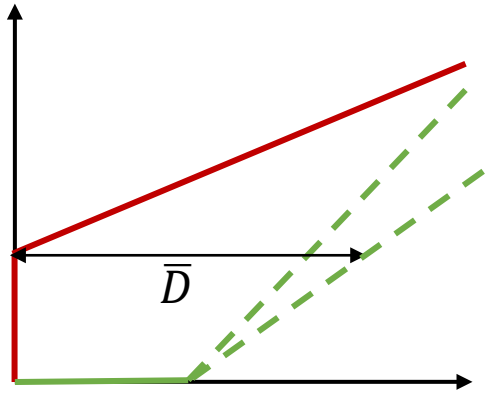
Online Admission Control

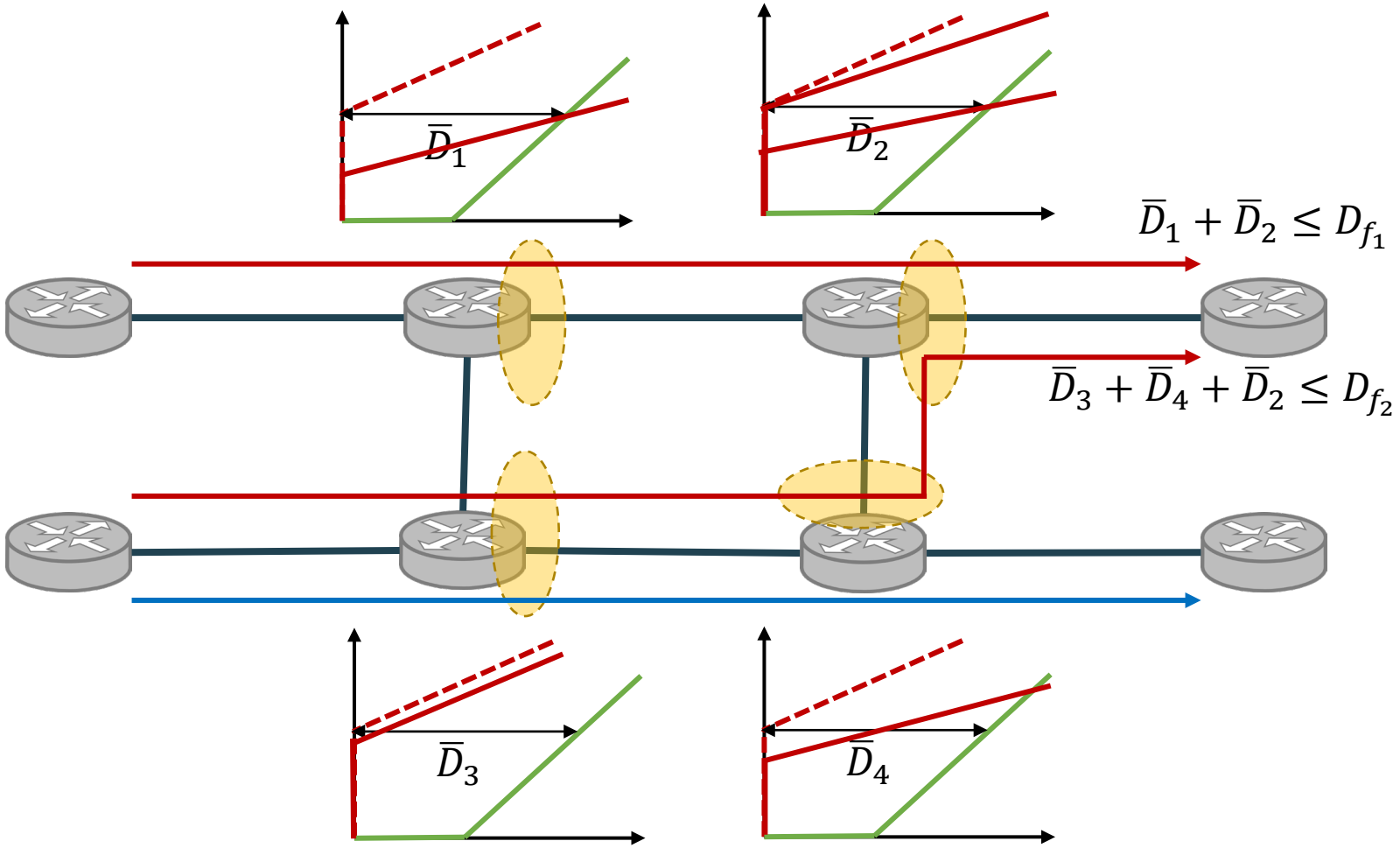
Alternative:

Online Admission Control

Delay
Defines ~~Resource~~ Budgets

Actual Delay ≤ Delay Budget





Offline vs. Online Network Flow Planning

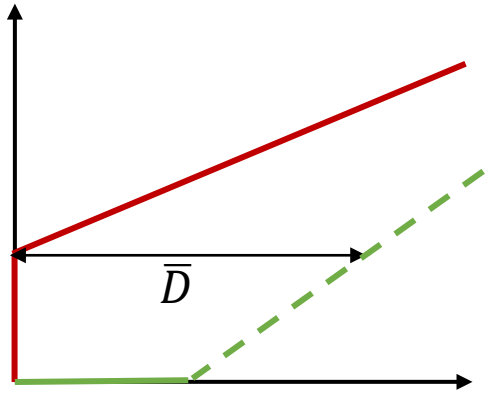
Online Admission Control

Alternative:

Online Admission Control

Delay
Defines ~~Resource~~ Budgets

Actual Delay ≤ Delay Budget



1. How to validate the delay budgets / calculate the actual delay?
2. How to choose the delay budgets?
3. How to reserve the flows?

Framework

Design Aspects

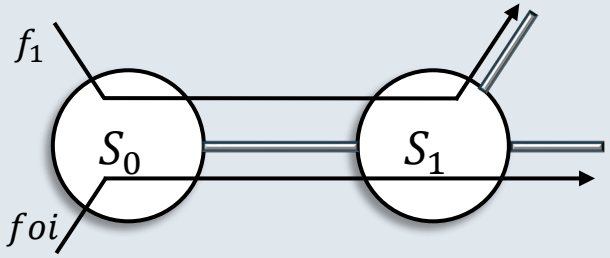
1. How to validate the delay budgets?
2. How to choose the delay budgets?
3. How to reserve the flows?

Delay Analysis Framework

Min-Plus Algebra

- Arrival Curve: $\forall s \leq t\colon R(t) - R(s) \leq \alpha(t-s)$
- Strict Service Curve: $\forall$ backlog-period $]s,t]\colon R^*(t) - R^*(s) \geq \beta(t-s)$
- Aggregation: $(\alpha_{f_1} + \alpha_{f_2})(t) = \alpha_{f_1}(t) + \alpha_{f_2}(t)$
- Max. Output: $(\alpha \oslash \beta)(t) = \sup_{u \geq 0}\{\alpha(t+u) - \beta(u)\}$
- Ind. Service Curve: $(\alpha \ominus \beta)(t) = \sup_{u \geq 0}\{\beta(u) - \alpha(u)\}$
- Max. Delay: $\mathrm{D}(\alpha,\beta) = \sup_{t \geq 0}\{\inf_{d \geq 0}\{d : \alpha(t) \leq \beta(t+d)\}\}$

Example



$$D_{foi}^{max} = D_{S_0} + D_{S_1}$$

$$D_{S_0} = D(\alpha_{S_0}, \beta_{S_0})$$

$$D_{S_1} = D(\alpha_{S_1}, \beta_{S_1})$$

$$\alpha_{S_0} = \alpha^{f_1} + \alpha^{f_{foi}}$$

~~$\alpha_{S_1} = \alpha^{f_{foi}} \oslash (\beta_{S_0} \ominus \alpha^{f_1})$~~

$$\alpha_{S_1} = \alpha^{f_{foi}}(t + \overline{D}_{S_0} + \underline{D}_{S_0})$$

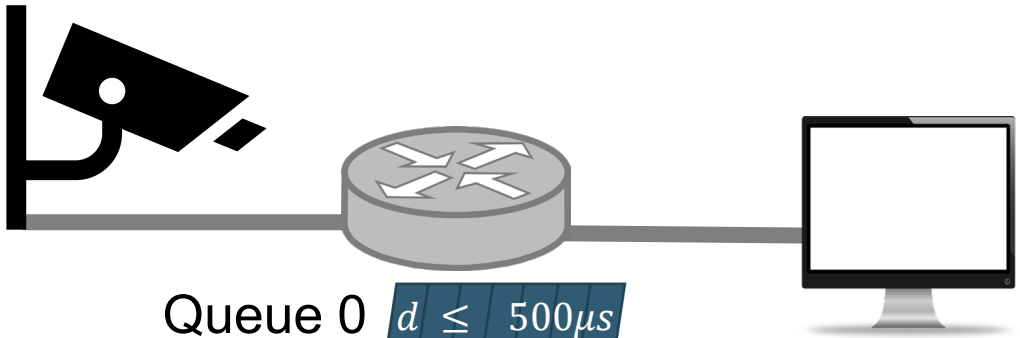
1 How to validate the delay budgets?

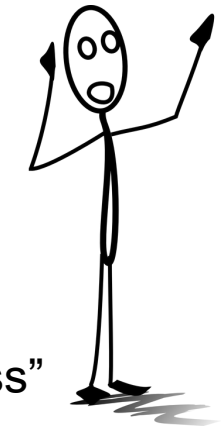
2 How to choose the delay budgets?

3 How to reserve the flows?

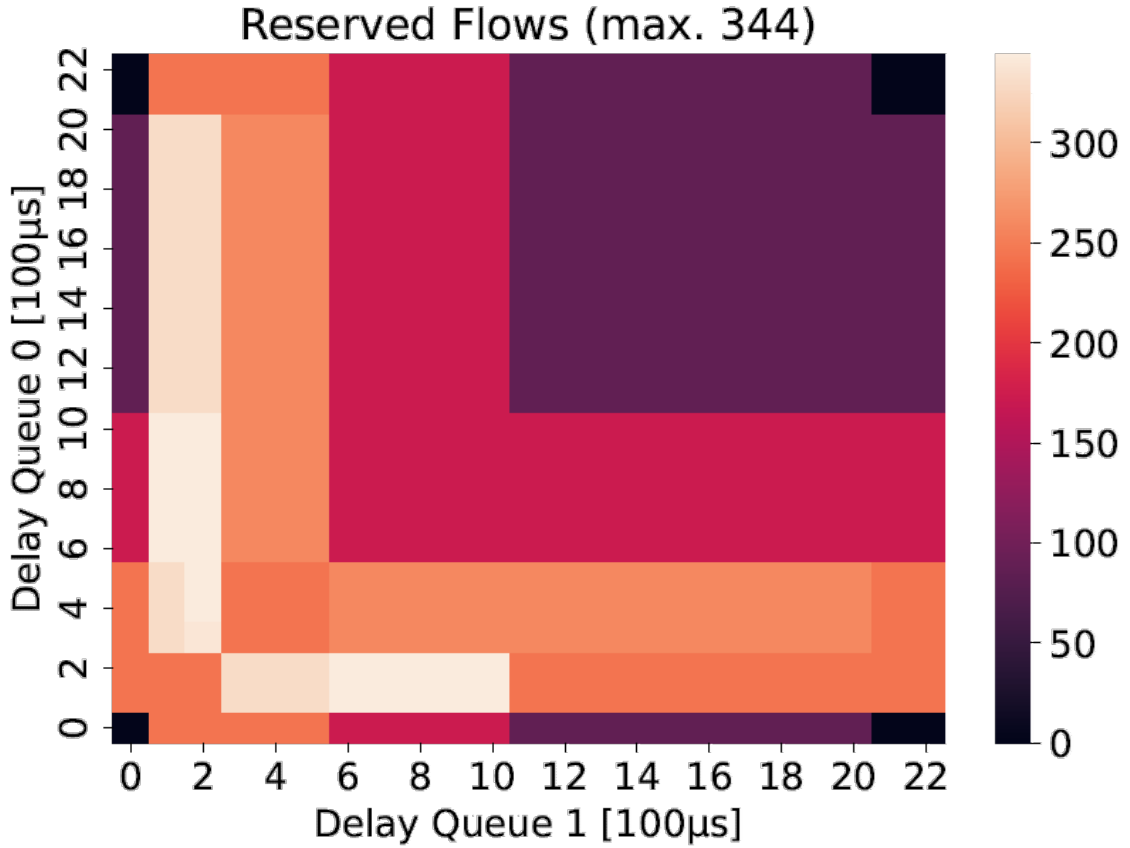
Delay Budgets

Importance

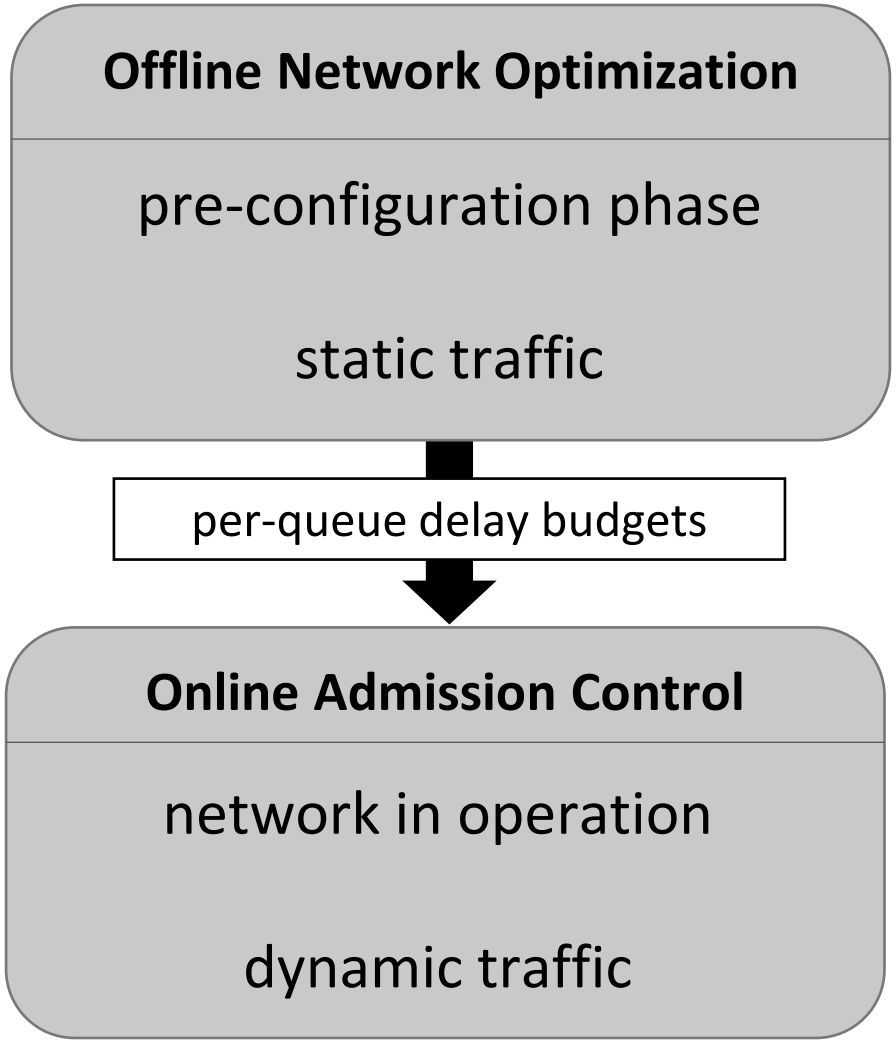




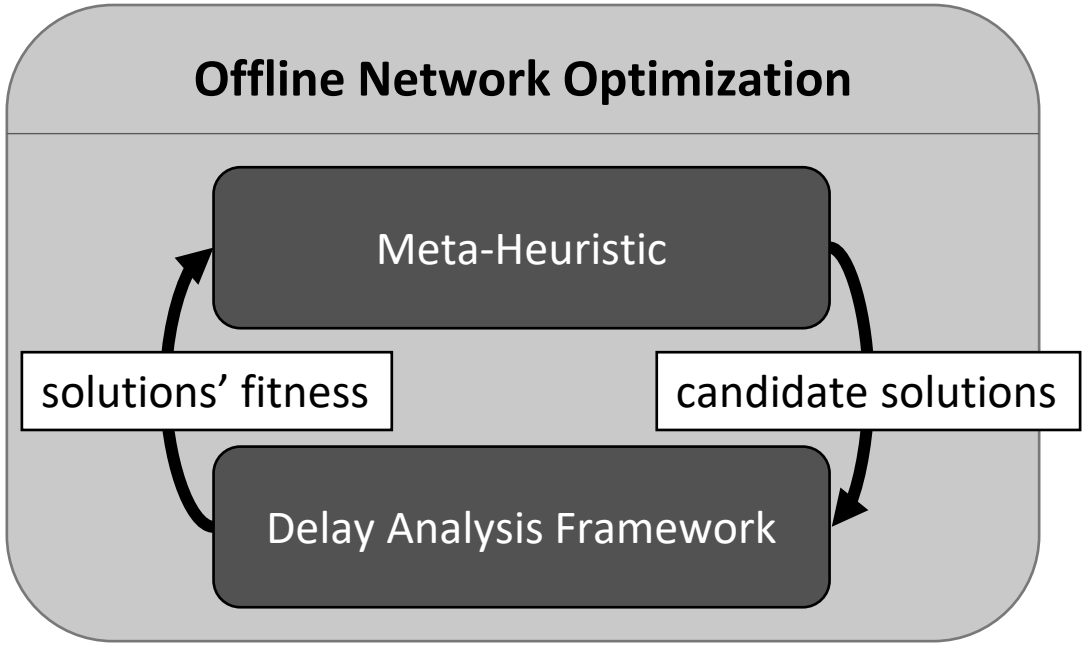
State of the Art: “Educated Guess”



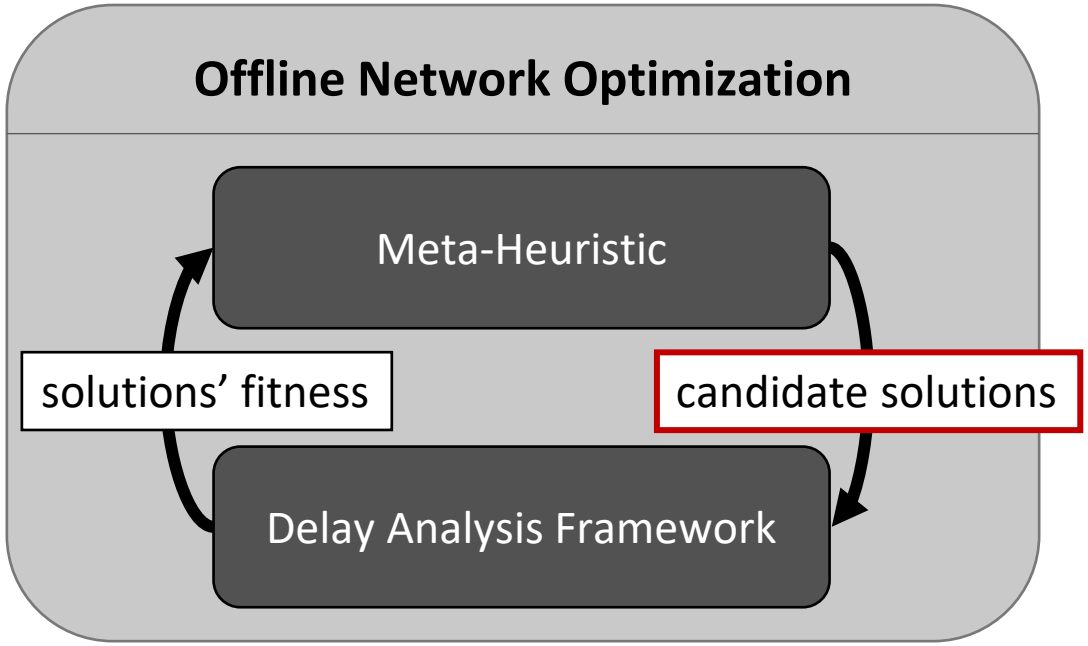
Framework

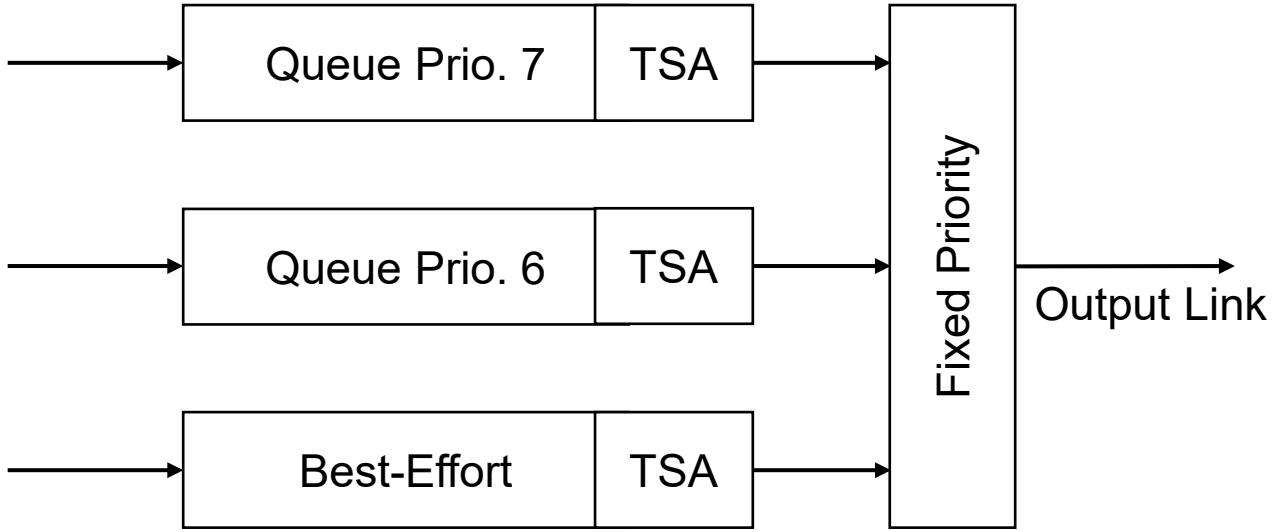

Offline Network Optimization
pre-configuration phase
static traffic
per-queue delay budgets
Online Admission Control
network in operation
dynamic traffic

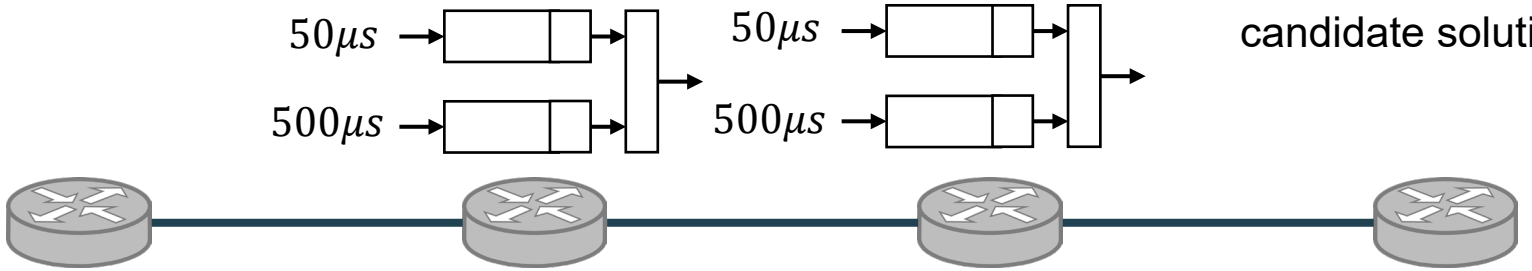
Candidate Solutions



Candidate Solutions



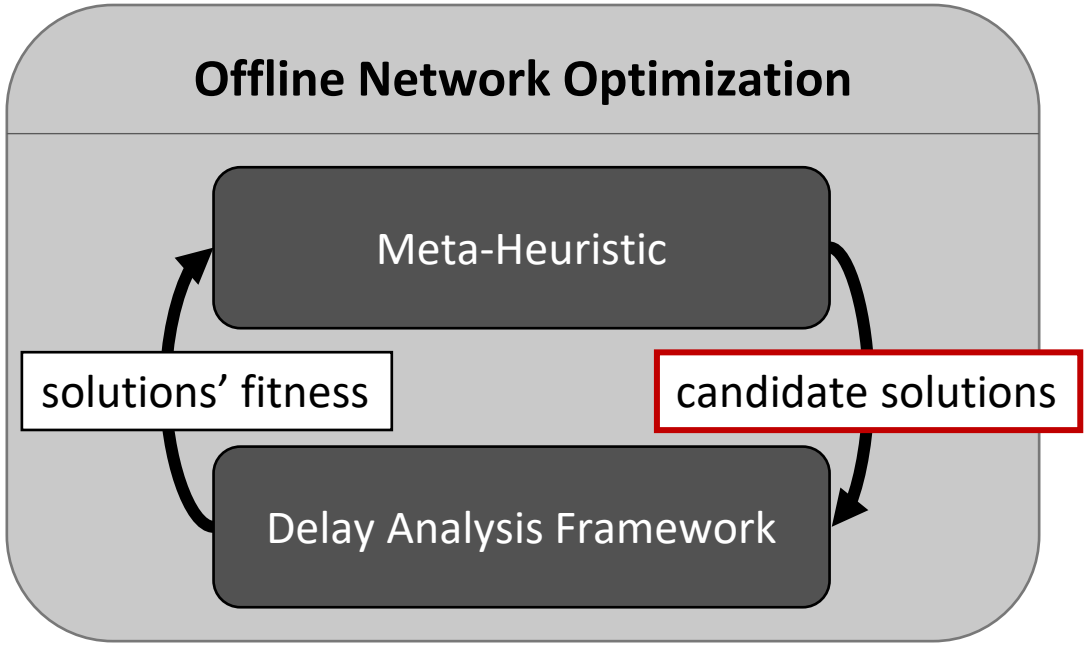


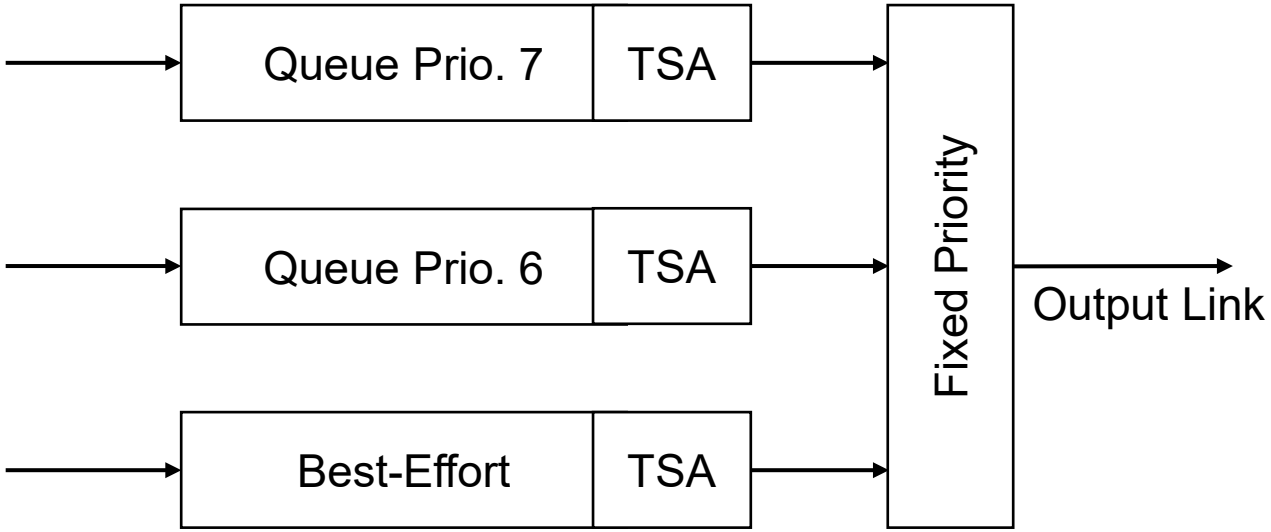


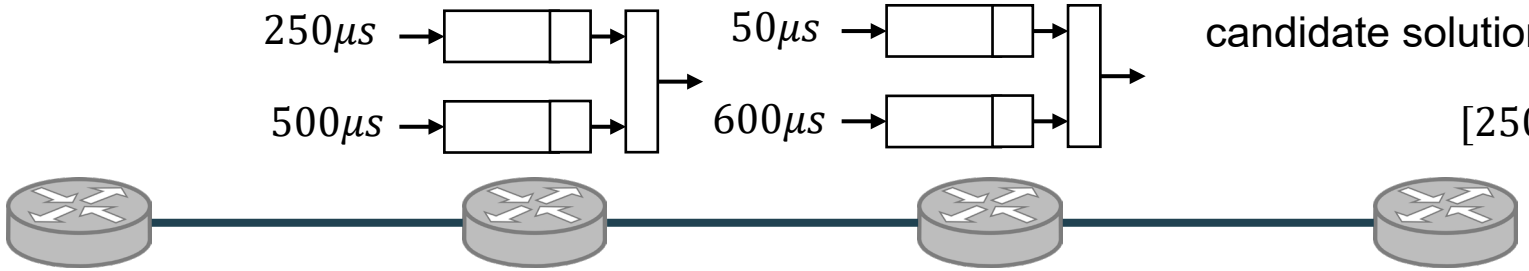
candidate solution with uniform delays:

$[50\mu s, 500\mu s]$

Candidate Solutions



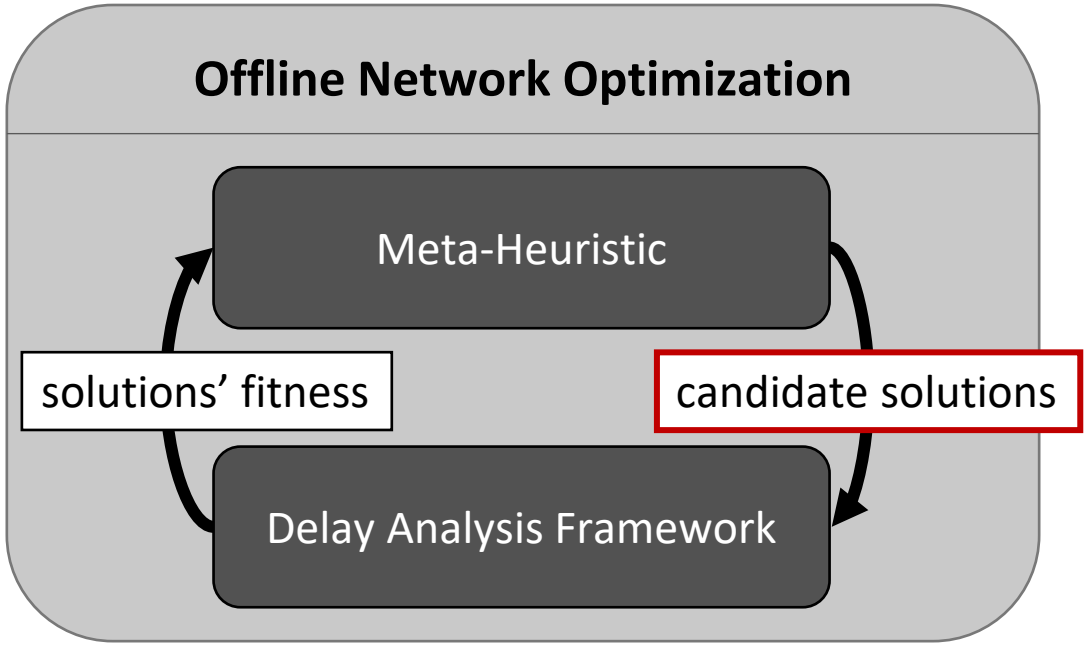


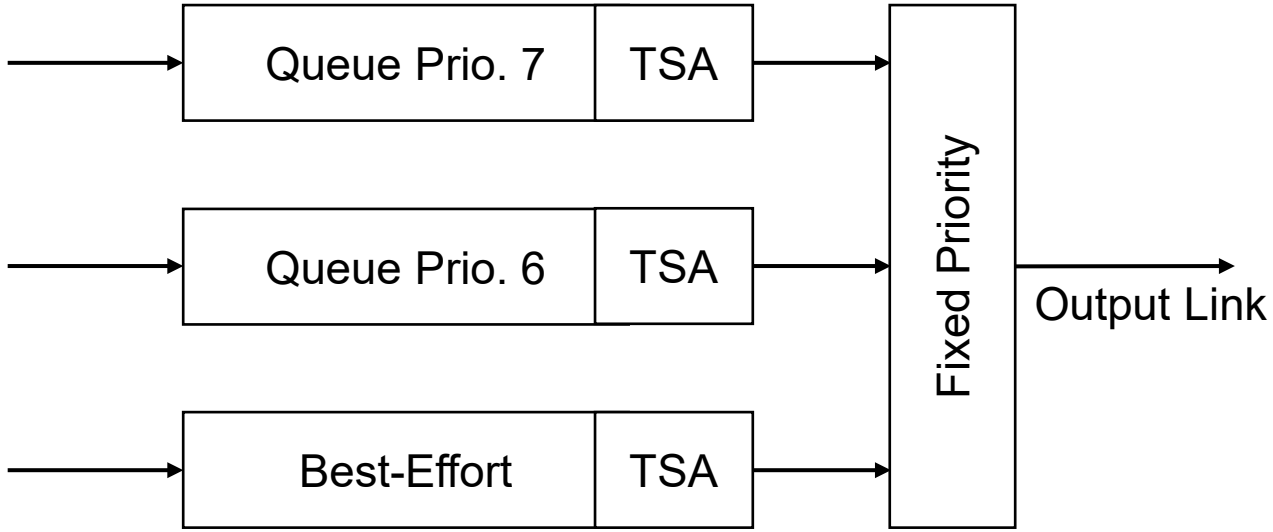


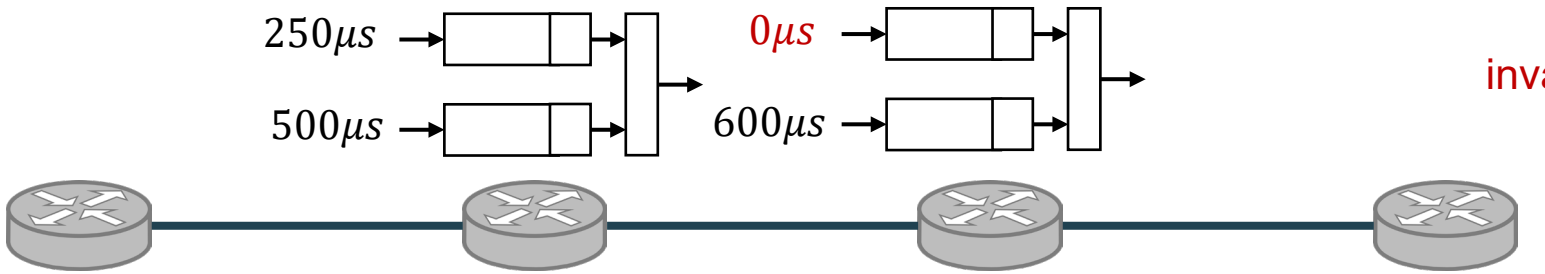
candidate solution with individual delays:

$[250\mu s, 500\mu s, 50\mu s, 600\mu s]$

Candidate Solutions

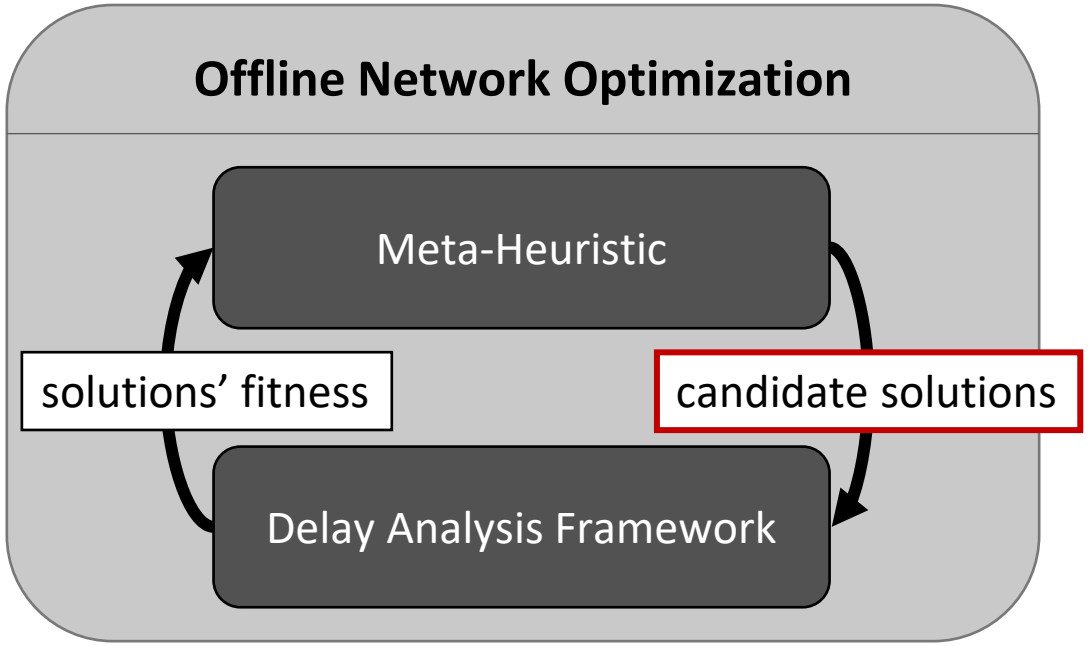


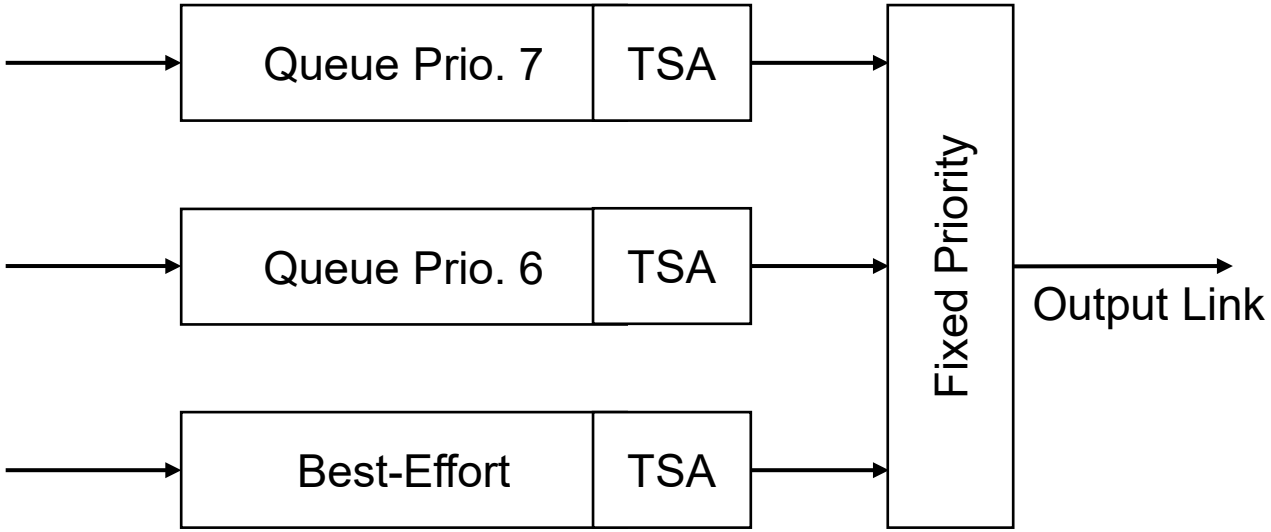


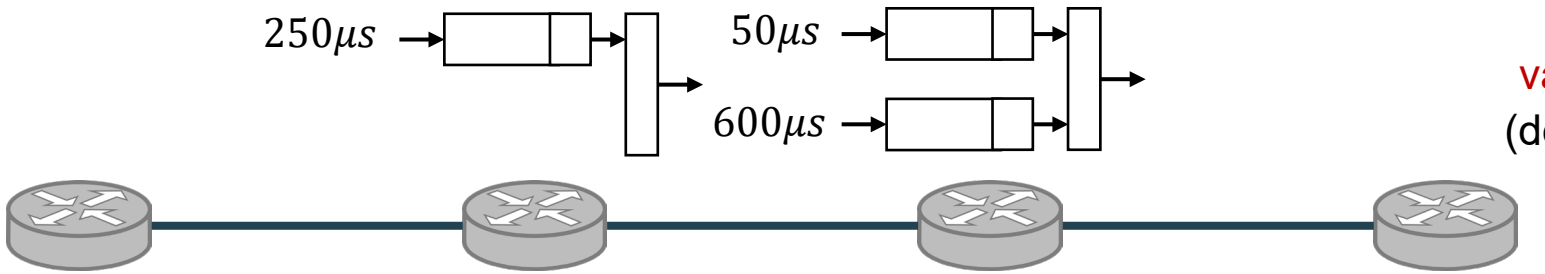


invalid candidate solution

Candidate Solutions





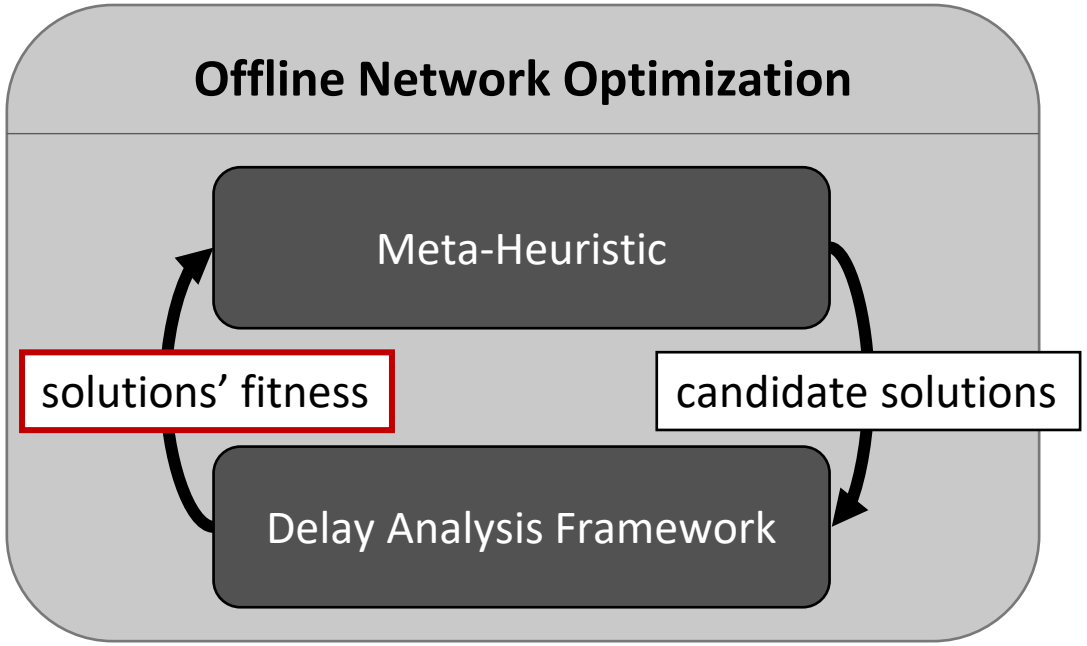


valid candidate solution
(defines no. of priorities)

Design Aspects

Solution‘s Fitness

Fitness / Reward Function



Solution‘s Fitness

Fitness / Reward Function

$$f(s) = \omega_1 \cdot f_R(s) + \omega_2 \cdot f_A(s) + \omega_3 \cdot f_D(s),\ \omega_1 + \omega_2 + \omega_3 = 1$$

$f_R(s) = 1$

if all static flows are reserved

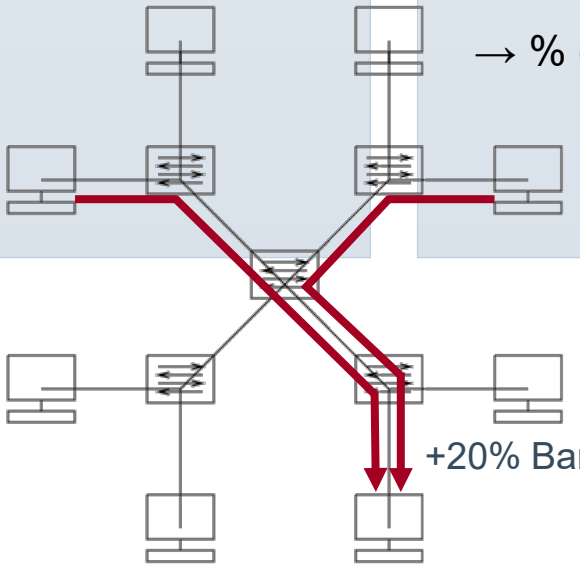
$f_A(s) = 1$

if dynamic future flows “have space”
→ % of bandwidth for defined traffic classes

$f_D(s) = 1$

if end-to-end delays match deadline requirements (within 30% interval)

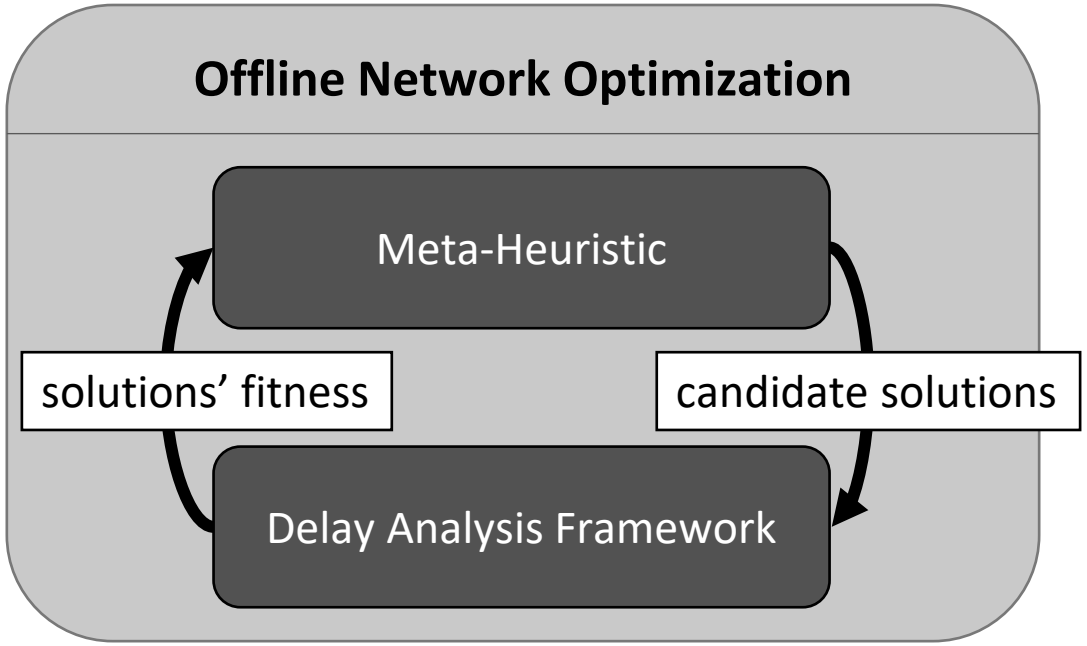
→ because low delays require more resources



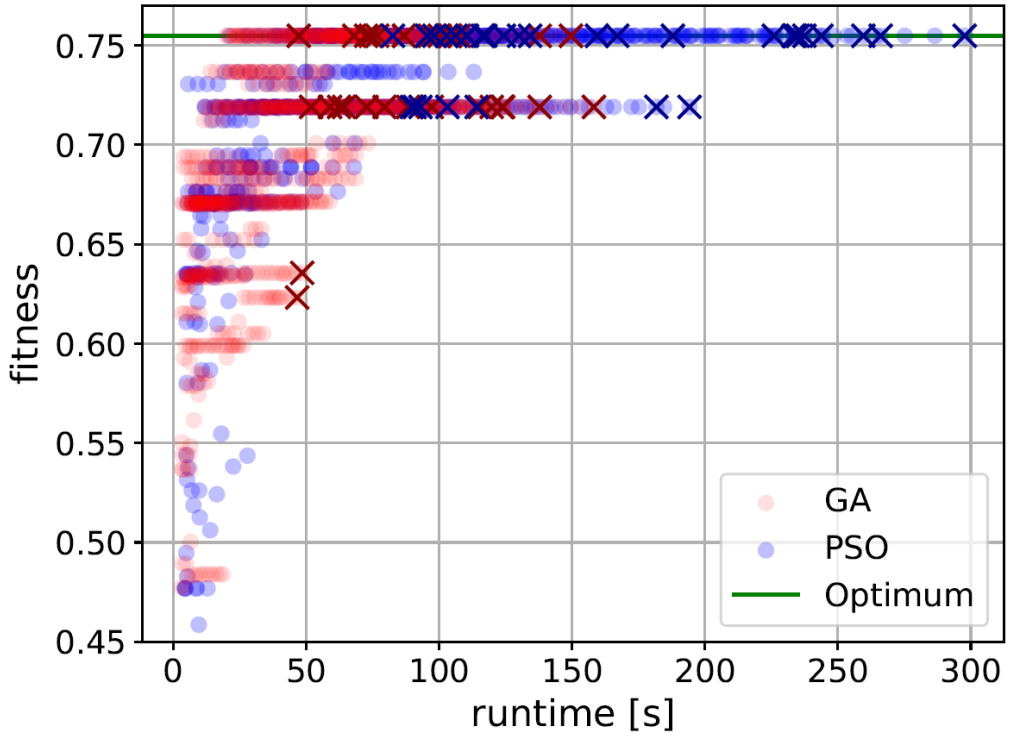
+20% Bandwidth for Profile X

	Sending Interval	Max. Frame Size	Max. Latency
Profile 1	250 µs	64B	250 µs
Profile 2	500 µs	128B	500 µs
Profile 3	1000 µs	256B	1000 µs
Profile 4	2000 µs	512B	2000 µs
Profile 5	4000 µs	1024B	4000 µs

Meta-Heuristic



Genetic Algorithm (GA)
vs.
Particle Swarm Optimization (PSO)



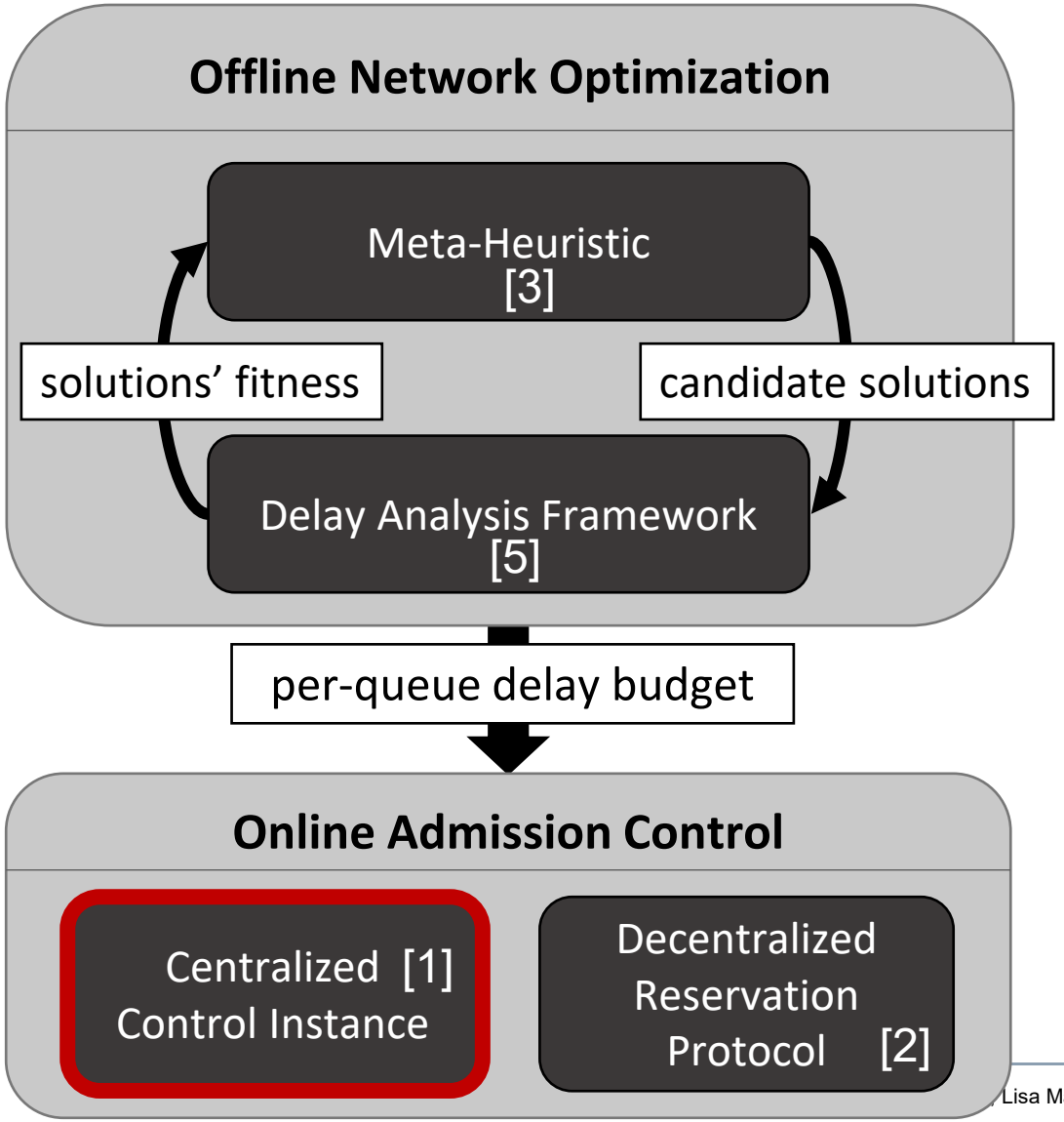
1 How to validate the delay budgets?

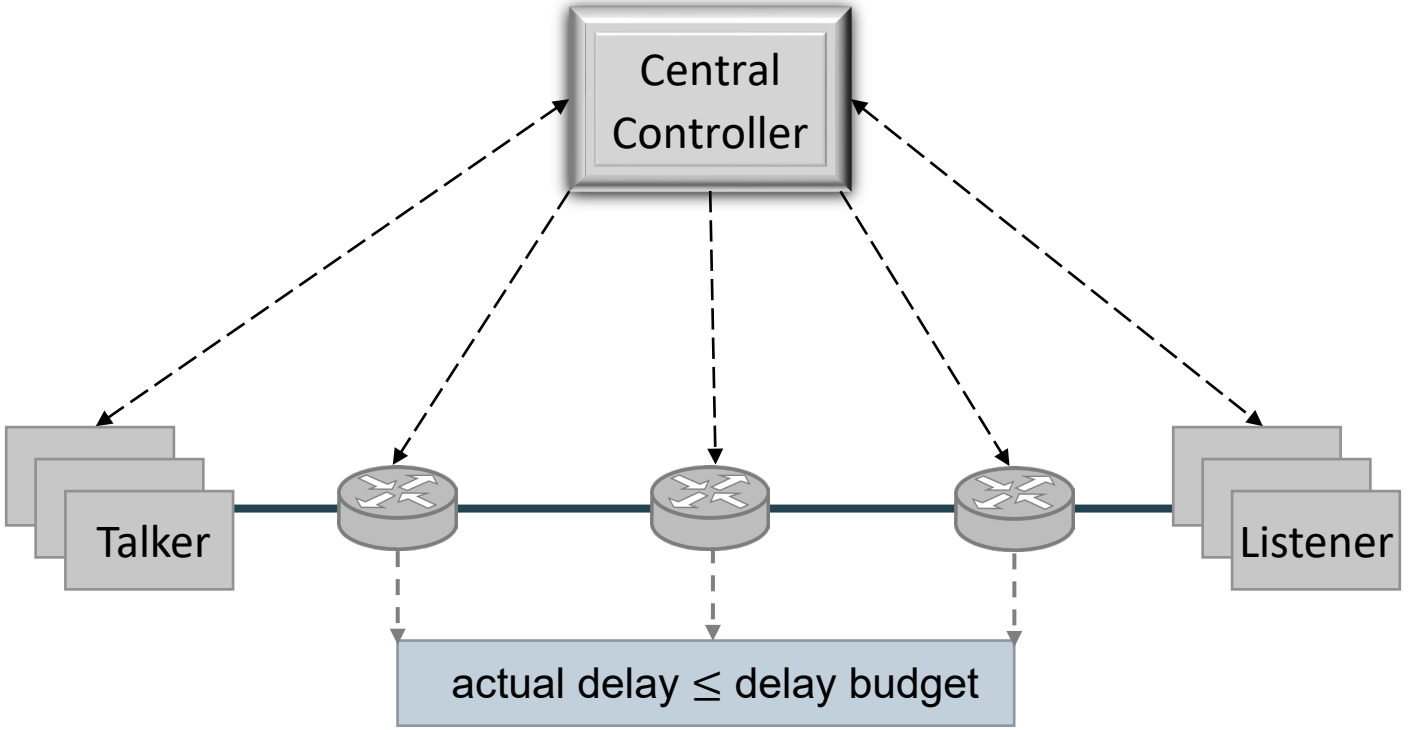
2 How to choose the delay budgets?

3 How to reserve the flows?

Framework Overview

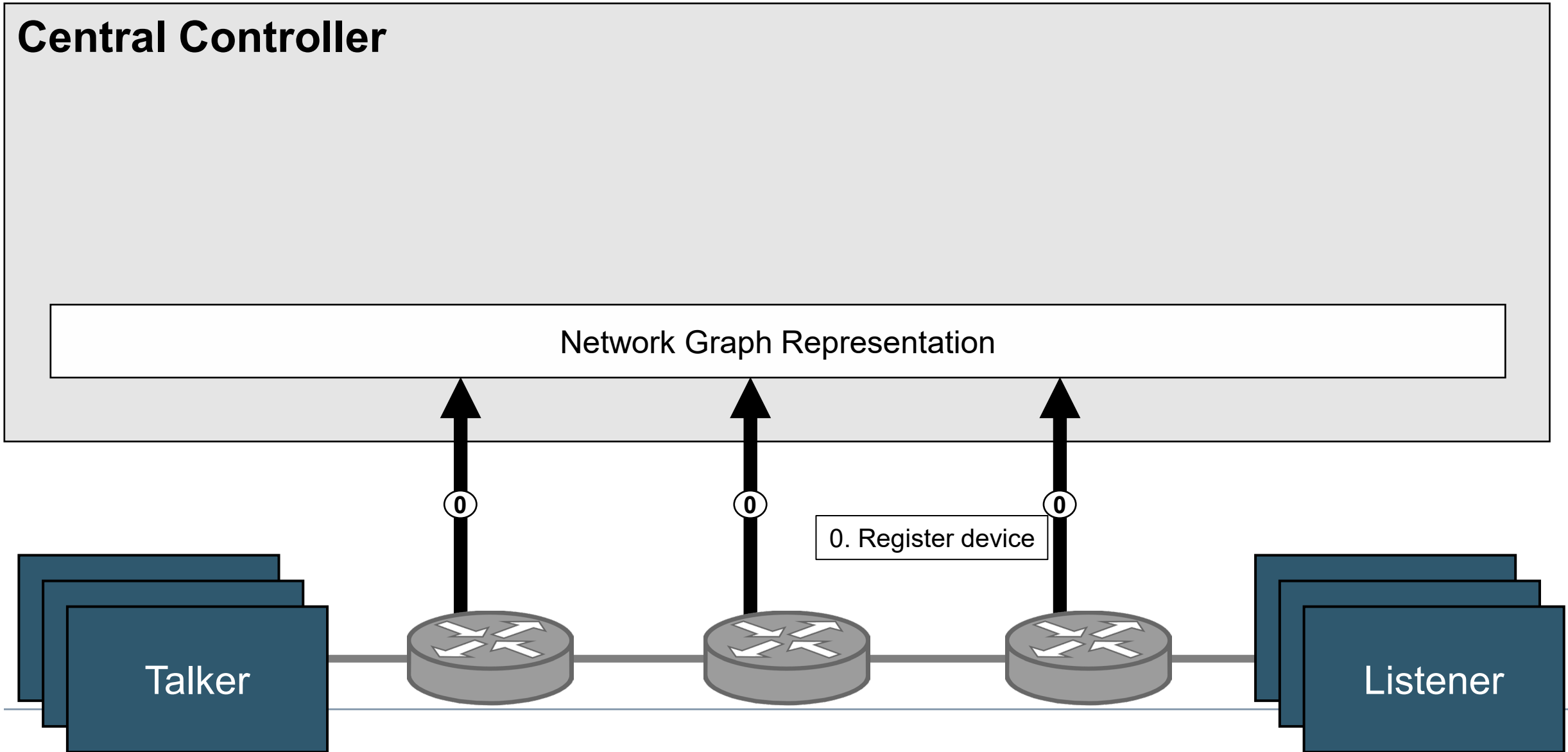
Combination of Offline and Online Control





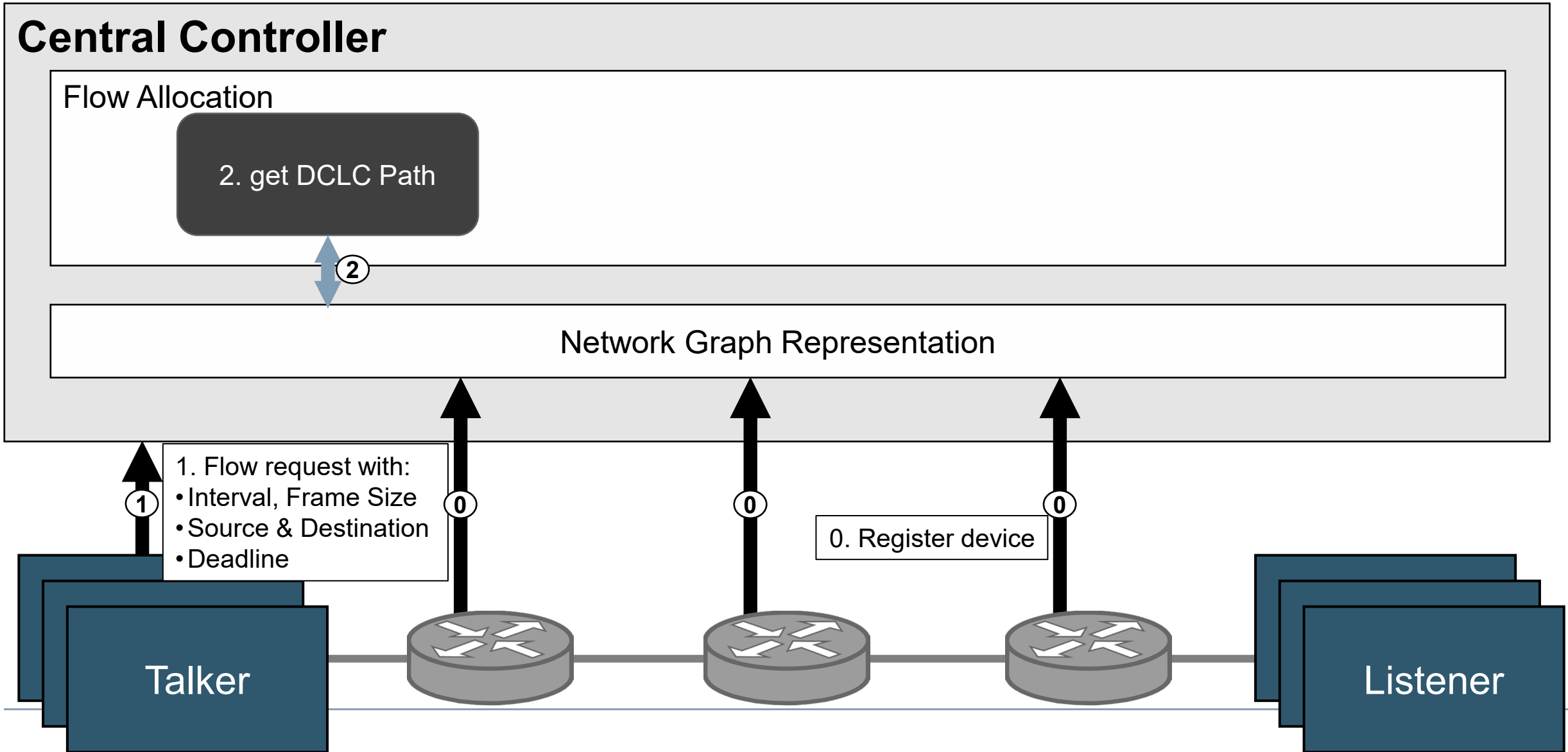
Flow Reservation

Central Controller



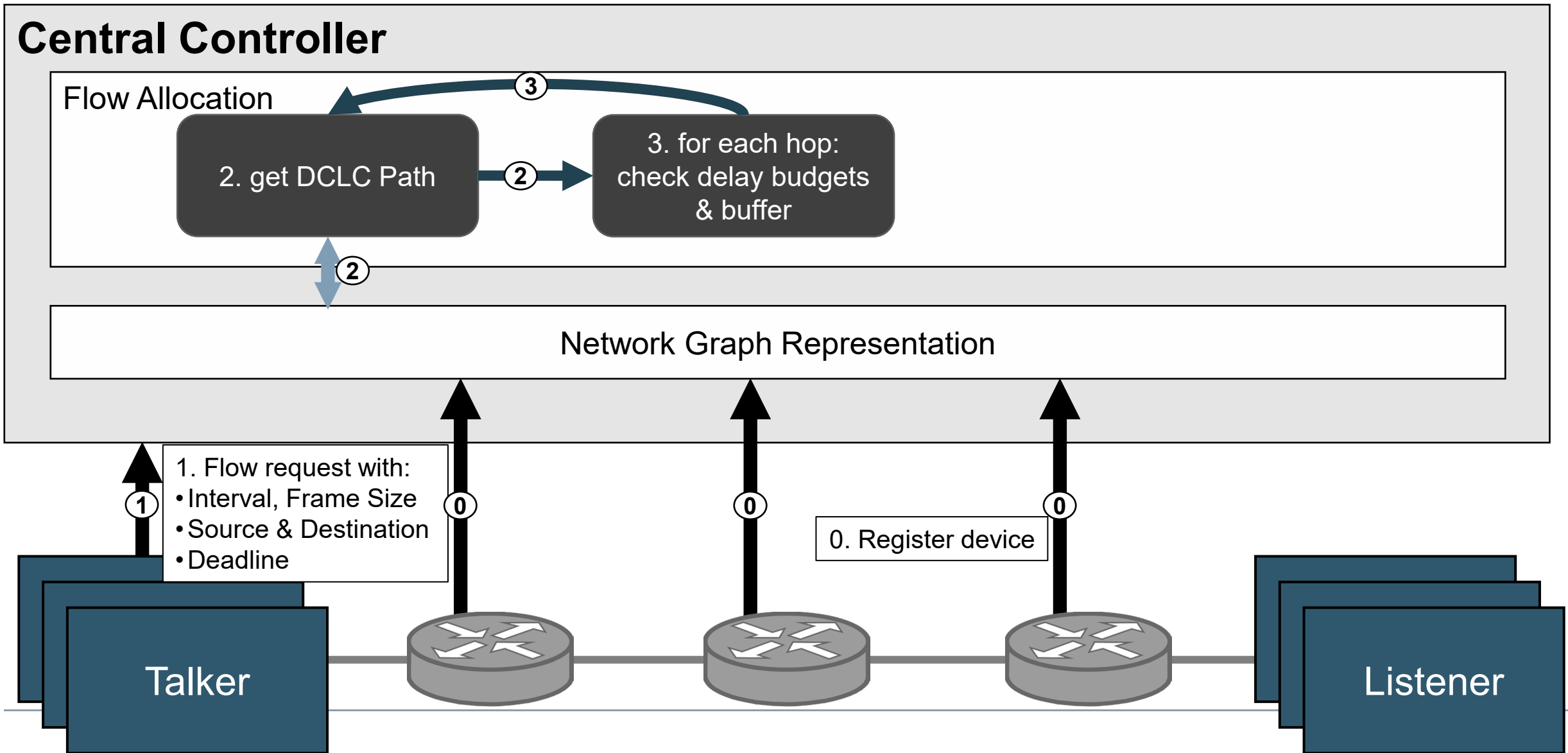
Flow Reservation

Central Controller



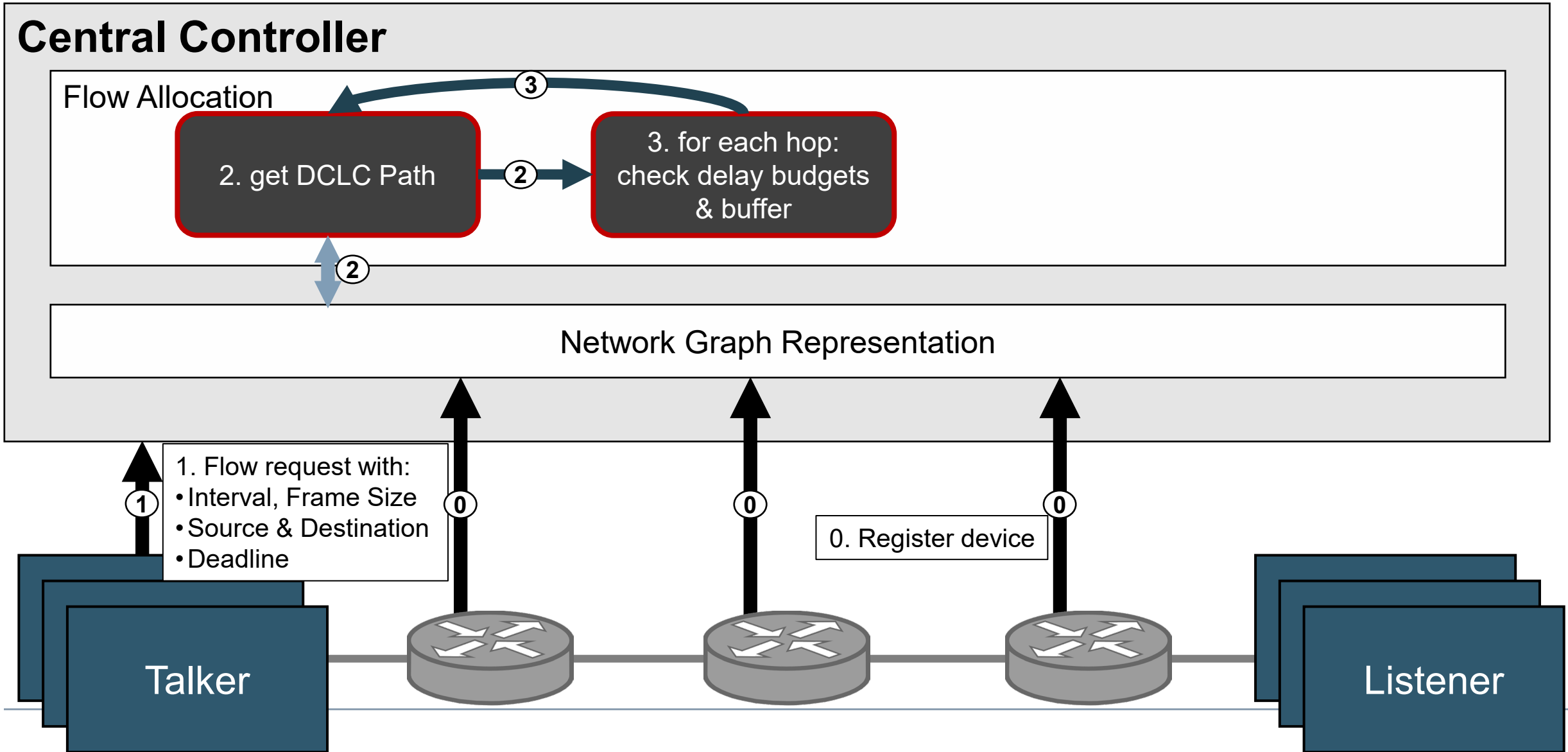
Flow Reservation

Central Controller



Flow Reservation

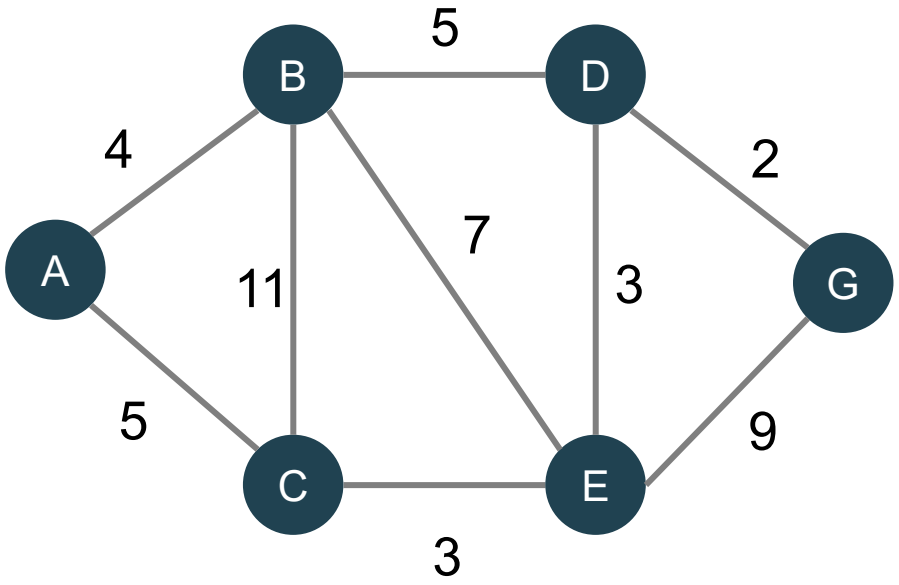
Central Controller



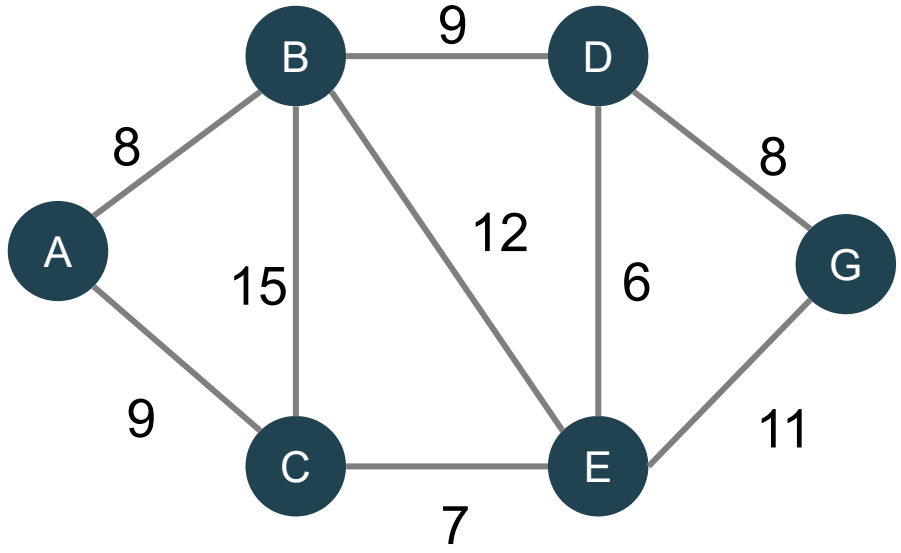
Flow Allocation

How to find the path(s)?

1. Delay Budgets can be used for Routing Algorithms ☺
2. Multiple Priorities: Separate Graph

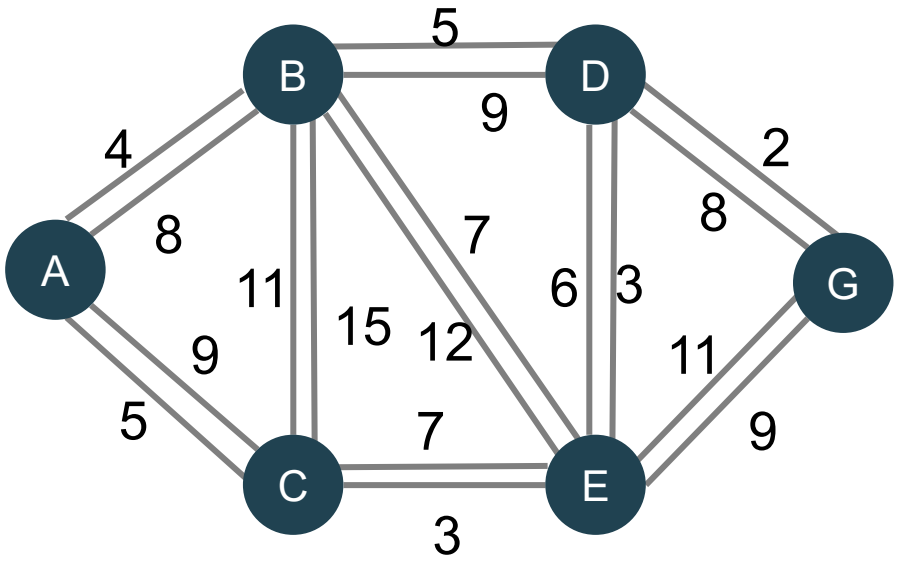


priority 7



priority 6

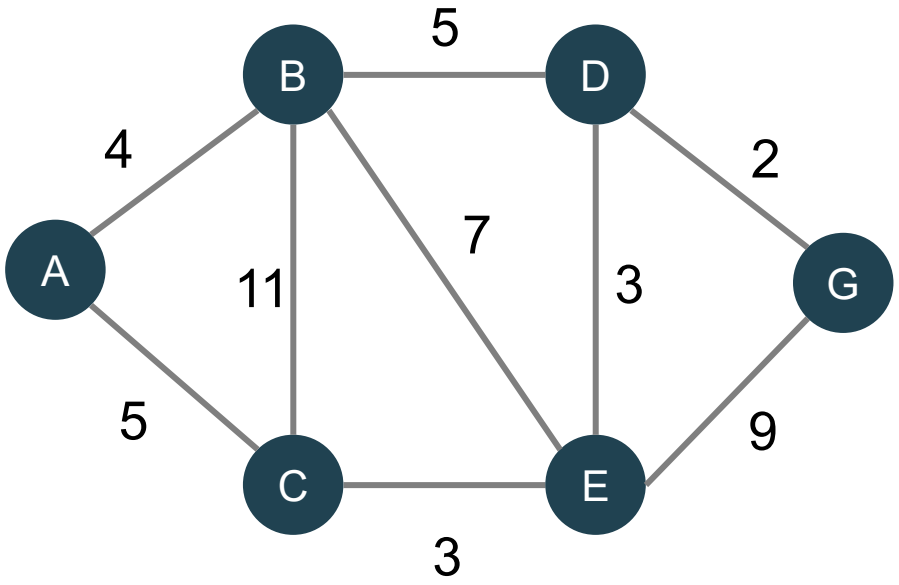
Flow Allocation



How to find the path(s)?

1. Delay Budgets can be used for Routing Algorithms ☺
2. Multiple Priorities: Separate Graph **or Combined**

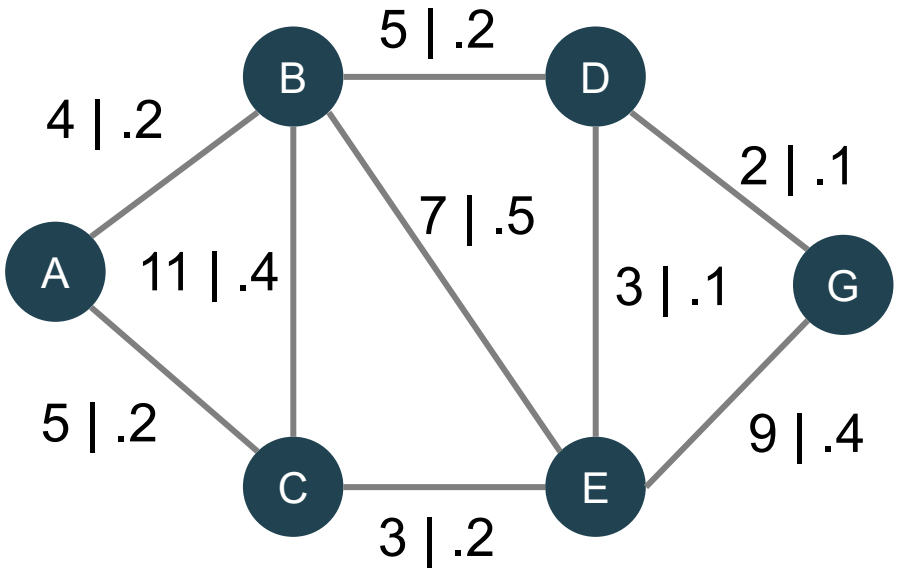
Flow Allocation



How to find the path(s)?

1. Delay Budgets can be used for Routing Algorithms ☺
2. Multiple Priorities: Separate Graph or Combined

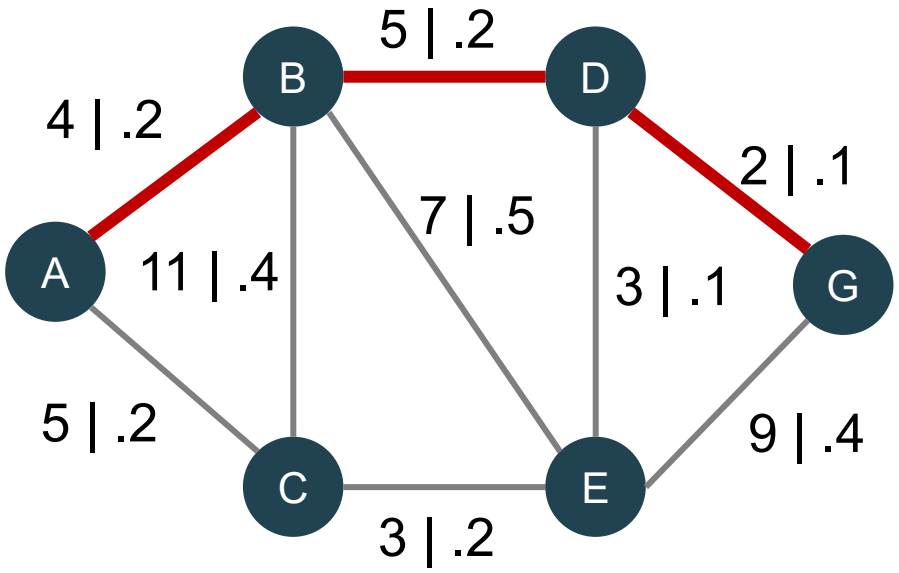
Flow Allocation



How to find the path(s)?

1. Delay Budgets can be used for Routing Algorithms ☺
2. Multiple Priorities: Separate Graph or Combined
3. “Bandwidth” Weights to Balance the Network

Flow Allocation

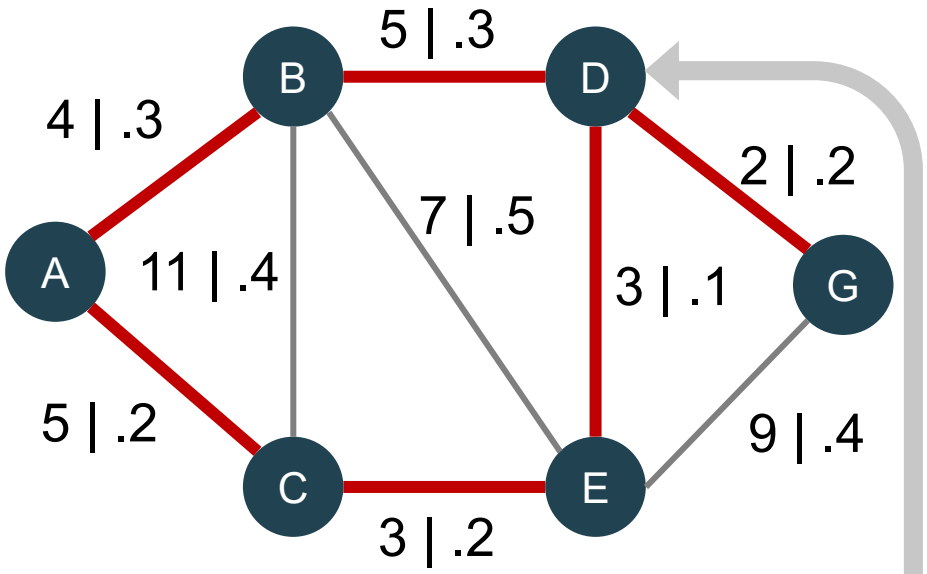


How to find the path(s)?

1. Delay Budgets can be used for Routing Algorithms ☺
2. Multiple Priorities: Separate Graph or Combined
3. “Bandwidth” Weights to Balance the Network
4. Algorithm:

```
until #paths found:
    get delay-constrained least-cost (DCLC) path
    check access
```

Flow Allocation



How to find the path(s)?

1. Delay Budgets can be used for Routing Algorithms ☺
2. Multiple Priorities: Separate Graph or Combined
3. “Bandwidth” Weights to Balance the Network
4. Algorithm:

```
until #paths found:
    get delay-constrained least-cost (DCLC) path
    check access
```

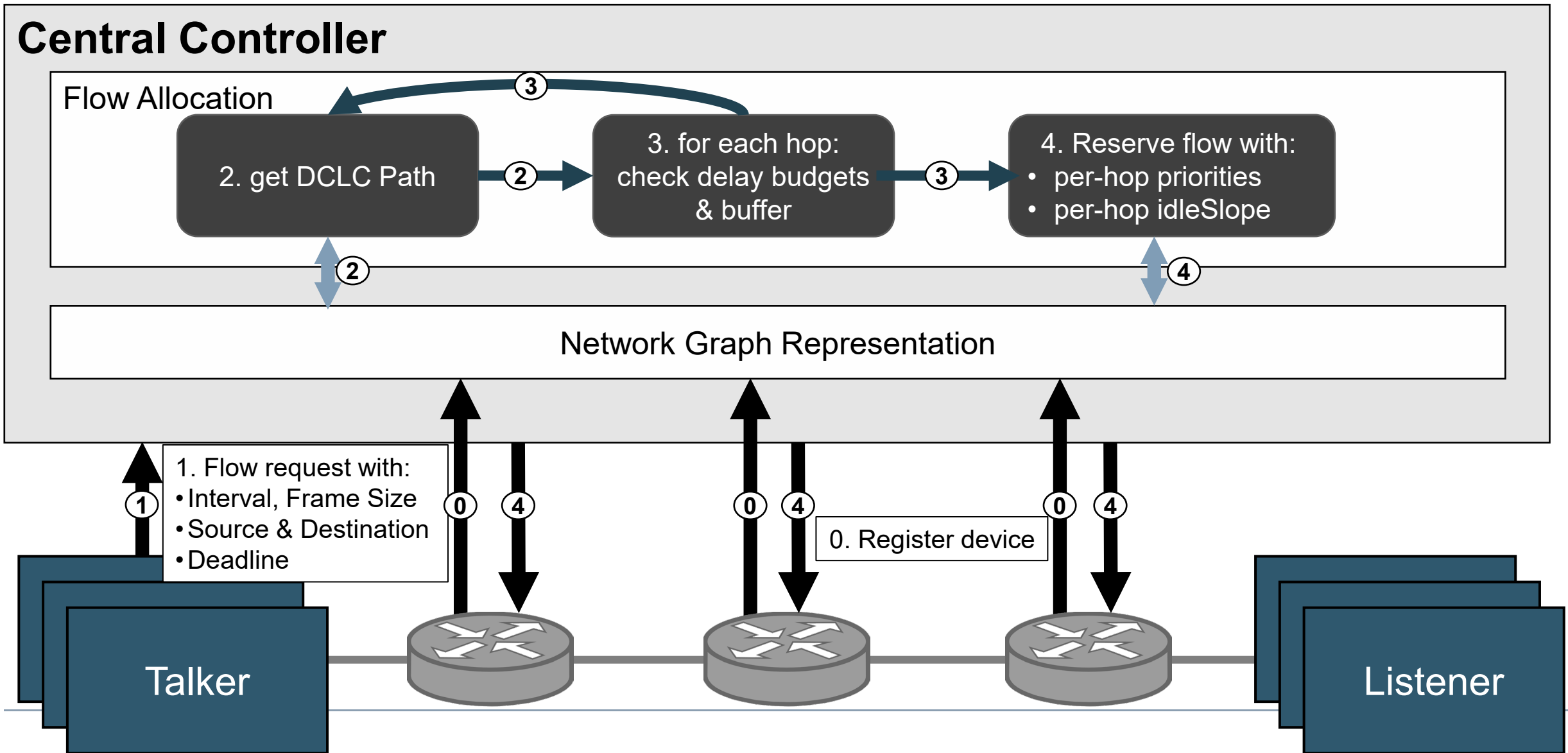
by adapting disjoint shortest path routing algorithms [6] (e.g., Suurballe, …)

5. Optional: Configure Redundancy Mechanisms [4] [7]

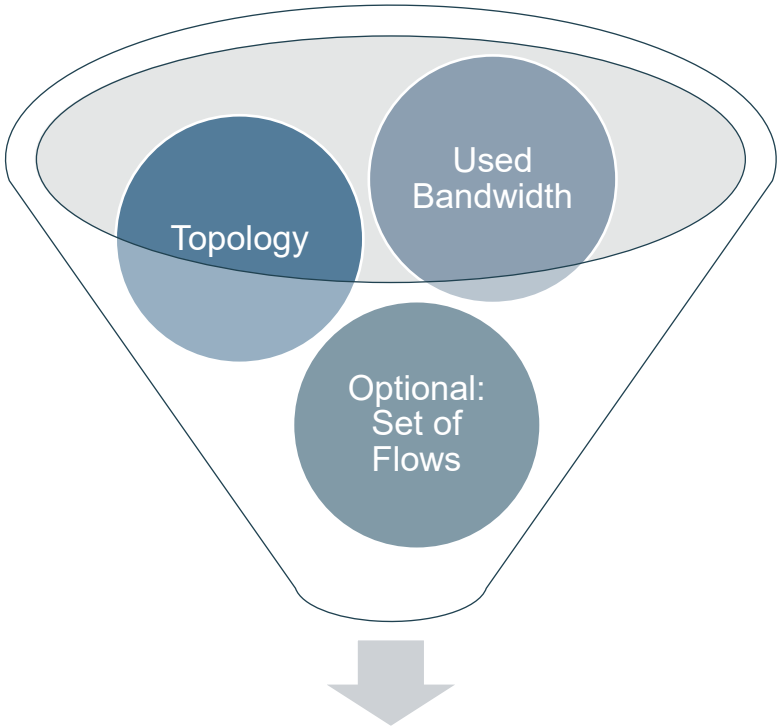
Design Aspects

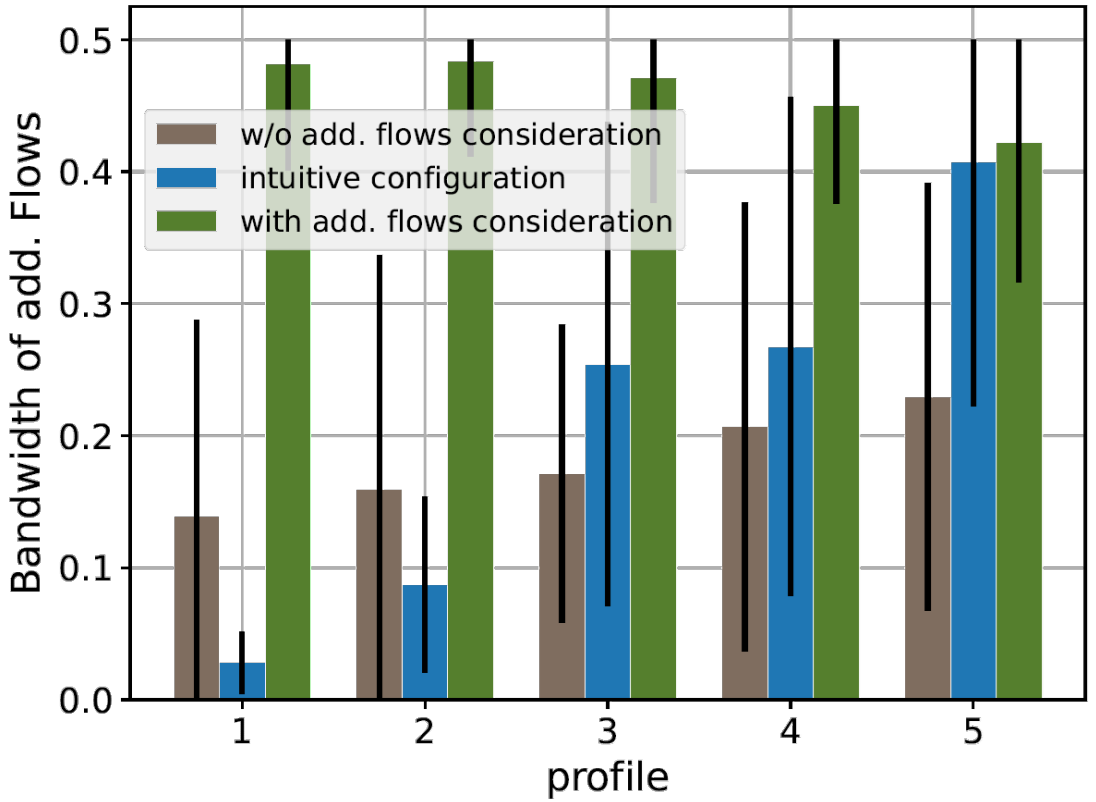
Flow Reservation

Central Controller



Result





Delay Guarantees → Forwarding Parameters → No. of Priority Queues → Prioritization → Path Selection → Redundancy Configuration

Conclusion

Conclusion

Ultra-reliable flows with save guarantees and redundant transmission

Only minimal user input

Combining offline and online configuration for TSN networks

Allows for efficient networks in dynamic scenarios

Future work: Heterogenous networks

References

Central Flow Reservation / Check Access:

[1] L. Maile, K.-S. J. Hielscher, and R. German, “Delay-Guaranteeing Admission Control for Time-Sensitive Networking Using the Credit-Based Shaper,” *IEEE Open Journal of the Communications Society*, vol. 3, pp. 1834–1852, 2022, doi: 10.1109/OJCOMS.2022.3212939.

Decentral Flow Reservation / Check Access:

[2] L. Maile, D. Voitlein, A. Grigorjew, K.-S. J. Hielscher, and R. German, “On the Validity of Credit-Based Shaper Delay Guarantees in Decentralized Reservation Protocols,” in *Proceedings of the 31st International Conference on Real-Time Networks and Systems*, in RTNS ’23. New York, NY, USA: Association for Computing Machinery, Jun. 2023, pp. 108–118. doi: 10.1145/3575757.3593644.

Delay Budgets Choice / Offline + Online Optimization

[3] L. Maile, K.-S. J. Hielscher, and R. German, "Combining Static and Dynamic Traffic with Delay Guarantees in Time-Sensitive Networking,” in *Proceedings of the 16th EAI International Conference on Performance Evaluation Methodologies and Tools*, in ValueTools’23. Crete, Grece. Forthcoming.

Redundant Configuration:

[4] L. Maile, D. Voitlein, K.-S. Hielscher, and R. German, “Ensuring Reliable and Predictable Behavior of IEEE 802.1CB Frame Replication and Elimination,” in *ICC 2022 - IEEE International Conference on Communications*, May 2022, pp. 2706–2712. doi: 10.1109/ICC45855.2022.9838905.

Network Calculus / Delay Analysis for TSN:

[5] L. Maile, K.-S. Hielscher, and R. German, “Network Calculus Results for TSN: An Introduction,” in *2020 Information Communication Technologies Conference (ICTC)*, Nanjing, China: IEEE, May 2020, pp. 131–140. doi: 10.1109/ICTC49638.2020.9123308.

(Disjoint) Routing:

[6] P. Navade, L. Maile, and R. German, “Multiple DCLC Routing Algorithms for Ultra-Reliable and Time-Sensitive Applications”, KuVS Fachgespräch - Würzburg Workshop on Modeling, Analysis and Simulation of Next-Generation Communication Networks 2023 (WueWoWAS’23). doi: 10.25972/OPUS-32217.

Delay Analysis for Redundant Transmission:

[7] L. Thomas, A. Mifdaoui, and J.-Y. L. Boudec, “Worst-Case Delay Bounds in Time-Sensitive Networks With Packet Replication and Elimination,” *IEEE/ACM Transactions on Networking*, pp. 1–15, 2022, doi: 10.1109/TNET.2022.3180763.

Friedrich-Alexander-Universität
Technische Fakultät

Thank you!

Questions?
lisa.maile@fau.de